Board 412: Thinking with Mechanical Objects: A Think-Aloud Protocol Study to Understand Students' Learning of Difficult and Abstract Thermodynamic Concepts

Beyza Nur Guler, Virginia Tech

Beyza Nur Guler is a 1st year PhD student in Engineering Education at Virginia Polytechnic Institute and State University, with a background in Structural Engineering. Her research interests include bridging the gap between theory and practice in structural engineering, neurodiversity in engineering, maker-spaces and making difficult & abstract concepts accessible to students by designing appropriate interventions

Mr. Talha Bin Asad, Virginia Tech

I was born and raised in Mandi Bahauddin, a small city whose claim to fame is that it is where Alexander The Great famously fought his last major campaign against Raja Porus.

In 2015, I completed my BS in Mechatronics Engineering from the University of Engineering and Technology, Pakistan, where I worked on designing the electrical and mechanical components of a wireless surveillance robot. My team and I developed and prototyped a fully operational UGV that provided multi-terrain surveillance. Our project presentation garnered a great deal of interest from industrial partners at our Open House.

The following year, I secured a fully funded MS position in the graduate Mechanical Engineering program at Shanghai Jiao Tong University in Shanghai, China. As a Research Assistant in the Robotics and Automation Lab under Professor Zhanhua Xiong, I discovered an aptitude for mechanical design. I utilized this newfound talent to build a one-handed, 6-axical robot joystick controller and validated its design through 3-D printing. I presented my novel design at the IEEE/ASME Advanced Intelligent Mechatronics 2018 Conference in Auckland, New Zealand.

While in Shanghai, I also began to play badminton a bit more seriously. Although I had played badminton competitively before in Pakistan, the quality of the opponents I faced in China honed my ability to a level I had never experienced before. A rather debilitating knee injury slowed down my semi-professional career, but I recovered enough to still win a number of championships and local tournaments.

Its difficult to describe one's entire life in a handful of words, but I've given it my best shot. Onwards and upwards has been my personal mantra throughout my academic and professional career. I now hope to continue my previous research in mechanical design while addressing the biggest problems in Engineering Education. My eventual goal is to address the ever-growing need of a better education system in Pakistan.

Dr. Diana Bairaktarova, Virginia Tech

Dr. Diana Bairaktarova is an Assistant Professor in the Department of Engineering Education at Virginia Tech. Through real-world engineering applications, Dr. Bairaktarovaâ€™s experiential learning research spans from engineering to psychology to learning

WORK IN PROGRESS:
Thinking with mechanical objects: A think-aloud protocol study to understand students' learning of difficult and abstract thermodynamic concepts

Abstract

Since Froebelian time, tangible objects have been used in education to facilitate learning of concrete and abstract phenomena. The efficacy of humanly made artifacts in educational settings are widely studied in art, communications, and more recently in STEM education. Physical objects have proven to promote the understanding of STEM concepts, increase test scores, improve technical communication skills, encourage participation in constructivist learning activities and manage cognitive load for difficult subjects [1] - [9]. In engineering education, the benefits of tangible objects have been predominantly studied in subjects like design. Studies have shown that engagement with mechanical objects improves students' performance on producing assembly instructions, students are more engaged and in-control of their learning helps with transforming their conceptual knowledge into ideas for product design [1].

Engineers are surrounded by physical artifacts throughout their education and work-place environments. Our research project addresses the effectiveness of such interventions for engineering design, problem solving, including conceptual understanding of abstract and difficult concepts. Further, the study explores the relationship of mechanical objects and mechanical engineering students when learning abstract and difficult concepts related to thermodynamics.

In order to identify cognitive processes involved in solving engineering related problems, the current study investigates how students engage in problem- solving and attempt to use mechanical objects. Therefore the research question this study investigates is: *How do interactions with mechanical objects cognitively support solving conceptually difficult problems in thermodynamics?* In this work-in-progress study, we present the initial coding procedure and initial emerging themes.

Methods

This work-in-progress presented study is part of a larger project (mentioned above) that looks at students' mental models when mechanical objects are present in problem-solving activities. These objects are based on the principles of simple machines. Participants (N=160) in the larger study are undergraduate junior students, enrolled in a semester-long thermodynamics class. Prior to the start of the semester, students were asked to complete a concept inventory. During the course, students were provided with 3 conceptually difficult and abstract problems (as identified by the literature): work and heat, psychometric applications, and entropy. The control and experimental group took place in two different sections of the course, taught by the same instructor. While the control group was provided with only the problem description, the experimental group was also given mechanical objects related to the problem at hand. Students' solutions were graded by two mechanical engineering graduate students who were blind to the treatment, and the improvement on student performance on the final exam was assessed. In addition, since the students took the concept inventory at the end of the course as well, the gains in conceptual understanding was also analyzed.

The study presented here invited students from both sections (with objects and without objects) to sit down for a think-aloud session. To ensure that all students have the opportunity to participate in the study, everyone was invited. The researchers also ensure participation from students in the categories of low, average and high performance on the three mentioned above problems. Using a think-aloud protocol, 60 selected participants (30 from the control group and 30 from the experimental group) were observed about how they verbalize their thoughts during the problem-solving activity. Participants from the experimental group were observed on how they attempt to use the mechanical objects if they choose to vocalize verbal labels for the mechanical objects present at the activity.

The data sources of the think-aloud protocols are recordings of audiovisual files and observational notes from the members of each participant session. After the data collection phase, the data was transcribed and coded for emerging typologies of object-use and mental models describing the cognitive processes involved in solving thermodynamics-related engineering problems. Excerpts from problems of the think-aloud study, the objects utilized, and the corresponding topic are summarized in the following table:

Table 1: Excerpts from the problem activities where the think aloud was conducted. The associated objects and the topic is also identified in the table.

Think Aloud Problem Prompt	Difficult Topic	Corresponding Object
"Consider a simple hand operated piston cylinder as shown below where the piston is initially at position one with pressure P1 and volume V1. The piston is then rapidly compressed to position two which is at a pressure and volume of P2 and V2 respectively. Sketch the process on a PV diagram."	• Work & Heat	• Piston (A cylindrical metal component of an engine that moves back and forth)
"Many people that wear glasses will clean their lenses by exhaling a deep breath on their glasses and then wiping the lens with a tissue napkin or clothing. Most people do this somewhat intuitively	• Psychrometric Applications	• Cold and small metal disc

without any significant thought, without the thermodynamics of the process. Briefly explain how this process works in a thermodynamic sense? You might want to consider concepts such as temperature, partial pressure, specific and relative humidity, dew point, condensation, et cetera"		
Rubber is a polymer that consists of long chains of molecules that are weakly crosslinked (i.e. there are weak bonds between adjacent chains). The figure below shows schematic diagrams of rubber when it is (a) relaxed (unstretched), and (b) stretched. *Recall that the entropy change of closed system can be written as* $\Delta S = \int_1^2 \delta Q / T + \sigma$ *, where* σ *is the entropy production. Recall also the "increase of entropy" principle:* $\sigma = \Delta S_{system} + \Delta S_{surroundings} \geq 0$. *A scientist states that since entropy can be thought of as a "measure of the disorder of a system" that when a rubber band is stretched, the entropy of the rubber band (the system) should decrease since the molecules become more ordered. For each of the following, briefly explain your reasoning.*	• Psychrometric Applications	• Plastic rubber band

Data Analysis

The audio transcriptions were coded adapting the method of systematic approach to problem solving framework [10],[11] . This framework presents a flowchart that is specifically developed for addressing thermodynamic problems [11], [12]. The systematic approach to problem solving is derived from the Program of Actions and Methods (PAM), which is based on four principal phases. The codes that support the qualitative analysis could be grouped under four phases. Phase 1 consists of carefully reading the problem, analyzing the data and the unknown by creating a scheme. Phase 2 involves determining if the problem can be solved by routine operations or if it needs to be converted to a standard problem by finding relationships between the data and the unknown. In phase 3, routine operations are executed to solve the problem. Finally, phase 4 involves checking the answer and interpreting the results [13]. Overall, utilizing the framework by Mettes et al (1981) helps with providing a credible baseline for identifying the cognitive processes involved in problem solving. Table 1 provides a summary of the codes utilized in coding the participants' transcripts.

Table 2: A summary table for the codes utilized in coding the transcripts. The different colors in the table indicate the four principal phases; yellow is for phase 1 (analysis of the problem) , green is for phase 2 (transformation of the problem), blue is for phase 3 (execution of routine operations) and red is for phase 4 (answer checking and interpretation of the results).

Code	**Code Definition**
Read	Student (re)reads problem statement
Make a Scheme	**1-** Student draws a model, figure, graph **2-** Student identifies known variables & values **3-** Student notes/describes unknowns **4 -** Student notes any constraints, limitations they know/ can think of **5 -** Student maps known and unknown values to a model/formula **6 -** Student recognizes pattern in the way the problem is solved, noting this problem is similar to others they've done before **7-** Student recognizes format/theme, noting this problem is similar to others they've done before **8-** Student invokes a law/principle, identifies law- like principles involved **9 -** Student makes an estimation for the answer
Determine a Standard Problem	Student determines whether typical formulas, etc can be used or if adjustments need to be made
Key Relations	**1 -** Student statement reflects conclusions made through logic or mentions relationship between factors (identification of key relations) **2 -** Student identifies equations/formulas needed to solved problem (identification of key equations) **3-** Student identifies criteria about the solution format (e.g. units needed, magnitude, etc)
Check Relations	Student validates their approach based on relations
Conversion to Standard Problem	**1-** Student converts non-typical problem to standard problem using fundamental relationships to generate usable equations **2-** Student converts non-typical problem to standard problem by algebraically editing formulas/ equations to format needed to find unknown **3-** Student sets up equation by plugging in specific values
If not Solvable	**1-** Student's first attempt is inconclusive and they check relationships between factors

	2- Student's first attempt is inconclusive and they back track to try something else (alternate problem solving procedures)
Solve	Student does mathematical calculation and calculates answers
Check for Mistakes	**1-** Student checks for errors related to sign, magnitude, dimension **2-** Student checks for errors related to model **3-** Student checks for errors related to their estimation **4-** Student checks for errors related to their understanding of factors' relationship to one another **5-** Student checks for errors related to mathematical calculation

Preliminary Findings

The preliminary findings of the study include 10 emergent codes, as summarized in the following table:

Table 3: A summary table of emerged codes from the think aloud study, associated definitions and example excerpts from student transcripts

Code	Code Definitions	Example Excerpt
"I don't know"	*in vivo* code; student acknowledges they don't know how to solve the problem by using the phrase "I don't know"	*"I don't know, I guess. ... Yeah, I don't know."*
Changing Answer from Survey	Student tells interviewer that although they solved the problem one way on paper in class, they have a different idea of how to solve it now and report their new thinking	*"okay, nevermind. Can I change this?"*
Experiences	1- Student comments on experiences with object in current class 2- Student comments on experiences with object in current class, with prompting (e.g., researcher follow-up question) 3- Student comments on experiences with Object in current class; without prompting 4- Student mentions personal life experiences that relate to the problem solving activity in class and/or an experience that helped them solve the problem	*"I think having it [the object] in front of me ... When you could feel the compression of the air, because I ... It resists, so when you could feel that it kinds of make you think, "Okay, yeah. There's more pressure." Then you can see. You can see at the beginning there's a lot of space for the air."*
Guessing	Student indicates that what they're explaining is a guess	*"I guess minutely the temperature would increase, even because it's compressed, but I feel like it would be negligible, so I would say equal to. Then, when it's done very slowly the temperature ... I guess it would be the same"*

Inability to Check for Mistakes	Student notes that due to the problem's abstraction (all algebra, no values), they can't check to see if their final answer makes sense numerically	*"If there were more calculations, than I would know for sure what my answers were, I guess, but - or feel more sure about them, but I kinda ... 'Cause it's kinda more, it feels more abstract without the calculations, which I guess I could've probably figures out a way to calculate it somehow, but ..."*
Interactions with Peers	Student's presence in classroom with peers impacts their problem solving decisions	*"So, this is the point where you're in a classroom and it's crowded and everyone else is believing when you say it's less than, and you move on (laughing) but let's see so."*
Realizing Mistakes	Student changes course in their problem solving, acknowledging they made a mistake previously	*"okay, so this is when we unravel the assumptions I made (laughing)."*

Conclusion

This work in progress paper is about understanding how mechanical objects cognitively support students in a thermodynamics class. Think aloud sessions are conducted in the presence and absence of mechanical objects and coded via the systematic approach to problem solving framework where emergent codes are identified. Currently, a different researcher is coding the transcripts to see if there will be any alignment with previous emergent codes that are identified. This will also help with the study's inter-rater reliability.

Acknowledgement

This material is based upon work supported by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

[1] Bairaktarova, D., Graziano, W., & Cox, M. (2017). Enhancing Engineering Students' Performance on Design Task: The Box of Parts. *Journal of Mechanical Design*, *139*(5), 052001.

[2] Davis, C., Younes, R., & Bairaktarova, D. (2019). *Lab in a Box: Redesigning an Electrical Circuits Course by Utilizing Pedagogies of Engagement*.

[3] França, V. C. P. L. A. de, & Campos, W. F. (2021). Interactive Metabolism, a simple and robust active learning tool that improves the biochemistry knowledge of undergraduate students. *Advances in Physiology Education*, *45*(2), 353–364.

[4] Khan, A. I. (2022). *Effectiveness of Hands-on Desktop Learning Modules to Improve Student Learning in Fluid Mechanics and Heat Transfer across Institutions and Program Types*.

[5] Justo, E., Delgado, A., Llorente‐Cejudo, C., Aguilar, R., & Cabero‐Almenara, J. (2022). The effectiveness of physical and virtual manipulatives on learning and motivation in structural engineering. *Journal of Engineering Education*, *111*(4), 813–851.

[6] Liu, Y.-C., Lu, S.-J., Kao, C.-Y., Chung, L., & Tan, K. H. (2019). Comparison of AR and physical experiential learning environment in supporting product innovation. *International Journal of Engineering Business Management*, *11*, 184797901983957.

[7] Nolen, S. B., & Koretsky, M. D. (2018). Affordances of Virtual and Physical Laboratory Projects for Instructional Design: Impacts on Student Engagement. *IEEE Transactions on Education*, *61*(3), 226–233.

[8] Nottis, K. E. K., Vigeant, M. A., Prince, M. J., Golightly, A. F., & Gadoury, C. M. (2019). COMPUTER SIMULATIONS VERSUS PHYSICAL EXPERIMENTS: A GENDER COMPARISON OF IMPLEMENTATION METHODS FOR INQUIRY-BASED HEAT TRANSFER ACTIVITIES. *Chemical Engineering Education*, *53*(4).

[9] Self, B., Widmann, J., & Adam, G. (2016). Increasing Conceptual Understanding and Student Motivation in Undergraduate Dynamics Using Inquiry-Based Learning Activities. *2016 ASEE Annual Conference & Exposition Proceedings*, 25668.

[10] C. T. C. W. Mettes, A. Pilot, H. J. Roossink, and H. Kramers-Pals, "Teaching and learning problem solving in science: Part II: Learning problem solving in a thermodynamics course," *Journal of Chemical Education*, vol. 58, no. 1, p. 51, Jan. 1981

[11] Taraban, R., Anderson, E., Craig, C., Fleming, J., DeFinis, A., & Brown, A. G. (2008, June). An assessment of problem solving processes in undergraduate statics. In *2008 Annual Conference & Exposition* (pp. 13-175).

[12] P. C. Wankat and F. S. Oreovicz, *Teaching engineering*. West Lafayette, Indiana: Purdue University Press, 2015.

[13] C. T. C. W. Mettes, A. Pilot, H. J. Roossink, and H. Kramers-Pals, “Teaching and learning problem solving in science. Part I: A general strategy,” *Journal of Chemical Education*, vol. 57, no. 12, p. 882, Dec. 1980