Student and expert conceptions of the word "efficiency"

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***Abstract*—Spoken and written language plays an important role in communicating ideas about engineering from instructors to students. Researchers in other disciplines have examined the barriers that differences between everyday and technical language can create to student understanding, but little, if any, such work has been done in engineering. In this study, we examine how students and experts in chemical engineering define and use the word efficiency to determine if this term might lead to misunderstandings or misconceptions. We find that experts consistently define efficiency in terms of inputs and outputs of a chemical process. Students, however, initially think of efficiency as completing a task or producing a product in the least amount of time possible – a definition that is sometimes at odds with experts' technical definitions. However, we see that students use the expert definition of efficiency when analyzing a process flow diagram. The results of this study highlight the need for instructors to be clear when using ambiguous technical language in the classroom.**

***Index Terms*—semantics, chemical engineering**

I. Introduction

Educational researchers have long been interested in the role of spoken and written language in science and engineering. Scientists and engineers use written language to represent their ideas and communicate those ideas to students, peers, and the public. Researchers in science education have documented how language can create barriers to student learning. In physics, commonly used terms have both technical and everyday definitions (e.g. force, acceleration, power), leading to student misconceptions about these ideas [1]–[13]. In biology and medicine, excess jargon introduces excess cognitive load in the classroom and interferes with student learning [14], [15]. We could find no studies in engineering education looking at the use of language in the classroom and how it might create barriers to student learning. This study represents a first step in critically examining the role of language in engineering classrooms.

In a previous study of student problem-solving, we found that students would frequently use "efficiency" as a criterion for evaluating how well a chemical process is functioning [16]. However, students would not define what efficiency meant, and would use it in inconsistent ways (e.g. saying that the process should be "environmentally efficient"). This inconsistent use of the word efficiency motivated us to study how students and experts define and use the term in both every day and technical contexts. Our research questions were:

1) How do students and experts define and use the word "efficiency" in different contexts?
2) Do students at different stages of their education exhibit different understandings of efficiency?
3) Do students exhibit misconceptions about efficiency?

Though our research questions are limited to one particular term, the results can provide insight into how language might create barriers to student learning in the engineering classroom. We hope this will motivate other researchers to examine the use of technical language (e.g. power, strain, stress, waste) and that greater awareness will motivate educators to be more aware of how they use language when communicating with students.

II. Theoretical Framework

Reddy presents a framework for communication called the "toolmaker's paradigm" [17]. He suggests that people construct meaning from messages they receive based on their prior knowledge, experience, and the resources available to them. This implies that the message itself is meaningless. The sender and recipient need to construct the meaning using a commonly understood set of signals and meanings. This establishes communication as an effortful act. Miscommunications and multiple interpretations of text are thus inherent in the system of communication.

One such example of potential miscommunications is what Ullmann [18] calls a "semantic pathology." A semantic pathology arises whenever the same text can have two different, incompatible meanings while used in the same context. For example, the phrase "I'm sorry" can either be an expression of empathy, or admitting fault. Both definitions might be used in the same context – when something bad has happened to another person (for which you may or may not be at fault) – but express fundamentally different sentiments. Thus, the recipient of a signal might construct a meaning different from that intended by the sender.

This framework suggests that meaning cannot be directly conveyed from one person to another (e.g. teacher to student) through text. The teacher needs to help the student construct their intended meaning by elaborating on the set of shared meanings they have already developed. Students can use these shared meanings to decode the new words presented to them. Brookes & Etkina provide a useful example [19]. When a physicist says that an electron is in the ground state, she means that the electron has a particular energy. If students do not have the same shared meanings as the physicist, they may interpret state as a spatial characteristic rather than something related to energy. This would be a misconception on the students' part, and the word "state" would thus be an example of a semantic pathology.

III. Methods

We took a phenomenological approach to answering our research questions. This approach was appropriate given the exploratory nature of this work and the lack of previous investigations of the use of language in engineering. We developed an interview protocol to probe participants' definitions of the word efficiency in different contexts. The protocol was designed based on the research questions listed above, and based on the protocol used in Ioannides & Vosniadou [7]; the full protocol is in Tab. I. We first asked participants about their general impressions of the word efficiency and how they would describe it to a child. We asked this before collecting information about the participants' technical backgrounds so as not to influence their initial definitions. We then asked participants how they would define efficiency in an engineering context, and whether they thought the definition might vary by engineering discipline. Finally we showed participants a process flow diagram and then asked them how they would evaluate the diagram, and whether there was enough information to determine whether the design is efficient. We concluded the interview by asking whether participants thought there were different kinds of efficiency. The interview protocol was reviewed by three experts in educational research, two of whom had studied semantics in physics.

We recruited participants from chemical engineering programs at two highly selective research universities in the United States; one a private, east-coast university and the other a public, west-coast university. We invited students to participate in a study of how engineering students think about the word "efficiency," and participants were compensated $25 for 30 minutes of their time. In total, 13 first-year students (in the first three weeks of their first engineering course), 16 senior students (in the first three weeks of their capstone lab and design courses), and 18 PhD students at various stages in their degrees responded and participated in the study. In addition, we asked three professors of practice at these universities to be interviewed to provide an "expert" perspective we could use for comparison.

The interviews were divided into three sections: how participants initially defined efficiency, how they defined efficiency in an engineering context, and how they applied the definition of efficiency to analyzing the process flow diagram we presented them. We found that the ontology of the word efficiency was consistent across interview sections and participants. All participants defined efficiency as a process characteristic: optimizing the outputs of some process with respect to the inputs of the process. This applied to processes from their everyday experiences (e.g. completing homework assignments in the minimal amount of time), as well as in engineering contexts (maximizing the production of a chemical product from the given amount of input material).

According to this ontology, we thus coded each section of the interview for the various process outputs and inputs that participants identified. We identified 11 unique inputs and 6 unique outputs that participants identified across the three interview sections, which we have listed in Table 2. We then calculated the frequency of occurrence of each input and output code among the four groups: first-year students, senior students, PhD students, and experts.

IV. Results

In Fig. 2, we plot the frequency of occurrence for each input and output code among each of the four groups of participants when initially defining the word efficiency. We find that experts unanimously define efficiency to be maximizing the amount of desired product produced compared with the amount of starting material, energy, money, and number of steps input into the process. Experts also mentioned minimizing the amount of waste produced as a byproduct.

> "It means high throughput and high yield. . . . I also mean minimal waste, which isn't the same thing. . . I get a fair amount of product per either space or time or energy put into it."

In addition to this technical definition, approximately 66% of the experts also defined efficiency as completing tasks in the least amount of time.

> "Let's say I have a certain person doing some work and it should take him about 30 minutes work, and all of a sudden, it takes him 35 minutes. You know something's not. . . he's not being very effective."

The vast majority of students (60-70%) defined efficiency only as completing a certain task as fast as possible. Approximately 20% of students also considered the resources or effort put into completing that task,

> "...trying to do the least amount of work possible and like achieve the same results. Like, that's the best way I can put it, like 'm working to achieve a result with less time, less resources."

but less than 15% of students provided a technical definition of efficiency similar to the one that experts produced.

When asked to define efficiency in an engineering context, students' responses shifted considerably (see Fig. 3). Only 30% of students still defined efficiency as completing a desired task in the shortest amount of time, while 40-50% of students defined efficiency as producing some desired product in the least amount of time possible.

> "I just think the most efficient way to do that is, like, it takes the least amount of time to get the most amount of product out of it."

Time was the most commonly considered input, though some considered the amount of starting material and energy required to produce a product.

> ". . . there's also the material sense of efficiency. . . "

TABLE I
INTERVIEW PROTOCOL

Question	Follow-up Question
1. Can you explain to me what you think of when you heard the word efficiency?	
2. How can you explain efficiency to a six-year old?	
3. What do you think the word efficiency means to an engineer or in an engineering context?	
4. Is this the same meaning as your fellow engineering students would have?	a. Do you think this interpreted differently for different fields of engineering?
5. Here is a chemical process block flow diagram based on some chemical pyrolysis reactions (see Fig. 1). What criteria would you use to evaluate this design?	
6. Do you have all the information you need to assess whether or not this design is efficient?	a. What information would you need to assess whether or not this design is efficient and why? b. How would you use that information to evaluate the design's efficiency?
7. What features of this design make it efficient? Which features of this design make it inefficient? Labor	
8. What would be the characteristics of an efficient chemical process?	
9. Are there different types of efficiency? If so, what are they?	

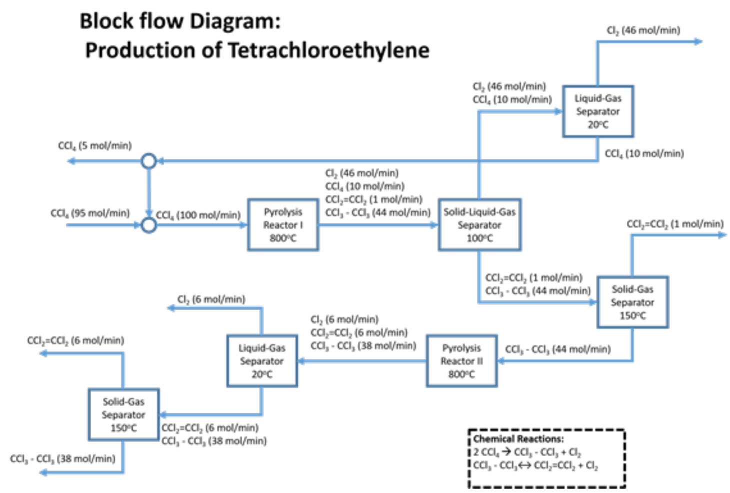

Fig. 1. Diagram given to subjects.

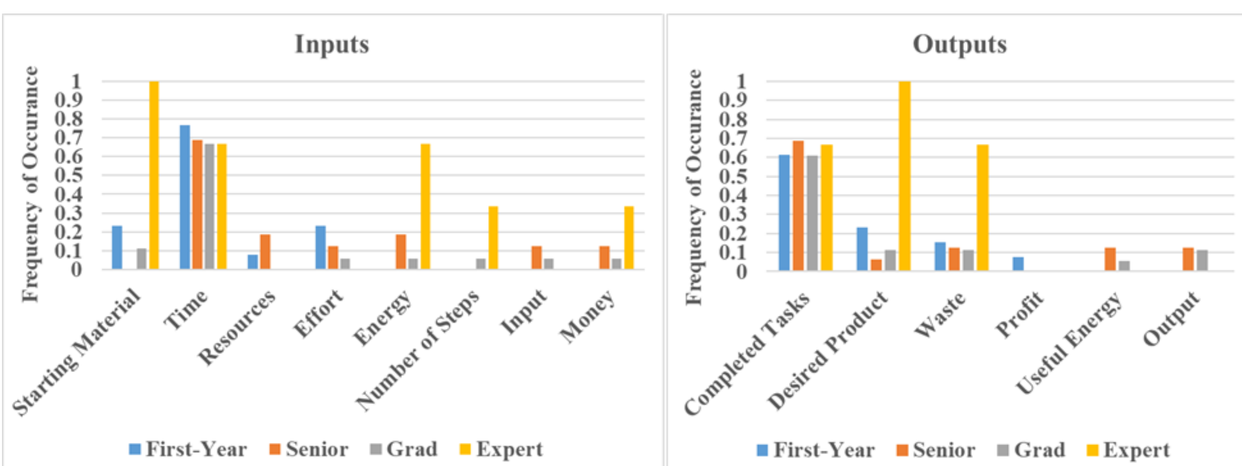

Fig. 2. Frequency of each input (left) and output (right) mentioned by participants when first defining the word efficiency.

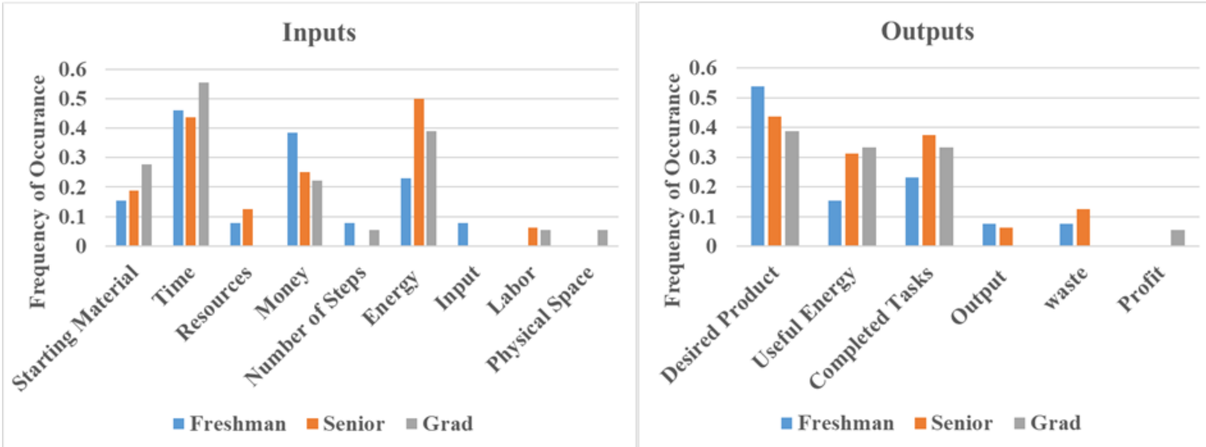

Fig. 3. Frequency of each input (left) and output (right) mentioned by participants when defining efficiency in an engineering context. Note that experts were committed from this graph because they gave engineering definitions of efficiency when first asked.

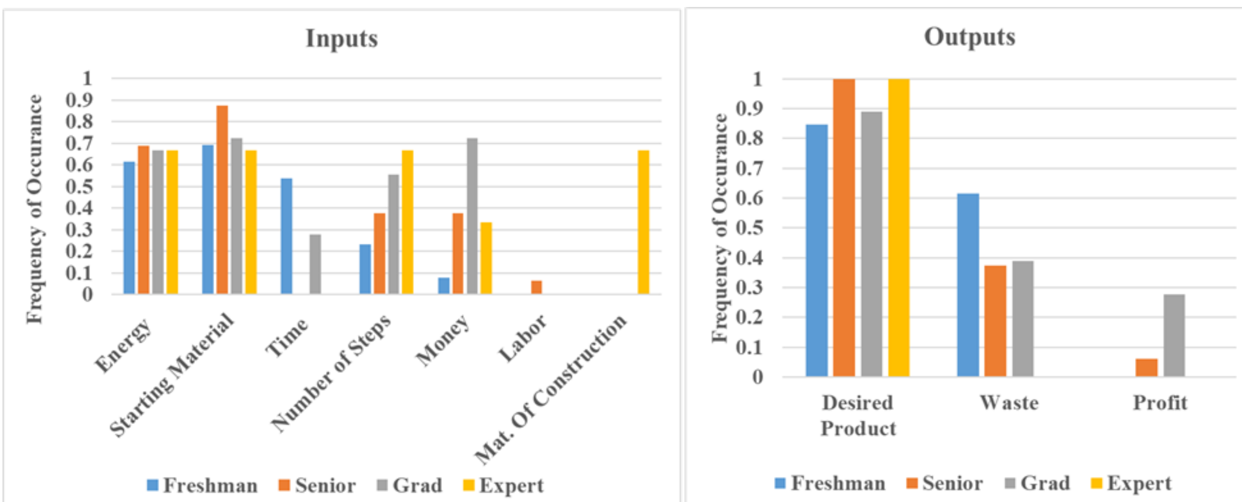

Fig. 4. Frequency of each input (left) and output (right) mentioned by participants when assessing the efficiency of a process flow diagram.

TABLE II

COMPLETE LIST OF INPUT AND OUTPUT CODES IDENTIFIED IN THE INTERVIEW DATA.

Inputs	**Outputs**
Time	Completed Tasks or Results
Resources	Desired Product
Effort	Waste
"Inputs"	"Outputs"
Starting Material	Profit
Energy	Useful Energy
Money	
Labor	
Number of steps	
Physical space	
Materials of construction	

In addition, approximately 20-30% of students gave a textbook thermodynamic definition of efficiency: the useful energy produced by a process compared with the amount of energy put into the process.

"Work out over work in, I think. Yeah."

We do not have expert data in Fig. 3 as experts responses in the first interview section already contained their definition of efficiency in an engineering context. We note, however, that some experts cited pump efficiency and fuel efficiency as specific instances of efficiency used in engineering.

In Fig. 4 we plot the frequency of inputs and outputs coded when participants were asked to assess the efficiency of a process flow diagram given to them. Again, experts said that efficiency was defined as maximizing the production of desired product, while minimizing the amount of starting material, energy, steps, money, and materials of construction input into the process. Unlike the previous sections of the interview, we see substantially more agreement between students and experts. Approximately 85-100% of students used efficiency to mean maximizing the amount of desired product while minimizing the amount of energy and starting material put into the process. A non-zero fraction of students still retained the idea of time, saying the process should happen as fast as possible, and some students also considered the number of steps in the process and the money put into the process as important variables. Some students also said that the amount of waste produced should be minimized, and the profit produced should be maximized.

V. Discussion

Our initial finding that the ontology of the word efficiency is consistent across contexts and participants is noteworthy. Though there are many varied specific definitions of efficiency, the basic definition of maximizing process outputs with respect to process inputs remains the same. This is different from investigations in physics education, which have largely centered on words like “force,” in which researchers found that scientists’ use of conceptual and grammatical metaphor resulted in many different definitions of scientific terms among students [19], [20]. These varying definitions have been linked to student misconceptions [20]; it thus seems unlikely that students would develop misconceptions about the word efficiency.

Experts’ definitions of efficiency were consistent across contexts, and consistent with what we expected based on disciplinary conventions of chemical engineering. They defined efficiency as maximizing desired products and minimizing waste, while minimizing the amount of material, energy, and money used in the process. Students’ definitions of efficiency, however, changed depending on the context. Students’ initial definitions of efficiency seem to be rooted in their everyday experiences: completing tasks as fast as possible (sometimes considering the effort required). Indeed, students cling to the idea that efficiency is doing something or producing something in as little time as possible when asked about efficiency in an engineering context. Curiously, students actually apply the idea of efficiency to a chemical process in the same way that experts do. It may be that the static representation of a process flow diagram discourages students from thinking about how long it takes to produce something, and more about the materials that are put into and out of the process.

Concerning our second research question, it is notable that students were consistent in how they defined efficiency in different contexts across cohorts. This suggests that a more nuanced and technical definition of efficiency comes with experience in industry, rather than from formal education. Indeed, it is notable that even the first year students with essentially no engineering knowledge were able to come up with a mostly correct definition of efficiency when analyzing a process flow diagram. This indicates that efficiency may be a relatively intuitive idea, though one that needs to be carefully defined and contextualized.

Students’ shifting definitions of the word efficiency and the difference between students and experts constitute a semantic pathology. Efficiency can have multiple different meanings in the same context which may be in conflict with one another. For example, the fastest way to produce something is often the most energy and resource intensive, so minimizing time as an input would be at odds with minimizing energy and starting materials. Based on Reddy’s toolmaker’s paradigm, such a semantic pathology could easily lead to misunderstandings between students and instructors when describing a process as “efficient.” These results suggest that instructors need to be very precise and clear when using the word efficiency. They should define which outputs are being maximized or minimized, and the inputs this optimization is occurring with respect to. This is already done in textbooks when defining ideas like engine efficiency or pump efficiency, but could easily be overlooked when interacting with students in the classroom. Indeed, one of the experts who participated in this study was motivated to incorporate a lecture on “efficiency” into their process design course.

While we only studied a single technical term here, there are many others which may cause barriers to student understanding in the classroom. “Stress” and “strain” are words which have everyday and technical definitions that differ – research from physics suggests that this will lead to misconceptions. Other technical terms have multiple different contexts in which they can be defined (much like the word efficiency) and thus care is needed to make sure that the proper meaning is conveyed. Such terms include “waste,” or “safety” – for example, one could consider process safety, consumer safety, food safety, personal safety, and many other types of safety.

VI. Conclusions

This work represents the first study, to our knowledge, of the role of semantics in chemical engineering education. Nonmathematical language plays an important role in communication between engineers, students, instructors, and clients, and thus deserves more attention in the research literature. In this particular study, we identified a term with many differing definitions, but all the definitions fit into the same ontological category, so we did not observe any misconceptions. However, we still identified the potential for misunderstandings between students and instructors, or even engineers and clients, when using the word efficiency. In the future, we will investigate students’ use of language in the classroom environment to determine if these differences in interpreting ambiguous language actually inhibit student learning.

We hope this work motivates other researchers to examine the use of technical language in the engineering classroom. For example, the words “stress” and “strain” have both precise technical and everyday definitions, which indicates there may be the potential for student misconceptions. We also hope that educators will be more aware of how they use language in the classroom. This study suggests that technical terms with ambiguous definitions need careful attention so that instructors can help students construct the discipline-appropriate meanings they are trying to convey.

Future work should address links between this ambiguous language and problems with student learning, but this study clearly demonstrates the potential for problems in the classroom. Indeed, in other disciplines instructors have found that ambiguity in technical language can interfere with students’ conceptual understanding of a subject, as can excessive use of technical jargon. Instructors should be aware of this issue and ensure that their students are correctly interpreting the material they are trying to convey.

References

[1] I. A. Halloun & D. Hestenes, ”Common sense concepts and motion.” American Journal of Physics, vol 53, pp. 20156, 1985.

[2] L. C. McDermott, ”Research on conceptual understanding in mechanics.” Physics Today, vol 37(7), pp. 24, 1984.

[3] M. Finegold & P. Gorsky, ”Students’ concepts of force as applied to related physical systems: A search for consistency.” International Journal of Science Education, vol 13, pp 97, 1991.

[4] L. Lebourtet-Barrell, ”Concepts of mechanics among young people.” Physics Education, vol 11, pp. 462, 1976.

[5] I. Galili & V. Bar, ”Motion implies force: where to expect vestiges of the misconception?” International Journal of Science Education, vol 14, pp. 63, 1992.

[6] J. B. Gerhart, ”Physics students: a mirror for physics history.” AAPT Announcer, vol 19, pp. 54, 1989.

[7] C. Ionnides & S. Vosniadou, ”The changing meanings of force.” Cognitive Science Quarterly, vol. 2, pp. 5, 2002.

[8] D. G. Schuster, in Proceedings of the International Seminar on Misconceptions in Science and Mathematics, ed.s H. Helm & J. D. Novak, Cornell University, Ithaca, NY, 1983, pp. 253-257.

[9] L. Viennot, ”Spontaneous reasoning in elementary dynamics.” European Journal of Science Education, vol. 1, pp. 205, 1979.

[10] D. M. Watts & A Zylberstajn, ”A survey of some children’s ideas about force.” Physics Education, vol. 16, pp. 360, 1981.

[11] D. E. Brown, ”Students’ concept of force: the importance of understanding Newton’s third law.” Physics Education, vol. 24, pp. 353, 1989.

[12] D. F. Styer, ”The word ’force’.” American Journal of Physics, vol 69, pp. 631, 2001.

[13] H. T. Williams, ”Semantics in teaching introductory physics.” American Journal of Physics, vol. 67, pp. 670, 1999.

[14] J. M. Zukswert, M. K. Barker, & L. McDonnell, ”Identifying troublesome jargon in biology: Discrepancies between student performance and perceived understanding.” CBE Life Science Education, vol. 18, 2019.

[15] B. O. Wong, B. A. Jacob, J. N. Batten, B. E. Turner, J. N. Lai, P. Hosamani, W. F. Hanks, & D. Magnus, ”Recognizing the role of language in the hidden curriculum of undergraduate medical education: Implications for equity in medical training.” Academic Medicine, 2020.

[16] E. W. Burkholder, L. Y. Hwang, & C. E. Wieman, ”Supporting problem-solving through a cornerstone design course in chemical engineering.” Chemical Engineering Education, 55(3) 2021.

[17] M. J. Reddy, ”The conduit metaphor: A case of frame conflict in our language about language.” in Metaphor and Thought, ed. A. Ortonoy, pp. 284-310, Cambridge: Cambridge University Press, 1979.

[18] S. Ullmann, Semantics: An introduction to the Science of Meaning, Basil Blackwell, 1957.

[19] 19. D. T. Brookes and E. Etkina, Using conceptual metaphor and functional grammar to explore how language used in physics affects student learning, Phys. Rev. Phys. Educ. Res. 3, 010105 (2007).

[20] 20. D. T. Brookes and E. Etkina, “Force,” ontology and language, Phys. Rev. Phys. Educ. Res. 5, 010110 (2009).