Exploring Differences in Senior and Sophomore Engineering Students' Mental Models of Common Products

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Exploring Differences in Senior and Sophomore Engineering Students' Mental Models of Common Products

Abstract

One might think that as students progress through an undergraduate engineering curriculum, their understanding of a system's inputs and outputs, component structure, and functional requirements would become more complete. This paper investigates the differences in sophomore and senior engineering students' mental models. Students who took part in this study were enrolled in either a sophomore-level engineering design course or a senior-level systems analysis course. This multi-part study involved an in-class activity to elicit the students' mental models of common household products and semi-structured interviews with students. Analysis of the completed in-class activity indicated no statistically significant difference between the sophomores' and seniors' mental model scores, so semi-structured interviews were conducted to gain clarity on the lack of difference. An affinity sort of the data revealed that some students may have relied on their understanding of functional modeling to complete the in-class activity, while others may have focused on component-based knowledge of the household products. Results of this study will be used to further improve the mental model instruments and the instrument deployment procedure.

1. Introduction

Consider the following skills being requested of new engineering graduates to be prepared to join the 21st century engineering workforce: adaptability, complex communication and social skills, self-management and self-development, and systems thinking [1]. For engineers, mental models serve a crucial role in systems thinking [2] as the cognitive interpretations of the universe and the organization, perception, and structure of knowledge [3]. Mental models allow one to be adaptable and to self-manage as they provide a framework for estimating the systems and systems of systems that engineers often find themselves working within. Assessing students' mental models of engineered systems and how those mental models of engineered systems changes over time may provide crucial insight into how to foster students' systems thinking abilities such that students may be bettered prepared to enter the 21st century workforce.

Herein, the results of a study exploring undergraduate engineering students' mental models of common, household engineered products are presented and discussed. Results come from two student populations, sophomores and seniors, both attending the same engineering undergraduate program at a medium (~20,000 students) public mid-Atlantic, liberal-arts research university. Through the comparison of sophomores to seniors, the authors look to explore how students' mental models develop over the course of an undergraduate engineering degree.

The study involved the completion of an in-class activity that elicits mental models of common household devices. The instruments prompt students to fill in components and the connections between those components to demonstrate their knowledge of the inner-workings of the household devices. This study is based on previous works [4-6] that investigated how mental models of functional relationships are expressed. Following analysis of the completed in-class instruments, students voluntarily participated in semi-structured interviews to help the research team understand the results. As the in-class portion of the study informed the semi-structured interviews, the in-class portion and the semi-structured interviews are presented as two studies herein: *Section 3: Initial Study: Mental Model In-Class Activity* and *Section 4: Follow-up Study: Semi-Structured Interviews*. These studies are followed by a discussion, which explores connections between the initial study and the follow-up study. The discussion also provides further exploration of the in-class activity results through affinity sorting to gain clarity into how the students may have interpreted the in-class activity.

Ultimately, this work is a first step to both eliciting student mental models and understanding how mental models change over the course of an engineering curriculum. Results from this work will inform future iterations of the methodology and mental model instrument. This work could affect how mental models are studied because mental models are cognitive and unobservable by external entities [7], or notoriously difficult to represent, and the results presented herein suggest successful elicitation of students' mental models with recommendations for future improvement.

2. Background

Through the 1980s and 1990s, [8-11] Johnson-Laird describes the underpinnings of cognition with his mental model theory in which, "propositional representations are interpreted with respect to mental models" [12]. Mental model theory describes mental model formation as being comprised of three phases: introduction and incorporation of an idea into the grander image of existence, attempt to falsify the original idea through counter-argument, and acceptance or rejection of the idea [13]. Mental models are a cognitive "tool" that allows a person to take external data and internalize it; through the process, one transforms their presumptions of the external data into mental models to explain phenomena [14].

Mental models may change over time. For example, Vosniadou's framework theory allows for two possible methods of alteration to mental models: revision and enrichment [6]. *Revision* strikes out parts of mental models which have been definitively proven false; whereas, *enrichment* appends the new information onto the preexisting mental model. Enrichment, which is the preferred mode of altering mental models [6], allows a person to meander down false paths of misconceptions.

Mental models have since been studied in various fields including physics [15], psychology [4], and engineering [16]. This work is focused on mental models in the field of engineering and design, where mental models have been specifically defined as an "understanding [of] the casual relations among several elements in a physical system" [14]. In this regard, engineering students' mental models of common systems should not only include the component architecture, but also include connections between those components, system inputs and outputs, and the flow of energy, material, and information through the system.

The study presented herein is heavily influenced by Lawson's bicycle drawing activity [4] and Nelson's et al. hairdryer drawing activity [5]. Lawson took psychology students, uninformed about the purpose of the study and had the students draw bicycles. She then evaluated the drawings for functionality. She repeated this experiment with both psychology students, informed that they were being scored on the functionality of their drawings, and bicycle experts, who were uninformed of the study's purpose, for a total of three groups. Each group possessed numerous errors in their bicycle drawings. While Lawson had participants draw the entire bicycle, Nelson et al. provided outlines that simply needed to be filled in with components.

Nelson et al. were studying how mental models are used in systems thinking. Students participating in the study drew and labeled the components of a hairdryer and a car radiator, which were selected because of their functional similarities. Their results showed that students performed significantly better on the hairdryer than on the car radiator, but that students did not make the expected analogous leaps between the two systems [5].

The study presented herein follows Nelson et al.'s methodology more closely than Lawson's methodology by having the participants draw components of each common household product inside outlines of those products – one of which being the same hair dryer model used by Nelson et al [5].

3. Population Background

All students who participated in the initial and follow-up studies attend a medium-sized, mid-Atlantic, liberal arts university (~22,000 students). While the University offers masters and doctorial degrees, the University is classified as primarily undergraduate. The study focused on students in the undergraduate-only engineering program at this University. The ABET-accredited engineering program offers a single degree Bachelor of Science with an emphasis on engineering design, systems analysis, and sustainable decision making. Students enrolled in the study were engineering undergraduates at either the sophomore or senior level by course work (i.e., students may have enough credits at the sophomore level to be classified as juniors or seniors, but have not completed the pre-requisite course work for senior classification in their academic program of study).

The background of the sophomore engineering students would be the completion of some pre-requisite mathematics and science requirements as well as completion of an introduction to engineering course that covers the application of human-centered design principles, agile management principles, and engineering design tools for engineering decision making as well as introductory CAD and MatLab. Sophomores who enrolled in these studies were completing their first formal engineering design course and would have completed modules covering design teaming, interviewing, listening, ethics, design objectives, constraints, and functional modeling.

The senior engineering students who participated in these studies would have completed nearly all of their engineering course work which includes: statics and dynamics, circuits and instrumentation, two courses in thermo-fluids, mechanics and materials, two courses in engineering management, and thus far, four courses in engineering design. Students would be enrolled in their first sustainability course, their fifth engineering design course, and a systems analysis course. Students would have been exposed and practiced skills requiring benchmarking and reverse engineering of multiple engineered systems, and they would have seen principles of functional and process modeling as well as systems modeling techniques such as free-body diagrams, circuit diagrams, mass-flow diagrams, and control block diagrams — all skills that we presume based on [14] would allow students to take external data, internalize it, and develop an understanding of the interconnected elements of a physical engineered system.

4. Initial Study: Mental Model In-Class Activity

4.1. Initial Study: Methodology

Students were recruited to participate in the initial study via presentations about the purpose of the study in their respective classes. A member of the research team presented and proctored the mental model activity to the potential participants. Upon recruitment of participants, participants were told that the study would require approximately 30 minutes of their time. All participants were at least 18 years of age. Student names were not recorded. Students not providing consent were allowed to excuse themselves from class during the study. This research was conducted in a normal engineering classroom setting.

Students were provided with outlines of four common household instruments: a hair dryer (HD), a clothes dryer (CD), a vacuum (VAC), and a leaf blower (LB) in that order. These instruments were adjusted from the research team's previous work [5] where only a hair dryer (HD) and car radiator (RAD) were used. Students were asked to add and label the key components that allow the system to complete its primary function, such as the example in Figure 1. Each instrument was accompanied by two binary questions asking if they had ever seen someone use the device and if they had ever used the device.

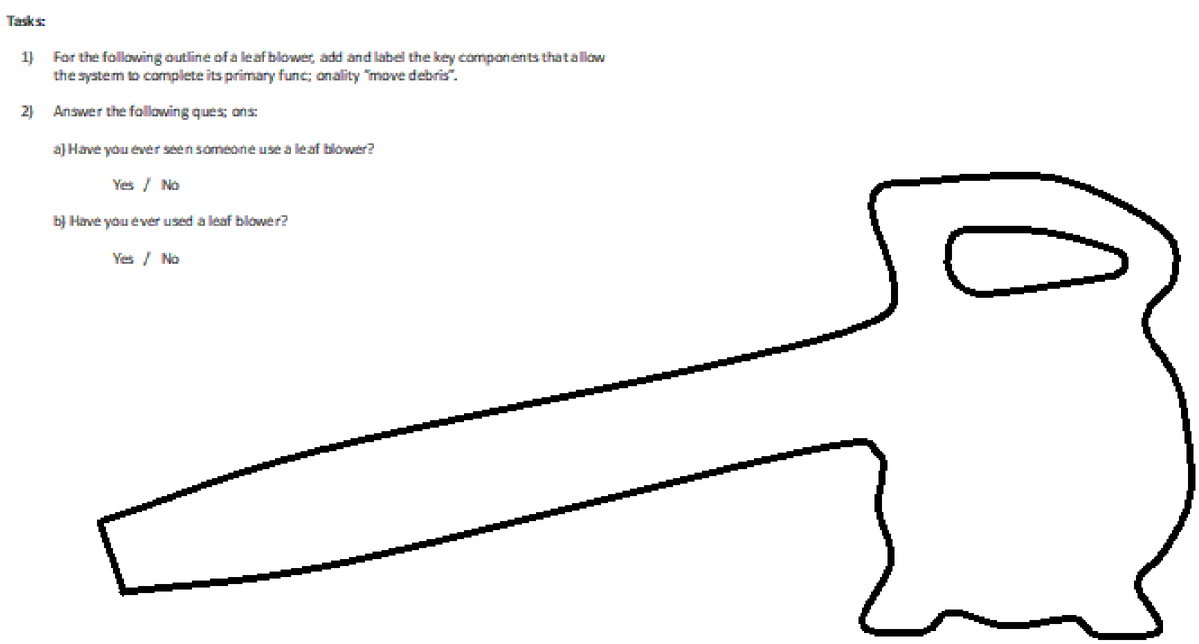

Figure 1. The leaf blower mental model instrument that students were asked to complete.

All participants completed the exercise during the allotted time of 30 minutes. The data was then analyzed, comparing the students' responses to an expert-generated solution such as the ones generated in [2]. This was done by assessing whether the student response matched the expert response for each component given. An abbreviated version of the HD rubric is provided in the appendix as Table A.1. The solutions were also evaluated on a function basis in which all the ways a student satisfied a function were noted and were scored on criteria adapted from a previously published and revised functional modeling rubric [2], [5], [17] respectively. The mental model instruments were scored on several criteria as either 0, 0.5, or 1 based on the level of completeness. A sample size of convenience, 15 seniors and 15 sophomores, was evaluated out of populations of 60 and 78 respectively. To randomize the selection of students, the first 15 alphanumerically were selected from their encoded identifier. The identifier was created by the student based on the first two letters of their mother's first name, the last three digits of their home zip code, the last two letters of their father's first name, and the first two letters of their birth city. No record was kept that could associate the student's name to the encoded identifier. The class years were kept separate as to be able to compare the sophomores to the seniors. Only the HD, CD, and LB instruments were evaluated. The decision was made after scoring the aforementioned three instruments that scoring the vacuum would provide no new information.

4.2. Initial Study: Results

Three of the four instruments were evaluated for a sample of the responses of fifteen sophomores and fifteen seniors. Both groups performed best on the hairdryer and worst on the clothes dryer.

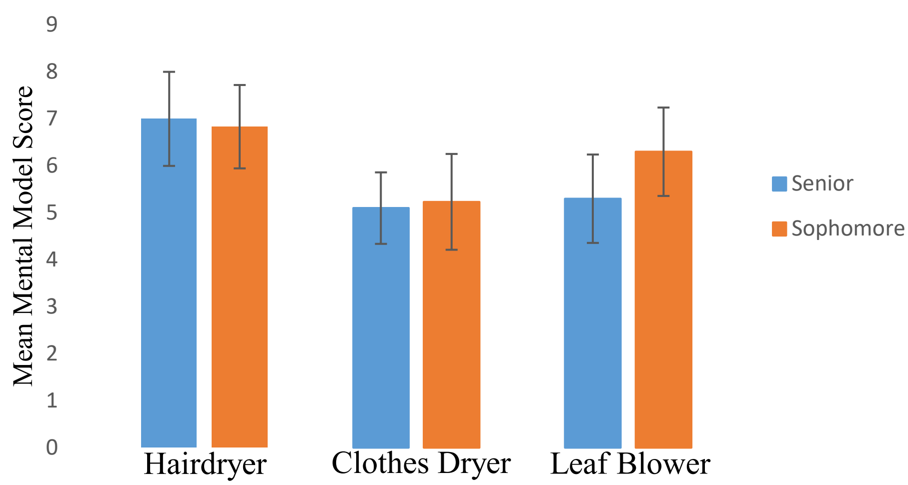

Figure 2. Comparing mean scores of sophomores and seniors on the instruments. (N = 15)

The three instruments were evaluated by two raters, one graduate student and one undergraduate student, independent of each other in different locations at different times. Of the three instruments evaluated, no statistical difference was found between the sophomores and seniors as shown in Figure 2. While not significant, the sophomores' average on two of the three instruments was higher than the seniors' average. Taking a random sample of 15 data points for just over 15% of the data presented in Figure 2, an inter-rater reliability analysis between two raters shows a percent agreement of 81.77% and a Cohen's kappa of 0.67, which indicates substantial agreement. For the mental model instruments, even the most detailed and thorough illustrations were far from complete answers.

Even with the low scores, the responses alone could indicate the causes of the scores [18]. Consequently, a follow-up study using semi-structured interviews was used to help gain clarity as to why there was a lack of change between the two groups of students.

5. Follow-up Study: Semi-Structured Interviews

5.1. Follow-up Study: Methodology

After all classes had participated in the mental model activity, follow-up interviews were conducted to elicit student perspective on the activity, gain insight into the individual students' experiences during the study, and to see if the study felt the activity fit within their academic studies. Students were asked to volunteer to take part in the interviews by supplying their email address. Those that wished to participate were blind copied on an email detailing date, time, and location of the interviews.

The interview portion provided a means for the study to receive feedback and identify changes in perception of the exercise. Students were first asked to recognize where in their lives they had encountered each instrument in the in-class activity. Students then identified the purpose of each device. Following this initial prompt, the questions were designed to help understand the pattern for how the aforementioned two student groups – sophomores and seniors – perceive the world. The process began as a discursive interview where the interviewee was allowed to continue talking on a topic until they felt they had exhausted their knowledge of the topic. The interviewer took a stance of deliberate naiveté in order to encourage the interviewee to add depth to their descriptions in their responses [19]. The questions asked follow.

1. Before we dive into the heart of the study today, let's go around the table and introduce ourselves. When doing so, please share a hobby that you do in your free time?

2. Describe your past experiences with problem-solving outside of school?

3. What experiences in your classes or hobbies seem most similar to the drawing activity you did today. How so?

4. Describe the level of difficulty you felt about the (device asked to draw). What obstacles did you confront when starting the activity and how did you feel about that?

5. Do you feel confident in your problem-solving abilities? Has it changed from prior to completing the exercise in part one of this study?

6 Describe how you worked through the activity?

7. Describe your familiarity with how the device operates. What are other devices like it?

8. What are the reasons you use it?

9. Is there anything that I haven't asked you, that you think is important to my understanding of your experience of this activity?

This approach was used to provide the students with a sense of comfort about expressing their views on the study, the instruments used in evaluation, and their perceived level of preparedness for the in-class activity. Ultimately the interviews sought to explore how the sophomores and seniors differently, if at all, perceived the tasks given to them and to categorize the students reported attitudes towards their generated mental models [20].

5.2. Follow-up Study: Results

Five students volunteered to participate in the interview portion of the study. Volunteers for the interview portion completed another standard informed consent form. Of the five students, three were sophomores, all men, and two were seniors, one man and one woman. Semi-structured interviews with participants sought to answer how and why the volunteers responded on the mental model instruments. Interviews ranged between 20 and 45 minutes, with the average length being 27 minutes. The first three interviews occurred within a week of the participants completing the mental model instruments; the latter two interviews occurred 2 weeks later. The latter two interviews were shorter and provided no new insight into the responses on the mental model instruments; therefore, the decision was made that the first three interviews provided sufficient vocabularies to understand the students' experiences. The first three of the interviews, two sophomores' and one senior's, were transcribed resulting in a total of 22 pages of single spaced pages. The transcribed interviews were coded using N-Vivo 12 Pro software package to identify recurring themes in the participants' responses. Data analysis followed two phases of coding. The first phase sought to examine the data closely, identifying what is occurring in the data at a micro-level. This was done by first searching the transcriptions for specific words and phrases and then going line-by-line coding based on the context, coding the transcriptions using what N-Vivo calls "nodes". Nodes are a system of labeling the data. First-level codes were produced from the in-vivo language of the transcripts. The three transcribed interviews were initially coded with 43-nodes into categories, using what N-Vivo parent nodes. These second categories include: classes, confidence, frustration, functional modeling, hands-on experience, mental model instruments, and similar. Full definitions of each of the second categories can be found in appendix Table A.2.

The seven parent nodes – classes, confidence, frustration, functional modeling, hands-on experience, mental model instruments, and similar – accounted for 310 of the 326 references. Each participant had experience using each featured device at least once, but the interviewees signified they had far more experience using the vacuum than the other devices. For the mental model instrument parent node, 42% was attributed to the vacuum, 28% for the hairdryer, 15% for the clothes dryer, and 15% for the leaf blower. The three students referenced analogous items to the instruments 33 times with the most common analogy being a toaster, which was referenced 6 times. The toaster reference only came after they referred to one of the other mental model instruments first, usually the hairdryer, and the interviewer asked them to provide more examples. It is worth noting that the hairdryer mental model instrument appeared first in the order of the mental model instruments, which suggests this influenced students' responses on the three other mental model instruments. Students made some reference to being unsure or frustrated with their knowledge nearly twice as much as they referenced confidence in their answers. The words "I don't know" were used 38 times compared to "I know" a mere 13 times. This theme of not knowing was pervasive throughout all the interviews especially when it came to asking how the mental model instruments work. Most admitted they did not actually know how the instrument operated, which they stated led them to keep their responses on the mental model instruments vague when it came to drawing components. The students related the exercise to five different classes; all three stated a relation to their freshman engineering seminar. One of the sophomores and one of the seniors stated they had hands-on experience with disassembling or building things.

6. Discussion

Review of the mental model activities indicated that students draw the components on the mental model instruments differently than anticipated. Students appeared to predominately label the components with generic placement inside the instruments. Students also indicated some of the inputs and outputs such as air intake and exhaust, see Figure 3, which was a typical, low scoring student response for this study. This example, provided as Figure 3, is an illustration of what we might term as a "black box" mental model illustration. Students here did not "open the black box" to explore the inner working of the system.

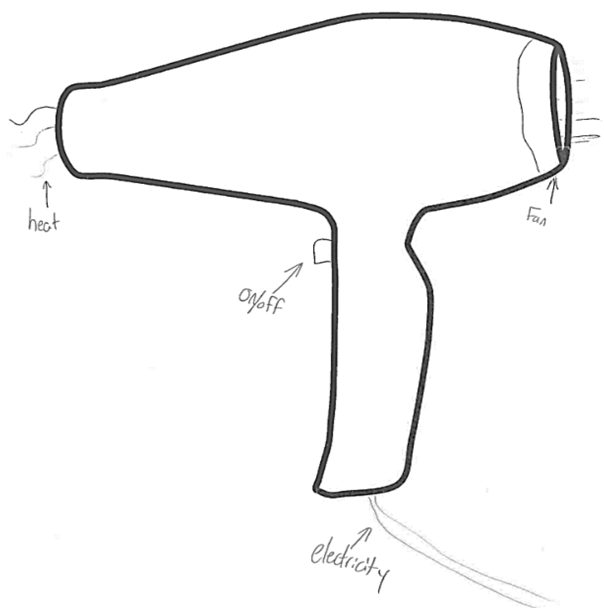

Figure 3. Typical low scoring student drawing of the hairdryer mental model instrument.

A few students provided more detailed depictions illustrating some relations between components inside of the box model and their components. For an example, see Figure 4.

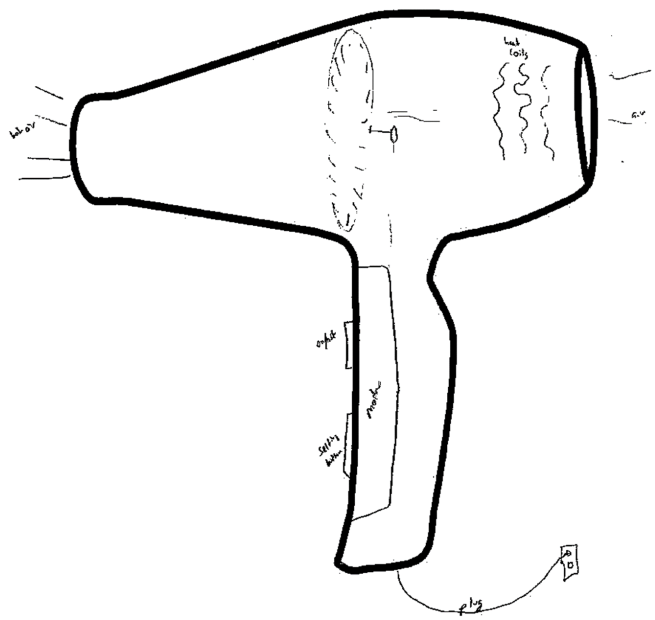

Figure 4. Relatively higher scoring student drawing of the hairdryer mental model instrument.

When asked what a vacuum reminds them of, one sophomore responded, with the following.

> *"It reminds me of about say the tube that you can disconnect from the vacuum, but I just remembered that was part of the vacuum."*

Indicating that at the time of the in-class activity, students did draw from their previous knowledge to formulate a mental model of the engineered system, but in reflection, the students realize that their mental model is either incomplete or false. Here one can hope that students follow the path of *enrichment* as described by Vosniadou [6] to append their mental model to include the remainder of the information not originally recognized as a part of the system.

Most of the interviewees assumed that the mental model activity must be similar to their coursework, as demonstrated in the following response.

> *"I say that um with my engineering 101 class [Engineering Freshman Seminar] and also my engineering 112 class [Introduction to Engineering] of that's very similar where we had to make."*

Interestingly, in the student's engineering 101 course, the students are asked to apply human-centered design to identify social issues to which engineering may have potential positive applications; the relationship to the in-class activity is not clear to the research team. In Introduction to Engineering, however, students explore engineered systems dissecting various engineered products, are introduced to functional modeling, and build small products for members of the community, which for this cohort, were adaptive musical instruments for the local elementary school.

Based on students drawing connections to prior courses, the research team's interest in functional modeling, the emphasis of functional modeling in the engineering curriculum, and the noted similarity of completed in-class activities with black box models, we choose to explore whether students were applying their functional modeling skills to illustrate their mental models on the in-class activity.

As a first pass to understand if students were using function-based approaches to illustrate their mental models, a binary sort between function-based approaches and component-based approaches was performed; this found approximately 18% of responses to be heavily function-based. We define a function-based approach as treating the mental model activity as a black box, supplying the inputs and outputs of the system.

To gain additional clarity into how heavily students were relying on their function-focused course work to complete the activity, a ten-point ranking was then applied based on model affinities with students scoring 0 for completely component-based, students scoring 9 for completely function-based, and students scoring 4 for completely mixed. As an example, consider Figure 3 and 4; using this approach Figure 3 rated highly function-based, while Figure 4 rated highly component-based. We define a component-based approach as completing the mental model activity by drawing and labeling the internal components of the system.

Following the rating of responses to the mental model instruments on the ten-point scale, no statistically significant difference in the sophomore and senior usage of a function-based approach was observed, as shown in Table 1.

Table 1. Comparison of sophomore and senior usage of a function-based approach on a ten-point scale.

	CD	HD	VAC	LB	Mean	% Function-based	Standard E
Sophomores	2.77	4.25	3.45	4.13	3.65	40.56	3.19
Seniors	2.65	4.23	3.74	3.73	3.59	39.89	3.05

The means of the sample mental model scores were compared to the means of the function-based ten-point scale scoring, as shown in Figure 5. Of the 30 data points, 7 were found to be outliers greater than two standard deviations from the mean line. For the remaining 23 data points, a p-value of 0.000007 was calculated, which means our comparison is statistically significant. A correlation of -0.73 was also calculated, which means that those who decided to use a function-based approach did not perform as well as those who used a component-based approach on the mental model instruments. This result is not surprising, though, as the rubric is designed to score mental models based on a component-representation, not a function-representation, so the rubric is biased toward scoring component-representations highly and functional representations poorly.

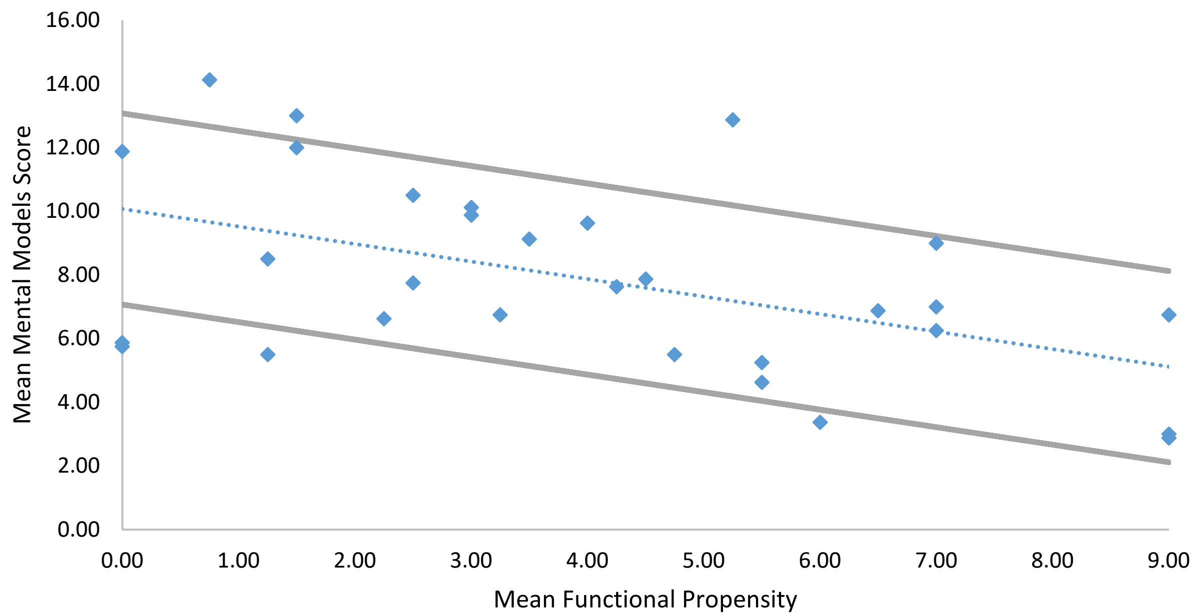

Figure 5. Comparing the mean of the mental model scores to the mean of the affinity scores. The solid grey lines represent two standard deviations from the mean line.

As no statistical difference was found between the sophomores and the seniors, the two groups were combined for further trend exploration provided in Figure 6. Provided as Figure 6 is a mapping of where student-generated mental model instruments fell on the 10-point ranking scale. Of the total 138 participants, 12 applied a purely component-based approach to the mental model activity: 5 sophomores and 7 seniors. Compared to the 4 students who applied a purely function-based approach to the mental model activity: 2 sophomores and 2 seniors. Of the statistically significant sample group of 23 students, the majority took a combined component-based and function-based approach to complete the mental model instruments.

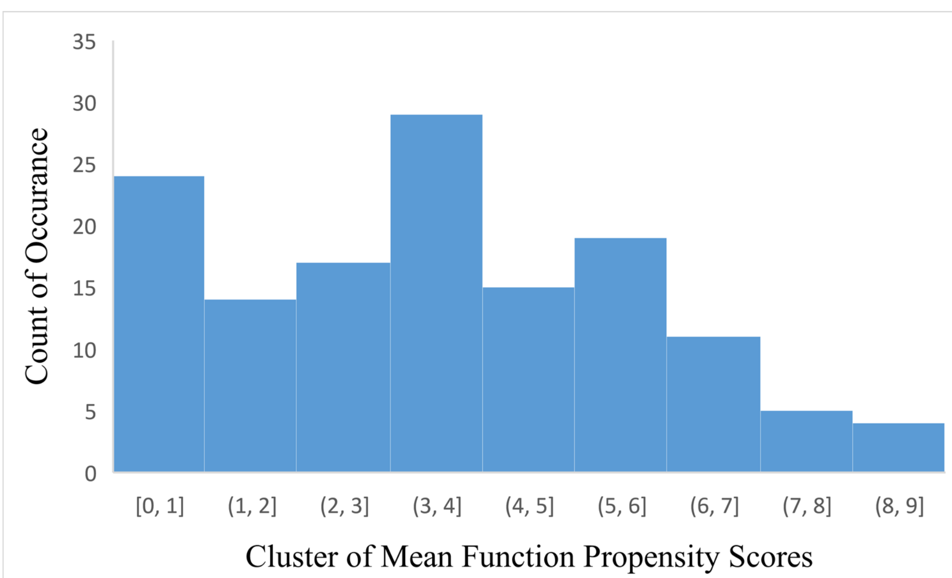

Figure 6. Distribution of mean function propensity scores.

By taking scores greater than 2 and less than 7 on the 10-point scale as students using a mixed component-function driven response, approximately 66% of the responses are mixed indicating that the majority of the students used a mixed approach when eliciting their mental models of the systems. An example of a mixed-approach mental model representation is provided as Figure 7. Figure 7 scored a 4 on the 10-point scale because it incorporated both component drawings and labeled the function. The example did not score lower on the 10-point scale because relationships between the components are not depicted, and the example did not score higher on the 10-point scale because only the output function is depicted.

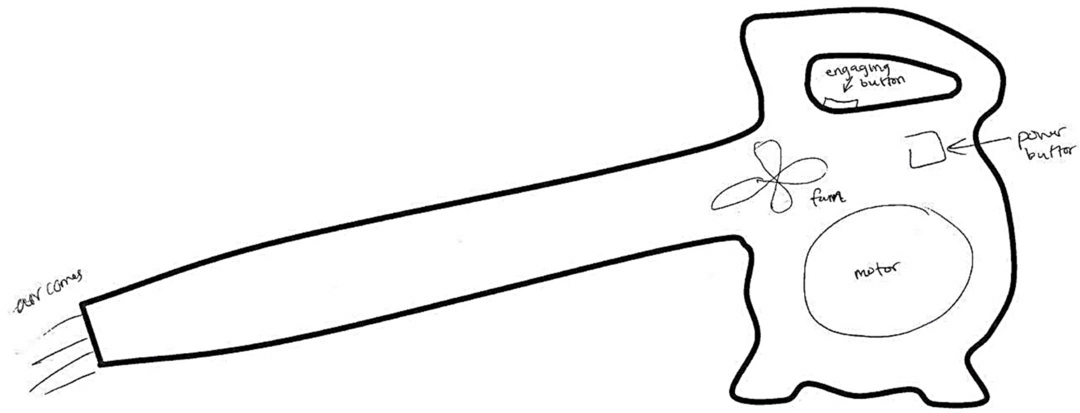

Figure 7. A function propensity middle scoring student drawing of the leaf blower mental model instrument.

Interestingly, though, we find that 39% of the students scored 4 or higher, meaning that 61% of the students took a primarily component-based approach. Additionally, we find that 83% of the students scored 2 or higher, indicating that, while most students thought about their mental models using a function-based approach, 27% of the students took a component-based approach (i.e., these students took the approach desired by the design of the instrument). One might argue based on this that students struggled to understand what depth of detail to provide in their responses rather than how to think about and represent the engineered systems.

7. Conclusion

In this study of whether or not students' mental models develop from sophomore year to senior year, no statistical difference was found between the students' responses. The semi-structured interviews demonstrated that the students may not know how exactly how the household products work. After analysis, an affinity sort of the data confirmed that while a majority of students took a component-based approach to the activity, a significant number of students used a function-based approach, and most of the students took a mixed-approach when representing their mental models. The rubric scoring the students' elicited mental models expects a component-based representation; consequently, it is not possible to say whether the students' function-based representations have changed from sophomore year to senior year.

To ensure that students understand that a component-based representation is desired, the language in the instrument will be further clarified from the previous version. Future plans for the mental model instruments also include providing an example of a completed mental model instrument prior to the students performing the activity to aid students with knowing how much detail is desired in their final submissions. In addition, the results presented in this paper will also inform changes to the rubrics used to score the student solutions to approach a formalized assessment tool.

Collins generalized that, "mental models are meant to imply a conceptual representation that is qualitative, and that you can run in your mind's eye and see what happens" [21]. Similarly, the study had students run through how devices function and what happens to allow for their functionality. Senge in his work, *The Fifth Discipline* [22], defined mental models as cognitive frameworks comprised of platitudes and conjectures one uses to form an understanding of the world and the engagements in the world. The use of mental models is commonplace in all aspects of life to every person; however, it is required of engineers to possess fundamentally and functionally correct mental models because of the impact of their decisions.

8. Acknowledgments

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Appendix

Please note that the following hair dryer (HD) mental model rubric has been provided in an abbreviated form. Only the questions have been provided. The detailed explanations, section labels, and scoring bins have been omitted to minimize space. Please contact the authors if you intend to implement the rubric and would like the complete rubric.

Table A.1: An abbreviated HD scoring rubric.

HD	Criteria
1	Is energy conserved across the system boundaries?
2	Is energy changed, converted, or transferred AND conserved within the system?
3	Is material conserved across the system boundaries?
4	Is material changed, converted, transferred AND conserved within the system?
5	Are signals used appropriately throughout the system?
6	Are correct inputs recognized?
7	Are correct outputs recognized?
8	Overall, does the model represent functional understanding of the system?
9	Is there an electric plug or alternate power source?
10	Is there a fan, air compressor, or air moving device?
11	Is there a heating element?
12	Is there a motor, engine, or similar device?
13	Is there an On/Off or power switch?
14	Is there a component for the control of the heating element?
15	Is a component for the control of the fan/air moving device?
16	Is the internal wiring complete/present?
17	Is the motor, engine, or similar device powered?
18	Is the fan/air compressor/air moving device connected to the motor, engine, or similar device?
19	Is the heating element powered?
20	Is the motor, engine, or similar device properly regulated?
21	Is the heating element properly regulated?
22	Does the model account for the movement of air through the system?
23	Does the model account for the transfer of heat to air within the system?
24	Does the model account for the control of electricity within the system?
25	Does the model account for varying modes of operation?

Table A.2: Secondary categories for coding nodes in N-Vivo.

Secondary Node Category	Definition	Child Nodes
Classes	Reference to a course taken in college and how it related to the activity.	101, 112, capstone, design two class, systems class, class
Confidence	Reference to certainty on a choice made during the activity.	I am pretty sure, I know, feel confident
Frustration	Reference to an empathetic feeling towards the study due to not knowing or not caring and being annoyed for being asked to do an aspect of the activity.	boring, I don't know, I was content, frustration
Functional Modeling	Reference to defining inputs and outputs of the mental model instrument.	power, FM
Hands-on Experience	Reference to prior experience using, assembling, or disassembling the device used for the mental model instruments.	I've looked inside, hands-on experience
Mental Model Instruments	Reference to any of the four mental model instruments used during the activity.	clothes dryer, hairdryer, leaf blower, vacuum
Similar	Reference to any analogy including to other mental model instruments.	broom, canned air, coil the pipe, elephants, fan, hose, ice cream ball, incandescent bulbs, merry go round, mower, pricks, rake, Swiffer, rude Goldberg, space, similar