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The Impact of Functional Modeling on Engineering Students' Mental Models

An Honors College Project Presented to

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College of Integrated Science and Engineering

James Madison University

by Jacob Thomas Nelson

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PUBLIC PRESENTATION

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Abstract

The ability to understand complexity and think holistically about systems is an increasingly important part of engineering design. This is embodied in the concept of systems thinking, a concept studied primarily in the fields of systems dynamics and systems engineering. Systems thinking ability is built off mental models, a loosely-defined construct people form to make predictions about their surroundings. Methods to evaluate systems thinking and underlying mental models rely primarily on self-evaluative methods such as questionnaires, or detailed simulations of systems or processes; however these methods fail to directly capture students' design tendencies. This work presents a visual instrument used to elicit and evaluate students' mental models of two simple systems, a hair dryer and a car radiator. This instrument is used to evaluate the changes in students' mental models after learning functional modeling, a systems abstraction method utilized in several engineering disciplines including engineering design. Two phases of analysis are presented. In the first phase of analysis, it is established that students had a significantly better understanding of the hair dryer than the car radiator system, based on the number of critical components students included in their responses; in this first phase, a component-based scoring strategy is presented. The second phase of analysis presents a scoring method based on Module Heuristics, a method for decomposing and categorizing flows and groups of functions within a functional model of a system. Module Heuristics are used to show the analogous functional flows between the hair dryer and car radiator. The scoring method is then used to investigate changes in students' mental models resulting from learning functional modeling.

1. Study Introduction

The world is filled with complex systems, and the ability to make decisions about these complex systems is valuable in many fields including systems dynamics, engineering, and business management [1, 2, 3]. This skill is known as systems thinking, a concept which primarily captures the ability of a person to recognize interconnectedness and think holistically about a system [4]. The natural question for companies and educators is how to evaluate a person's systems thinking ability. Most methods rely on a set of self-reported and self-evaluative questions, such as the CEST instrument developed by Frank et al. [1] and prior work has found that undergraduate engineering students struggle to reach even base levels of systems thinking [5].

Systems thinking is intrinsically linked to one's mental models. Senge [2] uses systems thinking in an explicit attempt to improve business managers' mental models. Richmond [3] views mental models as central to thinking in general, emphasizing that the use of this mental model is to simulate one's reality and make predictions. The ability to simulate and make predictions about reality is a core competency of a systems thinker, an activity dependent on one's underlying mental model. Mental models are a loosely-defined construct studied in cognitive psychology as well as systems dynamics. Doyle and Ford [6] review proposed definitions of mental models of systems and narrow the definition to "a relatively enduring and accessibly but limited internal conceptual representation of an external system whose structure maintains the perceived structure of that system" (p.19). Richmond [3] describes a mental model as a "selective abstraction" (p.4) used in decision making.

Decision making is an important part of many engineering tasks, and there are many tools to help engineers understand system characteristics for use primarily in conceptual design [7, 8, 9]. One of these tools is functional modeling, a flow-based method for abstracting a system in a manner that does not assume nor prescribe the specific components present in the system, instead focusing on transformations of energy, material, and information. Functional modeling also forces one to account for all of a system's input and output flows. This can be a valuable tool used to understand the relationships within systems, but does this help students think about systems? What impact does functional modeling have on one's mental model of a system?

In order to answer this question, one must first be able to elicit students' mental models of engineered systems; and consequently, this research provides two initial steps toward answering this question. First, one instrument has been developed to elicit students' mental models. The instrument consists of two engineered systems: (1) a household hair dryer and (2) a car radiator. Second, strategies are explored to evaluate students' mental models of the engineered systems, and two evaluation techniques are provided—one based on function and a second based on components. Using this instrument and the evaluation strategies, sophomore engineering students' mental models are evaluated at two data points during the semester—once before being taught functional modeling and again following being taught functional modeling—with the goal of exploring initial instrument implementation strategies. Based on students' completed instruments, some initial observations are made regarding students' mental models and the impact of functional modeling on students' mental models.

Two conference papers comprise the body of this thesis—one accepted for publication and presentation at the American Society of Engineering Education (ASEE) Design in

Engineering Education Division (DEED) and a second currently in review at the ASME International Design Education Conference (DEC). A summary of each paper follows.

The ASEE DEED paper is the initial presentation of the mental model instrument. A discussion is provided supporting the selection of the household hair dryer system and the car radiator as analogous systems when considering both systems functionally. This paper presents the component-based instrument evaluation strategy. Initial observations from the scored student functional models collected during the aforementioned sophomore design course are presented. Key findings include: (1) verification that the instrument does elicit students' mental models for analogous system and (2) a verification that a component-based scoring strategy may be used with demonstrable inter-rater agreement. When considering these two key findings with the initial instrument implementation, three preliminary conclusions are drawn, (1) students have a much stronger mental model of the household hair dryer than the car radiator when scoring for components, (2) student responses, when scored for components, do not change significantly after learning functional modeling, and (3) students do provide significantly more relevant components for the hair dryer than the car radiator following learning functional modeling.

The second conference paper, submitted to the ASME International Design Education Conference presents and demonstrates inter-rater agreement for a scoring method for the instrument based on functional modules identified using Module Heuristics as proposed by Stone et al. [10] The work also details the comparison of student-generated functional models for each system to the functional modules identified in the drawing portion of the instrument. Key findings include: (1) verification that a function-based scoring method applied to sets of analogous systems may be used with demonstrable inter-rater agreement, and (2) the average number of functional modules identified by students does not change after learning functional modeling. From this it is again concluded that students have a stronger mental model of the hair dryer than a car radiator system, and that it is unlikely that functional modeling aided students in the task as presented.

Though no clear relationship between students’ mental models of systems and functional modeling ability was found, this instrument and the two scoring methods developed offer a starting point for further exploration of engineering students’ mental models of systems. Both scoring methods demonstrated inter-rater reliability and the method can be applied to other sets of functionally analogous systems, making the instrument presented a potentially valuable tool for researchers and engineering educators.

2. The Impact of Functional Modeling on Engineering Student's Mental Models

Submitted to the ASEE 2018 Annual Conference Design Engineering Education Division

2.1 Abstract

Engineering continues to seek to teach our students more complex skills that will enhance their careers. This paper presents first steps in developing an instrument to measure a students' mental model (understanding of how a device works). The ability to think holistically and effectively pull from an interdisciplinary knowledge base is critical for engineers and companies to design effective systems. Functional modeling is believed to assist engineers in developing systems thinking skills and in porting their knowledge of one system to a new device with similar functionality. In this study, students were asked to draw basic component layouts for two functionally analogous devices, a home hair dryer and a car radiator. Students then learned functional modeling and were again asked to draw component layouts for these two devices. Results show two important facts critical to future work. First, students are more familiar with the functionality of a hair dryer, but not of a device with similar functionality, a car radiator. Second, simply learning the basics of functional modeling was not enough to assist students in leveraging their knowledge of hair dryers to understand a car radiator.

2.2 Introduction

Engineers from all disciplines rely on modeling in some form for much of their work, particularly in conceptual design [7,8,9]. These models help engineers understand and communicate complex system principles and phenomena, while informing the design process. Understanding how modeling processes impact engineers design choices and knowledge is important for the design community as engineered systems grow more complex.

Systems thinking is an important skill in many fields, including engineering. The ability to think holistically and effectively pull from an interdisciplinary knowledge base is critical for engineers and companies to design effective systems [11]. There have been studies to gauge the systems thinking ability of students and professional engineers [1, 12-16], but these studies often require specialized simulation equipment or utilize a questionnaire, limiting the amount of information one can gather about design tendencies.

Mental models are an integral part of systems thinking [2,17] and may be a more accessible window into a student's thinking about a system. This work is the first stage in an effort to evaluate student's mental models of systems in engineering design, and to investigate if and how student's mental models change when exposed to engineering design tools.

This study focuses on the development of an instrument to evaluate a student's mental models of two different systems that are functionally similar and compare their performance to identify knowledge transfer between the systems. Functional modeling, a qualitative modeling approach to represent systems through their transformations of energy, material, and information flows, is used to demonstrate this functional similarity by mapping components in each system to a common function. One system, a household hair dryer, was chosen for its familiarity to students, while the other, a car radiator, was chosen to be intentionally less intuitive for the students. Key questions in this research were as follows: (1) would students have a significantly better understanding of the more common hair dryer than the car radiator? (2) and, would students’ understanding of the two systems change following learning functional modeling? This research provides a starting point for research into functionally similar systems that can be used to analyze the ability of engineers to represent engineered systems.

2.3 Background

2.3.1 Function and Functional Modeling

Functional models are tools that allow a designer to abstract a system to its flows of energy, material, and information to enable exploration of problems in a "solution-neutral" manner. Flow-based models generally stem from the work of Pahl and Beitz [7] who helped to formalize and popularize the methodology in mechanical engineering design, but more broadly, functional models may be used across controls engineering, systems engineering, software engineering, and engineering design [8].

These models typically use two levels of abstraction: a black box model and a sub-functional model. A black box model describes the overall function of a system and all of the system's inputs and outputs relevant to accomplishing that overall function. The black box can then be decomposed by a sub-functional model that describes how the inputs are transformed through sub-functions into the outputs, tracing all flows of energy, material, and information along with the conversions they undergo. The sub-functional model traces all flows through the system. Flows must be conserved across all transformations as well as from the black box model to the sub-functional model.

Functions are generally described as a verb-noun or verb-object pair [9, 18], and can utilize a common lexicon of functional transformations in the Functional Basis [18]. This standard lexicon gives a list of flow transformations that can be performed by functions in a model and defines inputs and outputs for that function. In a functional model, flows are represented by different styles of arrows. A bold arrow represents material flows, a standard or thin arrow represents energy flows, and a dashed arrow represents the flow of information in a system.

2.3.2 Systems Thinking

Systems thinking is a concept that has been extensively discussed in system dynamics and systems engineering, but finding a consensus on the definition is challenging. Richmond describes the systems thinker as an interdependence specialist, understanding the dynamics of systems to inform decision making [17]. Senge [19] places systems thinking as a cornerstone to adaptive and productive organizations, and believes it could help organizations make better decisions, particularly when cause and effect may be de-coupled in time and space. Forrester views systems thinking as an ambiguous term, which constitutes a general awareness of systems and system dynamics [20]. The systems dynamics work of Senge, Forrester, and Richmond's systems thinking principles are applied beyond systems dynamics to inform systems engineering as well. Frank et al. [1] define systems thinking as a "major high-order thinking skill that enables individual's to successfully perform systems engineering tasks" (p. 32) in the development of their Capacity for Engineering Systems Thinking (CEST) instrument. Kordova et al. [21] describes systems thinking as a concept that prioritizes understanding of the relationships between components rather than knowledge of the components. These definitions all tie together the common threads of managing interdependence and complex relationships, while describing systems thinking as a skill, valuable for modern professionals.

Much work has been done to identify the competencies that make effective systems thinkers in engineering. Valerdi and Rouse [4] identify seven competencies. They describe a systems thinker as being able to define the world and the system appropriately, to see relationships and understand complexity, and to see things holistically. Along with this, systems thinkers are able to communicate their ideas and information across different disciplines and take advantage of a broad knowledge base. Camelia et al. describe systems thinking as a pattern of thought where a person questions system boundaries and structure, can understand interrelationships, interdisciplinary points of view, and system processes, while thinking holistically and seeing the “big picture.” [15] Camelia et al. also describe systems thinking as a “bridge between theory and practice” (p. 2) as well as between abstract, concrete, practical, and intellectual domains. Huang et al. [11] identify thinking holistically as a primary competency of a systems thinker. Derro and Williams [16] note the ability to find patterns across a system, and Chan [22] adds that effective systems thinkers see factors that influence a system and their importance to the outcome. Holism recurs as a primary competency, but it is also notable that interdisciplinary communication and the ability to pull from a large base of knowledge are identified. Systems thinkers must be able to make sense of a large variety of inputs.

A natural question for companies and educators is how to identify and evaluate a person’s systems thinking ability. Frank et al. [1] developed the Capacity for Engineering Systems Thinking (CEST) instrument, to evaluate engineers’ ability to perform systems thinking tasks. Frank notes high CEST engineers as being able to conceptualize solutions, use simulations and optimization, and implement systems design considerations. Camelia et al. [15] developed a questionnaire based off the CEST to evaluate student’s systems thinking using a seven-point Likert scale. Both of these instruments can be used to gauge systems thinking tendencies, but they force students to self-report and self-evaluate their skills, an exercise which may be prone to misrepresentation. An example of self-reported misrepresentation is the Illusion of Explanatory Depth as described by Kiel [23], where people chronically overestimate the detail in their understanding of systems, compared to when they are forced to draw a detailed diagram. It may also be interesting to examine the difference between students' perceptions of their skills, and how they apply those skills to a design problem. Due to this, a direct way to evaluate systems thinking tendencies through a student design problem would be advantageous. One way to evaluate direct evidence of systems thinking in design prompts is through a taxonomy of systems thinking skills. Hopper [24] describes characteristics of systems thinking and maps them to Bloom's Revised Taxonomy. The first level is recognizing interconnections, in which a person would be expected to be able to identify the components of a system and see connections between those parts. Assessment tools that may be appropriate to establish this level of systems thinking include a list of system parts, and connections shown through words or diagrams. This gives a framework for categorizing systems thinking tendencies directly in an engineer's work, as opposed to indirectly through a survey. The authors found, however, that this taxonomy was difficult to apply directly to undergraduate student work [5] as student responses generally failed to meet the minimum level for evidence of systems thinking.

Systems thinking is intrinsically linked to a person's mental models. In an effort to improve business manager's mental models of systems through systems thinking, Senge [2] notes that their mental models are generally poorly constructed, ignore system elements such as feedback, misrepresent time delays, and "disregard nonlinearities" (p. 1010). Senge proposes using software to challenge and correct manager's faulty mental models and help them better understand the interactions between systems understood in isolation. Richmond [3] uses the concept of mental models to define thinking, using the construction of a mental model as the pre-requisite for using that model to simulate our reality. Senge and Richmond's systems thinking is underpinned by the concept of mental models, and thus further discussion of this concept is warranted.

2.3.3 Defining Mental Models

The field of cognitive psychology has developed theories of long term knowledge and memory, while other researchers have studied cognitive structures involved with mental models. The study of mental models is difficult, and still many open questions exits. Likewise, in system dynamics literature, there is considerable disagreement on key aspects of mental models, as stated by Doyle and Ford [5]. Rouse and Morris [25] note that, while widely used, there are few concrete definitions of mental models. They note that most perspectives taken revolve around the common themes of describing, explaining, and predicting, regardless of the activity the person in performing.

Forrester describes mental models as a mental image that captures concepts and relationships which represent systems in the world in an imprecise, incomplete, and transient mental construct [26]. Sterman [27] defines mental models as the construction of the world by one's senses, and most are totally unaware of their own mental models. Sterman emphasizes the "implicit causal maps" (p. 294) held by people, and the networks involved in systems knowledge. Smith [28] reviewing Peter Senge's work, notes that Senge defined mental models as "deeply ingrained assumptions, generalizations" (p.7) or other factors that influence people's perceptions and actions. Richmond [3] defines a mental model simply as a "selective abstraction" (p.4) that people can use to model aspects of their reality, and inform decision making.

Doyle and Ford [6] propose a narrowing of the term mental models for system dynamics research, “A mental model of a dynamic system is a relatively enduring and accessible but limited internal conceptual representation of an external system whose structure maintains the perceived structure of that system” (p.19).

2.3.4 Evaluating Mental Models

Due to the individual and amorphous nature of mental models, experimentally testing one’s mental models poses a challenge. Endsley [29] proposes that personal models of situations provide a window to their mental model, as one’s perception of a situation is built on top of mental models. Bensard et al. [30] examine a similar phenomenon, where people’s mental models are built on co-occurrence of events that appear to have an effect on a situation and clearly disrupts their mental models. Bensard et al. [30] continue and discuss a case study of an air incident where concurrent events disrupted pilot’s mental models of a failure leading to a crash. Thus, mental models do manifest themselves in the real world through people’s responses to different situations and this can be a valuable way to study them.

In an attempt to replicate this, multiple studies have been done in which people are given control of an automated system, and their responses to different anomalies gives insight into their mental models. Kieras and Bovair [12] gave participants a control panel and a series of procedures for both normal conditions and malfunction conditions and recorded how subjects controlled the system with several variations. They concluded that a device model helped people formulate their mental models, so long as the model supports precise inferences about controls. They also determined that “relevant how-it-works” knowledge can be “superficial and incomplete” (p. 272) arguing that explanatory depth is not necessary to operate a system effectively. Finally, they caution that device models may be distorted or lead to misunderstandings if presented poorly, distorting an operator’s mental model.

Similarly, Seel et al. [31] put participants in control of a simulated distillation plant, which operated without input until a failure occurred. The experiments of Seel et al. showed that students pre-conceptions and prior knowledge was drawn on along with the knowledge gained in the experimental environment. Bußwolder [32] describes another experiment to examine mental models, putting participants in control of a new business with one product. Bußwolder’s experiment looks at the impact of a framework on the development of mental models in a system that is opaque, dynamic, and complex.

LaToza et al. [33] investigated Microsoft developers’ methods for communicating their mental models of a complex piece of software with other developers by surveying their activities, conducting interviews, and monitoring work habits. They found that a large part of a developer’s design knowledge is kept in a mental model of the system, and that this can foster personal ownership over pieces of code among a team. They also found that in small teams, team ownership of code was particularly strong, and update messages were used to inform each team member of changes to the code. Team members also updated cross-team design documents more frequently than internal documents.

Ibrahim and Rebello [13] examined undergraduate students from STEM majors’ mental models involved in solving kinematics problems, presented in different forms. Six tasks were presented to the students, who were then prompted for a mathematical solution or written response. They found that some of the students leaned more heavily on qualitative information and diagramming when applying the mathematics, while others applied the mathematics more blindly. They concluded that the students did not integrate “visual and symbolic representations” (p. 222) and did not form a mental model.

Zhang [14] studied student’s mental models of the Internet as they completed a search task. They thought of the Internet from various perspectives. The view students took impacted how long it took them to perform the task, and how well they performed in the task. Zhang utilized drawings to evaluate people’s conceptions of an abstract system because it is a primitive method of communication, can be used across age groups, and has a history of use in research into computers and the internet as a system. From these drawings, Zhang was able to classify a student’s mental model structure concerning the Internet and compare this to the students’ searching activities.

2.3.5 The Bicycle Problem

The instrument used in this study is based off of a problem from the field of cognitive psychology. Lawson [34] performed an experiment prompting people to place components on a drawing of a bicycle, and then draw the bicycle unassisted. Lawson evaluated the results based on number of errors committed, and the subject’s impressions of their knowledge of the task both before and after. She found that participants underestimated the depth of their knowledge and struggled to draw a functional bicycle. Even those who rode bicycles regularly performed relatively poorly. When shown a bicycle, the responses improved, but were still imperfect. Lawson corroborates Kiel’s [23] description of illusory explanatory depth, as people maintained a shallow mental model of the bicycle as a system in day-to-day life. People tend to be lulled into a notion of deeper understanding when they can see more parts of the system, regardless of what they know about the interactions of those parts. Many understood the points at which they interfaced with the bicycle, but not the underlying levels of function.

Kiel [23] proposes that most people have this Illusion of Explanatory Depth (IOED), meaning that they believe they possess a deeper knowledge about systems than they do. He claims that people may not understand the various levels a system can be analyzed, leading to confusion of “genuine insight at one level with insight at a lower level.” (p. 670) Generally, when people are rated on their explanatory understanding of a system, they show a significant drop from their perceived and their actual knowledge. When judged on fact-based knowledge, such as knowledge of capitals, people are much more aware of their level of knowledge. Kiel claims that this shows that the illusions in explanatory knowledge are particularly powerful. It is rare that they are prompted to give a detailed explanation, and it is also difficult for one to self-test their explanatory depth, due to the lack of concrete, final, and all-inclusive explanation.

Finally, Kiel notes that depth may be fleeting. People may have much more depth to their transient explanations when in a situation with the artifact or system in question. Knowledge of the parts and function of a bicycle may be enhanced when in the presence of a bicycle. People’s perception of the world around them, and their resulting mental models, are informed heavily by causal patterns they see around them.

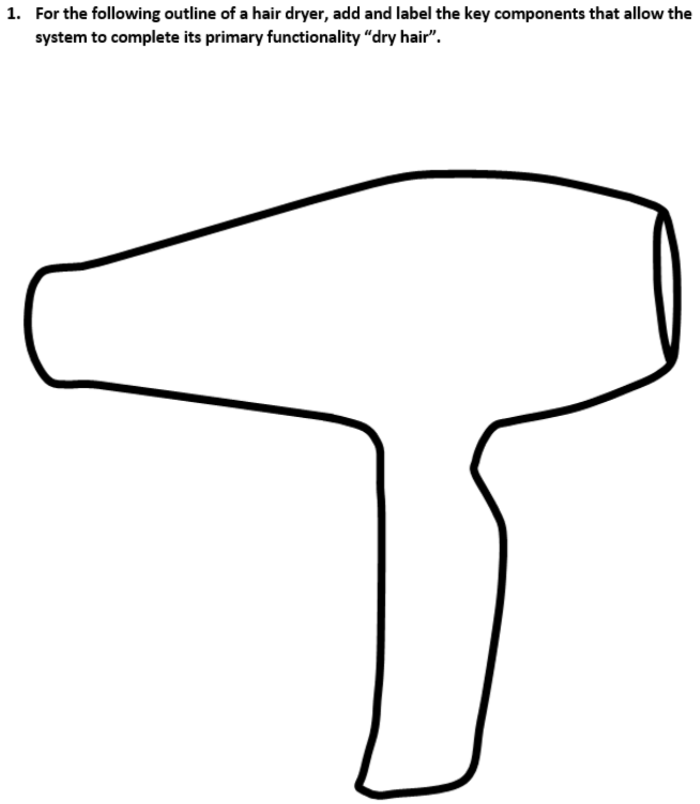
2.4 Methods

2.4.1 The Instrument

The instrument presented in this study prompts students to draw the components required for a hair dryer and a car radiator to achieve their system's respective function. This function, dry hair for the household hair dryer, and remove heat for the car radiator, relies on many of the same sub-functions to both remove heat and dry hair. One prompt, the hair dryer, was intentionally familiar due to its ease of use and prevalence in many American households, while the other, the car radiator, was present but less obvious unless one was familiar with workings of modern cars. The hypothesis for this instrument was that students exposed to functional modeling would be able to identify more components in the car radiator by recognizing the similar functions present in the hair dryer, and that students have a better understanding of the functionality of the hair dryer as opposed to the less familiar and visible car radiator.

The visual approach is based on Lawson's bicycle problem [34] in which a simple outline of the system is given to the participant, who is then prompted to place components where they exist in the system. Unlike in Lawson's study, the participants in this study were not given a bank of components to choose from, increasing the variety of answers received and drawing more on the components which existed in the participants' mental models.

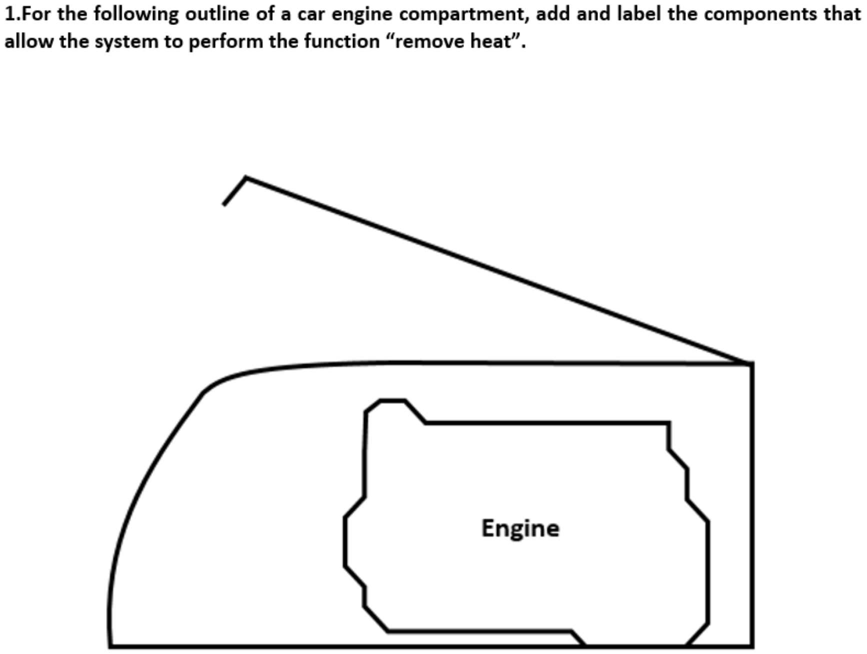
It was hoped that students would understand how a hair dryer works at a high level, that is take in room temperature air and expel hot air, and students have been exposed to the system inputs (electricity and room-temperature air), outputs (hot air). This would give them a base of knowledge from which they could begin to reason about the necessary transformations and arrive at requisite components. From this information, someone with exposure to functional modeling is likely to be able to create a representative functional model of the system and demonstrate a plausible understanding of the system. Figure 2.1 is the hair dryer element of the instrument.



1. **For the following outline of a hair dryer, add and label the key components that allow the system to complete its primary functionality "dry hair".**

Figure 2.1. Hair dryer instrument as presented to students

The car radiator system, provided as Figure 2.2, is intentionally less intuitive as it was not considered as a visible system in typical household life, but it has significant functional similarity with the hair dryer. The radiator was presented with the engine included in the prompt to give students unfamiliar with car radiators a reference point. The engine also serves as the source of energy in the radiator system, and it is functionally important to identify that the heat is flowing out of the engine and into the radiator system. The engine itself was considered outside the boundary of the radiator system for this exercise.



1.For the following outline of a car engine compartment, add and label the components that allow the system to perform the function "remove heat".

Figure 2.2. Car radiator as presented to students

The expected components of the hair dryer, provided as Figure 2.3, were identified by the authors, who were experienced with the function and components of commercial hair dryers. The fan, the heating coils, the control switches, and the electrical plug were identified as the most basic and functionally important components. The car radiator components, provided as Figure 2.4, follow the outline in the Bosch Automotive Handbook, 9th Ed [35], which describes a passenger-car water cooling system. The eight main components identified were the engine, a fan, coolant lines, a coolant pump, a main coolant radiator, a bypass line, an expansion tank, and a thermostat. The fans, coolant lines, main coolant radiator, and thermostat were identified as the components required to satisfy the basic function, and the engine was included in the prompt.

The expansion tank, pump, and bypass line were not coded for as they represented a level of detail beyond the expectations of this instrument.

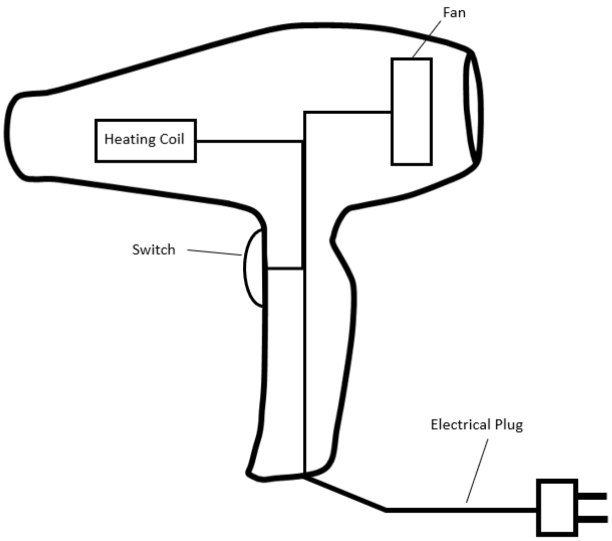


Figure 2.3. Complete solution for hair dryer

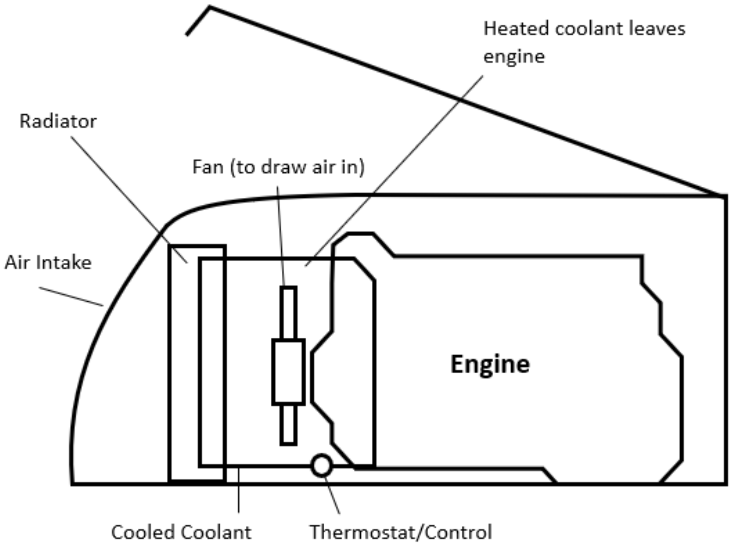


Figure 2.4. Complete solution for car radiator

2.4.2 Demonstration of Functional Similarity

The hair dryer and car radiator were selected as examples for this study due to their functional similarity. At an abstract level, both systems take energy from a source (either electrical or thermal energy from the engine) and transfer that energy into a fluid that is drawn into and flows through the system. Functional models of both the car radiator and the hair dryer were made.

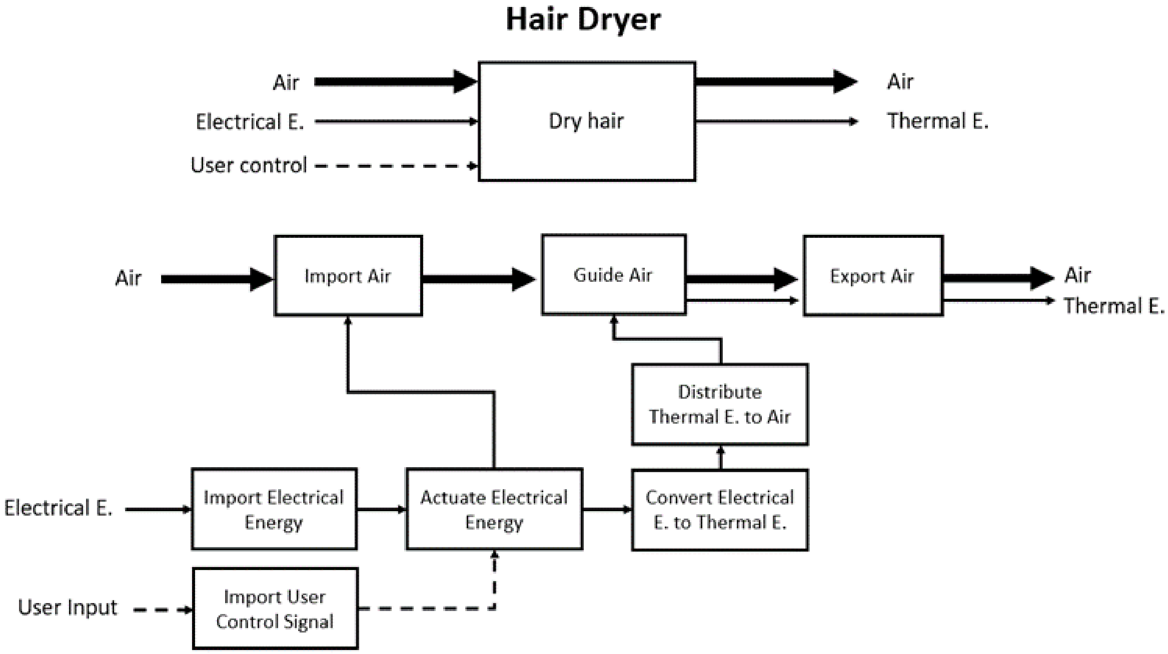


Figure 2.5. Functional model for hair dryer

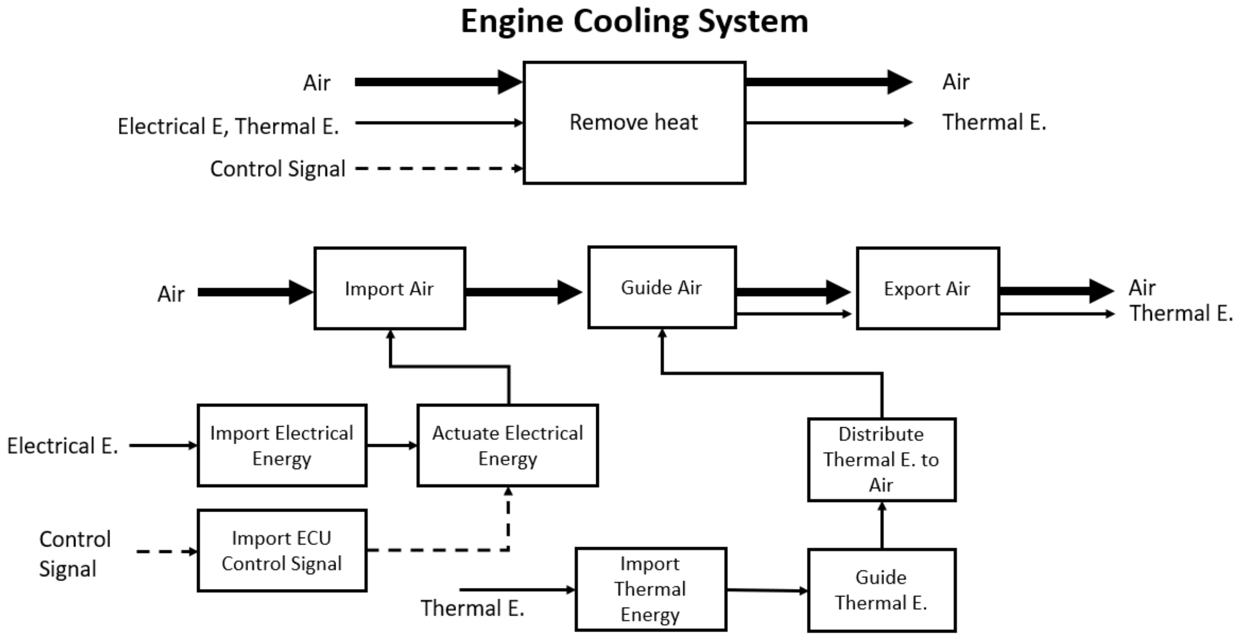


Figure 2.5. Functional model for car radiator

To evaluate a student's understanding of the systems, four critical components were identified in each system. Each of the components has a direct functional link to a component in the other system that fulfils the equivalent function, and these functions combine to fulfil the overall function of the system. These common functional relationships are shown in Table 2.1.

Table 2.1. Functional similarity mapped to common components between systems

Hair Dryer Component	Common Function	Car Radiator Component
Fan	Import Air	Fan
Heating Element	Transfer Thermal Energy to Air	Radiator or Heat Exchanger
Electrical Plug	Import Source Energy	Coolant Lines
Switch	Import System Control	Controller/Thermostat

This study was conducted with sophomore engineering students at James Madison University. This study was run in Engineering Design I, the first class in the design sequence of classes, and 47 students took part in the first testing session. The students were taught functional modeling and received feedback on homework relating to functional modeling in the time before the second session, which occurred approximately 6 weeks later, and 45 students participated in the second session.

At the end of a lecture, the students were given a brief introduction and then both portions of the instrument—each portion on its own sheet of paper. The students were allotted approximately 15 minutes to complete the instruments. They were not encouraged to start work with either system, nor were they prompted on how to divide their time between systems. They were directed only to follow the prompt on the page. The students were not given feedback on their prior hair dryer or car radiator submissions between sessions. The post-test followed the same procedure as the pre-test, but additionally included a prompt to draw a functional model for both systems. Students were provided approximately 30 minutes for the post-test to allow time for the additional task.

2.4.3 Scoring Procedure

Each student response received a composite score equal to the sum of points received for each component category. A composite score of 4 indicates a student included all four of the components in their response, while a score of 0 indicates they included none.

The scoring metrics for the components were posed in the form of a binary yes/no question. Data coders were instructed to award points only where a component was explicitly drawn or labeled in the appropriate manner. Each criterion in Table 2.2 attempts to capture the equivalent component from Table 2.1, which can then be mapped to its equivalent function.

Table 2.2. Criteria as used by reviewers when scoring student responses.

Hair Dryer Criteria	Car Radiator Criteria
Does the student include a heating element?	Does the student include a radiator or heat exchanger?
Does the student include a fan located in the nacelle?	Does the student include a fan in front of the engine?
Does the student include an electrical plug?	Does the student include a flow of a coolant fluid from engine?
Does the student include any switches to control the device?	Does the student include some form of control of system?

Two undergraduate researchers from James Madison University consisting of one Junior and one Sophomore engineering student evaluated the responses for the components. Both data coders had been exposed to functional modeling through the engineering program. To ensure inter-rater agreement, small samples of 10 student responses for both the hair dryer and the car radiator were scored, and those scores were evaluated by a third senior undergraduate researcher, who identified items where the two raters disagreed consistently. Group discussion was used to facilitate communication about points of disagreement and update the scoring rubric accordingly.

For the composite scores, Cohen's Kappa was used to evaluate inter-rater agreement. The hair dryer composite scores had a $\kappa = 0.685$ (95% CI, 0.584 to 0.786) and the car radiator had a $\kappa = 0.670$ (95% CI, 0.582 to 0.773). Both of these reflect substantial agreement according to the descriptors laid out by Landis and Koch [36]

2.5 Results

2.5.1 Impact of Functional Modeling

To identify change in student responses due to functional modeling, the result was analyzed in IBM SPSS Statistics version 23, using the non-parametric, independent sample Kruskall-Wallis 1-way ANOVA test.

Responses were grouped by the point administered, before or after learning functional modeling. The Kruskal-Wallis test showed no statistically significant difference between students who had learned functional modeling, and those who had not, $\chi^2(1) = 0.291$, $p = 0.590$, with a mean rank of 94.955 (n=94) before learning function, and 90.360 (n=90) after learning function.

2.5.2 Understanding by System

Though functional modeling did not change the number of components captured in student responses, students appeared to understand the car radiator far less than the hair dryer. The composite score represents the sum of the components identified in each student's response, with a maximum possible score of 4. Both data coders generated a composite score for each student response, and the average composite score between the undergraduate data coders was grouped by system. The average composite component score was higher for the hair dryer than the radiator, as shown in Table 3. In total, there were 92 hair dryer responses and 92 car radiator responses received from students across both the pre- and post- functional modeling groups.

Table 2.3. Average composite score by system

	Average	**Standard Deviation**	**Standard Error**
Hair Dryer (n=92)	3.00	0.963	0.100
Car Radiator (n=92)	1.28	0.921	0.096

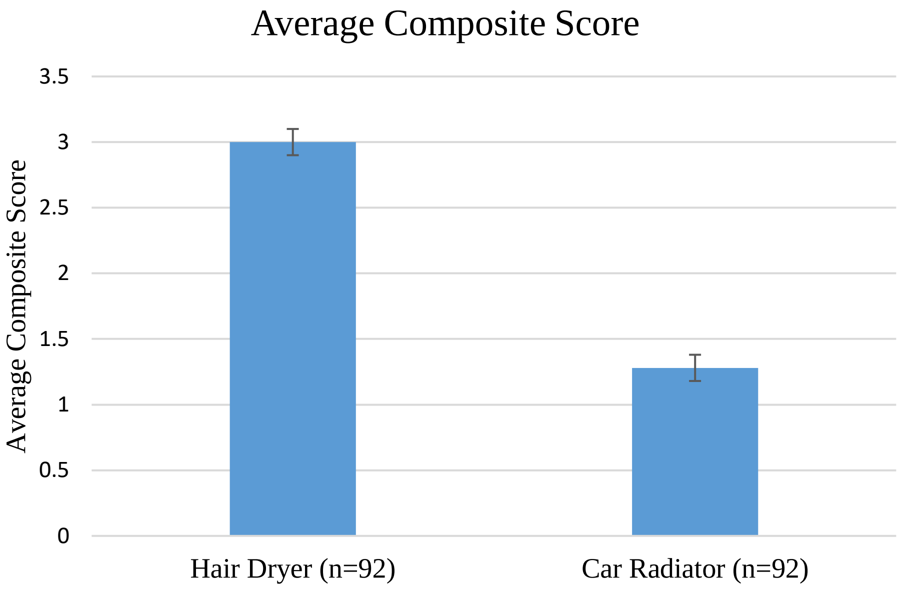


Figure 2.6. Average composite score

Table 2.4. and Table 2.5. contain the sum of each component identified in all of the hair dryers and car radiators evaluated. The most common component included in radiator responses was a fan. All components in the hair dryer system were recorded more times than any in the car radiator. The control element in the radiator was also notably low, particularly compared with the accompanying element in the hair dryer, the switch, which held the highest total component score for the hair dryer system. This may be due to the hair dryer control existing at an interface

with the user, while the car radiator system's control interfaces with a larger vehicle management system in most cases, and is rarely visible to the user.

Table 2.4. Summation of components for hair dryer system

Component	Sum of Components	Standard Deviation	Standard Error
Fan	64.5	0.445	0.046
Heating Element	55.0	0.470	0.049
Electrical Plug	77.0	0.332	0.035
Switch	79.5	0.324	0.034

Table 2.5. Summation of components for car radiator system

Component	Sum of Components	Standard Deviation	Standard Error
Fan	46.0	0.492	0.051
Radiator or Heat Exchanger	29.0	0.430	0.045
Coolant from Engine	39.0	0.450	0.047
Controller	3.5	0.185	0.019

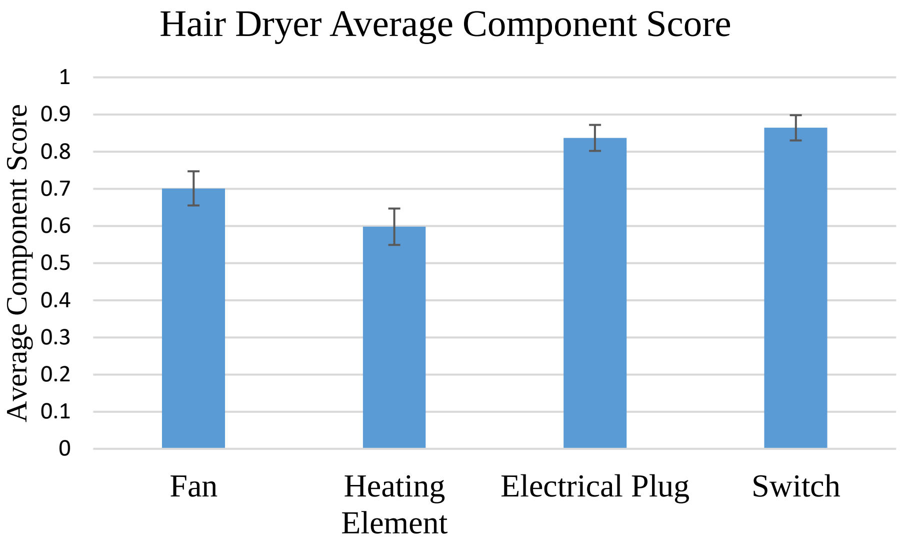


Figure 2.7. Average scores awarded by component for hair dryer system.

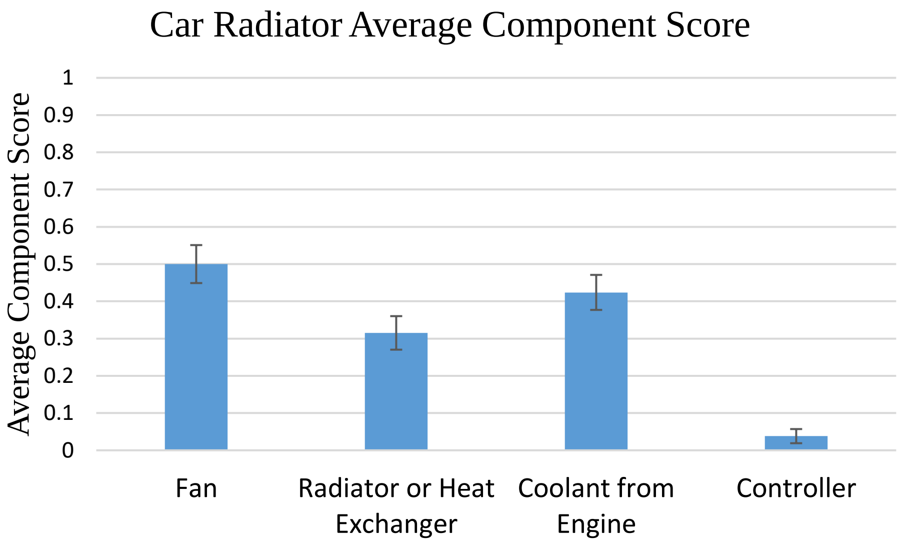


Figure 2.8. Average scores awarded by component for car radiator system

The Kruskal-Wallis test showed a statistically significant difference in composite score on the hair dryer and car radiator systems, $\chi^2(1) = 86.210$, $p < 0.001$. The mean rank of the hair dryer was 128.53, while the mean rank for the car radiator was 56.47.

2.6 Discussion

Students identified more relevant components when presented with the hair dryer than the car radiator. Students appear to be able to understand the hair dryer, which shows that an outline similar to the one presented in this study can allow students to make sense of a product and identify relevant components. This also demonstrates that students’ understanding of the radiator system was far less than that of the hair dryer. This fact makes the hair dryer and car radiator pairing an interesting set of systems for future work.

The instrument appears to set up a problem where participants are presented with a familiar and unfamiliar problem, which can be used to investigate questions surrounding how they approach and make sense of that uncertainty. In this case, results show that being exposed to a class module on functional modeling did not specifically help them handle this uncertainty. Perhaps providing the students with the functional models, instead of prompting them to make them, could help them bridge between the two systems.

System understanding may be gauged through components as described in this study, or through functional abstraction techniques such as module heuristics [10]. Other points of interest in further analysis will include the use of functional language in labels and visuals, the use of clearly identified flows, and the overall understanding of the system.

In addition to tracking components, reviewers were instructed to mark whether a student’s response showed functional understanding of the system for both the hair dryer and car radiator. This question was broad and difficult to achieve complete agreement between reviewers, but it does help identify samples for further qualitative investigation. The common thread through samples that failed to show functional understanding across both systems is completeness. This was particularly apparent in the car radiator, where many students only noted an air intake or grille at the front of the car, which happens to be the only aspect of the system visible to an outside observer. There were also several responses which understood the higher-level concept, of cycling fluid through the engine to remove heat, but key components such as the fan or even the radiator itself were omitted.

Figures 2.10 and 2.11 show interesting alternative responses to the prompt. Figure 2.10 shows an alternative solution to the hair dryer problem, substituting a battery for an electrical plug. This is functionally plausible, but uncommon in products sold on market. Figure 2.11 shows an abstracted hair dryer, with functional blocks replacing the components.

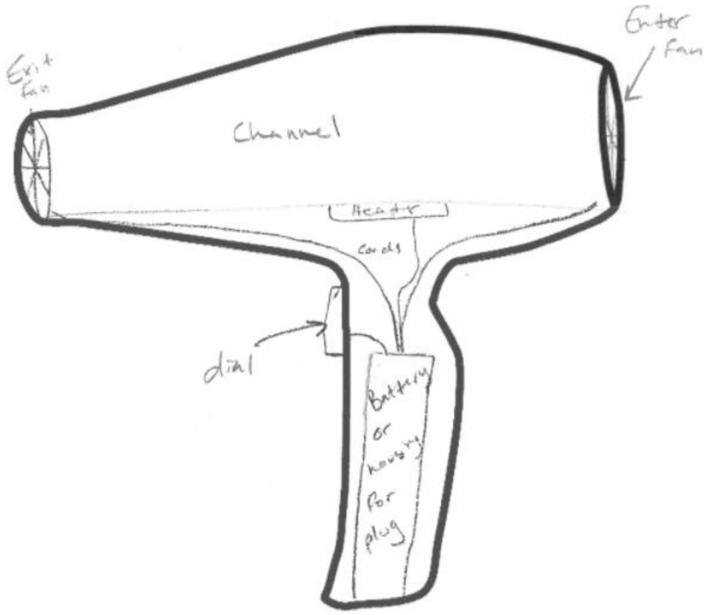


Figure 2.9. Example of an alternative solution response.

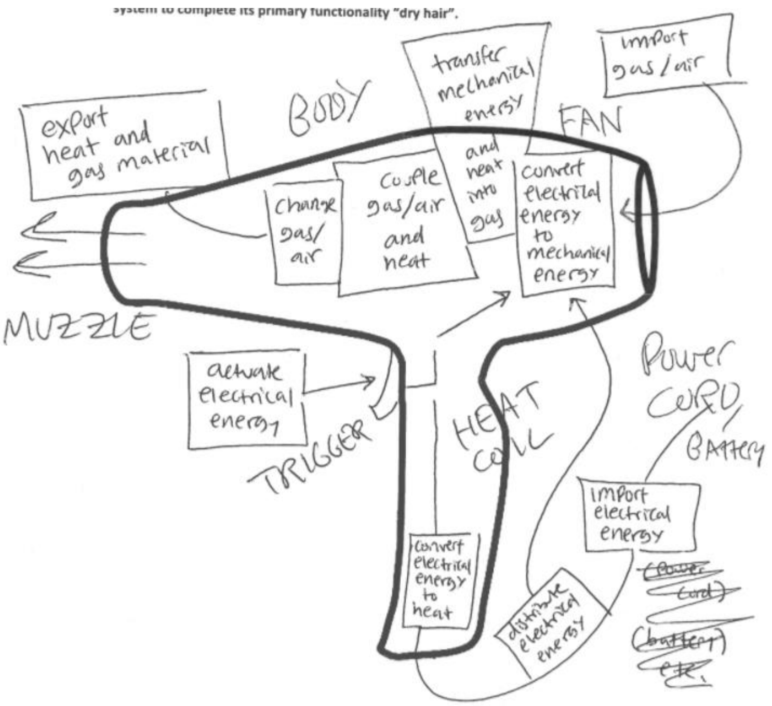


Figure 2.10. A functional hair dryer response

Car radiator responses varied considerably. A common response was simple notation of an air intake, grille, or air flow into the front of the car, as shown in Figure 2.12. This is an incomplete response, but it does represent perhaps the most intuitive judgement that can be made about the system. Other results, such as the one shown in Figure 2.13, showed general understanding of the existence of coolant, but either could not place it reasonably in the system or omitted key components, such as a fan to draw air over the system.

For the following outline of a car engine compartment, add and label components that allow the system to perform the function "remove heat".

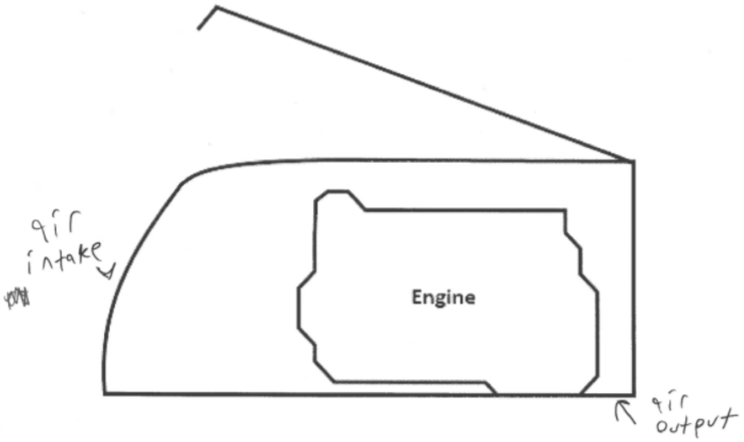


Figure 2.12. Example of an incomplete student radiator response, identifies only air flow

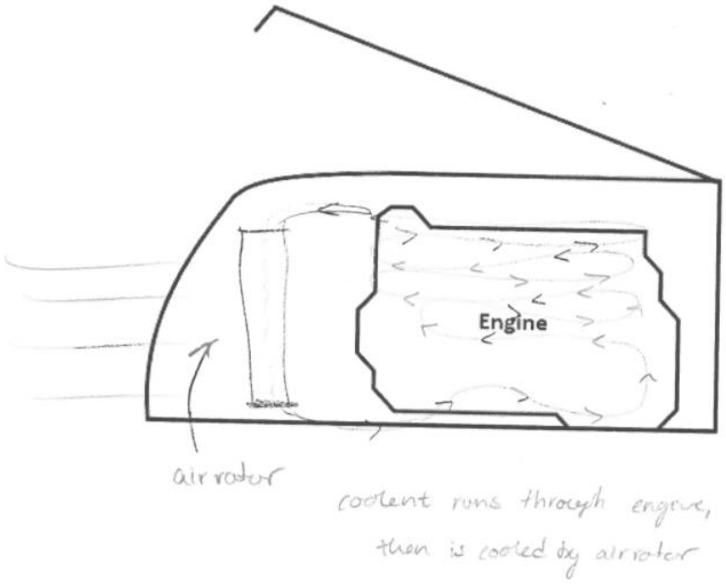


Figure 2.13. Radiator with general understanding but omitting key components

Many more students understood the general principle of the hair dryer, in which room-temperature air is accelerated and leaves the system with heat added to it. In the hair dryer, most students were able to recognize at least one of the key components, but many neglected at least one as well. A critical mistake was to neglect the power cord, which serves the vital function of importing energy into the system. Heating elements were more commonly omitted, perhaps due to students' unfamiliarity with resistive heating devices, a concept generally introduced to them in a Junior-level class. There were also students, particularly in the group post-learning functional modeling, that gave more direct, black box responses in place of components as discussed in Figure 2.11. Word descriptions of a function can be found both in pre- and post-groups, but post-responses generally use more formal functional wording.

Another study using these instruments could compare student responses to experienced engineers working in industry or research, to gauge the effect career experience could have on mental models of simple systems. Both the hair dryer and car radiator could be given to both groups in the same allotted amount of time. Concluding interviews with participants may also aid the identification of points of difficulty and thought processes in the completion of the experiment. Other systems could plausibly be used, particularly if they are relatively simple and have a functionally similar counterpart.

2.7 Conclusion

The students’ divergent responses to the pair of functionally analogous systems gives an interesting basis for future experimentation. Students understood the core components that allow a hair dryer to function significantly better than the core components required by the car radiator. This may indicate that students’ mental models of the hair dryer system were more concrete and complete than their mental models of the car radiator system by intuition alone. This opens discussion of several new questions. How might we illustrate functional transfer between systems that perform similar functions in different environments to students? How might we increase their ability to recognize common functional flows? What must be done to allow undergraduate students to abstract to a high enough level to identify these functional similarities, and does any of this make students better systems thinkers?

Future work in this area includes full analysis of the data collected from students and identify patterns in the changes before and after learning about functional modeling. While there was no significant difference between student component responses before and after learning function, preliminary analysis of data indicates that there may be more subtle differences that prove significant. This further work will incorporate broader analysis criteria, investigating items such as the use of flows and recognition of correct inputs and outputs. Interviews may also be incorporated to augment the use of the instruments, to gain insight into the thought process of students responding to the instrument. Studies using alternate system analogies, such as a coffee maker and a solar water heater, may also be deployed.

2.8 Acknowledgements

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3. Function-Based Scoring Method for Evaluating Student Mental Models of Systems

Submitted to the ASME Design Education Conference

3.1 Abstract

Mental models are loosely-defined constructs people form to reason and make predictions about their surroundings. These models are an important aspect of systems thinking for engineers, a concept that emphasizes holistic thinking when working with complex systems which is increasingly important in multiple engineering disciplines. Methods to evaluate systems thinking and mental models of systems traditionally rely on self-reported and self-evaluative means such as questionnaires, or detailed interactive simulations of specific processes. Both of these means fail to directly capture students' design tendencies. This work presents a method based on functional modules for evaluating student responses to an instrument intended to elicit students' mental models of two systems. Students were given a simple outline of the two systems, a hair dryer and a car radiator, and were prompted to fill and label the components required for the system to fulfil the functionality described. This was done in two sessions, once before learning functional modeling, and once after, to utilize the method of scoring to evaluate any changes in their mental models due to exposure to functional modeling. The scoring method identifies common functional modules between two systems using Module Heuristics, and then identifies students' recognition of those modules. This allows a direct comparison of the functional similarity between the two systems identified by the students and can capture a wider variety of correct answers than simply counting the components a student provides.

3.2 Introduction

Mental models are an important piece of how people make sense of the world. While many definitions for mental models exist, in systems dynamics, one's mental model tends to refer to one's power to describe, explain, and predict relationships and outcomes [25]. These mental models in systems dynamics form the basis for predictions made about systems [3] and underpin a person's systems thinking ability. This intrinsically-linked concept of systems thinking is critical for modern engineers [1,15]. Systems thinking skills allow one to have a holistic view of a system, understand its complexity, and manage its interdependence. Functional modeling has the potential to improve one's ability to comprehend complex systems during engineering design, and thus may influence an engineer's ability to develop accurate mental models of a system.

There have been studies to evaluate students' and engineers' systems thinking abilities [1,11,15,16,21], but these traditionally rely on a specialized simulation environment or a self-reported questionnaire. Methods are limited, however, when attempting to gauge design tendencies or the impact of techniques or tools on design ability.

This study presents an initial attempt to evaluate the differences in engineering students' mental models of two common and analogous engineered systems before and after learning functional modeling. The approach presented herein uses a visual instrument designed to elicit student's conceptions of the system by prompting them to place and label the components that allow the system to perform its primary function. This instrument consists of two drawings: (1) an outline of a hair dryer and (2) an outline of a car radiator. It was found previously that students had a higher level of accuracy for the hair dryer than the car radiator when reviewing students' knowledge of the components of each system [37].

To explore knowledge-transfer due to functional modeling, students' ability to functionally model the systems must first be established. Thus, the first hypotheses of the study were focused on students' abilities to generate functional models of the illustrated systems following having learned about functional modeling. These hypotheses follow:

- *Once taught functional modeling, students will be able to generate a functional model to represent a common household hair dryer such as the one illustrated in the instrument;*
- *Once taught functional modeling, students will be able to generate a functional model to represent a car cooling system such as the one illustrated in the instrument.*

As the overarching goal of this work is to understand how students' mental models of engineered systems change following learning functional modeling, additional hypotheses were explored in this study. Specifically, the team investigated the following three hypotheses to understand the change in mental models following learning functional modeling.

- *A student's mental model of an engineered system will change following learning to generate functional modeling.*
- *Following learning to generate functional models, a student's mental model of an engineered system will improve.*
- *Following the generation of functional models, students' can transfer knowledge from one system to an analogous system.*

Toward investigating these five hypotheses, this paper presents (1) an approach for scoring this instrument based on functionality and function-based modules as well as (2) an investigation of the student-completed instruments with an evaluation of the presented hypotheses.

3.3 Background

3.3.1 Functional Modeling

Functional modeling is a systems abstraction method that allows designers to explore problems in a solution-neutral manner by abstracting the system's flows of energy, material, and information. This flow-based approach was popularized by the work of Pahl and Beitz [7]. While functional modeling has been popularized in mechanical engineering design [9,38], functional modeling can also be used in other disciplines such as systems engineering, controls engineering, and software engineering.

Functional models generally contain two levels of abstraction, a black box model showing the overall transformation with all inputs and outputs, and a sub-functional model that describes the transformations each flow shown in the black box model in detail. Each transformation is represented by a function, which generally takes the form of a verb-noun pair [9, 18], and both functions and flows may be standardized with the use of the functional basis, a common lexicon for function description [18]. Flows of energy and material must be conserved at both the black box and sub-functional level. Each type of flow is represented by a different style of arrows. A standard arrow represents energy flow, a bold arrow represents material flow, and a dashed arrow represents information flow through a system.

3.3.2 Systems Thinking

Systems thinking is a concept that prioritizes understanding complex systems as a whole and is of value in many disciplines. Frank et al. [1] define systems thinking as a "major high-order thinking skill that enables individuals to successfully perform systems engineering tasks" (p.32) and Kordova [21] describes it as an understanding of the relationships between components in a system, instead of simple knowledge of those components. Interdependence and an understanding of complex relationships are central to systems thinking, which is regarded as a valuable skill for modern professionals. Systems thinkers are able to think and act holistically [4,15], find patterns across a system [16], and effectively assign importance to factors based on their effects on outcomes [22]. Valerdi and Rouse [4] identify seven competencies of systems thinkers including the ability to appropriately define the system and surrounding world, communicate ideas and information between disciplines, and capitalize on a broad base of knowledge, along with the aforementioned holism.

Evaluating one's systems thinking ability has traditionally been done with questionnaires or survey-type instruments. Frank et al. [1] developed the Capacity for Engineering Systems Thinking (CEST) which evaluates engineers' ability to perform systems engineering tasks with a self-reported questionnaire. High scores on the CEST instrument were shown to be correlated with project success among senior systems engineers in industry. Based off this instrument, Camelia et al. [15] developed a similar questionnaire to evaluate student's systems thinking skills on a seven-point Likert scale. While these instruments can be used to gauge systems thinking tendencies among engineers, they rely on self-reporting and self-evaluation of skills, which may be prone to misrepresentation. Kiel [23] describes the phenomenon of the illusion of explanatory depth, in which people chronically overestimate their detailed understanding of systems. Additionally, there may be value in comparing engineers' perceptions of their systems thinking abilities to the direct application of those skills to a design problem. A method for evaluating systems thinking skills in a design prompt is through a taxonomy such as the one described by Hopper [24], in which characteristics, competencies, and activities of systems thinking are mapped to Bloom's Revised Taxonomy. The base level of this taxonomy of systems thinking starts with recognition of interconnections, which may be assessed through the generation of al list of system parts and connections shown through words or diagrams. This taxonomy provides a framework for the direct evaluation of systems thinking in an engineer's work but the authors fond it challenging to apply to undergraduate responses [5] as students generally failed to demonstrate a recognition of interconnectedness which, in this framework, serves as the minimum level for evidence of systems thinking.

The concept of systems thinking and one's mental models are intrinsically linked. Senge [2], one of the pioneers of systems thinking, noted that business managers' poorly constructed mental models ignored critical system elements, non-linear responses, and misrepresented time delays in complex industry systems. Richmond [3] defines the act of thinking through the creation of mental models, claiming the construction of a mental model is a pre-requisite for evaluating systems present in one's life, thus underpinning any attempt at systems thinking.

3.3.3 Mental Models of Systems

Individuals' mental models have been a subject of research in the field of cognitive psychology for some time. Much of this work has served as the foundation for the understanding of mental models in systems dynamics, though Doyle and Ford [6] note there is considerable disagreement over key elements of mental models.

Forrester [21] describes mental models as an incomplete, imprecise, and transient mental construct used by individuals to represent systems in the world. Rouse and Morris [25] note that definitions of mental models while varied, mostly revolve around the themes of describing, explaining, and predicting one's surroundings. Doyle and Ford [6], after a review of a myriad of definitions from systems dynamics literature, define a mental model as "a relatively enduring and accessible, but limited internal conceptual representation of an external system whose structure maintains the perceived structure of that system" (p.19).

Efforts have been made to study mental models through several different means. Kieras and Boviar [12] examined participants ability to perform a set of procedures on a simulated control panel, both in normal operation and when faced with a malfunction. They argue that explanatory depth of a system is not necessary to operate a system effectively, and that device models improve an operator's mental model so long as it can support precise inferences about the controls. Conversely, a poorly presented device model can distort an operator's mental model of a system, leading to misunderstandings. Seel et al [31] simulate a distillation plant in which participants were given control. Seel et al. showed that participants drew on prior knowledge along with the knowledge gained in the experimental environment when responding to a simulated failure in the system. Bußwolder [32] examined mental models in a business environment, with participants controlling a new business with one product, investigating the impact of a framework on mental models of dynamic, opaque, and complex systems.

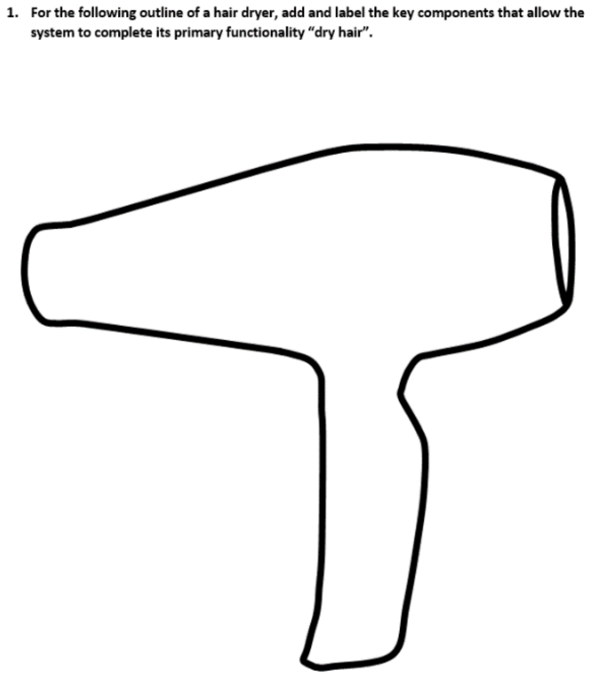
LaToza et al. [33] the communication of mental models among Microsoft developers working on complex software projects. They found that much design knowledge is kept in a mental model of the system, giving a sense of ownership over the code. This was also found for small teams. Ibrahim and Rebello [13] investigated students mental models of kinematics problems, finding that some students applied mathematics blindly while others relied heavily on diagrams and qualitative information, struggling to integrate "visual and symbolic representations" (p.222) of the system and not forming a complete mental model. Zhang [14] examined students' mental models of the Internet. Students were prompted to complete a search task and were found to think of the Internet from one of several different perspectives. These views impacted time taken and performance on the task. Zhang evaluated drawings instead of a questionnaire or interview, as it is a primitive form of communication that can be used across age groups to express conceptions of abstract systems like the Internet. These drawings were used to classify the different perspectives students held.

The basis for the instrument used in this study is an instrument developed by Lawson [34] in which participants were prompted to place components on a drawing of a bicycle, then draw the bicycle without the provided drawing. Participants were asked to self-evaluate their understanding of how a bicycle works both before and after completing the instrument. Lawson found that participants overestimated their knowledge of the bicycle system before the exercise, as many struggled to draw a functional bicycle despite rating their knowledge of how a bicycle works highly. Even those who rode bicycles regularly performed relatively poorly. These results indicate a phenomenon described by Kiel [23] in which people have an illusion of explanatory depth, believing that they possess a deeper and more complete knowledge about a system than they actually do. Kiel claims that people are prone to confusing "genuine insight at one level with insight at a lower level" (p. 670) of systems analysis, and that they don't understand that systems can be analyzed at different levels. Kiel also notes that depth may be dependent on context. When in the presence of the system in question, knowledge of parts and function may be enhanced. Lawson [34] gave participants a picture of a bicycle in another iteration of the test, and results improved, though there were still numerous errors. People's mental models are informed heavily by the causal patterns they see around them.

3.4 Instrument & Function-Based Scoring Procedure

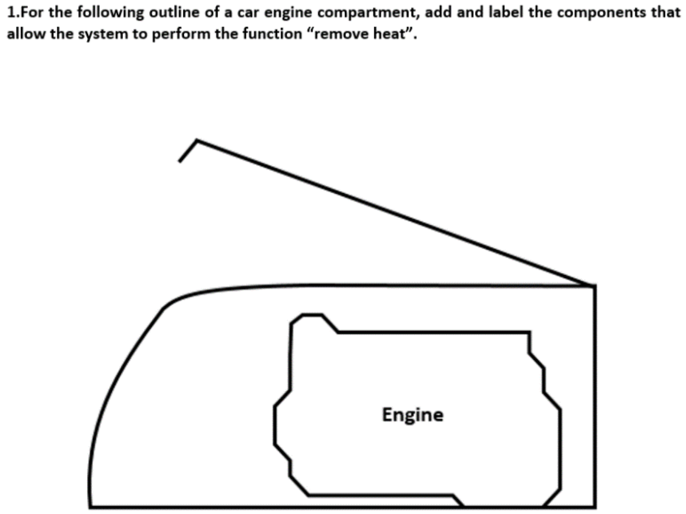
The instrument presented herein has been designed to elicit and evaluate students' mental models. The instrument is based on two functionally analogous systems, a hair dryer and a car radiator; these two analogous systems will allow for exploration of the knowledge transfer between the mental models of the two systems. Functional similarity of the two systems is demonstrated in [37] and using Module Heuristics [10].

The instrument is based on the visuals of Lawson's bicycle problem [34]; however, unlike in Lawson's study, the students were not given a bank of components, which increases the variety of answers and forces students to reason about likely components in the system. The instrument provides students with an outline of two systems and a prompt to draw and label the key components necessary for the two systems to perform their respective functions. To help ascertain whether functional modeling impacts analogy transfer, the instrument is modified for the second administration to include prompts asking students to generate functional models. The outline presented to the students, provided as Fig. 3.1 and 3.2, is similar in style to the visuals employed by Lawson [34].



1. For the following outline of a hair dryer, add and label the key components that allow the system to complete its primary functionality “dry hair”.

Figure 3.1. Hair dryer instrument as presented to students.



1.For the following outline of a car engine compartment, add and label the components that allow the system to perform the function “remove heat”.

Figure 3.2. Car radiator instrument as presented to the students

The hair dryer system was chosen due to its familiarity, as it is easy to use and is common in many American households. The car radiator is present, but less visible, and it is unlikely that a student would have an in-depth knowledge of the system unless they have worked extensively with cars. This difference is intended to elicit a mental model of both a familiar and an unfamiliar system. This allows for the examination of knowledge transfer between two systems facilitated by a tool like functional modeling, especially if one is initially understood less than the other. Previous work showed that students were able to correctly identify more components in the hair dryer system than the car radiator system, corroborating this hypothesis [9]. It was theorized that students would be able to use functional modeling to identify and utilize similarities in the function structures of the two systems to make predictions about the components likely to exist in the unfamiliar system (the car radiator). Expected components and a component-based analysis of the results is presented in [37].

The functional models for the hair dryer system and the car radiator system are provided as Fig. 3.3 and Fig. 3.4 respectively. When considering the systems using a functional abstraction, both may be thought of as systems that take energy from a source, transfer it to a fluid imported to the system (air in both cases), and then export the heated fluid. The end goal of both systems is, however, different. The hair dryer focuses on producing heat, while the car radiator works to remove heat from the system; this functional similarity means that both have the same core functionality.

To develop a generally applicable function-based scoring system (i.e., the approach can be applied to other systems beyond the hair dryer and the car radiator), the Module Heuristics approach [10] was used to compare the maximum possible functional similarity between the two systems. The Module Heuristic approach developed by Stone et al. provides three heuristics with which modules can be identified: 1) Dominant Flow, 2) Branching Flow, and 3) Conversion-Transmission [10]. For the functional models in question, the dominant flow heuristic was used, with one of the dominant flows, subdivided into two modules, the energy source and energy transfer modules to better represent the components involved in both systems as overlaid on the functional models provided as Fig. 3 and 4. Four functional modules were common to both systems: energy source, energy transfer, energy removal, and control.

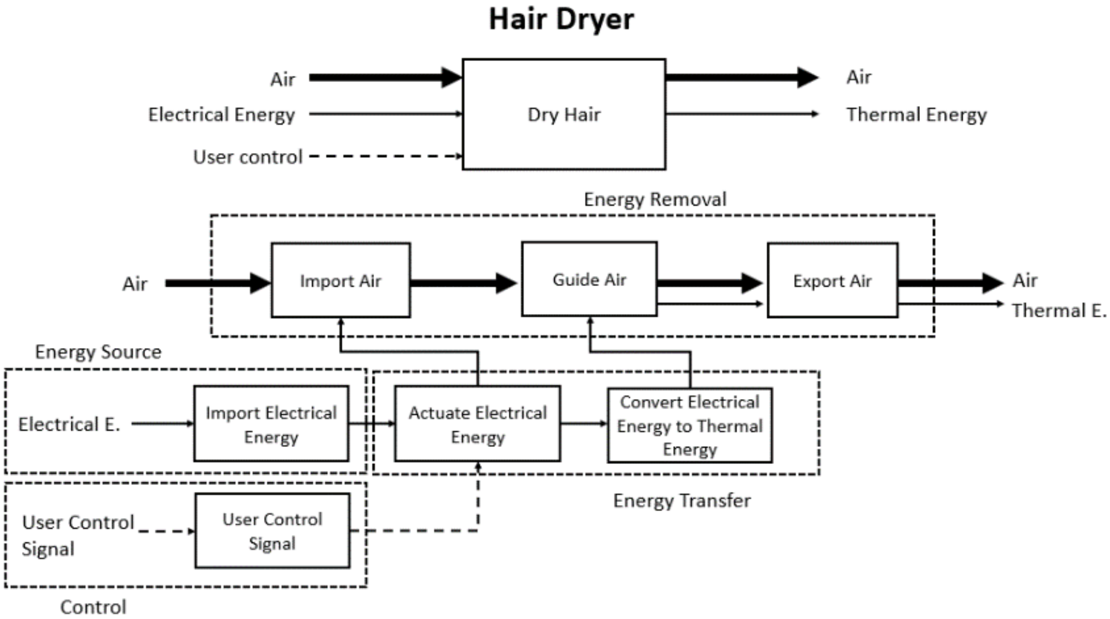


Figure 3.3. Hair dryer functional model with identified modules

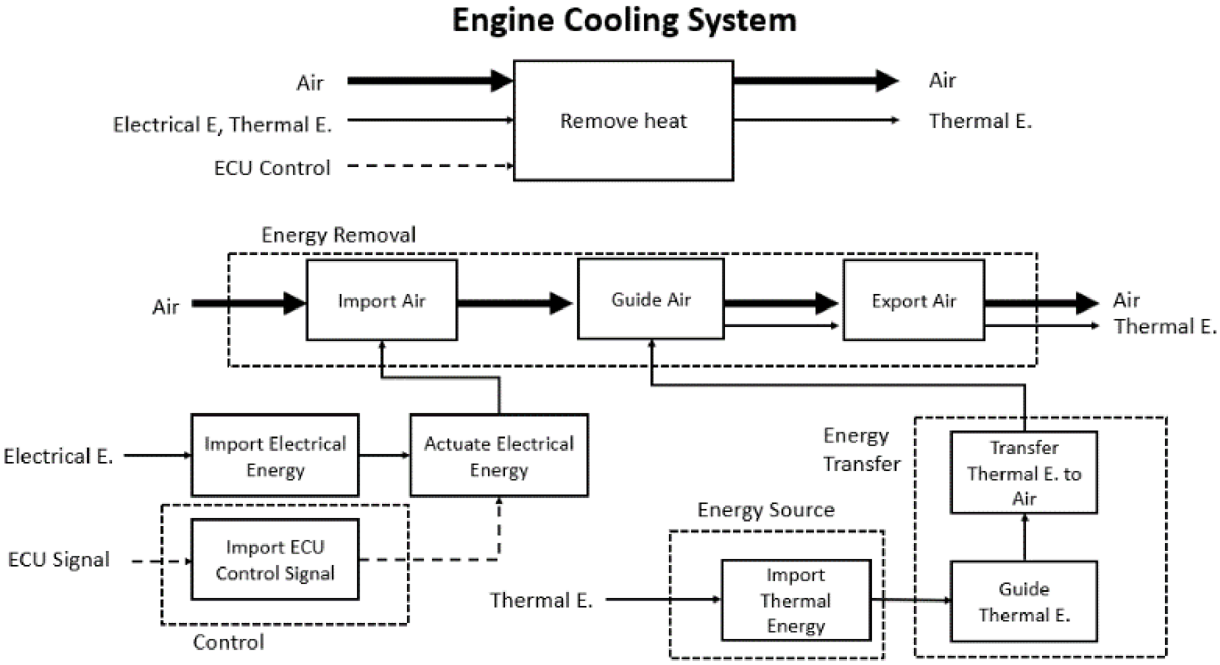


Figure 3.4. Car radiator functional model with identified modules.

The function-based scoring of the instrument investigates the students' generated functional models and their relationship to functionally analogous modules identified in student responses. The scoring procedure evaluated students' responses to the instrument for evidence that their mental model of the system included the four functional modules common to both systems. For each module, a list of components and notations that would signify acknowledgement of the module was generated. This is a broader approach than simply identifying components, as it allows for the student to note a module as a functional description, or as explanatory text and be credited with including the module in their mental model of the system. For example, a resistive heating coil may be used to acknowledge the module of energy transfer in the hair dryer, while a heat exchanger or radiator would do the same in the car radiator system. One could also draw a black box containing "heat air" or "transfer energy to air" and be credited with acknowledging that module. Table 3.1 provides the module descriptions for each functional model as well as the descriptions of the means used by each of the systems.

Table 3.1. Module descriptions and means

Module	System	Description of functional module
Energy Source	Hair Dryer	Electrical energy imported to run heating coil
	Car Radiator	Engine produces heat that is transferred to coolant
Energy Transfer	Hair Dryer	Heating coils take EE and transfer to air flow
	Car Radiator	Radiator/Heat exchanger takes heat from coolant to air flowing over
Energy removal (Fluid flow)	Hair Dryer	Fan pulls in air from surroundings over the heating element
	Car Radiator	Fan pulls air over radiator to cool coolant before pumping back into engine
Control	Hair Dryer	User controls dictate temperature of coil, speed of fan, on/off
	Car Radiator	Vehicle may have automated control of radiator fan, on/off state for when radiator is not needed

Table 3.2. Criteria for recognition of modules as used by coder

Module	System	1 - Recognition of function	0.5 - Partial Recognition	0 - No recognition of function
Energy Source	Hair Dryer	Electrical E. coming in (usually from a wall plug)		No source of Electricity entering the system
	Car Radiator	Coolant/fluid shown being exported from the engine.	Coolant/oil/fluid shown circulating but not leaving engine, heat drawn coming off engine	No coolant exported from engine or explicit heat transfer from engine
Energy Transfer	Hair Dryer	Heating coils, a heating element, something turning E.E. to Heat		No heating element
	Car Radiator	Radiator or heat exchanger with coolant flowing through being cooled by a flow of air	Air cooled system	No explicit demonstration of heat being transferred to medium
Energy removal (Fluid flow)	Hair Dryer	Fan or device to pull air into the hair dryer nacelle. Air flow shown	Only air flow shown	No fan or air flow included
	Car Radiator	Fan or device to pull air into engine compartment and air travels over E. Source	Only air flow shown	No fan or air flow included
Control	Hair Dryer	User controls included		No control mechanism included
	Car Radiator	Control of a pump or fan included		No control mechanism included

A scoring rubric was developed based on the modules identified for each of the two systems. This rubric contains a description of the functional module as seen in Table 3.1. Data coders are also given the information in Table 3.2, which further describes items that can constitute recognition of the module, partial recognition, and no recognition. This takes the form of further functional description and potential components that could satisfy the criteria. A partial recognition category is included to improve interrater agreement among ambiguous responses, where initial scoring trials struggled to agree.

3.5 Methodology

This study presented herein asked students to complete both portions of the instrument before and after learning functional modeling in a sophomore engineering design class at a central East coast, regionally-focused, liberal arts university. All students are enrolled in a general engineering program of study. The sophomore engineering design class is the students' first class in the programs six-course engineering design sequence, and the class provides students with their first introduction to functional modeling. During the class, students are taught the high-level skills associated with functional modeling, then are worked through a functional model example. Students then use the Grammar-based approach [39] to develop functional models in small groups while the instructor walks around and provides guidance. Students generate functional models individually for homework on a product not related to the course project, as well as in teams for the course project following feedback on the individual homework. Students are also tested on functional modeling during the final exam for the course.

The instrument was administered twice, once prior to learning functional modeling and once following learning functional modeling. Forty-seven students participated in the pre-functional modeling session, while 45 students participated in the post-functional modeling session. The second session took place approximately six weeks after the first. Students were compensated 5 points of extra credit to their in-class participation score for both administrations of the instrument.

Students were given approximately 15 minutes to complete the instrument at the end of a lecture. Students were given both systems at the start of the 15 minutes and were encouraged to start work with either system and to move between systems as desired. Their only other direction was to follow the prompt on the page. For the post-test, students were also directed to create a functional model for each system in addition to filling in the components in the outlines provided as Fig. 3.1 and 3.2, and they were given 30 minutes in total to allow for the added task. Fifteen minutes was deemed to be an appropriate amount of time to complete the instrument based on Lawson's method which allotted 10 minutes [34]. An additional 15 minutes was added for the functional modeling component based on the research team's experience working with students and functional modeling assignments.

3.5.1 Scoring Procedure

Each student response was evaluated based on the modules it contained as outlined by the criteria laid out in Table 3.2. Scoring was completed by two undergraduate engineering students, one Junior and one Sophomore. Both data coders had been exposed to functional modeling through the engineering program. To ensure interrater agreement, a sample of ten radiators and ten hair dryer responses were scored by both. A third senior undergraduate student evaluated the responses to the sample scoring for inter-rater agreement and facilitated group discussion over points of disagreement and updated the scoring rubric. Interrater agreement for each module was assessed with Cohen's Kappa, as shown in Table 3.3. Lowest interrater agreement existed in the car radiator questions, which received far more varied and ambiguous answers, still rated as fair agreement above random chance as classified by Landis and Koch's criteria [36].

Table 3.3. Evaluation of Inter-rater agreement using Cohen's Kappa (p<0.001)

Module	System	Cohen's Kappa	95% Confidence Interval	Level of Agreement [35]
Energy Source	Hair Dryer	0.877	0.739 to 1.0	Almost perfect
Energy Transfer	Hair Dryer	0.681	0.534 to 0.828	Substantial
Energy Removal	Hair Dryer	0.629	0.462 to 0.796	Substantial
Control	Hair Dryer	0.793	0.597 to 0.989	Substantial
Energy Source	Car Radiator	0.351	0.198 to 0.504	Fair
Energy Transfer	Car Radiator	0.443	0.300 to 0.586	Moderate
Energy Removal	Car Radiator	0.698	0.571 to 0.825	Substantial
Control	Car Radiator	0.710	0.398 to 1.0	Substantial

Each sample was given a module score by adding the total number of modules recognized. The two scorer's module scores given were averaged to give the final module score.

3.5.2 Functional Modeling Scoring

To accompany the instrument outline, students were instructed to generate a functional model for both the hair dryer and the car radiator during the post-functional modeling session. These functional models were evaluated using a 19-question rubric [40] developed to assess the mechanics of functional models. This rubric was applied by the same two undergraduate students who assessed the component drawing responses. As provided in Table 4, there was no to little agreement between the two reviewers. A discussion following the scoring of the functional models indicated that the reviewers were unsure how to score the functional models as they were difficult to read, difficult to follow, and followed few if any of the functional modeling standards taught and demonstrated by the students during class, on homework assignments, and on the exams. Consequently, functional modeling scores are provided as percent correct scores only to illustrate trends in the data.

Table 3.4. Interrater agreement for Functional Model Scoring

System	Cohen's Kappa	95% Confidence Interval	Level of Agreement [35]
Hair Dryer	0.056 (n=45)	-0.056 to 0.168	No to Little agreement
Car Radiator	0.029 (n=44)	-0.069 to 0.127	No to Little agreement

It should also be noted that as many students did not generate black box models with their functional models, the rubric results are separated into those relating only to the black box and those relating only to the functional model. This issue was not surprising as it has been shown in prior studies that when not asked to make a black box model, students tend to not make a black box model [41]. Eleven of the 19 questions in the functional modeling rubric can be used to score functional models, while eight of the questions pertain to the black box model.

3.6 Results

The functional model is scored out of 19 possible points; therefore, it is does not appear that students were able to create a mechanically correct functional model for either system based on the exposure they had been given, and a visual inspection of functional models confirms this result. Tables 3.5 and 3.6 show the breakdown of percent correct responses for questions 1-8 (black box questions) and 9-19 (functional model questions), respectively. The most common errors noted in the students' functional models were related to questions 5, 6, 8, 9, 17, and 18. Questions 5 and 6 deal with input and output consistency in the black box. Question 8 evaluates the black box for taking the form of a verb-noun pair, and question 9 addresses the overall plausibility of the functional model. Question 17 relates to the appropriateness of flow paths for product representation, while Question 18 evaluates flow conservation. That these questions scored low is not surprising given the challenges faced during the functional model scoring process.

Table 3.5. Breakdown of percent correct for rubric black box questions

Question	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Hair Dryer	43.2	43.2	34.1	28.4	4.5	2.3	23.9	12.5
Car Rad.	35.2	34.1	27.3	19.3	0.0	2.3	12.5	4.5

Table 3.6. Breakdown of percent correct for rubric functional model questions

Question	**9**	**10**	**11**	**12**	**13**	**14**
Hair Dryer	23.9	38.6	30.7	27.3	30.7	37.5
Car Rad.	23.9	45.5	23.9	33.0	33.0	42.0
Question	**15**	**16**	**17**	**18**	**19**	
Hair Dryer	28.4	43.2	29.5	29.5	26.1	
Car Rad.	36.4	34.1	13.6	21.6	25.0	

Table 3.7 provides the average functional model scores for the hair dryer and for the car radiator. Students had an average functional model score of 4.66 (representing 42.3% ‘correct’) and 2.48 (representing 35.9% ‘correct’) for the car radiator. Table 8 shows that students who created black box models earned more points out of questions 1-8 on the hair dryer than the car radiator, but the average score remained very low, 4.44 out of a possible 8.

Table 3.7. Average Functional Model Scores (Q 11-19) based on 19-question rubric for all students

System	n	Percent correct	Average Functional Model Score	Standard Deviation	Standard Error
Hair Dryer	33	42.3%	4.66	3.05	0.54
Car Radiator	37	35.9%	3.95	2.13	0.35

Table 3.8. Average Black Box Scores (Q 1-8) based on 19-question rubric for all students

System	n	Percent correct	Average Functional Model Score	Standard Deviation	Standard Error
Hair Dryer	19	55.6%	4.44	1.24	0.29
Car Radiator	24	31.0%	2.48	0.90	0.18

Several additional hypotheses related to changes in the students’ mental models were also posed based on the impact learning to generate functional models; these were explored through the change in students’ module scores. Table 3.9 provides the average number of modules identified by the students pre- and post-learning functional modeling for both the hair dryer system and the car radiator system. Results do not indicate that the average number of modules changed from the first time the instrument was administered to the second. Consequently, the students do not appear to have gained insight regarding the system through function, nor through another unintended source. Students' mental models did not change significantly following learning to generate functional models.

Table 3.9. Average Number of Modules Identified Among all Students

	System	n	Average Modules Identified	Standard Deviation	Standard Error
Hair Dryer	Pre-Function	47	3.027	0.828	0.121
	Post-Function	44	3.091	0.904	0.136
Car Rad.	Pre-Function	45	1.261	0.915	0.136
	Post-Function	44	1.221	0.833	0.126

Figure 3.5 shows the students' changes in scores in the hair dryer plotted against the scores from the car radiator. This plot shows that most students generally improved at least slightly, on the hair dryer, recognizing more modules in the post-test, though there were several examples of large regressions as well. Roughly equal numbers of students improved and regressed on the car radiator, and no clear correlation exists between the change in hair dryer modules identified and the change in car radiator modules identified.

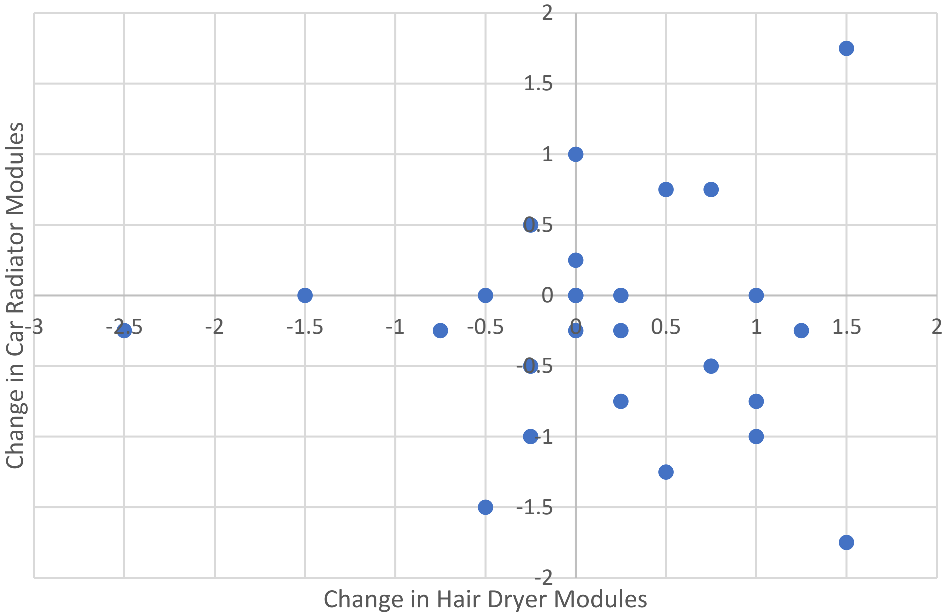


Figure 3.5. Individual's change in hair dryer module score vs. their change in car radiator module score (n=26)

Figures 3.6 and 3.7 show the change in module scores plotted against the functional model score (out of 19). In this case, only students with responses for both sessions and both systems were considered. This set contained 26 complete sets of student responses. Figure 3.6 shows that on the hair dryer the majority of students did improve in the post-session. This improvement is dominated by students who scored below 10 on the functional model. It is possible that students spent more time drawing than making the functional models. This is illustrated in Fig. 3.8 as well, where high scoring hair dryers varied greatly in the quality of their functional models. This trend does not carry over into the car radiator, as module score changes were generally lower. Similarly, Fig. 3.9 shows that car radiator module scores plotted against the functional model scores, with more varied and generally lower module scores. Individual students' mental models of the hair dryer did improve, but there were individuals who regressed as well. There is not evidence that students' mental models of the car radiator changed significantly.

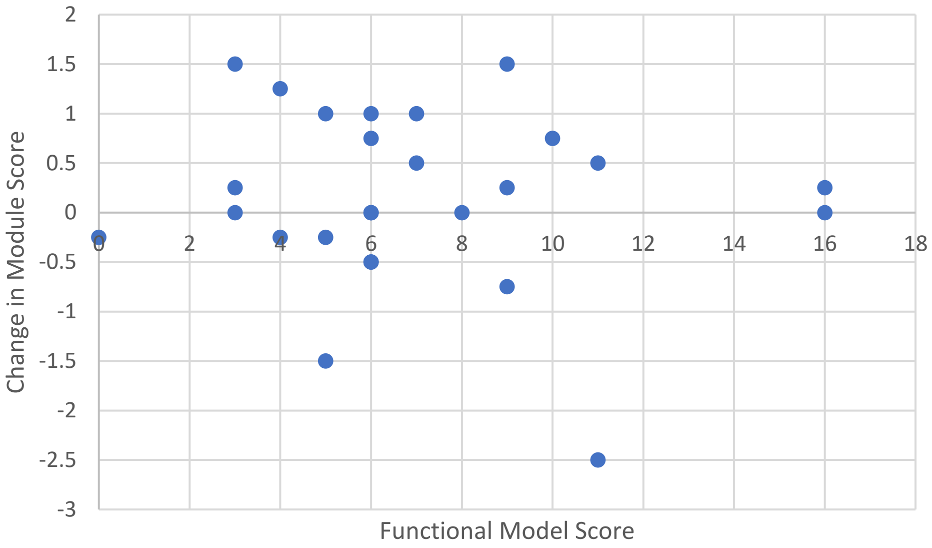


Figure 3.6. Change in module score compared to students' scores on functional models for hair dryer system (n=26)

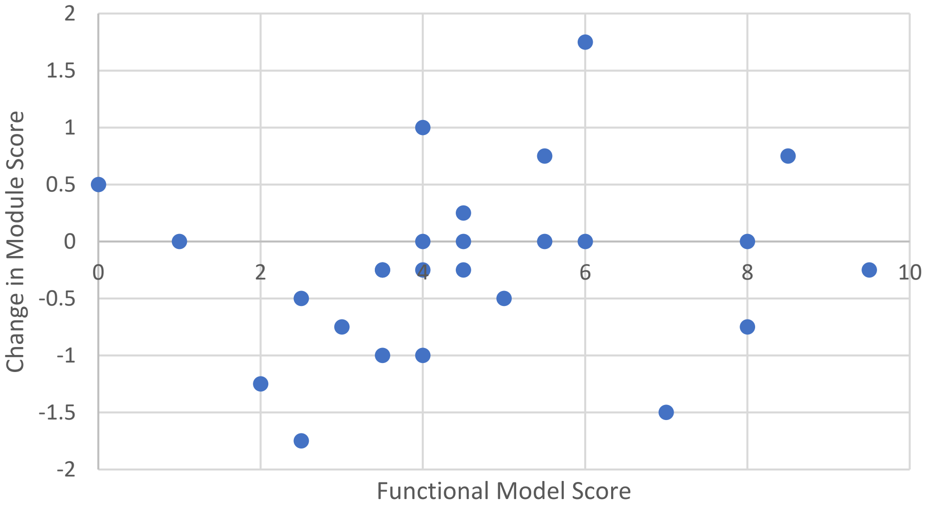


Figure 3.7. Change in module score compared to functional model score for radiator system (n=26)

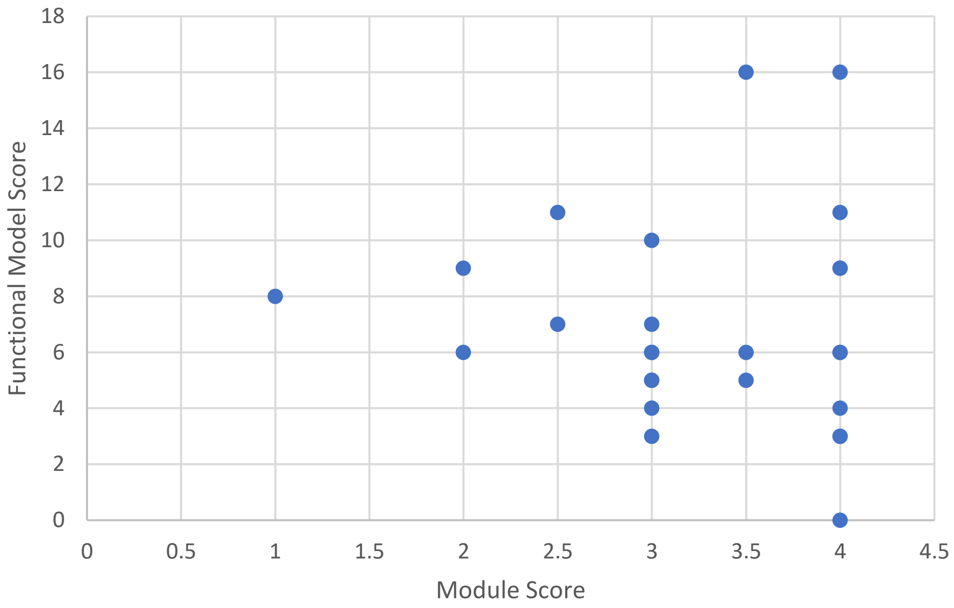


Figure 3.8. Change in module score compared to functional model score for hair dryer system (n=21)

For Fig. 3.8 and Fig. 3.9, only students who created functional models of the system were considered. Students providing only the black box portion were omitted, but students who provided functional models in addition to black box models were considered. Comparing Fig. 3.8 and Fig. 3.9 shows again that students generally recognized more of the functional modules in the hair dryer than the car radiator, but as a whole were unable to generate mechanically correct functional models of either system.

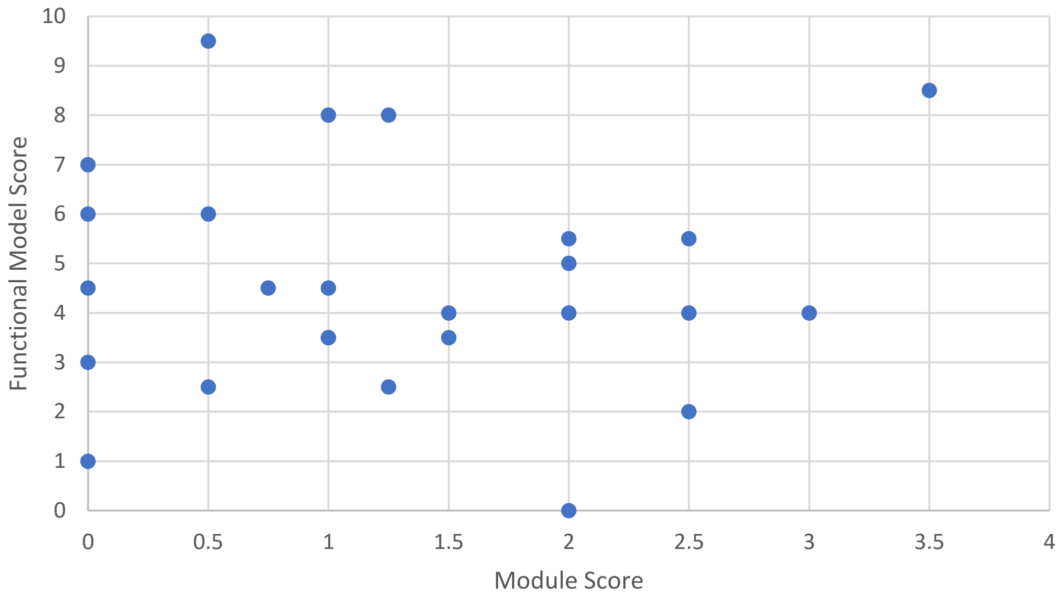


Figure 3.9. Change in module score compared to functional model score for the hair dryer system (n=25)

3.7 Discussion

3.7.1 Scoring Schema

Analysis of the open-ended responses such as the hair dryer and the car radiator present challenges due to the breadth of possible responses [5], but the technique presented herein based on functional modeling and Module Heuristics allows for a direct observation of students' design tendencies. This rubric that can be conformed to the solution space rather than defined by a list of expected components; further, it does not limit a researcher to self-reported survey questions. Instead, this scoring schema illustrates and captures similarities between analogous systems and aids a researcher to identify if knowledge transfer occurs between those systems at the Module Heuristic-level.

Consequently, we believe that this approach provides flexibility to allow for evaluation of students' design work directly, and we demonstrate that with a Module Heuristic-based rubric, high interrater agreement is attainable.

3.7.2 Student Responses

Students did not make complete or mechanically correct functional models of either the hair dryer or car radiator system. The average modules identified remained the same, so as a group students' mental models did not change appreciably.

Students who had participated in both sessions generally improved the modules recognized in the hair dryer; however, this improvement does not relate to a high-scoring functional model. The car radiator had a less-defined trend when examining change against functional model scores. This indicates that individual increases in the hair dryer were not due to the functional model, as similar improvements were generally not seen in the car radiator. It also appears unlikely that students were able to transfer knowledge between the analogous systems using functional modeling, based on the lack of change in scores and the fact that students may not have completed their functional models until after completing the drawing exercise. It should be noted, though, that as this was the first use of the instrument presented herein, the authors were trying to provide minimal instruction such as to gain an understanding of the students' behavior when confronted with such an open-ended prompt; it is clear now that more instruction will be required to help students recognize that they could consider the two systems together instead of independently.

Fig. 3.10 shows a high-scoring hair dryer with all four modules represented, and Fig. 3.11 shows the accompanying functional model, which was a high-scoring functional model as well. Fig. 3.12 shows a typical car radiator response, which was incomplete and often fixated on the intake air flow and placement of the air inlet.

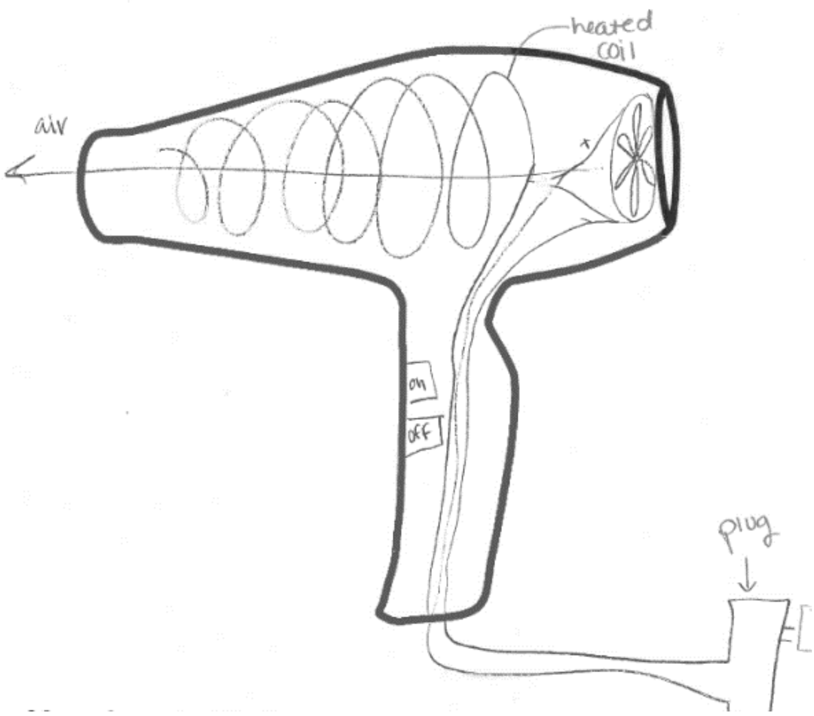


Figure 3.10. A high scoring hair dryer with four modules

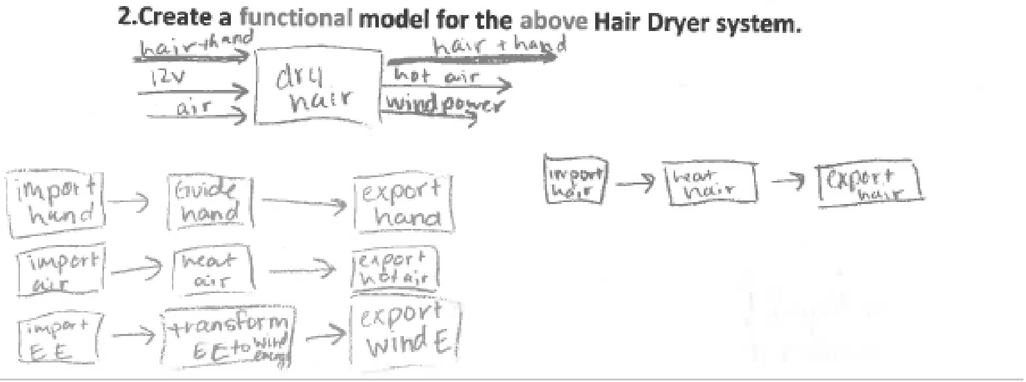


Figure 3.11. Corresponding functional model for Figure 3.10 (Score of 16).

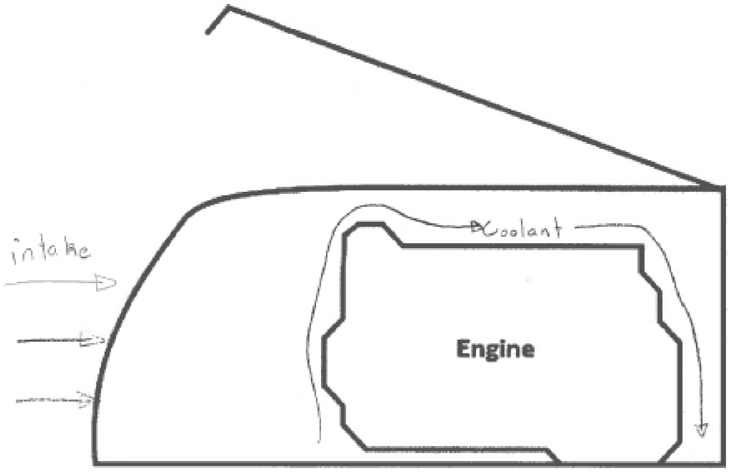


Figure 3.12. A typical car radiator response with score of 0.75/4

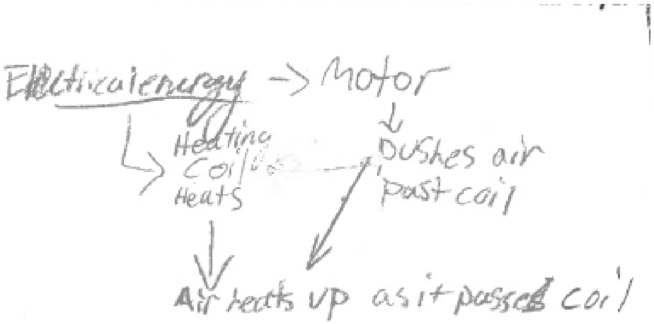


Figure 3.13. Low scoring functional model from a high scoring hair dryer.

High understanding of the modules present in a hair dryer (as seen in Fig. 3.10) did not correspond to a better functional model, as functional model scores ranged from 0 to 16 among students that had all modules accounted for (a module score of 4). Fig. 3.11 scored a 16. Fig. 3.13 shows a functional model generated for a hair dryer by a student who recognized all four modules in the hair dryer. The functional model in Fig. 3.13 received a total score of 1.5.

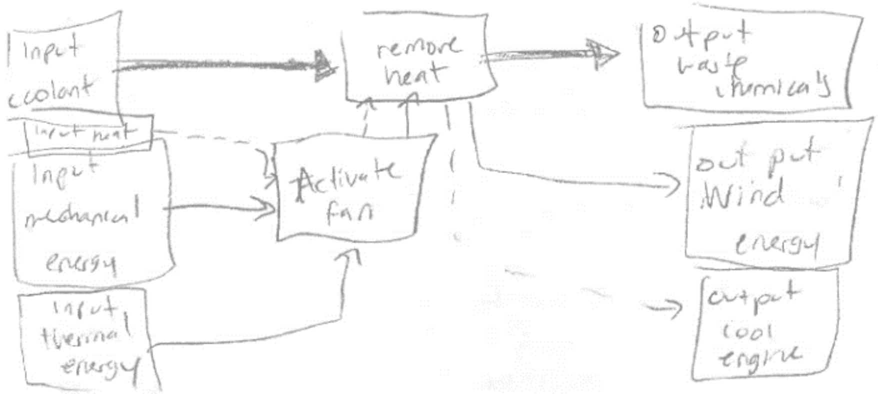


Figure 3.14. A difficult to interpret functional model of a car radiator

In the future, the authors would prompt students to create functional models before completing the drawing assignment, to encourage them to see connections between the functional model and the system. One may also provide students with expert functional models of the two systems to aid them in the exercise, in addition to asking them to draw their own. That may allow them to better recognize functional similarity between the two systems, based on limited functional modeling experience. It also ensures that students complete the drawing of components while having a functional model to reference. In this study, we postulate that the students likely made their functional models after completing the drawing activity, meaning they would not have referenced the model in completion of the activity; future studies will include the functional modeling steps before the hair dryer and radiator component activities.

Many of the student responses provided only a black box or a sub-functional model, and in general, models appeared to be rushed; rushing, however, did not appear to be an issue when studying the components added to the hair dryer or the car radiator. Consequently, students may have spent most of their time on the drawings and then rushed to complete their functional models (based the assumption that functional models were completed second). Alternately, students may have chosen to focus on the familiar as they had already seen the hair dryer and car radiator prompts before.

Time may be an issue as well, as fifteen minutes may not be enough time for students to reason about the functional similarities between two unfamiliar systems. Likewise, for the post-test, 30 minutes may not be an adequate amount of time to reason about two unfamiliar systems and generate two mechanically correct, thoughtful, and complete functional models.

3.8 Conclusion

The work present herein provides initial steps toward a method to evaluate mental model transfer between two analogous systems. Instrument and the scoring schema presented herein provide promise as allowing the research team to begin studying students' mental models and the relationship between mental models and functional models. While results concerning mental model transfer between analogous systems and student use of functional models during representation of mental models were inconclusive, one system clearly is more straightforward for students, while the other is more difficult. It is believed that if transfer is to be studied, analogous systems with this difficulty difference will be required.

Further, a functional Module Heuristic-based approach to rubric development is presented and demonstrated with high interrater agreement for scoring the instrument. This scoring approach provides a generalizable scoring approach focused on modular similarity between systems rather than focusing on specific listed components as categorical data. This gives comparable criteria in two functionally similar systems with different end goals, allowing for the evaluation of knowledge transfer in aspects of the systems. Future studies will explore this generalizability.

3.9 Acknowledgments

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4. Discussion

The instrument presented in this work elicited students' mental models for the two functionally-analogous systems. The research team hypothesized that the hair dryer would initially be more intuitive for students, and the results from the instrument confirm this. Students had more complete mental models of the hair dryer than the car radiator when evaluating based on components as well as based on function. It is perhaps not surprising that students would hold a more incomplete mental model of the car radiator, as it is not a visible system, the user does not directly interact with the system, and it has no visible inputs and outputs. This knowledge disparity between systems is potentially valuable when identifying points where knowledge was transferred from one system to its analogous counterpart. There is little evidence of knowledge transfer in this study; however, the research team believes that alterations to the presentation of the instrument and functional modeling task may allow for students to better identify and utilize the functional similarity to inform mental models of the unfamiliar system.

A component-based scoring method and a function-based scoring method can be used to evaluate student responses to this instrument. This work demonstrates that both methods can give insight into student responses and can demonstrate inter-rater agreement with two data coders. A function-based approach is more generalizable and can capture a wider range of potentially valid responses, but for a simple system, a component-based method may be adequate to provide insight into students' mental models. In addition, both methods presented similar results, that students had more complete mental models of the hair dryer than the car radiator, and that the introduction of functional modeling did not significantly change the student's responses.

Additionally, it was observed that students were unable to make accurate and complete functional models of either system, achieving low scores on a rubric for functional models. These low scores and a lack of improvement in both systems makes it unlikely that students utilized functional modeling to transfer knowledge between the more-familiar hair dryer and the less-familiar car radiator. This may be due, in part, to the layout of the study itself. Students were not instructed to complete the tasks in the session in any particular order, but the paper instrument given to students presented the instrument above the functional model prompt. Thus, there is no guarantee and little likelihood that students created functional models before completing the component drawing activity, and therefore are unlikely to have referenced their functional models when thinking about the system.

Though no clear positive relationship was observed between the quality of mental models elicited and the introduction of functional modeling, the instrument and methods developed in this study provide a useful starting point for further exploration of students' mental models and how they are influenced by design tools, ultimately aiming to inform the development of systems thinking skills among engineers. The instrument and methods presented in this work can be adapted for any set of functionally analogous systems, and allow for a direct observation of system knowledge as opposed to an indirect self-reported observation of perceived knowledge.

5. Future Work

To investigate the impact of functional modeling further, the presentation of the tasks in this study may be changed. In the post-functional modeling section, students are prompted to generate functional models for the system after filling in the components for the system above. Though not required to proceed in any particular order, it is unlikely that students created functional models for one system before doing the drawing activity for that system. Future studies should ask students to create functional models before completing the drawing activity and give them a separate sheet of paper to do so on. It may also be beneficial to specify a space for the black box model and functional model, as a common issue in this study was students doing only one element, a black box model or a functional model. It may also be interesting to gain more personal insight into thought processes, which may be done through interviews with willing participants.

Continuing work using this instrument may apply these changes and gather more data, with the goal of allowing students' to generate more complete functional models in addition to eliciting their mental models. Students should be able to use their generated functional models to inform their responses to the instrument. This instrument could be implemented again in the Fall of 2018, and one of the remaining undergraduate researchers has experience utilizing both component-based and function-based methods for evaluating responses.

An updated study procedure for the post-functional modeling session may follow this order:

1. Students are instructed to generate functional models of the hair dryer and the car radiator;
2. Students are then given instrument to complete; and

3. Student interviews are conducted regarding knowledge of the system and perception of the instrument.

Future studies may also include different sets of analogous systems, for instance a coffee maker and a solar water heater. This work provides a framework for identifying and analyzing these analogous systems, as the Module Heuristics-based scoring method allows a researcher to identify the maximum possible functional similarity between two systems and adjust scoring criteria accordingly.

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