2018 ASEE ANNUAL CONFERENCE & EXPOSITION
JUNE 24–27, 2018
SALT PALACE CONVENTION CENTER
SALT LAKE CITY, UT

Paper ID #21795

# The Impact of Functional Modeling on Engineering Students' Mental Models

**Jacob Thomas Nelson**
**Dr. Julie S. Linsey, Georgia Institute of Technology**

Dr. Julie S. Linsey is an Assistant Professor in the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technological. Dr. Linsey received her Ph.D. in Mechanical Engineering at The University of Texas. Her research area is design cognition including systematic methods and tools for innovative design with a particular focus on concept generation and design-by-analogy. Her research seeks to understand designers' cognitive processes with the goal of creating better tools and approaches to enhance engineering design. She has authored over 100 technical publications including twenty-three journal papers, five book chapters, and she holds two patents.

**Dr. Robert L. Nagel, James Madison University**

Dr. Robert Nagel is an Assistant Professor in the Department of Engineering at James Madison University. Dr. Nagel joined the James Madison University after completing his Ph.D. in mechanical engineering at Oregon State University. He has a B.S. from Trine University and a M.S. from the Missouri University of Science and Technology, both in mechanical engineering. Since joining James Madison University, Nagel has helped to develop and teach the six course engineering design sequence which represents the spine of the curriculum for the Department of Engineering. The research and teaching interests of Dr. Nagel tend to revolve around engineering design and engineering design education, and in particular, the design conceptualization phase of the design process. He has performed research with the US Army Chemical Corps, General Motors Research and Development Center, and the US Air Force Academy, and he has received grants from the NSF, the EPA, and General Motors Corporation.

**Prof. Matt Robert Bohm, Florida Polytechnic University**

Matt Bohm is an Associate Professor of Mechanical Engineering at Florida Polytechnic University (Florida Poly). He joined the University in 2016 after spending 6-years as an Assistant Professor of Mechanical Engineering at the University of Louisville (UofL). Bohm's research examines the intersection of 3 distinct areas, engineering design, engineering education, and big data. Currently, Bohm has an active NSF grant under the Division of Undergraduate Education to examine the effects of systems modeling paradigms with respect to design outcomes and systems thinking and understanding. While at UofL, Bohm was primarily responsible for overseeing the Mechanical Engineering Department's capstone design program. Prior to his position at UofL, Bohm was a visiting researcher at Oregon State University (OSU) after completing his PhD at the Missouri University of Science and Technology (S&T) in 2009. While at S&T, Bohm was also a Lecturer for the Department of Interdisciplinary Engineering and was responsible for coordinating and teaching design and mechanics related courses.

## 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.

## Introduction

Engineers from all disciplines rely on modeling in some form for much of their work, particularly in conceptual design [1,2,3]. 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 [4]. There have been studies to gauge the systems thinking ability of students and professional engineers [5, 6, 7, 8, 9, 10], 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 [11,12] 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 students' mental models of systems in engineering design, and to investigate if and how students' 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.

## Background

### *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 allow exploration of problems in a "solution-neutral" manner. Flow-based models generally stem from the work of Pahl and Beitz [1] 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 [2].

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 and from the black box model to the sub-functional model.

Functions are generally described as a verb-noun or verb-object pair [3, 13] and can utilize a common lexicon of functional transformations in the Functional Basis [13]. 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.

### *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 [11]. Senge [14] 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 [15]. 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. [8] define systems thinking as a "major high-order thinking skill that enables individuals' to successfully perform systems engineering tasks" (p. 32) in the development of their Capacity for Engineering Systems Thinking (CEST) instrument. Kordova et al. [16] describe 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 [17] 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." [9] 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. [4] identify thinking holistically as a primary competency of a systems thinker. Derro and Williams [10] note the ability to find patterns across a system, and Chan [18] 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. [8] 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. [9] developed a questionnaire based on 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 [19], 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 [20] 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 [21] 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 [12] 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 [22] 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.

### *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 [23]. Rouse and Morris [24] 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 [25]. Sterman [26] 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 [27] 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 [22] 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 [23] 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).

### *Evaluating Mental Models*

Due to the individual and amorphous nature of mental models, experimentally testing one's mental models poses a challenge. Endsley [28] 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. [29] 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. [29] 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 give insight into their mental models. Kieras and Bovair [5] 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. [30] 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 were drawn on along with the knowledge gained in the experimental environment. Bußwolder [31] 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. [32] 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 [6] 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 [7] studied students' 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.

### *The Bicycle Problem*

The instrument used in this study is based on a problem from the field of cognitive psychology. Lawson [33] 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 the number of errors committed, and the subject's impressions of their knowledge of the task both before and after. She found that participants overestimated 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 [19] description of the Illusion of 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 [19] proposes that most people have this Illusion of Explanatory Depth, 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.

## **Methods**

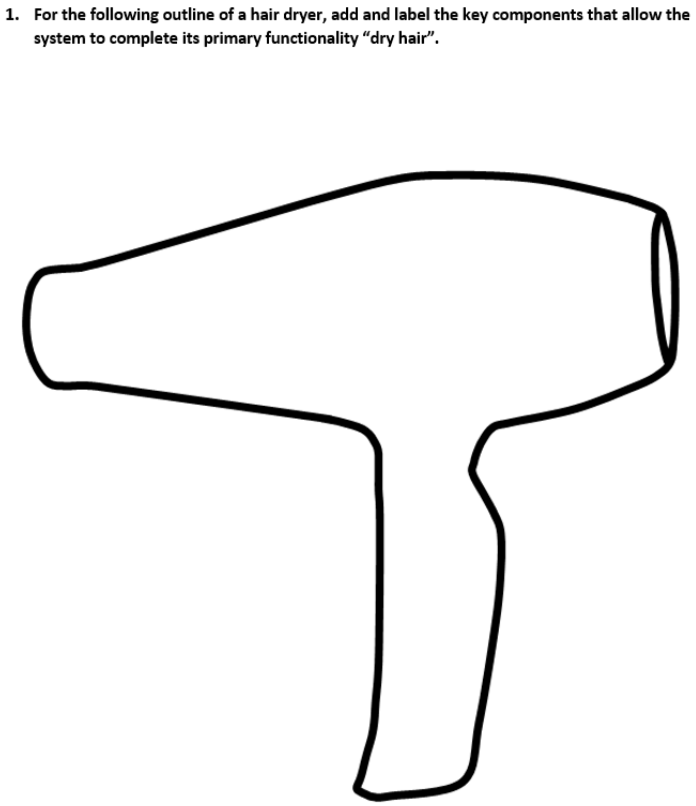
### *The Instrument*

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. It is intended to elicit students' mental models allowing them to be externalized. The main 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 these instruments 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 instrument is presented with the goal of eliciting students' mental models of systems, to identify and help correct misconceptions and evaluate changes in students' perceptions of systems. Students' recognition of gaps in their mental models may also serve to improve their mental models of systems if given feedback using this instrument.

The visual approach is based on Lawson's bicycle problem [33] 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 theorized 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 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 1. Hair dryer instrument as presented to students**

The car radiator system, provided as Figure 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".**

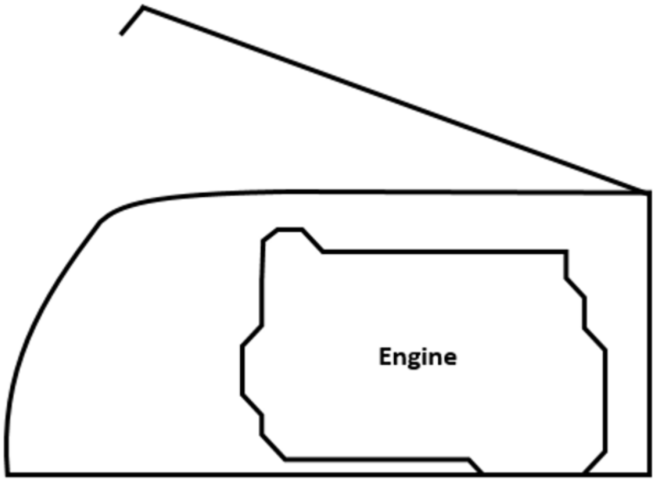


**Figure 2. Car radiator as presented to students**

The expected components of the hair dryer, provided as Figure 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 4, follow the outline in the Bosch Automotive Handbook, 9th Ed [34], 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.

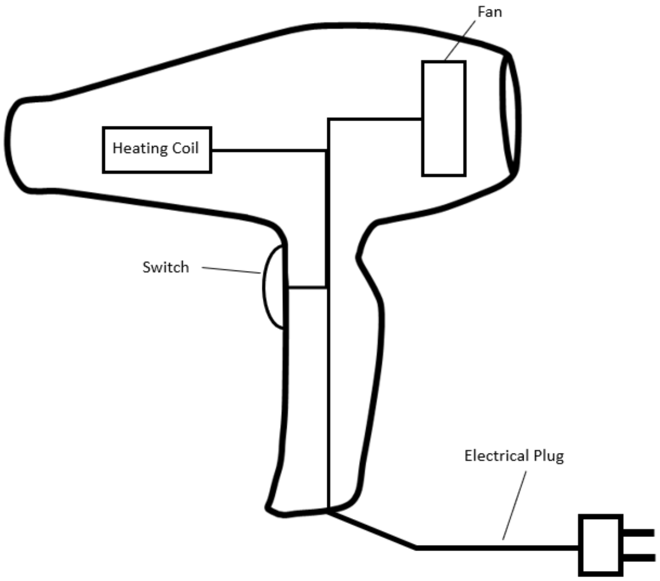


**Figure 3. Complete solution for hair dryer**

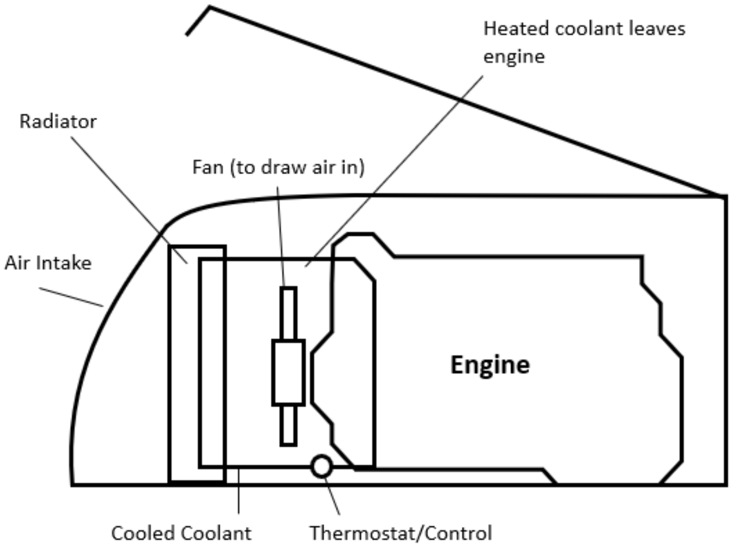


**Figure 4. Complete solution for car radiator**

*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.

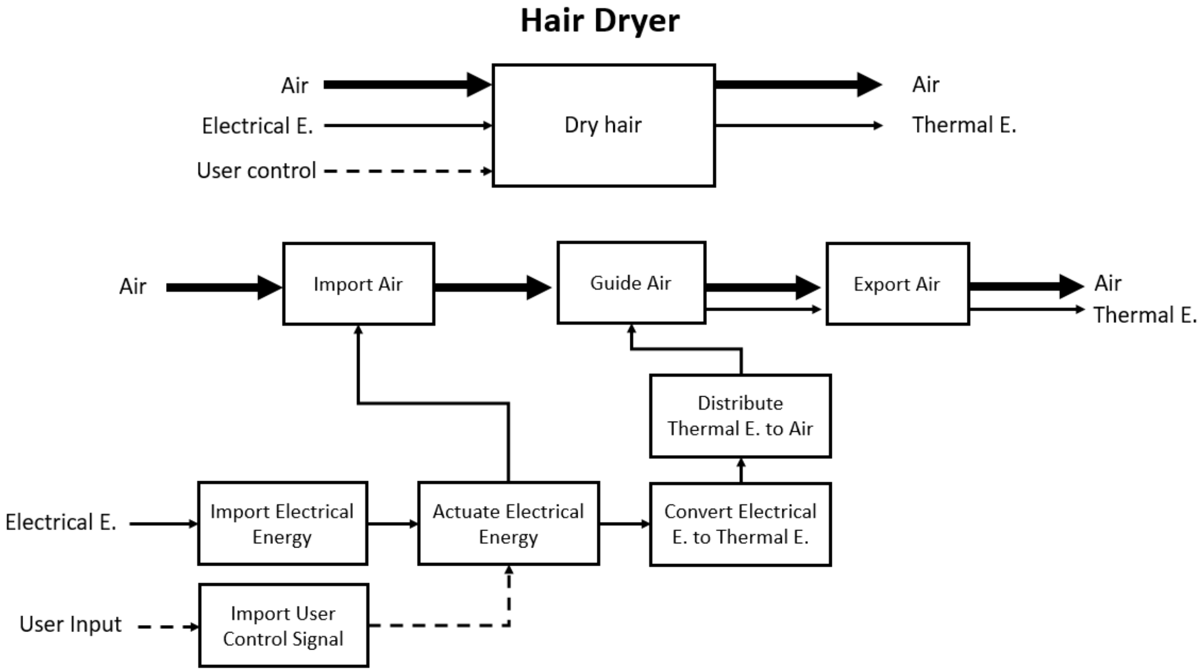


**Figure 5. Functional model for hair dryer system**

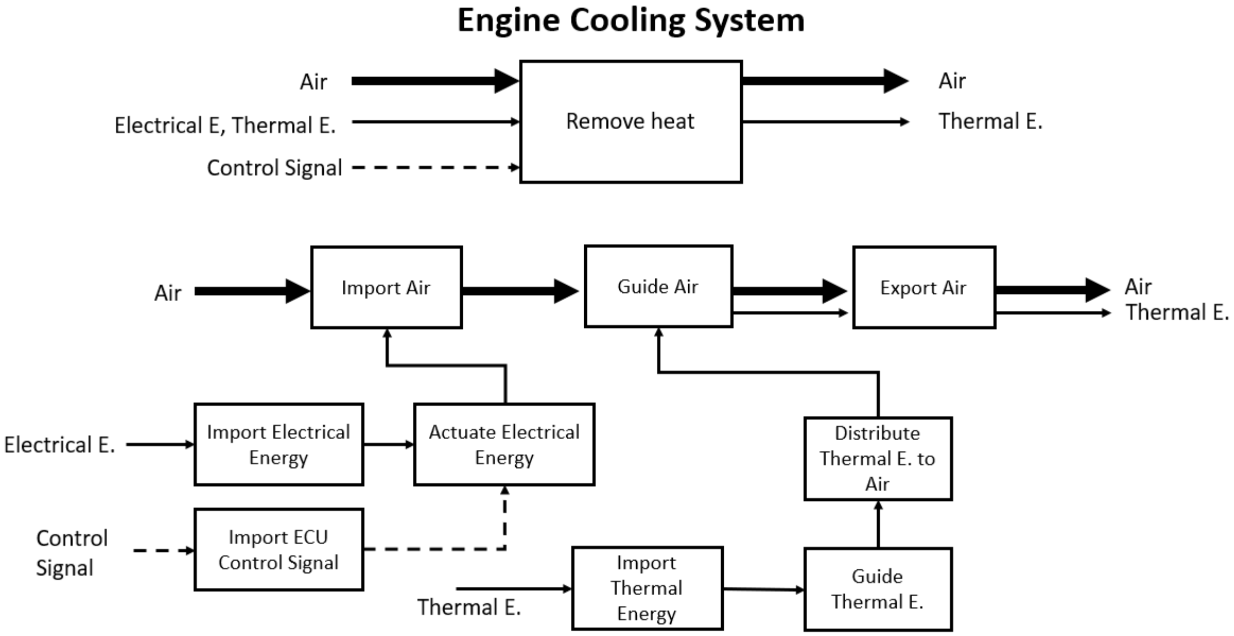


**Figure 6. Functional model for car radiator**

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 1.

**Table 1. Functional similarity mapped to common components between systems**

| Hair Dryer Component | 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 a comprehensive US East coast university. This study was run in 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 instruments on paper. The students were allotted approximately 15 minutes to complete the instruments. This time was based off the amount of time given to participants in Lawson's bicycle problem [33]. Lawson reported that the bicycle problem was completed in 5-10 minutes, and the team allotted an additional 5 minutes beyond that. Future work will evaluate if 15 minutes is sufficient time. 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. The additional 15 minutes were added based on available class time and the instructor's experience teaching functional modeling.

### *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 criteria in Table 2 attempts to capture the equivalent component from Table 1, which can then be mapped to its equivalent function.

**Table 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 the same comprehensive US East coast 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 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 [35]

## Results

### *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.

### *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 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 |

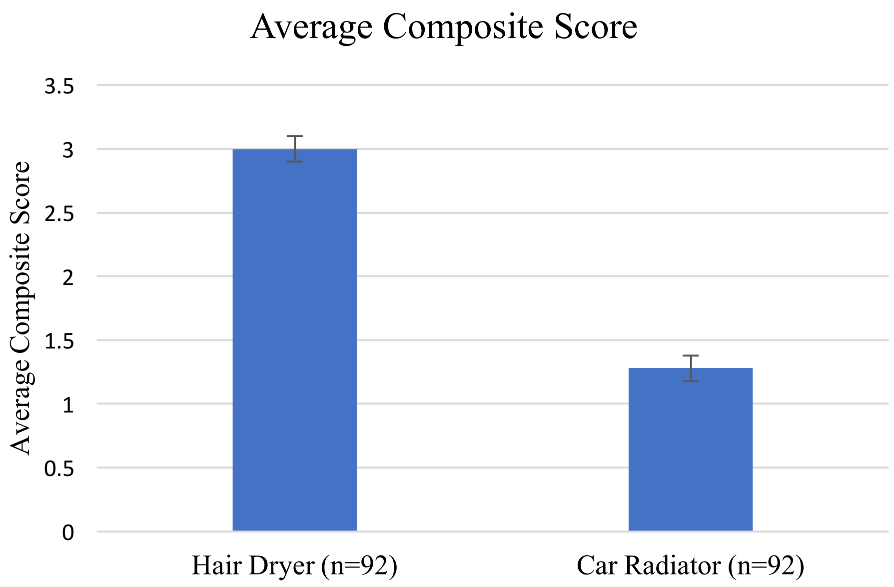


**Figure 7. Average composite score**

Table 4 and Table 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 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 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 |

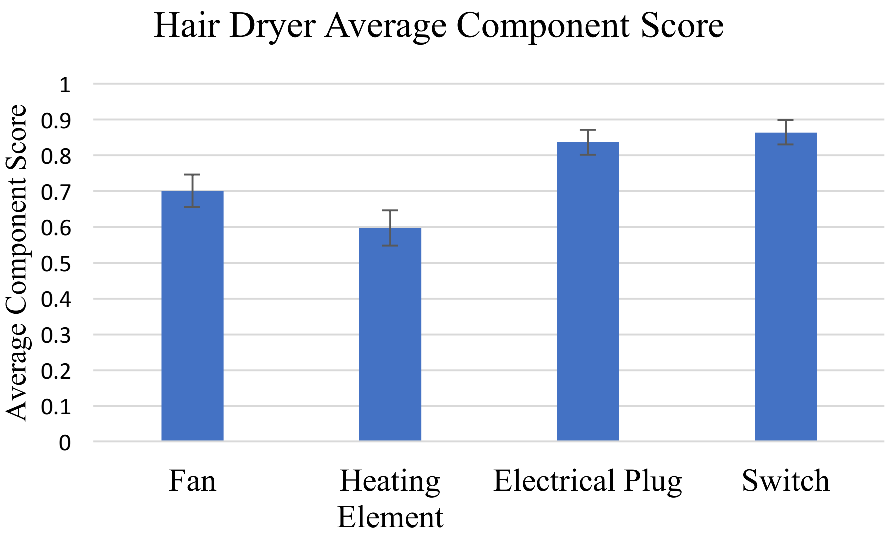


**Figure 8. Average scores awarded by component for hair dryer system**

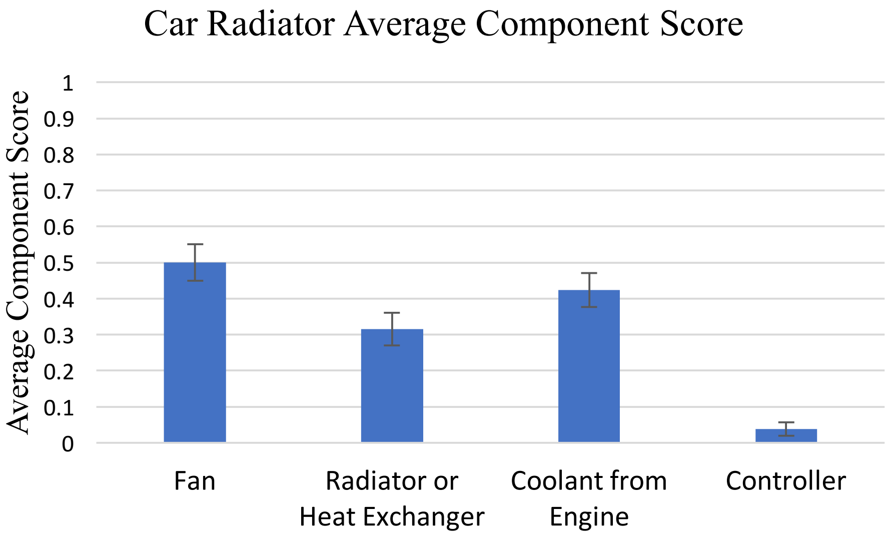


**Figure 9. Average scores awarded by component for car radiator system**

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.

## 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 instruments 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 [36]. 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 hairdryer 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 10 and 11 show interesting alternative responses to the prompt. Figure 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 11 shows an abstracted hair dryer, with functional blocks replacing the components.

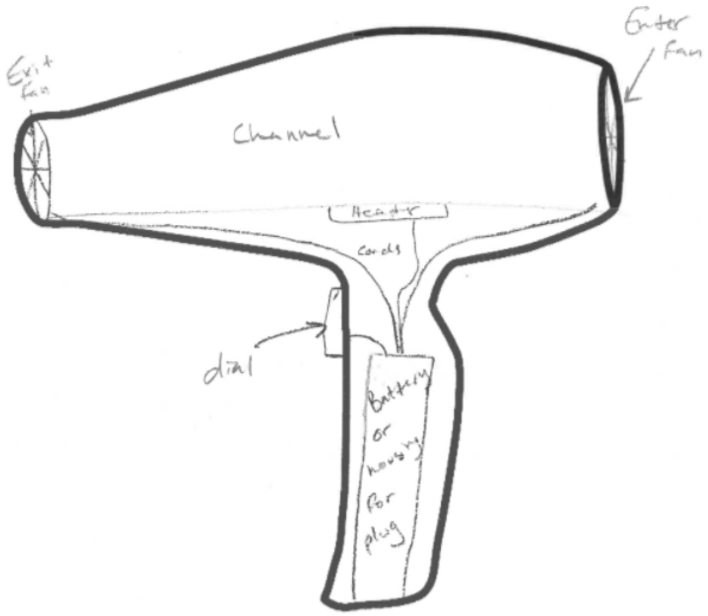


Figure 10. Example of an alternative solution response

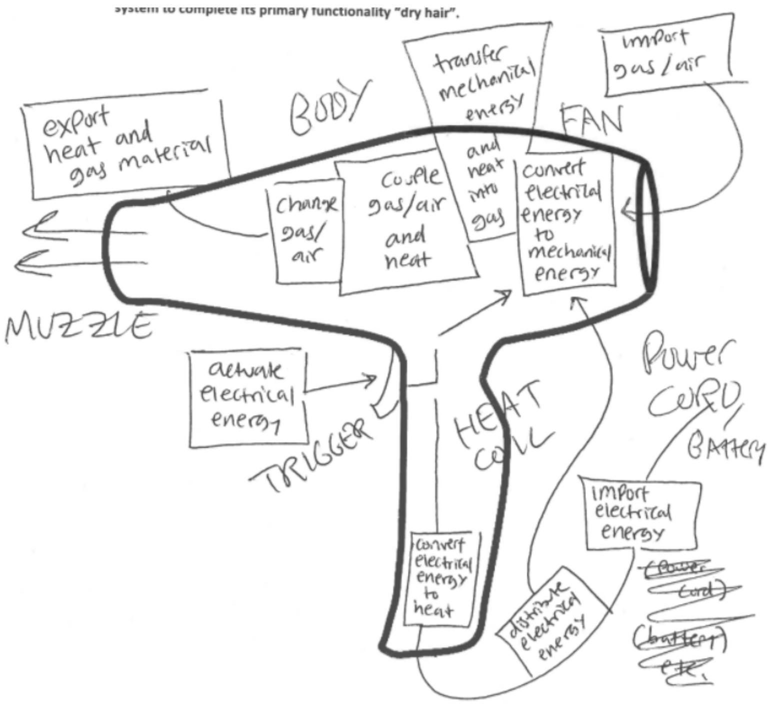
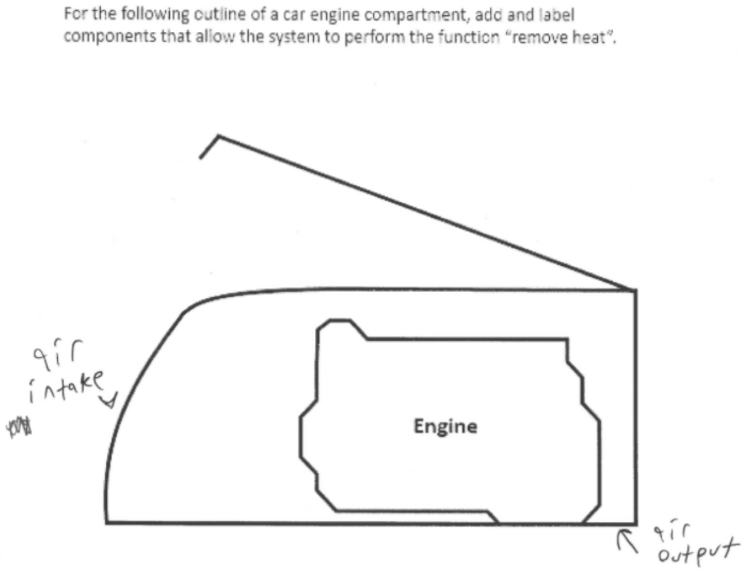


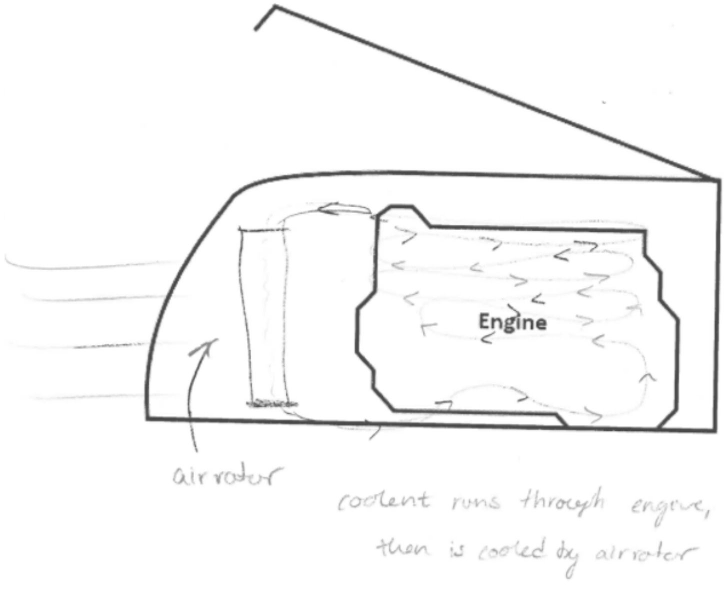
Figure 11. A functional hair dryer response

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 12. This is an incomplete response, but it does represent perhaps the most intuitive judgment that can be made about the system. Other results, such as the one shown in Figure 12, 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 12. Example of an incomplete student radiator response, identifies only air flow**



coolent runs through engine,
then is cooled by airrotor

**Figure 12. 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 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.

## Conclusion

The students' divergent responses to the pair of functionally analogous systems give 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 complete than their mental models of the car radiator system. 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 identifying 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 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.

## Acknowledgments

This work is supported by the National Science Foundation through Award No. DUE 1525449, 1525170, and 1734519. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of National Science Foundation.

## References

[1] Pahl, G., Beitz, W., Feldhusen, J., 2007, "Engineering Design: A Systematic Approach," Springer, London.

[2] Nagel, R. L., and Bohm, M. R., 2011, "On Teaching Functionality and Functional Modeling in an engineering curriculum," ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, ASME, Washington, D.C.

[3] Dym, C.L., Little, P., and Orwin, E.J., 2014, "Engineering design," Wiley, New York.

[4] Huang, S, Muci-Kuchler, K. H, Bedillion, M. D, 2015, "Systems thinking skills of undergraduate engineering students," IEEE, pp. 1-5.

[5] Kieras, D. E., and Bovair, S., 1984, "The Role of a Mental Model in Learning to Operate a Device," Cognitive Science, **8**(3) pp. 255-273.

[6] Ibrahim, B., and Rebello, N. S., 2012, "Using Johnson-Laird's Cognitive Framework of Sensemaking to Characterize Engineering Students' Mental Representations in Kinematics," Physics Education Research Conference, (1413) pp. 219-222.

[7] Zhang, Y., 2007, "The Influence of Mental Models on Undergraduate Students' Searching Behavior on the Web," Information Processing and Management, **44** pp. 1330-1345.

[8] Frank, M., Sadeh, A., and Ashkenasi, S., 2011, "The Relationship among Systems Engineers' Capacity for Engineering Systems Thinking, Project Types, and Project Success," Project Management Journal, **42**(5) pp. 31-41.

[9] Camelia, F, Ferris, T. L. J, and Cropley, D. H, 2015, "Development and Initial Validation of an Instrument to Measure Students' Learning about Systems Thinking: The Affective Domain," IEEE Systems Journal, **PP**(99) pp. 1-10.

[10] Derro, M. E., and Williams, C. R., 2009, "Behavioral competencies of highly regarded systems engineers at NASA," IEEE Aerospace Conference pp. 1-17.

[11] Richmond, B., 1993, "Systems Thinking: Critical Thinking Skills for the 1990s and Beyond," System Dynamics Review, **9**(2) pp. 113-133.

[12] Senge, P. M., and Sterman, J. D., 1992, "Systems Thinking and Organizational Learning: Acting Locally and Thinking Globally in the Organization of the Future," European Journal of Operational Research, **59**(1) pp. 137-150.

[13] Hirtz, J., Stone, R. B., McAdams, D. A., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," Research in Engineering Design, **13**(2) pp. 65-82.

[14] Senge, P.M., 1994, "The Fifth Discipline," Currency Doubleday, New York.

[15] Forrester, J. W., 1994, "System Dynamics, Systems Thinking, and Soft OR," System Dynamics Review, **10**(2-3) pp. 245-256.

[16] Kordova, K, S, Ribnikov, G, and Frank, M., 2015, "Developing systems thinking among engineers: Recent study findings," IEEE, pp. 50-53.

[17] Valerdi, R, and Rouse, W. B, 2010, "When systems thinking is not a natural act," IEEE, pp. 184-189.

[18] Chan, W. T., 2015, "The Role of Systems Thinking in Systems Engineering, Design and Management," Civil Engineering Dimension, **17**(3) pp. 126-132.

[19] Keil, F. C., 2003, "Categorisation, Causation, and the Limits of Understanding," Language and Cognitive Processes, **18**(5-6) pp. 663-692.

[20] Hopper, M. A., 2007, "Proposing Measures for Assessing Systems Thinking Interventions," University of Nevada Las Vegas.

[21] Tomko, M. E, Nelson, J. T, Linsey, J, Bohm, M., & Nagel, R. L, 25 August, 2017, “Towards assessing student gains in systems thinking during engineering design”. International Conference on Engineering Design.

[22] Richmond, B., 2005, "An Introduction to Systems Thinking," ISEE Systems.

[23] Doyle, J. K., and Ford, D. N., 1998, "Mental Models Concepts for System Dynamics Research," System Dynamics Review, **14**(1) pp. 3-29.

[24] Rouse, W. B., and Morris, N. M., 1986, "On Looking into the Black Box: Prospects and Limits in the Search for Mental Models," Psychological Bulletin, **100**(3) pp. 349-363.

[25] Forrester, J., 1971, "Counterintuitive Behavior of Social Systems," Theory and Decision, **2**(2) pp. 109-140.

[26] Sterman, J, 1994, "Learning in and about Complex Systems," System Dynamics Review, **10**(2-3).

[27] Smith, M., 2003, "Peter Senge and the Learning Organization," Training & Management Development Methods, **17**(5) pp. 1039.

[28] Endsley, M. R., 2000, "Situation Models: An Avenue to the Modeling of Mental Models," Proceedings of the Human Factors and Ergonomics Society Annual Meeting, **44**(1) pp. 61-64.

[29] Besnard, D., Greathead, D., and Baxter, G., 2004, "When Mental Models Go Wrong: Co-Occurrences in Dynamic, Critical Systems," International Journal of Human - Computer Studies, **60**(1) pp. 117-128.

[30] Seel, N., Daraibi, A. A., and Nelson, D., 2006, "Understanding Models for Learning and Instruction," Tech, Inst. Cognition and Learning, **4**pp. 303-329.

[31] Bußwolder, P., 2015, "The Effect of A Structured Method on Mental Model Accuracy in Complex Decision Making," Clinical Microbiology Newsletter, **37**(4) pp. 33.

[32] LaToza, T., Venolia, G., and DeLine, R., May 28, 2006, "Maintaining mental models," ACM, pp. 492-501.

[33] Lawson, R., 2006, "The Science of Cycology: Failures to Understand how Everyday Objects Work," Memory & Cognition, **34**(8) pp. 1667-1675.

[34] Robert Bosch GmbH, 2014, "Automotive Handbook," Bentley Publishers, Germany.

[35] J. Richard Landis, and Gary G. Koch, 1977, "The Measurement of Observer Agreement for Categorical Data," Biometrics, 33(1) pp. 159-174.

[36] Stone, R. B., Wood, K. L., and Crawford, R. H., August 1998, "A Heuristic Method to Identify Modules from a Functional Description of a Product", IDETC DTM Conference, ASME.