AC 2011-1088: CHARACTERIZING RESPONSES TO OPEN-ENDED QUESTIONS IN HEAT TRANSFER BASED ON EVERYDAY SITUATIONS

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Characterizing Responses to Open-ended Questions In Heat Transfer Based on Everyday Situations

Abstract

In this study, eight graduate students in heat transfer were given a series of written questions, based on everyday situations, and the responses were analyzed. The responses included a range of approaches to answering these questions, as well as a variety of content that was included. This paper looks at an in-depth analysis of the responses to the questions that were asked and suggests expert-like thinking in heat transfer includes following different problem solving approaches for different types of problems, depending on the prompt for the problem. Future research should verify these initial findings.

Introduction

In order to improve the learning experience of our students, we aim to contribute to the understanding of the learning process. This characterization of what expert heat transfer understanding looks like could help both educators and students to better guide towards expert-like thinking as well as contribute to the research database on expertise. Heat transfer is a core component of most Mechanical Engineering bachelor degree programs and a field of growing technical importance. For example, in the integrated circuit industry, heat transfer analysis is a key factor in designing components, such as memory devices and transistor density, and systems, such as personal computers and servers. Many energy conversion processes in developing clean energy technology fields rely on heat transfer analysis and precise thermal management in order to function optimally.

While there is much work studying expertise in many areas including chess[1], physics[2, 3], computer science[4], and medicine[5], there is little work characterizing what experts do that is different from novices in the field of heat transfer analysis. In addition, while there is much work on understanding experts' knowledge structure in these different fields, there is very little work on how experts solve so-called open-ended problems. This paper sheds some light on expert problem solving in the field of heat transfer, so that we may better understand where our students are going and enlighten us in aiding them there.

This paper aims to address the question of "what characteristics of problem-solving are used by experts when solving open-ended heat transfer problems?" and "what are the characteristics of the problem statement that correlate with different types of responses?"

Methodology

This research considers how eight individuals with a background in engineering and heat transfer solve 11 heat transfer problems. Our discussion on methodology begins by describing who these eight individuals are (and why they do or do not quality as "experts"). Then we consider the types of heat transfer problems we asked them to solve. This is followed by a description of our analysis methods---in other words, how we coded the responses of the eight in order to make sense of their answers.

Selecting Participants

This research considers how eight individuals schooled in engineering and heat transfer solve a set of heat transfer problems. The eight individuals reported on in this paper had three or more years of post-bachelors study in heat transfer at a leading research institution at the time of data collection. In addition to having passed a Ph.D. qualifying exam in heat transfer consisting of conceptual and analytical components, these individuals have each conducted at least two years of research in topics in heat transfer. Upon completion of their Ph.D.s they will likely go on to hold expert positions in industry, become leading researchers at government labs, or be hired as experts in their field of heat transfer at other prominent universities.

Can these eight be considered heat transfer experts? Here the idea of relative expertise[7] is relevant. While these participants may not qualify as experts in absolute terms, they are considered experts when compared to people who are novices in the field. The people referred to here as experts would fall under the category of "journeyman" according to Hoffman's levels of expertise due to having achieved a level of competence yet still working under supervision[8]. In addition, we chose to use graduate students as our expert population because of the nature of our study. Students are familiar with, and possibly experts with more than 10 years of experience on, being assigned written contrived problems to respond to through written responses. Additionally, from limited piloting of the questions and format with heat transfer experts with more than 10 years of experience in industry, we saw much hesitation to writing answers and uneasiness in answering questions. We attributed this uneasiness to a lack of familiarity with the written contrived question and written answer format. Thus the eight participants are experts in heat transfer, in a relative sense.

Here, we will refer to our graduate student participants as experts. While we are grouping our eight experts in a single category, we acknowledge that there may be differences between experts in how they conceptualize their field[9]. The experts completed 12 to 15 written open-ended questions in addition to a brief survey describing their specific area of expertise and their current research project.

Designing and Identifying Questions

Questions were designed to tap into thinking and reasoning in heat transfer through open-ended deep reasoning questions, prompting long answers, and questions requiring more than recall (e.g. application). The questions aimed to cover a wide range of heat transfer topics to provide a balanced view of the subject. Inspiration for the prompts came from work on concept inventories and misconceptions.

Open-ended questions that intentionally lacked details were chosen because of the similarity to problems encountered in the role of heat transfer expert. Experts are rarely confronted with a situation in which they are given all of the necessary information and then asked to solve for a specific value as is common in the problems found in text books. Because of the lack of detail, answers to solutions to these problems depend on the assumptions that the expert makes, just as they do in expert experience. In referring to the ambiguity of the problems, one of the co-authors, a professor who has studied heat transfer for more than 10 years, said "This is the real stuff." In addition, this professor commented "that is the art" in reference to making simplifying assumptions[10]. Everyday situations were used to allow novices who do not have the background vocabulary to be able to understand the questions. All eight of the participants were asked the same 12 questions, 11 of which are analyzed here. One question was omitted from the analysis because of a discrepancy in the meaning of the words used in the question.

Questions were more open-ended than are possible on a forced choice concept inventory, so a very rich data set was established. All of the questions could be considered "long-answer questions" (eliciting more than a one-word response)[14], falling under the category of deep-reasoning questions (asking why, what if, and how) and deep questions according to Graesser's interpretation of Bloom's taxonomy[14]. Graesser labeled any questions that pertained to Bloom's Taxonomy level of 1.2 or higher as deep questions[14].

Bloom's taxonomy includes the levels Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation[15]. Anderson's revised version has the levels Remember, Understand, Apply, Analyze, Evaluation, and Create[16]. Our questions fall in the "application" level of Bloom's taxonomy[15] or the "Apply" column and "Conceptual knowledge" row of the revised version[16] as the students were asked to apply their knowledge about heat transfer to a new situation in order to predict or explain what would happen in that situation. The questions also require "comprehension" or to "understand" as the respondent must interpret what is meant in the problem statement. If the expert was familiar with the specific situation and knew the answer without needing to reason through the concepts, the question would fall under "knowledge" or "remember." Bloom states that "here again the nature of the previous instruction is the deciding factor rather than the appearance of the item" (Bloom, 1954, p.82).

Inspiration for the questions came from concept inventory work and common misconceptions identified by Olds[11], Streveler[12], and Prince[13]. In addition, comprehensive questions addressing multiple modes of heat transfer and different key concepts were included to further characterize the experts' approach to solving general heat transfer problems. Examples of comprehensive problems are Questions 1, 5, and 9 from Figure 1.

The order in Figure 1 is the order that the problems were presented for 5 of the eight experts. The order was determined based on the order that the material is presented in the undergraduate level introductory heat transfer course. The questions were piloted with graduate students who were familiar with heat transfer, yet were just shy of qualifying as experts in this study. The piloting determined the approximate time needed to answer each question in addition to identifying unclear wording.

1. Oven Mitt

How does an oven mitt successfully keep your hands from getting too hot when you reach into a hot oven?

Inspiration: Comprehensive question including conduction, convection, radiation, temporal components, and material properties.

2. Cookie

You have a chocolate chip cookie that recently came out of the oven. You touch the outside of the cookie and it seems cool enough to eat. As you bite into it, a melted chocolate chip burns your tongue. How does this happen?

Inspiration: Comprehensive question including conduction, convection, radiation, temporal components, and material properties. Also includes contact temperature[13].

3. Carpet

When standing in a cool room that has both carpet and tile flooring with one bare foot on each type of material, the tile will feel colder than the carpet. Please explain why.

Inspiration: Concept inventory work on contact temperature[12, 13].

4. Seatbelt

You get into a car that has been sitting in the sun on a hot day. You notice that the metal part of the seat belt buckle feels like it burns you but the plastic part of the seat belt buckle does not. Why? Please explain.

Inspiration: Concept inventory work on contact temperature[13].

5. Cookie Sheet

You are baking cookies and have just pulled two cookie sheets out of the oven. The cookie sheets have the same thickness (which is very thin) and same ratio of width to length, and one of the cookie sheets is twice as long as the other. Will one cookie sheet cool more quickly than the other? If so, which one cools faster and why? If not, why do they cool at the same rate?

Inspiration: Concept inventory questions on factors affecting rate of heat transfer[13]. Comprehensive question including conduction, convection, radiation, temporal components, and material properties.

6. Punch

You are planning on making punch and you would like to cool it with ice. At the store, there are 2 different one-pound bags of ice to choose from: one that contains large ice cubes and one that contains small ice chips. You only want to purchase one bag of ice and will add the entire bag to the punch.

a) Would one of the bags cool the punch at a faster rate? If so, which one and why? If not, why?

b) Would one of the bags of ice cool the punch to a lower temperature? If so, which one and why? If not, why?

Inspiration: Concept inventory questions on rate versus temperature[12, 13].

7. Egg

I have always wondered if the saying "it was hot enough to fry an egg on the sidewalk" could be true. Please describe how you would determine if this could really happen. State any assumptions you would make. State any additional information that you would need and what you would do with the additional information.

Inspiration: Comprehensive question including conduction, convection, radiation, temporal components, and material properties.

8. Car

You are buying a new car and the only thing that you are concerned about is how hot it will be when you get in it each day on the way home from work. (You work during the daytime, don't have a covered parking spot, and want the car that feels least hot when you get in it.) The cars that you can choose from are identical except for the outer finish and your choices include a car painted white, a car painted black, and a car with a polished shiny metal finish. Which car would you choose and why?

Inspiration: Concept inventory work on understanding factors affecting radiation[13].

9. Plane

In a recent movie about snakes and a plane, there was a need to turn the air circulation system on the plane off. In the movie, the inside of the plane became hotter once the air system was turned off. In real life, do you think the inside of the plane would get warmer or cooler without the air circulation system (do you think the air circulation system acts as a heater or air conditioner)?

Inspiration: Comprehensive question including conduction, convection, radiation, temporal components, and material properties.

10. Hot Chocolate

Imagine that you have just walked outside on a cold day with a mug of hot chocolate. Do you think your beverage will:

____ Stay the same temperature
____ Become cooler
____ Become warmer

Please describe what you think is happening to the heat in your beverage.

Inspiration: Comprehensive question including conduction, convection, radiation, temporal components, and material properties.

11. Air vs Water

Please explain why walking around campus in 60 °F weather feels comfortable, but swimming in the ocean at 60 °F feels very cold.

Inspiration: Concept inventory work on feeling rate of heat transfer versus temperature[12,13].

Figure 1. The prompts for each of the eleven questions

Data Collection

Each expert participant was given the written questions and told that the expectation was that each question would take about five minutes to complete. The experts were also asked to answer each question without consulting books or getting help from others. Each question was on a separate page, and they were told to answer the questions in the order that they were presented. This minimized "flipping back" to answer previous questions, and thus the amount of time spent thinking about each question should roughly match the amount of time was spent looking at that question's page. The participants spent anywhere from three minutes to 10 minutes on each question.

The prompt for each question began with: *Please answer completely and to the best of your ability. State any assumptions that you need to make in your answer.* Each question page ended by asking the participant to *Please indicate your confidence in answering each question* on a four-point Likert-scale indicating the expert's self-reported confidence in their answer (1=Guessing, 2=Smart Guessing, 3= Confident, 4=Very Confident).

Analysis Procedure

Initially, each question was coded for both the content of the response and the methods used to communicate the response such as equations and diagrams. The idea to look at content and methods is based on work by Elio and Scharf which identified "strategies or basic approaches" (Elio and Scharf, 1990, p. 580) and "content and organization of problem solving knowledge" (Elio and Scharf, 1990, p. 581) as two characteristics of problem solving that vary by level of expertise[17].

The first round of coding considered content. Responses were coded for content by counting each reference to each mode of heat transfer: conduction, convection, and radiation; material properties; relative importance; thermal resistances; temporal relevance; assumptions; and other specific concepts that varied by question.

The first round also considered the tools used in the response. Responses were initially coded for approach by counting diagrams, thermal circuits, and equations. Each response was coded by checking whether or not diagrams were present, checking whether or not thermal circuits were present, etc. In heat transfer, thermal circuits are used as an analogy to electrical circuits because the equations prevalent in heat transfer are of the same form as the equations used in electrical circuits[18]. An example of thermal circuits can be seen in Figure 2 part C. In addition, experts' levels of confidence were coded.

During this first round of coding it became apparent that some questions elicited much more thorough responses which led to developing a measure for depth of response; to capture this there was a second round of coding. In addition, it was noted that some questions seemed more likely to have responses that include the option that the answer is only correct some of the time, or under certain circumstances; this resulted in a third round of coding.

The second round of coding aimed to capture something about the length of the responses. To this end the concept of "unique ideas" was defined, where an idea is the smallest discrete unique thought that is represented by thermal circuits, text, diagrams, or equations. As an example "*they would cool to the same temperature, assuming no heat transfer to the environment*" would be counted as two ideas. The assumption of "*no heat transfer to the environment*" would count as one idea, and the conclusion that "*they would cool to the same temperature*" would count as another idea.

Furthermore, if ideas were present in a diagram or equations that were not present in the text, they would be included. For example, a response including a diagram indicating convection to the air would count as an idea. Alternatively, if a response included a statement of the conclusion, an explanation, and then restated the conclusion again, the conclusion itself was only counted once. Distinct ideas were only counted once, even if they were presented multiple times in the text, diagrams, and equations. Additionally, assumptions that were not explicitly stated were not counted. As a result, some of the experts responded to the car problem with statements like "*you should pick the one with the lowest emissivity, so that it absorbs the least energy.*" This statement makes sense if the expert is acting under the assumption that the emissivity and the absorptivity are equal. However, if the response does not include equating the emissivity to absorptivity, that assumption is not counted as a separate idea. The length of response was determined by counting the number of distinct ideas that were included in the response.

In coding for length, another feature emerged; namely that some answers were written in a way that indicated that the answer is correct all of the time while other answers included indicators that they would only be correct some of the time, under certain circumstances, or within certain bounds. This prompted a third round of coding. In this round responses were classified as belonging to the "correct some of the time" group if there was present a word or phrase allowing variation in response. Mentioning assumptions, bounds, or caveats garnered placement in the "correct some of the time" category. Examples of words or phrases that were coded include the following: "*some oven mitts…*" which indicates that some oven mitts have those characteristics and others do not; "*assume cookie sheets are laying flat on horizontal surface (insulating)*" which indicates that the response would be different if it were based on a different assumption, possibly based on a different orientation or with different material properties; and "*while the heat generation probably won't counteract the large temp. difference*" which indicates that it is possible, although perceived to be unlikely that the result of heat generation could be dominant. Responses were coded as "correct all of the time" if the response did not have qualifiers.

After the third round of coding, the questions were grouped according to the frequency of "correct some of the time" responses from the eight experts. The question prompts were then investigated by looking for similarities that led to higher frequencies of "correct some of the time" responses.

Bias in interpreting the responses may have entered the analysis due to the researcher's expectations for the results. The researcher expected to see differences and similarities between the experts. The researcher also expected to see logical and cogent responses from the experts. Selection bias may affect the results as many of the participants had worked closely with one another for some time. This may lead to trends in similarities in responses both in terms of content and in terms of problem solving approach.

Results

The Participants

Participants expressed different levels of confidence in their answers. While three participants responded with the same confidence level for every question (Experts C, G and H, in Table 1), two participants changed the reported confidence level between "smart guessing", "confident" and "very confident" depending on the question. The self-reported confidence values for each participant are shown in Table 1. None of the experts indicated that they were "guessing" at the answer.

Table 1. Reported confidence on 11 questions by experts

		Expert							
		A	B	C	D	E	F	G	H
Reported confidence	1- Guessing	0	0	0	0	0	0	0	0
	2- Smart guessing	5	3	0	2	0	0	0	0
	3- Confident	6	7	11	5	4	2	0	0
	4- Very confident	0	1	0	2	7	9	11	11

Participants also differed in the use of graphs, diagrams, thermal circuits, and equations, as seen in Table 2. One expert included a diagram or graph on all but one of the responses. Two experts did not include diagrams, graphs, equations, or thermal circuits in any of their responses. There was variation in how often the experts made assumptions, as seen in Table 2. Experts ranged from making an assumption on only one of the eleven questions (Expert D) to making an assumption on almost half of the questions (Experts C, F, G, and H). Recall that the instructions for each question asked for participants to state their assumptions, and none of the questions included detail such that assumptions were not needed.

Table 2. Number of questions that elicited use of thermal circuits, diagrams, equations, and graphs for each expert. Average number of ideas in responses to questions by expert.

		Expert							
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Number of questions	**Thermal Circuits**	0	1	0	0	0	0	2	0
	Diagrams	2	10	0	1	1	0	3	0
	Equations	1	4	2	0	2	0	7	0
	Graphs	0	3	1	0	0	0	0	0
	Assumptions	2	3	5	1	2	5	5	5
Average (Std. dev) over all questions	**Ideas**	4.6 (3.6)	9.3 (3.1)	6.5 (3.1)	4.8 (2.6)	7.2 (3.5)	8.7 (3.7)	8.4 (2.5)	5.8 (3.1)

Responses were also analyzed in terms of "ideas." Using "ideas" as a measure of responses, we see that participants differed in the amount of information included in responses (seen in Table 2). Some experts were more inclined to give longer responses, such as expert B, and others were more inclined to give short responses such as expert D.

When graphs, diagrams, equations and/or thermal circuits were included, they usually appear to be used as tools to help the expert arrive at a conclusion and not presented as the solution in themselves. Examples of using representations as tools can be seen in Figure 2. Figure 2, Part A indicates using sketches and equations as a tool because they are drawn in the margins and evidence of thought process from scratch outs. Figure 2, Part B indicates using diagrams as a tool as they were drawn before much of the answer was written and part of the answer refers back to the diagram. Figure 2, Part C indicates using thermal circuits as a part of the process of achieving a solution.

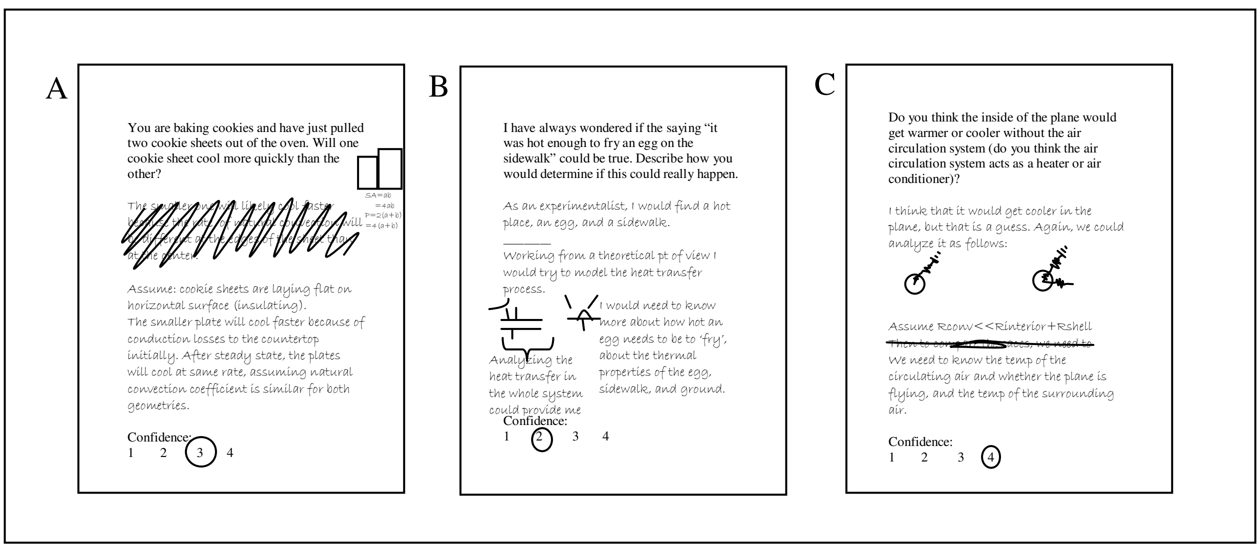

Figure 2. Examples of diagrams and thermal circuits used as tools.

Experts varied somewhat in their tendency to include qualifiers in their responses that would indicate that a different solution might be correct depending on the specific assumptions in modeling or material properties. Figure 3 shows the number of responses that include qualifiers for each of the expert participants. The expert participants varied from including caveats on about a third of the questions (experts A and D) to including caveats on almost all of them (expert F).

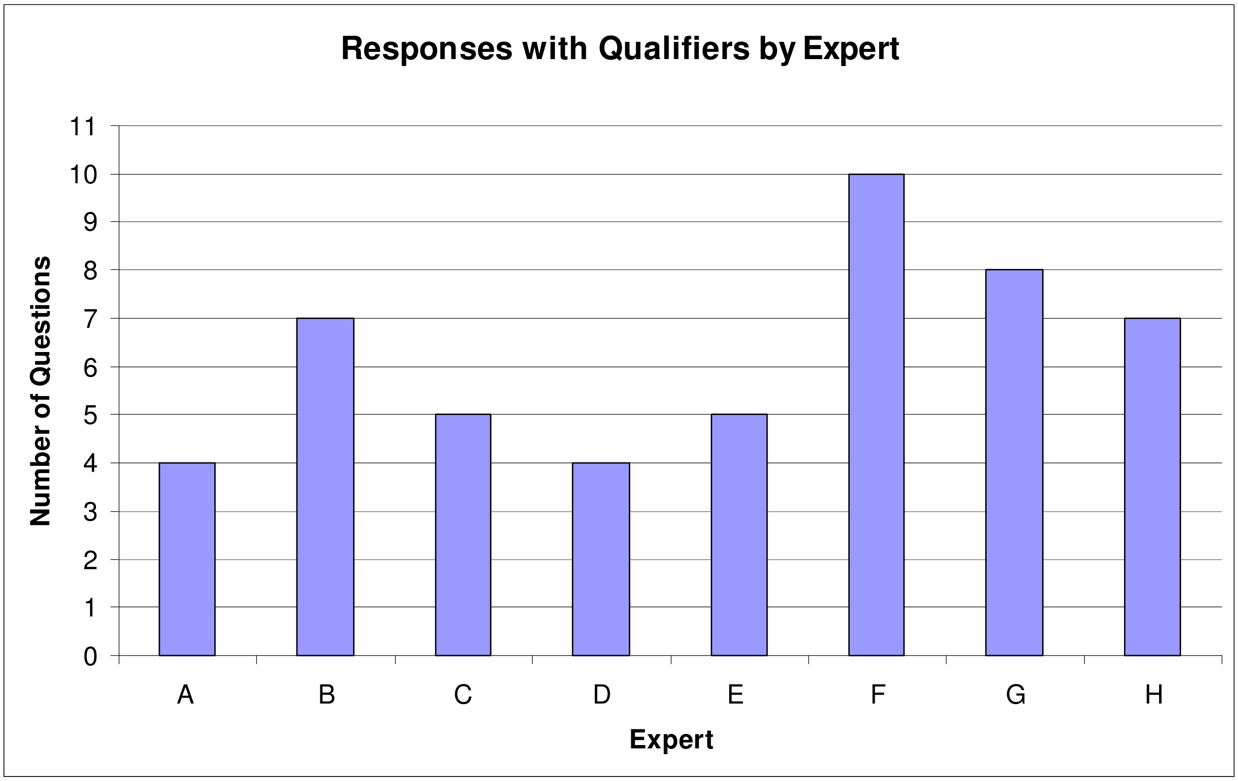

Figure 3. Number of responses with phrases that indicated that the answer could be different.

Overall, the experts did set bounds or make assumptions in their responses even though there is some variation in the number of assumptions that experts made. Greater variation is seen in including graphs, diagrams, thermal circuits, and equations in responses. There are similarities in how these representations seem to be used. There is also only slight variation between experts' use of qualifiers, with all experts indicating that their answers would be correct only some of the time on at least four of the eleven questions.

The Questions

There was an issue with the word choice on the Hot Chocolate question, seen in Figure 1, Question 10. The language used in asking the participant to "describe what you think is happening to the heat" is imprecise for the heat transfer domain. More precise language would have been "describe what you think is happening to the thermal energy." In order to maintain accessibility for the novices who may encounter this question in subsequent studies, we kept the colloquial term "heat." While this imprecise language was pointed out by some of the expert participants, the participants answered according to the colloquial meaning of heat.

The open-ended questions used in this study intentionally lacked details, so that participants could arrive at different, potentially correct, answers depending on the assumptions made when reading and interpreting the question. However, explicit assumptions were stated by the experts on only some of the questions, seen in Figure 4, even though they were prompted to articulate them in the instructions for each question. It is possible that there is some characteristic that is similar between the prompts for the Cookie Sheet, Punch, Egg, Car, and Plane questions that leads to more assumptions being stated. Alternatively, there might be some characteristic that the Oven Mitt, Carpet, Hot Chocolate, and Air vs Water questions have that reduces the tendency to state assumptions.

The use of graphs, diagrams, equations, and thermal circuits is similar across all of the questions with the exception of the Cookie Sheet question and the Plane question, as seen in Figure 4. Characteristics of the Cookie Sheet and Plane questions that may lead to greater use of representations are discussed further in the Discussion and Implications section. Our observation that experts do use physical representations in problem solving is consistent with work comparing how experts and novices solve physics problems[3].

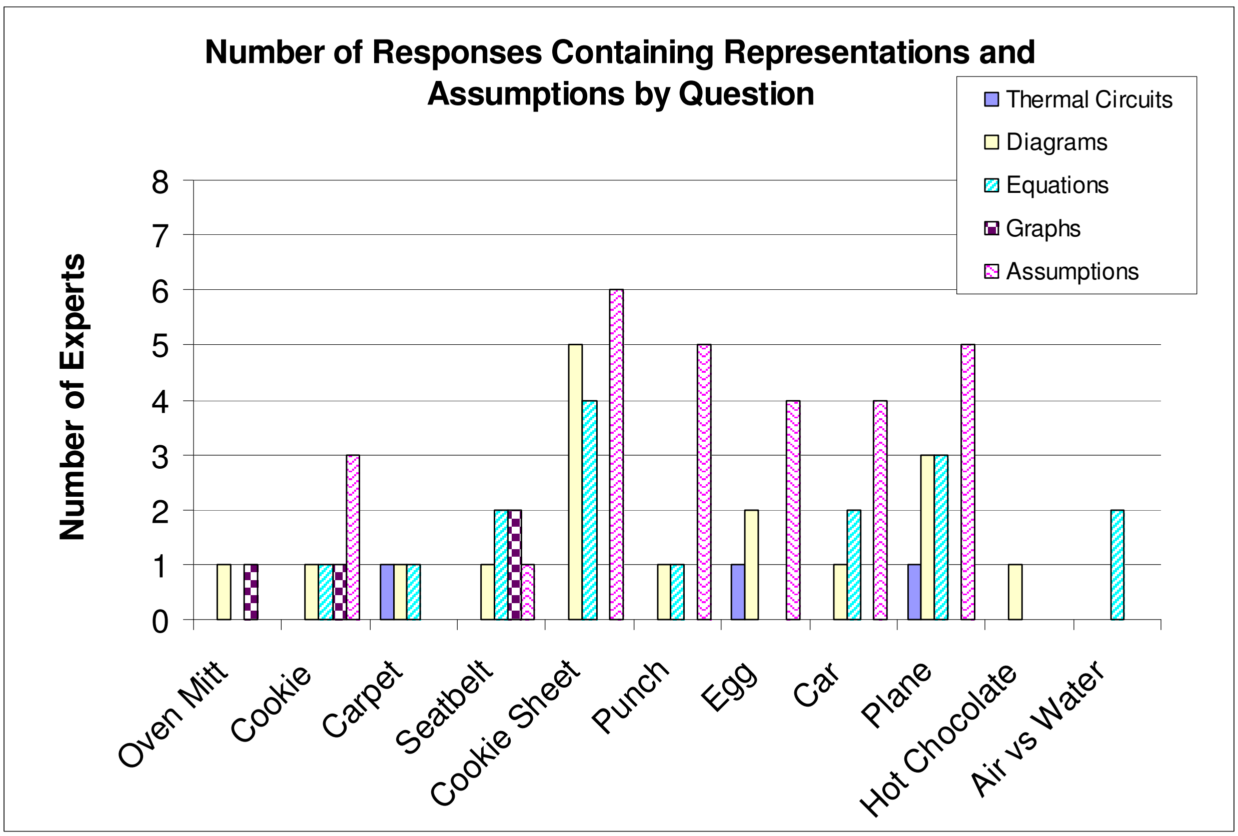

Figure 4. Number of experts who included thermal circuits, diagrams, equations, graphs, and assumptions in their responses.

As shown in Figure 5, some questions elicited responses containing more unique ideas than other questions elicited. While all of the questions are considered long-answer questions, the questions can be grouped into categories based on the number of distinct ideas represented in the responses. Particularly noteworthy is that the top four questions (Cookie Sheet, Punch, Egg, and Plane) have on average more than twice as many ideas presented as compared with the bottom four questions (Oven Mitt, Carpet, Seatbelt, and Hot Chocolate).

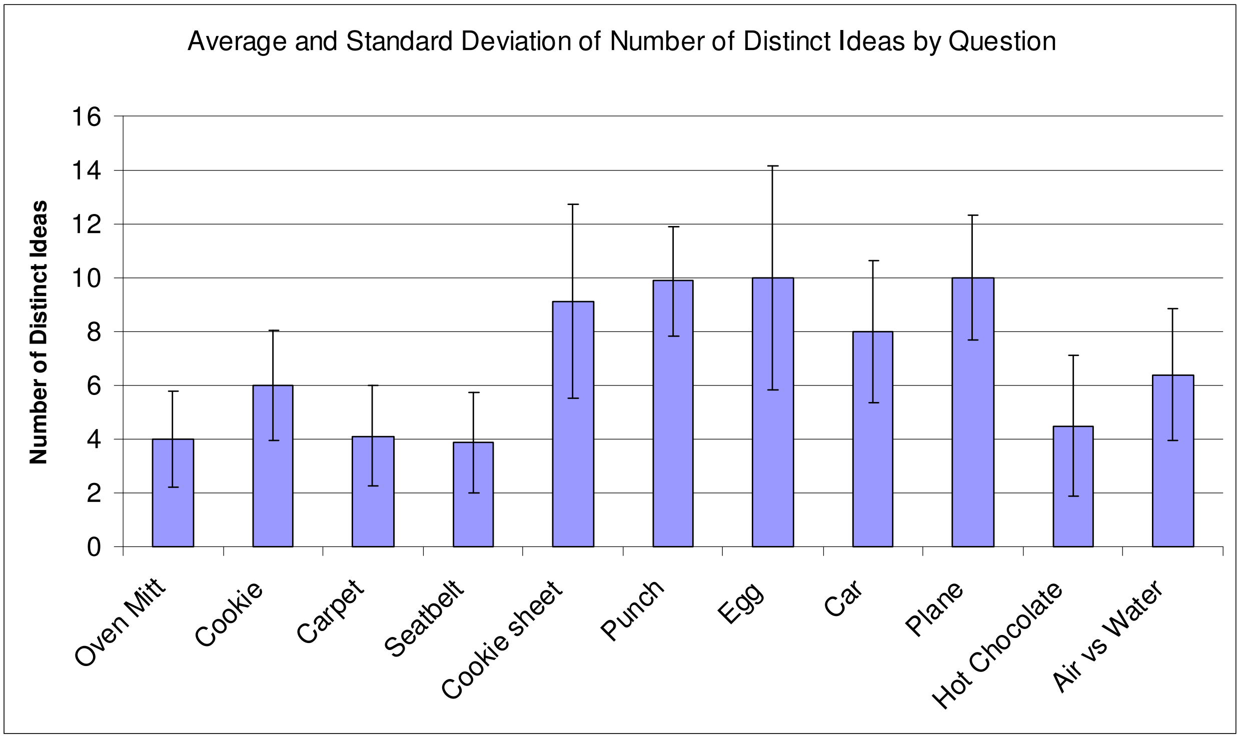

Figure 5. Average and standard deviation for the number of ideas mentioned in the responses by question.

Many responses from experts indicate that the answer or solution may be correct only some of the time. Figure 6 shows the number of responses that included these caveats for each question. Not all of the questions elicited responses with these terms. The questions can be grouped into categories based on how likely they were to receive responses that are open to having a different correct answer depending on different factors. Questions in the *High Openness* category include Plane, Punch, Egg, Car, and Cookie Sheet. Questions in the *Low Openness* category include Carpet, Seatbelt, and Air vs Water. The *Medium Openness* category includes Oven Mitt, Cookie, and Hot Chocolate questions with only half of the experts writing responses that included the possibility of different answers.

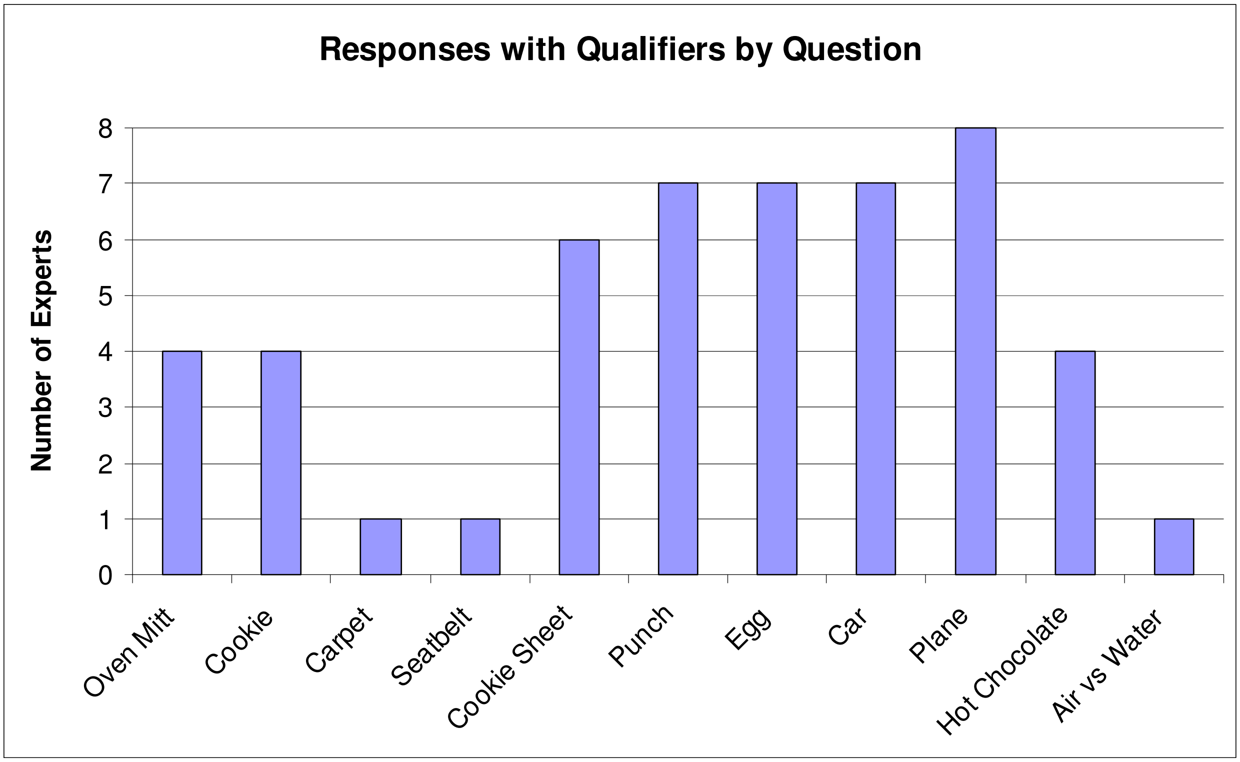

Figure 6. Number of experts whose responses include phrases indicating that the answer could be different.

It should not come as a surprise that the questions that included the possibility of other correct answers depending on the situation would be the same questions that had many ideas presented and included many assumptions. These measures are linked as each assumption that was stated would be counted as an additional idea when measuring length of response. In addition, a common method of indicating that the answer is only correct under certain circumstances is to state an assumption. Thus speculating on the attributes of questions that lead to responses indicating that the answer may be different may account for the trends that we see.

Discussion and Implications

The responses of the eight experts to the Cookie Sheet and the Plane questions contained more diagrams and equations than the other nine questions. For the Cookie Sheet question, this may be attributed to a partial description of the sheets' geometry in the problem statement prompting participants to sketch the dimensions of the sheets. For the Plane question, which has many competing effects, the additional sketches and equations may have been written down as experts were writing much more information on the page, possibly in an attempt to expand the amount of information accessible to them through external memory.

Responses differed in the openness of the response to different answers based on the details of the situation. The questions with *Low Openness* include the Carpet, Seatbelt, and Air vs Water questions. These prompts all stated an observation about how a situation feels followed by asking the participant to explain why this may have happened. The questions with *High Openness* include the Plane, Punch, Egg, Car, and Cookie Sheet questions. These prompts, with the exception of the Egg question, asked participants to decide between two or three options and explain the choice. The Egg question asked participants how they would determine the result. While this prompt does rely on "applying heat transfer knowledge to a new situation", it boarders on "creating a plan", which would be placed in a higher level of Bloom's and Anderson's taxonomies, and we may expect answers to it to be more thorough. The *Medium Openness* category includes Oven Mitt, Cookie, and Hot Chocolate questions which had prompts asking for the participant to explain how a heat transfer phenomenon happens.

It is interesting that the Hot Chocolate question has responses that more closely resemble the responses of the questions asking why and how than the responses of the questions asking participants to choose and explain. This might be due to the simplicity of the situation, as all of the heat transfer considerations would compound the cooling effect, or due to the prompt "describe" being closer to being asked "why" or "how."

We see these differences between responses even though these questions all came from the same level on Bloom's taxonomy (Application)[15] and Anderson and Krathwohl's taxonomy (Apply)[16] and they are all "deep reasoning questions"[14]. We see that questions asking for an explanation are more likely to get an answer that is presented in a very closed, factual way such as "*the metal transfers heat to you more easily than the plastic because it has higher heat capacity and thermal conductivity*" as opposed to more open answers that say "*depending on the orientation of the buckle, there may be temperature gradients along it*." To test that the difference in response is due to the phrasing of the prompt, a second version of the *High Openness* questions could be formulated. The second version would have the same phrasing of the *Low Openness* questions, including a statement followed by the prompt "why?" Testing this hypothesis with a larger number of experts, from a variety of schools and industry, would be beneficial in making conclusions about expertise in heat transfer.

The Cookie, Carpet, and Seatbelt questions each deal with the contact interface temperature. Some of the experts recognized the underlying simplicity of these questions and explained that the determining factor in the contact interface temperature is the effusivity of the materials. These questions were answered in very similar ways. Mostly, the expert attributed the difference in temperature to effusivity and left it at that, without taking into consideration any additional constraints, such as the time scale needing to be long enough to register the temperature with the nerves and short enough that diffusion does not reach a boundary. Additionally, the effusivity argument in contact temperature relies on a homogeneous material. An assumption that could have gotten around that requirement is to use an effective effusivity. It is possible that some models of solutions in heat transfer are so well ingrained that experts do not realize either the need to state the limitations of the model or what those limitations might be.

In addition, the experts' responses were not without mistakes. For example, one participant stated that "*[it] has a large thermal mass due to the use of low heat capacity materials*." In actuality, a high heat capacity would contribute to a large thermal mass. The participant either confused the relationship between thermal mass and heat capacity or had memorized the relationship incorrectly. Additionally, there were mistakes such as "*higher effusivity transfers heat faster and thus feels hotter…*" which is partially correct. For semi-infinite materials in contact, materials with higher effusivity would transfer a greater amount of heat over some period of time. This is due to a combination of transferring heat quickly (related to thermal conductivity) and having a large amount of heat to transfer (related to specific heat and density). This error is either due to not understanding the concept of effusivity thoroughly enough or due to laziness or dumbing down of the answer. Overall, mistakes were rare without a noticeable pattern in either the questions or the participants.

While we see many similarities between experts, we also see many differences. This serves as a reminder that our experts are individuals with differences in style and experiences. Some of the experts used diagrams, thermal circuits, equations, and graphs as tools. All of the experts who participated in this study displayed the characteristic of being open to different possible answers to a problem based on the details of the situation. This expands on the work that has been done on how experts solve closed-form questions[3] by investigating the responses of experts to open-ended questions. The use of tools and being open to different answers might both be reflective of how experts in heat transfer organize their knowledge and how they approach problem solving, adding to what has already been done on expert organization and strategies[17].

The implications for heat transfer educations include being aware that they types of questions that are asked of the students may prompt responses that vary in the use qualifiers. For educators and researchers wishing to observe expert-like responses in the use of qualifiers, they should include questions that provoke thinking beyond the explanations given for the “deep reasoning questions” of “why?” and “how?”

A promising area for future work involves comparing responses from experts as described in this paper to those of novice heat transfer learners taking their first heat transfer course. Interesting areas of comparison include the use of diagrams, thermal circuits, and equations; the length of responses; and how the two groups differ in openness of responses to the possibility of the answer changing based on the details of the situation. Additionally, comparing frequency and types of mistakes made by novices and experts may lead to additional insights.

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