“Hearts Pump and Hearts Beat”: Engineering Estimation as a form of model-based reasoning

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Abstract: Professional engineers are often required to make estimates of physical quantities and processes, as well as user requirements and system performance. However engineering undergraduates, as part of their curriculum, do not learn how to make such estimates. In order to design a technology-enhanced course in engineering estimation, we conducted a study of experienced engineers working on estimation problems. A three-phase process for engineering estimation, and the cognitive mechanisms underlying them, emerged from the analysis of this data. We highlight the roles of mental simulation and external representation in the estimation process. These results will be used to design learning environments for engineering estimation.

Keywords: engineering estimation, expert study, technology-enhanced learning environment

Introduction

Engineers build things: they build bridges across oceans and tiny memory devices that can store 30 full length feature films in less than 1 cm^2 of physical space. But before they build anything, they analyze whether they *can* build it, whether the designs are feasible or not (Linder, 1999; Mahajan, 2014). For instance, consider the following problem, “A toy company has designed a remote-controlled toy car for kids driven by a 5W hand-cranked generator. They expect that a child will be able to play with it for 5 hours before needing to crank again. Is this reasonable?” Professional engineers must routinely answer questions such as this, which involve estimating an unknown quantity and using it to make a judgement. Formally engineering estimation has been defined as “An analysis to determine all quantities to some level of specificity” (Linder, 1999). Such estimates are difficult to make and even the definition of a good estimate is unclear, as it varies from situation to situation and may include a range of values rather than a finite number of options. However such estimates are necessary in engineering practice when complete accuracy is unnecessary or adequate information is not available. Yet, estimation has not been included in engineering curricula, nor teaching-learning strategies developed specifically for it. Consequently, even graduating engineering students cannot make estimates of physical quantities such as force and energy (Linder, 1999). It is thus important for researchers and educators to provide appropriate learning environments so that engineering students can explicitly learn how to do estimation.

In order to design a learning environment for estimation, either for classroom or a computer-based learning environment, we need to articulate the learning goals, the process and the skills and sub-skills required in this estimation process (Jonassen et al, 1999). This will enable us to include the appropriate learning strategies and necessary scaffolds. While Mahajan (2014) has developed a set of tools to perform approximations and estimation in science and engineering, and Linder (1999) has identified a set of effective actions for solving engineering estimation problems, these methods and actions are not in sufficient for learning design. Paritosh (2007) proposes a model for back-of-the-envelope reasoning, but the set of problems that this applies to are not engineering-specific. One way to identify the learning goals and the required component skills of engineering estimation is to study the estimation process of experienced engineers to understand the cognitive mechanisms they use. To the best of our knowledge, a study identifying the characteristics of the engineering estimation process has not been done. In this paper, we report a study of the estimation process of two experienced engineers as they work on an estimation problem, with the broad goals of understanding the process of engineering estimation and the cognitive mechanisms underlying it.

Related Work on Expertise

There exist several research studies documenting the characteristics of experts in various domains and the multiple approaches followed to study expertise (Ericsson et al, 2006). For instance, there is sufficient evidence documenting the differences between experts and novices in the solving of physics, chemistry and mathematics problems (Ericsson et al, 2006). While there have been no studies with experienced engineers solving engineering estimation problems, Wankat & Oreovicz (2015) have compiled the expert-novices differences identified in various problem-solving domains and summarized them along the dimensions of problem representation, solution strategies, monitoring etc. There is ample evidence, however, documenting the characteristics of experts and experienced practitioners in the process of engineering design (for example, Dym et al, 2005; Atman et al, 2007; Cross & Cross, 1998), which often requires estimation as a first step.

In engineering estimation, Linder (1999) compared the performance of experienced engineering practitioners and students on two engineering estimation tasks and observed significant differences. In particular, practitioners were able to provide values of the right order of magnitude for quantities in their domain of expertise and values off by a few orders of magnitudes for quantities outside their domain of expertise. Students, on the other hand, in both cases provided estimates off by several orders of magnitudes. Linder analyzed student solutions and conjectured that these differences were due to the reasons that 1) students do not have a sound understanding of fundamental engineering concepts, much lesser in fact than was expected and 2) students do not relate the estimates they make to their physical significance, do not have reference values for the quantities they are estimating and have difficulties working with units. However, Linder did not offer a model for engineering estimation as done by expert practitioners who obtain order of magnitude estimates.

Theoretical Basis

In order to identify the probable cognitive mechanisms that could be at work in engineering estimation, we looked at related work in engineering thinking, design and problem-solving. We identified the critical role of visual thinking in engineering as documented by case studies of engineers (Ferguson, 1994). An example of this is given by Nelson (2012) when he says, “Engineers are visual or non-verbal thinkers in general. Not only do we represent physics in our minds, we are also able rotate static objects to understand them better.” A recent study found that practicing engineers describe visualizing and improving by manipulating materials, mental rehearsal of the physical space, sketching, and doing thought experiments as engineering habits of mind (Lucas, 2014). Unpacking visual thinking, we note that it has the following components – imagination of statics, mental simulation of dynamics, and external representations of procedures, systems or objects, design or analysis.

The role of mental simulation in science and engineering has been extensively studied. Using think-aloud protocols of experts solving problems outside their domains, Clement (2009) argued that “imagistic simulation” (mental simulation) played a role in the thought experiments used by experts and that these simulations generated new knowledge. Similarly, Nersessian (1999) studied the artefacts produced by scientists in the process of developing new concepts and argued that mental simulation is the mechanism by which model-based reasoning produces conceptual change. Hegarty (2004) has a review of research which provides evidence for the use of mental simulation in mechanistic reasoning. The role of mental simulation for uncertainty resolution in engineering design has been discussed in Ball & Christensen (2009) and for creating knowledge and technologies in Nersessian (2009). Research also suggests that gestures result from these mental simulations (Hostetter & Alibali, 2008). Since engineering estimation begins with understanding how a system works (Linder, 1999), we conjecture that experts must be performing mental simulations when they are identifying the working of the unfamiliar problem system in engineering estimation.

Recently the role of representations in engineering has received a lot of attention (Johri et al, 2013). In Moore et al (2013) the authors found that students use multiple representations and translate across representations during a complex modeling task. In Aurigemma et al (2013), the authors found that building external representations serves more purposes than offloading cognitive load in the engineering design process. The theory of distributed cognition suggests that cognition emerges from the interaction between internal and external (environmental) resources because external representations allow processing that is not possible in the mind (Kirsh, 2010). External representation allow actions such as rearrangement, reformulation and sharing as described in Kirsh (2010). In the domain of problem solving, Zhang (1997) showed that external representations are more than merely memory aids and/or stimuli to the internal mind. He argued that the form of the representation determines what information is perceived and how the problem is solved. In mathematical problem solving research, Hegarty & Kozhevnikov (1999) found that using schematic spatial representations rather than pictorial representations improves problem solving performance. Martin and Schwartz (2009) found that experts take the time to create external representations before starting because it improves their overall performance on a medical diagnosis task. We conjecture that experts will use external representations extensively in their estimation process and we will identify from the data how and where they use them.

Methods

The broad research questions guiding this study were,

1. What is the process by which experienced engineers perform estimation?
2. What are the roles of mental simulation and external representation in performing estimation?

Data Collection

Problems

The problems given to the experts are below and were chosen after pilot studies, based on their potential to elicit a wide range of problem solving behaviors from the experts. The first problem required estimation based on the structure of an object, while the remaining two required estimation based on function. The problems progressed from simple to complex, and from requiring little to more domain knowledge. Each problem had two versions which were conceptually similar but worded differently as it was conjectured that this would elicit different estimation behaviors from each expert. For example, the expert 2 version of problem 2 is formulated as an evaluation question whereas the expert 1 version is a numerical estimation problem. Therefore it is plausible that rather than estimate the power of the human heart and then compare it to the power required by a wine opener, experts would consider the human heart and wine opener as a system and evaluate whether the heart could drive wine opener. Thus we may observe different problem solving behaviors from both experts.

Table 1: Problems given to the experts

Expert 1	Expert 2
Suppose I told you that the pit spacing on an ordinary CD is 2 μm, would you agree with me? Why/why not?	How far apart are the pits on a CD?
What is the output power of the human heart?	Could a human heart run a wine opener?
The hand cranked radio is for use far from supplies of domestic electricity or batteries. For decent sound performance (say a single 5 W speaker) how heavy would you expect the radio to be?	Consider radios used far from supplies of domestic electricity or batteries. They have to be cranked by hand for them to work. How heavy would such a radio have to be to be heard within a tent at a campsite?

Procedure

Two experienced engineers specializing in electrical engineering were chosen for the study. These experts are faculty members at a premier technology university in India, and have several years of industry experience as well. They have active research programs in their respective areas of research. The study was done separately with each expert, and conducted in a location of the experts' choosing. Each expert was given a sheet with a problem written on it. They were told to write as many details while solving the problem. They were free to use any books or other materials they wanted to consult in solving the problem, including looking up supporting information needed to solve the problem on the Internet on their personal laptop/computer. In permitting the experts to look up the Internet we were trying to simulate a natural work environment as it exists in the engineering workplace where engineers often consulted the Internet for domain related facts and knowledge.

In order to record every action that the expert took towards estimation, the entire session was recorded using two video cameras. The first was focused on the task area (i.e. the sheet of paper and surrounding area on the desk) to capture their sequence of writing and small hand gestures. The second was focused on their face in order to capture facial expressions and large body movements. Their interactions with the computer were captured using the screen capture software CamStudio (http://camstudio.org/). The researcher recorded regular unstructured observations while the expert solved the problems, looking out for critical events which would require elaboration in the follow-up interview. The experts were free to solve in their natural mode, silently or talking aloud as they felt comfortable. The researcher didn't interrupt except to offer a new problem sheet. We did not require experts to think aloud as doing this effectively without placing a cognitive load on the solver requires extensive practice which was not possible with the experts. So we interviewed experts immediately after they had completed all problems using a semi-structured interview protocol. In all we had 45 minutes of video with expert 1 and 2 hours and 20 minutes with expert 2.

Data Analysis

We followed the method of cognitive ethnography which is based on traditional ethnography but is concerned with identifying how members of a cultural group make meanings (Williams, 2006; Hutchins & Nomura, 2011) by interpreting observed behaviors. The analysis began by creating detailed transcripts using ELAN (https://tla.mpi.nl/tools/tla-tools/elan) of the two videos plus the screen capture and the follow-up interviews for each expert. Threading these transcripts together, a single researcher wrote, for each problem, a detailed description of the problem solving process as it happened sequentially in time. From this description, the authors of this study collaboratively abstracted out the stages or phases of the problem solving. Finally we focused on specific episodes which were interesting in the larger context of the study because they allowed the expert to move forward in the task and identified what were the mental and physical activities that contributed to forward progress during this episode. Specifically, we analyzed the roles that gestures, talk, writing and computer search played in these episodes. The analytical framework evolved as we did multiple passes through the data.

Results

While we have analyzed all the problems solved by each expert, in the interest of space we restrict ourselves in this section to the description of the second problem as solved by each expert.

Workflow of Expert 1

Expert 1 (E1) is an academic with three years' experience in academia and eleven years' experience in industry. She spoke out loud intermittently while solving the problems. After reading the problem, E1 almost immediately searched "Flow rate of blood" on the Internet. She scrolled through the results, highlighted two links related to blood velocity, but did not click either. She picked up the pen to write, dropped it and then picked it up again and began writing. Initially she started writing "Pressure = F × ", but after a while she struck through that and wrote "Power = $\frac{mgh}{t}$", then after a pause added another equality "= $\frac{F\times h}{t}$". After a long pause, she wrote "=$\frac{P\times A\times h}{t}$". After another pause, she searched for "Blood pressure" on the Internet and clicked on the first search result that popped up called "Normal Blood pressure" and read it. She stated that there were two readings given for blood pressure whose meaning she didn't know so she chose a value between the two which is 100 mm Hg and wrote down that value.

Next, she wrote down "$F = P \times A$", said "r is the distance - the head that it pushes the blood around" and added "$\times\, h$" next to the equation "$F = P \times A$". She identified that she knows "pressure" by underlining the value she had written down, "100 mm Hg" and then stated that "A" (area) is probably the cross-section of the two blood vessels. This she estimated to be "2 cm^2". Next she said that *"h"* was hard to determine "because the diameters of the pipes keep changing". She added that it's a closed loop system and went silent for a while. For part of that duration her pen was hovering over the equation "=$\frac{P\times A\times h}{t}$". After this she added "Okay flow rate. That's what I need to know" and searched for "Flow rate of the blood from the heart" on the Internet. She clicked on the Wikipedia page titled "Blood Flow" and read the section "Velocity". She noted down the cross-sectional area of the aorta and the blood velocity and calculated flow rate and then power as "flow rate × pressure". She decided to convert all values into MKS units and for that searched "100mm Hg Pascal" on the Internet. She noted down the value, 13332 N/m^2 and completed the calculation arriving at the result of 6 Watts. Her problem solving process (as drawn by her during the follow-up interview) is shown in Figure 1.

This problem was followed up with the other version of the same problem "Could a human heart run a wine opener?" E1 began by saying that she was going to consider the work done as the work against friction between the cork and the bottle neck. So she needed to determine this force of friction since work done is "force × displacement" and she estimated distance to be 2cm. For a while she was silent and then said "Work done is just power × time". After a brief pause she added that "…given the right contraption it could take forever and still open the cork." She wrote this down and ended. Her solution approach (as drawn by her) is shown in Figure 2.

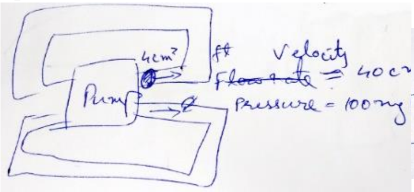

Figure 1: E1's diagram for the heart problem

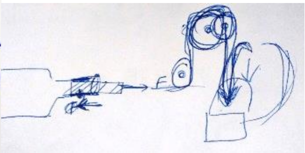

Figure 2: E1's diagram for the follow-up problem

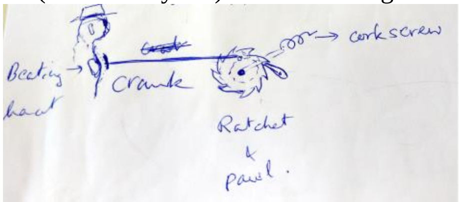

Figure 3: E2's diagram for the heart problem

Workflow of Expert 2

Expert 2 (E2) is an academic with seven years' experience in academia and three years' experience in industry. He worked silently and only spoke to report that he had finished a problem. E2 spent some time reading the problem and after this, while he stared straight ahead silently, the index finger on his left hand moved to and fro a few times. Then he searched for "ratchet"' on the Internet, briefly scrolling through results and changing the search term to "to and fro" before returning to the search results for "ratchet". He clicked on the Wikipedia page for "ratchet" and read the "theory of operation". While reading, he made a small turning movement with his right hand. Then he wrote down two assumptions, ``Assumption 1: It is a beating heart. Assumption 2: It is inside a human body."

After this E2 spent some time reading the computer screen and then he drew a part of the diagram shown in Figure 3. Next, he air drew what seemed to be a straight line between the man and the ratchet. He formed a “C” with his right hand and rotated it about his wrist. He again drew straight lines and circles in the air. After a while of looking away, he searched for “to and fro motion to rotational motion” and read the first link titled “reciprocating motion”. As he read the screen, he intermittently looked at paper and looked away. Next he searched for “crank machine” and read the Wikipedia link for “Crank (mechanism)”. Then in Figure 3, he drew the straight line from the rectangle to ratchet and labeled it “crank” and completed the rest of the drawing. He drew the flow chart below this diagram to depict his solution approach “Beating heart → Crank (turns gear on ratchet) → Ratchet & pawl → cork-screw. This concluded his solution.

Engineering Estimation as a form of model-based reasoning

In this section, we present the answer to our first research question. Based on our analysis of the entire corpus of data, we identified the phases in engineering estimation shown in Figure 4.

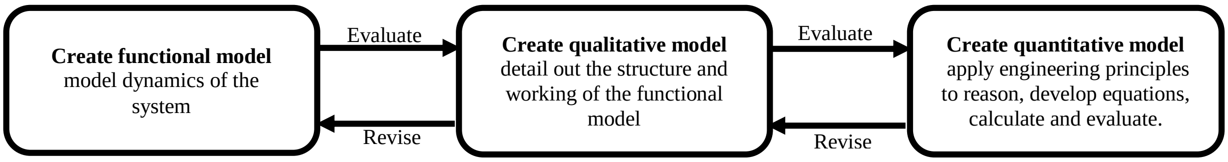

Figure 4: Phases of the Estimation Process

Create a functional model

When faced with an unknown system, experts first focused on the dynamics of the system and modeled the dynamics in terms of the dynamics of a known system. In the case of E1 as she reported later “…the first thing that came to my mind was the heart is a pump.” In E2’s case as he reported later he “…thought what does the human heart do that can help me? Which is that it beats. So there’s a rhythmic motion.” In both cases, the experts began by modeling the function of the heart. Its dynamics gave experts a way to identify an object or system with similar dynamics. For E1, the similar object which immediately emerged was the pump and for E2 the heart was reduced to an object that executes repetitive motion. These converted systems that experts began working with were their functional models and their structure was similar to the given system.

Create a qualitative model

Next, experts developed a model of the structure of the system and how its various components work together. We call this the qualitative model. The functional model was constantly evaluated in the mind until it met the requirements of the solution. It was broken down into components to see which component could be modified to get the solution. Thus the final solution was always kept in mind. Since E1 had modeled the heart as a pump, she needed to determine the power of this pump. She identified that the power of a pump is determined by the flow rate and head. Thus her task changed to determining the flow rate and head of this heart “pump”. She was aided in this restructuring by her knowledge and familiarity with pumps due to her recent experience with them. However, when she looked for “flow rate of blood” on the Internet, she thought of “…how much work this pump is accomplishing in this system ... so what does the system look like?” She started to think of the lengths of the veins and arteries, their diameters and the pressure. At this stage E1 fleshed out the details of her model of the heart “pump”. This was her qualitative model.

In E2’s case, because he had modeled the heart as something which moves rhythmically, his task was to find a way to “run” the wine opener (or cork screw as he assumed) using that motion. Thus his problem reduced to converting the rhythmic motion of the heart to the rotational motion of a corkscrew; he changed the nature of the task to coming up with a mechanism for accomplishing the above. Then E2 had to identify the components of a mechanism to convert the beating motion of the heart into the rotation of the corkscrew. He recognized that the heart goes to and fro but he did not want the corkscrew to go both clockwise and anticlockwise, only in one direction. Here he recalled having recently read about the ratchet and that it had something to do with one-way rotation. So he looked it up and decided that it was suitable to the task of turning the corkscrew in one direction. He indicated his partial solution by drawing the heart and the ratchet & pawl. At this point he realized that before the corkscrew could be turned, the linear motion of the heart would need to be converted to rotational motion. As he didn’t know what mechanism could accomplish this, he looked it up on the Internet, learned of the crank and inserted it into drawing of the mechanism that he had already drawn (Figure 3). Thus E2 also re-examined and restructured his model resulting in his qualitative model.

Create a quantitative model

It is at this third and final stage that experts applied engineering principles and developed (if necessary) a quantitative model or equation corresponding to their qualitative model to calculate the estimate. E1 wrote out the general equation for power and restructured that to arrive at the equation for the power of the heart “pump” in terms of the blood pressure of the heart, namely “Power = $\frac{P\times A\times h}{t}$” where P is the blood pressure that she looked up. In this new structure, she still did not know “h” in the equation. She evaluated the qualitative model to determine what *“h”* was; as she reported later, “…basically to what extent is the heart pumping the fluid. So I was trying to think, ok then what are the various diameters of the various arteries and how long are they and all that. But then I was thinking whatever the energy with which it pushes the blood out is expended by the time the blood comes back to the heart.” By re-examining the equation she realized that $\frac{A\times h}{t}$ was actually flow rate and that the distance through which the heart pumps the blood, h doesn’t matter. Thus she restructured the equation again and arrived at an equation in which all the quantities’ values could be looked up. She then looked up the standard values on the internet, namely blood pressure and velocity of blood in the veins and completed the estimate.

E2 did not develop a quantitative model of the system or calculate power of the heart to compare it with the power of the corkscrew. Recall that we had expected this to happen due to the wording of the problem given to him. During the follow-up interview, when he was asked to evaluate whether the heart had enough power to turn a corkscrew, he qualitatively reasoned that it probably didn’t. He added that by including two gears – a small one and a large one – which would together turn the corkscrew “very slowly”, he would be able to able the wine bottle, though “it would take forever”. Thus by restructuring his qualitative model he was able to evaluate this alternative scenario and develop another solution.

This process suggests that engineering estimation is an instance of model-based reasoning in which a functional model was iteratively evaluated and fleshed out multiple times, culminating (in the case of a numerical estimation problem) in the calculation and evaluation of the estimate and, if necessary, revision of the model (Figure 4). We also observe that experience or familiarity with certain systems played a critical role in estimation as experts began the process by considering systems from their experience as functional models. In the following, we elaborate on the underlying cognitive mechanisms which support this estimation process.

Cognitive Mechanisms Underlying Engineering Estimation

In this section, we answer our second research question and elaborate the roles of mental simulation and external representations in engineering estimation.

Mental Simulation

The data shows that when experts read a problem they mentally simulated the dynamics of the problem system, entirely or in part. Some system the expert knew about was used to ‘instantiate’ the simulated dynamics (e.g. heart is a pump). Experts simulated the end point (e.g. the wine opener/corkscrew) or the entire system (e.g. working of the heart) in sufficient detail to evaluate whether their instantiated functional model achieved the desired result. Evidence for this comes from both experts. E1 thought of the heart as a pump and that “it has 4 pipes coming out of it - 2 of which are pumping out and 2 of which are pumping in. So essentially if it has 2 pipes ...I mean, if it’s pushing water out…” In E2’s case, he thought of the heart as “It’s something that is executing repetitive motion.” This simulation helped them to develop their initial functional model of the situation. Further evidence for this mental simulation comes from experts’ gestures. When E1 described the heart, she gestured dynamically with her hands to indicate the flow of water in the pipes, while E2 had been moving his index finger to and fro in the initial phase of the problem solving when he was developing his model. As known from literature (Hostetter & Alibali, 2008), gestures are evidence of mental simulation.

These mental simulations did not stop with functional model building; as experts fleshed out the qualitative model, the functional model was simulated and constantly compared to the desired end-point to ensure that it was still valid. Experts were willing to modify their models if they did not give the desired result. For instance, in the case of E1 while solving problem 3, she initially developed a functional model of a crank and mass attached to it. However, working with the model and re-simulating it, helped her realize that the radio works on electricity and “turning the crank means you are running a generator”, so mass meant the mass of the magnet. Thus constant evaluation of the model led to a breakthrough in problem understanding.

External Representations

Diagrams

We found that E1 did not draw diagrams while solving problems. However she had imagined very clear models for problems 1 and 2 while solving them as was evident from the diagrams she drew when asked during the follow-up interview. We conjecture that because of these clear imagined models she was able to easily restructure and solve these problems. From her very rudimentary diagrams and her verbal reports for problem 3, it appears that she did not have very clear imagined models of this problem, which could have been the reason for her difficulty with this problem, especially because the system had many more components than the previous two problems.

E1 drew diagrams while solving problems 1 and 2. For problem 1, since the question was to estimate pit spacing, by drawing a diagram of his model of the CD he was able to create the other representation required for solving the problem, namely the equations for pit spacing. For problem 2, the final diagram that he drew was his solution. After he drew the first and third parts of his solution, the diagram helped him identify that the solution was incomplete and he needed something in the middle to convert the linear motion to the rotational motion. For problem 3, he did not draw a diagram but a flow chart describing his approach to the problem.

Equations

E1 and E2 both used equations extensively, which is not surprising in engineering. Equations were the way to assign numerical values to physical quantities. However equations served other purposes besides this in the estimation process. For instance, in problem 2, E1 used equations as an external representation that can be rearranged and reformulated (Kirsh, 2010) and arranged them into a form that was conducive to further action. Equations helped her in mapping the details of her model with the given problem system. Originally she thought that to calculate power she would need to know flow rate and head, but later realized that head was not a valid parameter in this context. Thus working from the basic equation of power ($\frac{mgh}{t}$) she was able to rearrange and reformulate it to a form in which everything was known to her ($\frac{P \times A \times h}{t}$) In the follow-up to problem 2 and in problem 3, she used equations as persistent objects to think with (Kirsh, 2010), as equations helped her in splitting the problem into factors, and in identifying a clear path to the solution.

E2 used equations as persistent objects to think with and for restructuring the problem when he was trying to arrive at an estimate for the weight of the magnet in problem 3. He wrote down a set of equations and then tried to assign approximate values to the physical quantities involved in them in order to determine the volume of the magnet and hence weight. This restructuring of the problem from weight to volume was aided by the equations, which again helped in factorizing the problem and identifying a path to the solution. E2 very often transitioned between text (written by himself and on the computer screen), equations and diagrams in the solving of problems; an instance of this was seen in problem 1 when his pen went back and forth in the air between the diagram and the equation before he wrote; this indicates that he was making a connection between the equation and diagram or using information from one in the other. While this may seem to be obvious to do in engineering, it has been shown that students begin with the equation rather than the model (Wankat & Oreovicz, 2015). While experts used equations to converge their estimation process, which started off with the simulation of dynamics, students may start with the equation, which may not help generate the simulated dynamics or model of the system. Experts used equations to evaluate the simulated model; students may use equations as the only model.

Conclusions and Implications

In this study, we have identified a three phase iterative model-based reasoning process for engineering estimation which may be performed in different ways depends on the problem and the solver. We have also identified the roles of mental simulation and external representations in each phase of the estimation process. The process begins with experts simulating the dynamics of the given system and identifying a system with analogous dynamics as a model. The specifics of the initial model may change, especially during the second and third phases, in which it is used to identify, refine and evaluate the structure, working and equations governing the problem system, by constant comparison to the expected behavior from the problem system. These results show us that engineering principles help detail and converge mental simulation and model-based reasoning, and are not themselves generators of solutions. This is different from the classical case of model-based reasoning in science (Nersessian, 1999) in which models are used to infer general principles; in estimation the detailed structure of the models, along with qualitative reasoning and engineering principles, are used to make estimates.

It is interesting to note that while E1 thought hearts pump and E2 thought hearts beat, both arrived at the conclusion that it would take forever to open the bottle “using” the heart, but that it can be done. Their starting dynamics and instantiated models were different, yet their final solutions were conceptually and functionally similar. The latter two phases contributed to this convergence, and how this happened would be examined in future work. Further, we will repeat this study with two novices and identify the differences with expert performance. The learning environment for estimation will then be guided by learning science principles aimed to reduce the identified differences between experts and novices. If, as we suspect, students do not begin with mental simulation and functional modeling but rather with equations, we propose that the learning environment should require students to work with computer simulations of the given problem systems and model them before writing equations. The exact details will depend on the details of the expert-novice differences.

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