Identifying the Components of Modeling Through Protocol Analysis

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Introduction

The art of engineering involves a variety of skills, and one of them is modeling.   While the terms "model" and "modeling" are not simple to define, within engineering, Piel and Truxal[1] offer a helpful account: "a model is the simplest possible system description that includes all important aspects." One might add to this "*at the appropriate level of detail and accuracy*", which helps to capture the significant amount of judgment involved in modeling.

While the importance of modeling process is obvious, and while on the surface it appears to be a mainstay of engineering education, we would argue that engineering instruction focuses much more heavily on *model analysis*, rather than on *model formulation or development*. Indeed, there would appear to be little more on model formulation than "watch me do it"; this suggests that educators operate on the hope that students will somehow draw together their various exposures to modeling experiences to become competent. Departing from this norm, we advocate explicit modeling instruction, based on these premises: while modeling is a complex mental task, it can be articulated, and that only with such articulation can we help students learn this skill. To this end, this paper describes an approach to uncovering the basic elements of modeling.

Within the educational literature there does not appear to be yet an articulation of the constituent components of the modeling process. Fortunately, though, the literature of cognition and instruction has moved from studies of well-defined subjects, such as physics, to open-ended tasks, such as design. Goel and Pirolli[2] studied the structure of design by constructing design problems from several fields. They recorded interviews with designers engaged in these problems and asked them to "think aloud" as they proceeded. The transcribed interviews ("protocols") were divided into statements, which were labeled ("coded") according to a protocol-coding scheme similar to existing schemes of previous design studies. From this analysis, they identified twelve invariants, or, twelve components, of the design task.

With such an approach as guidance, we also sought to determine whether similar task decomposition is meaningful from the viewpoints of cognitive theory and instruction. Lovett and Greenhouse[3] applied cognitive theories to instruction in statistics and performed a task decomposition. They supported their approach by appealing to Anderson and Lebiere's[4] theory of cognition, according to which declarative knowledge ("know that") can be broken down in chunks, upon which procedural knowledge ("know how") operates via production rules. As support for the instructional benefits of a task decomposition, they cited the work by Catrambone[5], who demonstrated that both labeling and visually isolating subtasks in examples improved the performance of students in solving novel problems.   In earlier work, Lovett[6] had categorized approaches to task decomposition into a matrix of theoretical versus

empirical (observing subjects engaged with the task) and prescriptive (expert or ideal performance) versus descriptive (less-than-ideal performance of learners).

This paper begins with a brief description of efforts to take a prescriptive (theoretical) approach to identifying the elements of modeling. Then, we set forth the main emphasis of the paper: a normative (empirical) approach to identifying the elements of modeling, based on the analysis of recorded examples of graduate students engaged in modeling. This leads to a framework describing the primary tasks of modeling, which could be the basis for instructing students in modeling.

Prescriptive Approach

In a *prescriptive* approach, researchers focus on what the particular cognitive task *should* look like, judging from their experience as either seasoned instructors or experts in the respective discipline, or both. Examples of the prescriptive approach are found in the educational literature, including physics[7], and more open-ended tasks, such as general problem solving[8]. The prescriptive approach was also the initial choice of the authors of this paper. Reflecting on our own experiences as researchers and instructors and calling upon the thoughts of our colleagues, we independently formulated ideas on modeling, organizing them into a framework. We then each critiqued the other's framework, prompting each to reformulate our individual frameworks, with this process continuing for several iterations.

Our respective frameworks had many commonalities. We both believed that modeling should have a qualitative stage, followed by a quantitative stage. In the qualitative stage, decisions are made regarding the relevant phenomena, the part of the physical system to focus on, and the nature of the simplifications and approximations. All of these are inferred from interpretations of the information given in the problem statement. In the quantitative stage, these ideas are translated into variables, values for properties and equations. The details of the frameworks at the successive iterations are not presented here. Suffice it to say, despite the commonalities, we were unable to reconcile important differences in the details. It was difficult to argue strongly for one side or the other, without being able to appeal to concrete examples of modeling. This prompted us to gather evidence that could help validate some of our contentions and sort out irreconcilable details. In fact, the examples of modeling we gathered lead to the more systematic approach, which is described in the next sections.

Normative Approach

The examples of modeling we gathered were based on interviewing subjects. Interviewing subjects is one standard approach to obtaining experimental evidence in cognitive science. Subjects are asked to talk (or "think aloud") with minimal pauses as they are engaged in a task; they are suitably prompted to continue when they stop talking, in order to minimize self-editing of thoughts[9-10]. Such verbal protocols offer the closest possible glimpse into what a cognitive task *actually looks like*. Hence, such methods are referred to as *normative*, to differentiate them from the prescriptive approaches discussed in the previous section. Once the recorded interviews (protocols) are transcribed (converted to written text), (i) the text is segmented into groups of utterances or statements, (ii) each statement is coded (labeled) according to a topic-specific scheme consisting of suitable categories and (iii) the coded statements are analyzed to answer specific research questions[11]. Judgment is exercised in determining the coding scheme (the labels), in breaking the protocol into segments and in labeling each segment with one of the coding categories. Nevertheless, the normative

approach achieves a considerable reduction in subjective judgment, by permitting the coding categories to be confirmed during protocol analysis. Here, the coding labels are intended to capture the major categories of focus that engineers attend to during modeling.

Protocols of Modeling

We conducted six interviews in total. Two interviews were conducted as pilots in order to test the feasibility of the protocol study; comprehensive hand-written notes were obtained during these interviews. Following the encouraging results of the pilots, we tape-recorded and transcribed four additional interviews. Three protocols were used for the development of the coding scheme and the final framework. The fourth protocol was used to test that the developed coding scheme worked satisfactorily for problems other than those that helped create it.

We constructed three modeling problems, all involving a real situation or object, from the areas of solid mechanics, groundwater flow - contaminant transport and soil mechanics. Two were real case-study problems, and while the third was synthetic, it did involve an existing artifact. Problem statements avoided suggesting the problem formulation or solution method by using everyday language (no abstractions). The mechanics problem involved a bike rack, including sketches and pictures from the product manual and web page, and asked what would happen if an extra bike were added (beyond the four it was designed for). The flow and transport problem asked how one would confirm or discard the possibility of a contaminant spill from a specific location. Data consisted of an air photograph, a contour map of groundwater table elevation and sampling locations. The soil mechanics problem involved a retaining stone wall, with a drawing from an actual project.

Protocols were produced by four graduate students, from Civil and Environmental Engineering and Mechanical Engineering Departments, each having a specialization in the general area of at least one of the three problems. This number of subjects is not atypical of studies based on protocol analysis[2,11]. Graduate students (and these ones in particular) were chosen, rather than undergraduates or faculty, in part because they were viewed as having a fair ability at modeling, but still sufficiently new at the task that they were likely to be better able to articulate their thought process.

Prior to the interview, we gave the subjects a description of the research project, which explained the focus on modeling physical artifacts and phenomena of interest for engineering applications and the aim of understanding what is going on during this task. We emphasized that the *process* leading to answers to problems posed was critical; hence, all preliminary, tentative or dead-end ideas and partial solutions were very useful. Apart from the materials describing the problems (a short written description with one or two additional pages with drawings, pictures or maps), the subjects were given a notepad and a pencil. Besides prompts to continue speaking or non-guiding requests for elaboration (e.g., if they mentioned properties, we might ask them "what kind of properties?"), the only guiding prompts we allowed in the last four interviews were of the type "how would you show this with a sketch?" We made this exception because the pilot interviews indicated that sketches appear to play a catalytic role in making some key modeling decisions regarding subsystem definition and analysis type. When "anything else to add?" prompts did not produce new thoughts, the interviews were terminated. The transcribed interviews lasted about 10 to 25 minutes. The written and drawn materials produced by the subjects were collected and cross-referenced with the interviewer's notes and the transcripts.

Protocol Analysis

Our goal was to devise a coding scheme, with categories corresponding to the components of the modeling task. The coding scheme would be truly meaningful if independent readers of a transcript could unambiguously describe each utterance in a modeling protocol as focusing on a *single* component of modeling (a single category), and if the choices of the readers were in agreement. Since no prior set of categories existed, our work consisted of both devising the set of categories and of determining whether the transcripts could be faithfully coded with such categories. Hence, we went through an iterative process that included developing the coding scheme, analyzing transcripts and discussing our results. Iterations were typically separated by a month or two; thus, each time we went back to reanalyze a transcript, our experience was one of viewing the protocols with a fresh eye (with no clear memory of the details of coding from previous iterations).

In the first attempt at protocol analysis, we each separately segmented the protocols and coded them in "free form", often choosing labels from the various descriptive frameworks that we had already developed. After discussing each other's coding to understand the rationale behind each other's choices, we attempted to replace the free-form labels with a single coding scheme having categories similar to the components arrived at in the prescriptive approach. This first coding scheme contained the following categories of focus: *phenomena, subsystem specifications, simplifications, variables, properties, solution type, solution method* and *miscellaneous*.

Upon using this first coding scheme, relatively encouraging agreement was found between our respective segmentations (divisions of the protocols) and our assignment of categories to these segments. In some instances, the segments were coded with the same label. In others, segments were labeled differently because they could admit different interpretation. For example, when the subject focused on a quantity to be calculated, this could be labeled as either *variable* or as *solution type*, if the variable pointed directly to a certain type of analysis. When the subject talked about a material property, this in turn pointed to certain phenomena. For yet other segments, no agreement or obvious reason for disagreement could be found and our discussions did not settle differences one way or another.

To resolve issues, another iteration of this type followed, consisting of modifying the coding scheme, coding independently, and discussing differences. Based on our experiences with coding and taking into account the nature of our disagreements, we decided to develop both a final coding scheme consisting of the modeling components and detailed annotations describing what would count as evidence that the subject is focusing on each component. We tested this final version of the coding scheme by recoding independently one last time the three protocols. We then conducted another interview and coded, again independently, this fourth protocol. The agreement was very good, and the nature of the remaining disagreements helped us refine the annotated coding scheme. The final version of the annotations of the coding scheme allowed us to resolve all remaining disagreements in recoding, this final time jointly, the four protocols.

Final Framework

According to the final coding scheme, modeling can be described with ten components. All interviews contained versions of *problem statement* (1). Students spent a good portion of the

interview identifying the setting and quantities that are relevant for the problem, namely *phenomena* (2), *parameters* (3) and *variables* (4). They also talked about the elements of the solution approach: *analysis type* (5), *subsystem specification* (6), *qualitative form of solution* (7) and *solution method* (8). Various attempts at simplifying the problem were explicitly mentioned during the interviews. Although these attempts were related to one or more of components 2 through 8, *simplifications* (9) were acknowledged as a separate modeling component to emphasize their important role in transforming real physical systems to the representations analyzed and solved. The last component of modeling found from the interviews was *reflection on decisions* (10). We found it useful to give numbers to these categories as above, and to organize them for study as shown in Figure 1. However, the numbers do not imply any order in which these components appeared in the transcribed interviews nor any apparent organization on the part of subjects. In fact, protocols invariably contained jumps and loops, and any individual protocol lacked some of the ten components. While a number of the elements from our earlier prescriptive frameworks were found to be present, there was no evidence of distinct qualitative and quantitative stages during modeling.
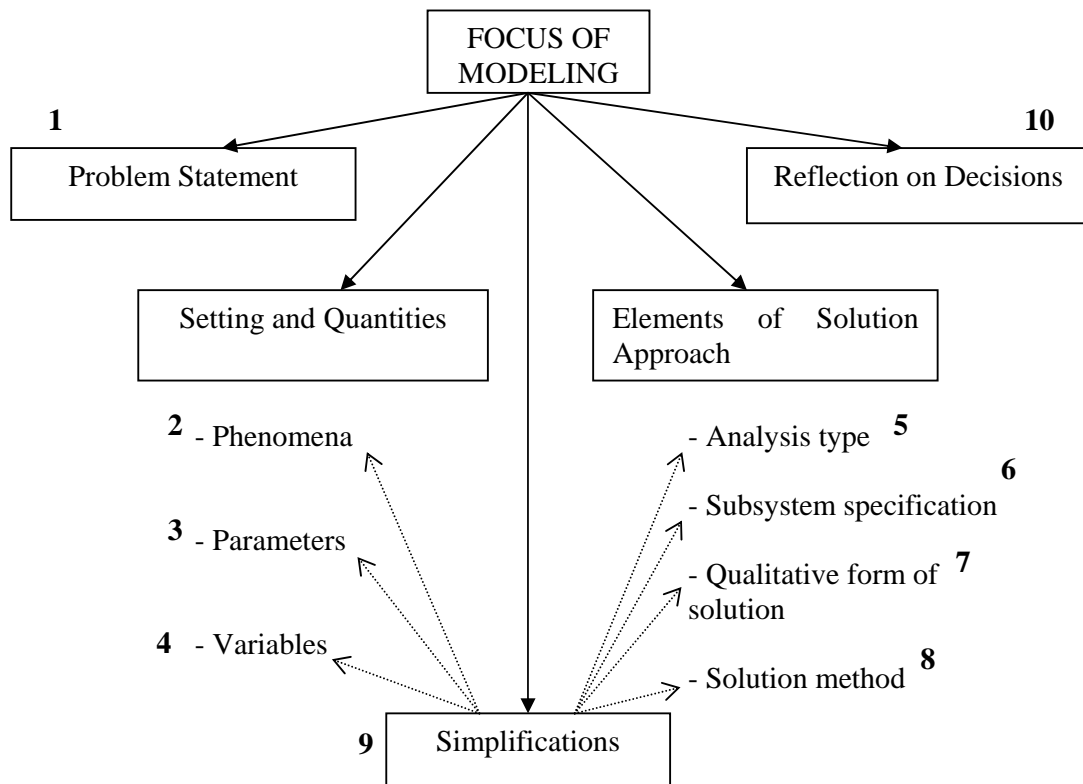

Figure 1. Categories of focus for coding protocols of modeling physical systems.

As an illustration of the coding scheme, consider the following excerpt from a protocol on the bike rack problem.

Excerpt from Protocol	Modeling Category
…and so that vertical force is going to have to be supported by the pin down here. My suspicion is that this thing has been designed to carry much more weight than it does, so, you know, just let's say we assume that all the weight is carried by this one bolt even though there is another one up here. If your calculations say it is fine carrying that load then…	Simplification (Analysis Type)
…and you could account for any kind of dynamic effects associated with riding along the road... it's going to bump around…	Phenomena
…and it comes out saying that it is safe well then you are fine because that pin is going to support some of it anyway…	Reflection on Decision

As mentioned, we found it useful to produce a detailed annotated version of the coding scheme, in order to minimize ambiguity during coding. With the annotated version, we tried to capture a combination of how we define the categories of focus and what would count as evidence of them in the protocols. One example of these annotations is the following for phenomena:

- Statements about what is happening physically – e.g., "it's going to bump around"
- Causal relationships or interactions between effects or events
- Related physical effects which would be relevant if present (often not obvious from problem statement) – e.g., "and you could account for any kind of dynamic effects associated with riding along the road"
- Statements about what can go wrong (failure modes or critical conditions)
- Proper names for physical phenomena

Implications for Instruction

At the early stage of development of this work we can make only general statements regarding the relevance of this paper for instruction. First, it should be re-emphasized that the modeling of unstructured engineering problems, such as the problems used in our protocols, is not a mainstay of engineering curricula at most universities. This may be due to the fact that devising such problems is hard and evaluating student work is time consuming and ambiguous.   An additional reason, though, may be that instructors do not know how to teach this skill. Our results might suggest that instruction concentrate on exercising the individual components of modeling, such as explicitly acknowledging simplifications and later reflecting on those decisions, clearly identifying the results (variables) which would answer the questions of interest, and identifying the parameters that are likely to affect the result. In addition, having a list of the categories of focus during modeling might serve as a useful prompt. It would not be appropriate though to coach students to adopt a particular order in which they consider the components of modeling.   Some initial efforts to use this in class are underway.

Conclusions

This paper discussed two alternative approaches for identifying the components of modeling of physical systems. The prescriptive approach relies on teaching experience and domain expertise, while the normative approach is based on subject interviews and protocol analysis. Using primarily the latter method, we developed a framework for the modeling process, consisting of ten components, together with detailed explanations for each component. While subjects did not address these modeling components in any consistent order, all statements in the protocols were identified as addressing one or more of these components. Although it remains to be verified, teaching of modeling may benefit from explicitly addressing these components.

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