Cognitive Research: Uncovering How Designers Design; Cognitive Modeling: Explaining and Predicting How Designers Design

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Abstract. In this paper we describe: 1) A research approach that can produce cognitive models of the design process and 2) A particular model that illustrates the approach.

Cognitive models describe the complex behaviors required to solve engineering problems in terms of underlying functional mechanisms. Because the models describe cognitive systems at the level of functional mechanisms, they can generate explanations and predictions about the behaviors being studied. This makes the model useful to theorists; it also provides insights concerning support and teaching tools for practitioners.

To illustrate our approach we present a model of learning to program by analogy. Within the model we describe mechanisms that simplify the processes of mapping, evaluating and debugging newly acquired knowledge in a complex domain. We also discuss the theoretical and practical implications of the model.

1 Introduction

This paper has two goals. First, to describe a research approach that can produce cognitive models of the design process; second to describe a particular model illustrating that approach.

The utility of a cognitive model: the level of description produced. A cognitive model, like the one presented in Section 5, describes the processes that underlie, and so give rise to the set of behaviors that constitute a skill. The model is specified as a set of mechanisms with defined functionality; each mechanism is described as a process that can transform classes of input into classes of output. The model also specifies the interactions among the mechanisms. Because the model describes a cognitive system at the level of its functional mechanisms it generates explanations and predictions about the skill being studied. This makes the model useful to theorists; it also provides insights concerning support and teaching tools for practitioners.

2 The Research Paradigm: Choosing a Skill and a Task

A given piece of cognitive research begins with choosing a cognitive skill to be modeled; constructing a task that will allow the skill to be observed; and selecting a method for recording the performance of the task.

With regard to choosing a skill, the model will only be interesting to the extent that it describes a skill that is central to solving a range of engineering problems. The researcher's intuitions as to what skills are important can be checked here by making an explicit argument concerning the problems that require the skill.

The next issue concerns choosing a problem-solving task that will allow observation of the skill that is required to solve it. The central tasks, the ones representative of engineering design are inherently complex. In order to make studying the chosen task tractable, a small-scale example of the task must be found. However, if the size of the example makes the solution process nonrepresentative, the model will not be valid. The answer is to explicitly state the features of the task that are of theoretical interest and then to pick an example that, while scaled-down, can be seen to retain the features of interest.

Once the task is decided on, protocols can be collected of subjects performing the task. Protocol studies have several strengths. The first is that protocol analysis allows the researcher to look at complex, interacting behaviors which is necessary to
the goal of studying real-world problem-solving. The traditional paradigms of experimental psychology were constrained to look only at simple behaviors in isolation in order to yield reaction time data with the low variability necessary for detailed and normative descriptions of human behavior. While not yielding precise timing data, protocol analysis allows the researcher to collect data that goes beyond the description of simple behaviors, and instead yields explanation of complex mechanisms.

The second strength of protocol analysis concerns its ability to yield data bearing on the questions generated by cognitive models. Cognitive models are specified in terms of explanatory mechanisms. Currently, the qualitative rather than quantitative properties of those mechanisms have been defined. As a result the models generate predictions about process interactions; protocol analysis is particularly suited to test these predictions. An example of the kind of predictions that these models generate and protocol studies that can test the predictions can be seen in Adelson and Soloway (1985). In studying software designers they initially found that designers would conduct mental simulations when combining familiar modules in new ways. The model that they then developed asserted that the simulations were done in order to identify unwanted interactions between software modules. This assertion generated the testable prediction that these simulations would be done only when the interactions among modules were unknown. Protocol studies were conducted to look at designers creating a variety of systems; some with familiar interactions, some with novel interactions. The data supported the model’s prediction; only novel assemblies were simulated. An additional example of the kind of issues raised by these models and addressed by protocol data is presented in Section 5.1.

Additionally protocol studies allow the researcher to study behavior in a natural setting, protecting the results against distortion by the experimental environment. And, because they are less subject to environmental distortion they allow the researcher to observe unanticipated behavior that may be vital to correcting, refining, or extending a theory (Simon and Ericsson, 1981; Newell and Simon, 1972).

The introduction of protocol analysis as an empirical method has enabled advances in the range of disciplines that use cognitive models for both theoretical and practical purposes. Scientists concerned with the modeling of cognitive processes are no longer limited to studying simple, isolated behaviors. Instead they can construct and test more powerful theories that concern the most central issues in thinking and problem-solving that had not until now been tractable.

In this section we have discussed the utility of cognitive modelling and described the process of designing cognitive research. Cognitive models, because they describe the functional systems that give rise to skilled behaviors allow explanation of the behaviors. The models are generated by a process in which an important skill is identified, a task requiring the skill is chosen and the performance of the task is observed and recorded. Once the performance of the task has been analyzed, a model can be hypothesized explaining the skill exhibited in performing the task.

3 Software Design: Learning to Program by Analogy

In what follows we describe research on the development of a theoretical model of learning to “design” computer programs by analogy. This work will serve to illustrate our approach to cognitive theory development. Additionally, we believe that the theory itself is relevant to engineering design in three ways: First, learning is inherent and central in designing. Second, analogy is a central approach to learning. Skilled designers and talented students, although they are always learning, rarely start from scratch; instead they build on their expertise, comparing current problems to one previously solved. Finally, programming problems have features common to other engineering problems. All require reasoning about the relationship between function and structure, about constraints on the ordering of sub-tasks, etc.

3.1 A General Theoretical Framework

Recent research on learning by analogy suggests a class of theory which rests on the following set of processes (Carbonell, 1983 and 1986; Falkenhainer, Forbus, and Gentner, 1986; Holyoke and Thagard 1985; Burstein and Adelson 1987; Kolodner, 1985; Kedar-Cabelli, 1984):

- Retrieval: An initial conceptual model1 of a familiar source or base domain is retrieved from memory. This retrieval process is complex. It will recur throughout the learning process. Additionally,

1 In cognitive research, the term model has two meanings. It can refer to a representation of the domain being learned or a computer system that embodies the process for learning the domain. The distinction between the two meanings should be clear in context.