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Understanding Relevance Vis-a-Vis Internal Transfer

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1. Introduction

Understanding methods of problem solving is a main goal of both Cognitive Science and Artificial Intelligence. Although general problem solvers that use weak methods have been developed, they are not sufficient for reasoning about complex problems in complicated domains. For such tasks, the search is generally intractable: the height of the search tree is determined by the complexity of the solution, and the branching factor at each level is determined by the large number of applicable operators. The principle problem is that weak methods operating on large domain theories provide the problem solver with only a very limited notion of which operators might be relevant to which goals.

What is needed to solve this problem, then, is a set of learning methods that can select and retrieve past experiences that are relevant to the current goal. Here, we define a *relevant* experience as one that can inform the problem solver about which operators will lead it more directly to its current goal, thus, increasing its efficiency. Analogical learning accomplishes this by retrieving a relevant source solution instantiation from memory and modifying and transferring it to solve the the current target problem. Since analogical reasoning permits inexact matching of goals and flexible adaptation of solutions, it is widely applicable.

One of the main difficulties for system designers constructing computational analogical learning systems, however, is defining the *similarity metric* that measures which of the previous experiences in episodic memory are the most relevant to the current situation. Frequently, these metrics are hand-coded and are reported as being based on the "salient" features of the domain, which only pushes the question down another epistemelogical level. What are the salient features of a domain? Although the similarity metrics are hard to code, they are extremely important since search in the modification space can overpower search in the base problem space if the retrieved artifact does not closely match the current specifications.

In response to this difficulty, we designed a verbal protocol experiment to gather more data on analogical learning in the physical sciences and on the similarity metrics people use in particular[2]. The first result of the experiment is that the subjects used both the quantity type of the goal and *information-contents* of the source and target problems as the relevant indices for all the within-domain analogies. A second result is that the subjects had tests similar to the information-content metric encoded in the applicability conditions of the iterative macro-operators [4] they used to perform the remainder of the internal transfer in the study. Thus, the same tests were used to find the relevant experience regardless of whether the learning mechanism employed was the more flexible but deliberate internal analogy or the more compiled and efficient iterative macro-operators.

The next section briefly describes the design of the verbal protocol experiment. Section 3 discusses the effectiveness and efficiency of the analogical problem solving. In addition, it describes the formation and use of iterative macro-operators and closes by pinpointing the subjects' relevance measure for internal transfer.

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[2]The experiment and its preliminary results were first reported in our earlier work, [2].

Finally, we conclude with a summary and a discussion of the extensibility of these principles to other types of computational reuse systems.

2. Experimental Design

This section briefly outlines the experimental design of the verbal protocol experiment we ran to elicit analogical reasoning from subjects solving problems in the DC-circuits and fluid statics domains. The complete description and analyses can be found in [3].

In the study, the problems were designed to facilitate three kinds of transfer: internal analogy, within-domain analogy, and cross-domain analogy. Internal analogy transfers experience from a previously solved subgoal to a current subgoal that is contained in the same problem. In contrast, within-domain and cross-domain analogy transfer problem solving experience from one problem to another in the same and different domains, respectively.

The four subjects in the study had all earned an A or a B in a year-long college physics course, but they had not solved any problems in these domains for several years. We chose subjects with this level of proficiency because we believed that they would be the most likely to exhibit the desired transfer. Subjects with a high level of expertise tend to use compiled knowledge rather than analogical reasoning; subjects with very little expertise tend to use brute force search. The subjects were given a remedial, which was in a two-column format, covering the knowledge necessary for the experiment. The left column contained the circuit information, and the right column contained the fluid statics information. Analogical concepts were presented directly across the page from each other. In order to verify the remediation, the subjects were asked to explain sparse written solutions to three example problems. These example problems were also designed to serve as analogical sources for some of the five test problems that the subjects were asked to solve next.

3. Results

3.1. Aggregate Data on Analogical Transfer

When analyzing the protocol data, we were conservative in what we were willing to call an "analogy." The requirement for an action or verbalization to be coded as an analogy was that the subject explicitly verbalize the recognition of the similarity between the two goals before transferring the solution procedure. Some such example verbalizations that can be found in the protocol data in [3] are: "It's all analogous (Subject 1, Problem 1, line 137 - S1,P1,L137)", "I_2 is a similar thing (S1, P1, L140)", "It looks almost exactly like problem two (S1, P4, L6-8)", etc. This is a conservative approach because as subjects get more facile in transferring knowledge in the domains, they tend to verbalize less and less. For instance, they tend to no longer state the equations they are transferring but only verbalize the numeric answer. Likewise, there may be instances where they use the same equation to solve a similar goal immediately after solving the source goal but do not explicitly verbalize the similarity. In those situations, our criterion would not recognize the behavior as analogical transfer. However, we wanted an objective criterion that would dictate which verbalizations to code as analogical transfer. Therefore, the reader should realize that the frequencies of transfer reported may be underestimated, not overestimated.

Several important points stand out in the data. The first is that internal analogy happened more frequently than either within-domain or cross-domain analogy, even considering that there were more opportunities for internal transfer. However, a fair amount of within-domain analogy was attempted, even though only 5 attempts produced successful transfer. We found that cross-domain transfer in our study happened only once, even when we identified the reference problem for the subjects. This cross-domain finding is consistent with the literature [1] In examining the occurrences of internal analogy, we see that in the circuits domain the subjects performed about 63% of the possible internal analogies on the test problems, while not taking advantage of any of the opportunities in the fluid statics domain. This is because they used a different learning method, iterative macro-operators [4], to take advantage of the regular substructure in the fluid statics problems. In fact, it turns out that in 97.2% of the cases where the subjects failed to use internal analogy to effect a possible internal transfer, they used iterative macro-operators to take advantage of the regular substructure of the problem. Therefore, almost all the opportunities for internal transfer in the test condition of the experiment are capitalized on by one or the other of these learning methods In the next subsection, we show how iterative macro-operators evolve from the subjects' internal analogical process.

From the above data, the analogy process was clearly effective in helping the subjects successfully solve the problems. The next question is whether the transfer actually made the problem solving more efficient. We claim that it did as the target problems in the internal transfer of the test condition required an average of about 53% of the time it took to solve their associated source problems.

3.2. The Formation and Use of Iterative Macro-Operators

Macro-operators are problem solving control knowledge acquired by concatenation and parameterization of useful operator sequences. Iterative macro-operators, then, are macro-operators that allow for generalized iteration [4]. We recognized the existence of the iterative operators in the protocols by phrases like, "which is equal to the sum of the currents through *each* of the resistors (S1,P1, L238-240)," and "we can reexpress *each* of those currents as a voltage over a resistance (S1,P1,L242-244)."

On problems 1 and 2, Subject 1 initially works the problem via internal analogy, but *explains* the problem back to the experimenter using iterative macro-operators. This also happens with Subject 3 on Problem 1, who works through the first analogical or source subgoal, then explains the other two subgoals using an iterative macro-operator. Therefore, it seems as if the internal analogy process is the precursor to forming the more compiled iterative macro-operators. More than likely, it serves to elicit and/or cache the preconditions that are needed to form the iterative operator. Subjects 2 and 4, who are more expert than Subjects 1 and 3, seem to start the experiment with this kind of compiled knowledge, and it accounts for their relatively low usage of analogical reasoning.

3.3. Identifying the Relevant Experiences

In Section 1, we asked what were the "salient" features of the domain that determined which of the experiences in episodic memory were relevant. From our experience with the subjects in this study, the answer seems to be two-fold. First, the subjects always chose as a source goal a goal which is of the same *quantity-type* as the target goal (e.g. resistances for resistances, currents for currents, etc.). Second, they chose source goals for whom the dependent quantities in their associated solutions had the same status of known or unknown in the target problem as they did at the outset of problem solving in the source problem. This makes sense because if the subject had additional knowledge during the previous problem solving, that knowledge, which is missing in the current state, may have been crucial to the success of the solution strategy. Without that knowledge, the subject may be unable to recycle the old solution to solve the current target problem. The *information content* of the candidate source, then, is the set of known information required to make the solution successful. The information content of the current target goal is computed by calculating the subset of this knowledge that is known in the current state.

An example of this type of matching behavior can be seen in Figure 3-1 where the goal is to find the values of I2, R1, I3, and R4. Subject 4 maps the analogous subgoals at the outset of the problem solving before embarking on his forward-chaining problem solving. He first maps the subgoals by quantity type and information content in lines 9 and 10 when he says, "so - I have - two resistors where the current is given and the resistance is left unknown (R_1 & R_4) - and two resistors where the resistance is given and the current is left unknown (R_2 & R_3)." He then solves for I_2 and R_1. When he starts to solve for I_3, he says, "similar situation here," and reposts and reinstantiates the equation from I_2 for I_3. Another example can be seen when Subject 1 in Problem 1 in [3] states, "I_2 is a similar thing, and we know the resistance, and we - and again through all the paths (L140-143)."

Each subject explicitly verbalizes the mapping by information-contents during the first instance of analogical transfer that they perform. After that, the verbalization becomes more sporadic, and the matching process becomes less conscious. In any event, during 26.7% of the internal analogies, the information-content is explicitly mentioned, as it is in 60% of the within-domain analogies. It is not mentioned in the single instance of the cross-domain transfer. However, the subject was given the appropriate reference problem and not required to retrieve it himself. Had he

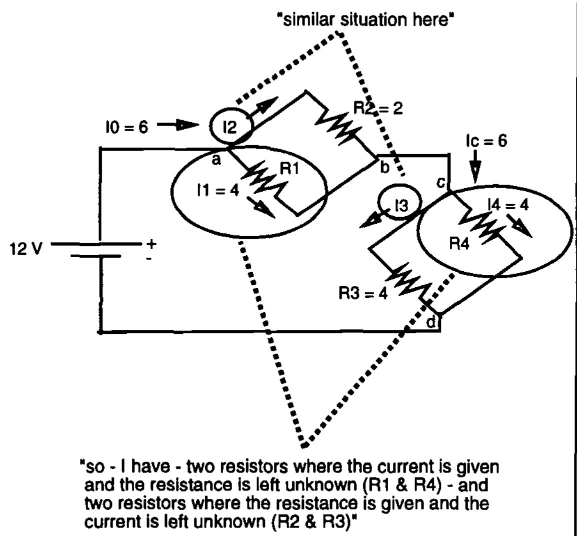

Figure 3-1: Subject 4 working problem 5.

performed the retrieval on his own, he might have verbalized the similarity metric. Even during the internal analogies for which the subjects do not verbalize the information-content during the match, the source and target problems are consistent with these matching criteria.

If, as hypothesized, the iterative macro-operators evolve from earlier instances of internal analogy, it would be likely that their applicability conditions also contain tests derived from the information-content measure. Indeed, we found this to be true. It turns out that all the subjects except Subject 3 mentioned the information-content of the example problems. Subject 3, along with Subjects 1 and 4, mentioned it on the first of the test problems. Overall, it was mentioned 13 out of the 22 times the iterative macro-operators were applied, or 59.1% of the time.

4. Conclusions

Relevant experience can inform general problem solvers about which operators are more directly applicable to their current goals. As such, being able to identify that relevant experience is instrumental in increasing the efficiency of general problem solvers using weak methods.

Analysis of the data from our verbal protocol experiment designed determine what similarity metric people use when solving analogical problems in the physical sciences produced some interesting results. First, the subjects used both the quantity type of the goal and *information-contents* of the source and target problems as the relevant indices for all the within-domain analogies. In addition, they had tests similar to the information-content metric encoded in the applicability conditions of the iterative macro-operators they used to perform the remainder of the internal transfer in the study. Thus, the same tests were used to find the relevant experience regardless of whether the learning mechanism employed was the more flexible but deliberate internal analogy or the more compiled and efficient iterative macro-operators.

In closing, we should mention that the measure of relevancy presented above is not unique to problem solving. It can be applied to other artifacts, such as plans and program modules, whose weakest preconditions can be articulated or computed.

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