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How Human Tutors Employ Analogy To Facilitate Understanding

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Abstract

A corpus consisting of eighty-one one-on-one tutoring sessions with first-year medical students carried on by two professors of physiology at Rush Medical College was analyzed for the use of analogies to facilitate understanding of the topics covered. Analogies were infrequently used, but had a positive effect on improving student comprehension of the topics tutored. The human tutor's goals, topics, discourse strategies, follow-up, and clarification in the presence of misunderstanding were analyzed with the long term goal of implementing analogies in an intelligent tutoring system.

Introduction

Analogies play a major role in learning. Eighty-one one-on-one tutoring sessions carried out by two professors of physiology at Rush Medical College were extensively marked for analogies using SGML. Instances of analogies were then classified in terms of the goals, targets, bases, and whether they were proposed by the student or the tutor.

Current advances in education, cognitive science, linguistics, and expert systems make it feasible to generate analogies in an intelligent tutoring system using a computational model. To date, as far as we know, no one has used full-scale natural language generation to implement analogies in an electronic tutoring system. The goal is to use computational models of memory retrieval and analog mapping to simulate the human tutor's behavior in our intelligent tutoring system, CIRCSIM-Tutor.

Analogies in Cognitive Science

Gentner defines analogies as:

partial similarities between different situations that support further inferences. Specifically, analogy is a kind of similarity in which the same system of relations holds across different objects. Analogies thus capture parallels across different situations (Gentner, 1998, p.107).

Analogical reasoning is essential to cognitive ability (Gentner, 1998; Kurtz, Miao, & Gentner, 2001), and scientific inquiry and study (Dunbar, 1993; Goldblum, 2001; Michael & Modell, 2003; Modell, 2000; Thagard, 1997). Research studies exist that:

- analyze the way humans store and retrieve analogues from memory (Forbus, Gentner, & Law, 1995; Hofstadter, 2001; Holyoak, Gentner, & Kokinov, 2001; Holyoak & Thagard, 1995; Kokinov & Petrov, 2001; Kolodner, 1993)
- use computational models to simulate the results of human studies (Forbus, 2001; Forbus, Gentner, & Law, 1995; Holyoak, & Thagard, 1995)
- analyze the use of analogy in problem solving/reasoning (Holyoak & Thagard, 1985; Holyoak, Gentner, & Kokinov 2001; Kolodner, 1993; Thagard, 1997)
- analyze the use of analogies in education, medicine, and scientific inquiry (Dunbar, 1993, 1995; Goldblum, 2001; Thagard, 1997)

Gentner's (1983, 1998) structure mapping theory (Gentner & Markman, 1997; Holyoak, Gentner, & Kokinov, 2001; Holyoak & Thagard, 1995; Kurtz, Miao, & Gentner, 2001) seems to closely match the way our expert tutors work. New knowledge (the target) is learned by mapping its structure to existing knowledge (the base). Inferences are made from these mappings. The representation of mappings is discussed in length in Yan, Forbus, & Gentner (2003). When retrieving possible analogs from memory, the goal is to find mappings that have predictive value (Gentner, 1983).

Further studies have demonstrated that analogical encoding—the “process of comparing two examples and deriving an abstraction on the basis of their commonalities” (Loewenstein, Thompson, & Gentner, 1999, p. 586)—can be effective in facilitating the learning of similar problems. Abstractions of schemas gained through the intensive comparisons of two analogous concepts that are not fully

understood not only facilitate the understanding of the new pieces of information, but the general schemas derived can be applied to similar problems encountered later (Gentner, Loewenstein, & Thompson, 2003; Kurtz, Miao, & Gentner, 2001; Loewenstein, Thompson, & Gentner, 1999). Studies involving the learning of negotiation skills in undergraduates and graduate management students (Loewenstein, Thompson, & Gentner, 1999) and presentation of heat flow scenarios to teach the concept of heat flow (Kurtz, Miao, & Gentner, 2001) demonstrated that the intentional and intensive comparisons of two concepts that are not fully understood are as effective in knowledge transfer as structural alignment. Gentner (1983) demonstrated that this approach to teaching by analogy bypasses the common problem that humans have when trying to retrieve relevant information from memory to connect to new knowledge that one is attempting to learn. Mutual alignment is especially relevant to electronic tutoring systems that cannot always rely on the presence of existing knowledge when presenting new concepts.

Possible problems resulting from misunderstandings when reasoning analogically in a scientific domain are well-recognized (Feltovich, Spiro, & Coulson, 1989). Holyoak and Thagard (1995) have studied misconceptions and devised the multiconstraint theory that addresses the problems resulting from the use of inappropriate analogies. They recommend placing certain restrictions—of similarity, structure, and purpose—on the analogy. If all three constraints are met, only one interpretation of the analogy can be gleaned from the mapping. In cases where the three constraints are not met, misunderstandings can be identified and corrected. We have observed this behavior in our expert tutors' human sessions, as discussed below.

Analysis of Analogies Found in the Corpus

In order to understand our human tutoring session, one must first have background information on what is being tutored. The human body requires a blood pressure within a certain range to sustain life. The baroreceptor reflex is a negative feedback system that controls blood pressure in the cardiovascular system to ensure that the pressure remains within this range. When a perturbation in the system occurs, the response has three phases: direct response (DR) of the system to the perturbation, the reflex response (RR) to the new values of affected variables, and the steady state (SS), or state of the system after it has re-stabilized. CIRCSIM-Tutor asks the student to predict the qualitative changes in several important variables at all three stages. The variables are: Heart rate (HR), Cardiac Contractility (CC), Stroke volume (SV), Cardiac output (CO), Mean arterial pressure (MAP), Total peripheral resistance (TPR), Central venous pressure (CVP). Eighty-one hour-long tutoring sessions with first year medical students solving problems about the baroreceptor reflex were conducted by our experts, two professors of physiology at Rush Medical College, Joel Michael and Allen Rovick. Face-to-face sessions were recorded and transcribed. Keyboard-to-keyboard sessions

were recorded using Computer Dialogue System (CDS) discussed in Li, Seu, Evens, Michael, & Rovick (1992). CDS forces each person to take turns typing. An annotation language based on SGML (Kim, Freedman, Glass, & Evens, 2002) was used to mark up the human sessions by hand. The following examples (discussed in Lulis & Evens, 2003; Lulis, Evens & Michael, 2003) were selected from the analogies found in these expert human tutoring sessions. They are representative of sessions where the tutor uses analogies: new material is explained, misconceptions are corrected, and prompts—successful and unsuccessful—are made to the student to make analogies and inferences. In each of the examples listed, the tutors used analogies after the student made an incorrect inference. The identifiers at the beginning of each sentence make it possible to find the original context at any time: initial F or K indicates whether the session was face-to-face or keyboard-to-keyboard; the session number comes next; st (student) or tu (tutor) indicates who is speaking/typing; this is followed by the turn number and the number of the sentence within the turn. A complete set of marked-up transcripts will be provided on request.

Example 1. Face-to-face session number one (F1) contains examples of the use of analogy to explain domain material and a correction by the tutor. The analogy of comparing the heart to a sink is proposed by the student (st). However, the sink is not a compliant object and the heart is. As a result, the tutor (tu) offers a better analogy—the heart is like a balloon.

F1-st-62-1: If I make an analogy of you try to fill a sink with water and you...

F1-tu-63-1: Try to fill a balloon with water, since that's what we're dealing with, a distensible object.

F1-st-64-1: OK.

After making a one-to-one mapping of the base (balloon) to the target (heart), a correct inference is made. In accordance with Holyoak and Thagard (1995) and Gentner's (1983) theory of structure mapping, the following structures underlie what the tutor does (as discussed in Lulis & Evens, 2003; Lulis, Evens, & Michael, 2003):

Structure for the balloon

- fill a balloon with water
- it will distend
- the pressure in the balloon increases as it distends

Structure for the heart

- fill the right atrium
- the right atrium will distend
- the pressure will increase as it distends

The above example demonstrated the effectiveness of the accepted structure mapping approach of connecting new knowledge to knowledge already understood by the student.

As a result, the student develops a better understanding of the new concept (Gentner, 1983, 1998; Goldblum, 2001; Holyoak & Thagard, 1995).

Example 2. We see the tutor correcting a misconception in face-to-face session #7.

F7-tu-267-1: Well, let's give it another thought, OK?

F7-tu-267-2: We can look at that central blood chamber that means the big veins and the atria together as though they were an elastic chamber.

F7-tu-267-3: Is that not correct?

F7-st-268-1: Yeah, and the heart is the pump.

F7-tu-269-1: Well, let's stick to this elastic chamber and look at it first more or less in isolation.

F7-tu-269-2: If you have an elastic chamber what are the things that determine the pressure inside that chamber.

F7-st-270-1: Size.

F7-st-270-2: No.

F7-st-270-3: I mean if you..

F7-st-270-4: I mean...

F7-st-270-5: Area is one but I gather for the heart..

F7-tu-271-1: Area of what?

F7-st-272-1: Area that..

F7-st-272-2: I mean if you want to know what the pressure is of a gas or well liquids aren't that..

F7-st-272-3: We're not talking about gas, we're talking about liquids.

F7-st-272-4: And liquids are not affected by size because you can't compress the molecules that much.

F7-tu-273-1: Oh, you mean the volume occupied by the liquid, expansion and condensation of the liquid.

F7-tu-273-2: No.

F7-tu-273-3: That's not an issue.

F7-st-274-1: No, because we're talking about liquids and liquids aren't affected.

F7-st-274-2: Like with gas, besides the container matters a lot...

F7-tu-275-1: Let's throw away this atria central venous system and take instead something inanimate elastic stretcher, say like a balloon.

F7-tu-275-2: Right?

F7-tu-275-3: What determines what the pressure is inside the balloon?

In the above example, an analogy of the atria as an elastic chamber is proposed by the tutor, but the structure of the intended base analog—the atria or central venous system as a reservoir—is not understood by the student resulting in a failure to make the connection between existing knowledge and the new knowledge. The tutor suggests a base that the student is familiar with—a balloon to compare the atria to. A correct structure mapping is made allowing the student to understand the new concept.

Example 3. In keyboard-to-keyboard session number one (K1), the tutor prompts the student to make an analogy between neurally controlled variables in the DR (direct response) period. The behavior of the variable TPR during the DR period has already been tutored. The inference is that all neurally controlled variables will behave similarly during this period. The student makes the connection between the analogs resulting in a correct inference.

K1-st-29-1: During the DR period it would remain unchanged.

K1-tu-30-1: Correct.

K1-tu-30-2: What other variables are neurally controlled?

K1-st-31-1: CC, HR

K1-tu-32-1: Again correct.

Example 4. An example of the student not getting the point of the analogy is seen in keyboard-to-keyboard session #5 (K5). After tutoring the neurally controlled variable CC, the tutor attempts to get the student to make an analogy between it and other neurally controlled variables. The student fails to make the analogy and the tutor finally tells the student the analogy that he is seeking.

K5-tu-31-1: No, it is under neural (sympathetic) control, rily.

K5-tu-31-2: We are now discussing what happens in the DR period, before any neural (reflex) effects.

K5-tu-31-3: Sowhat will happ en to CC in this pe;riod?

K5-st-32-1: Cc 0.

K5-tu-33-1: Correct.

K5-tu-33-2: While we're on the subject, what other variable is underneural contro l and how will it be affected in the DR?

K5-st-34-1: SV 0.

K5-st-34-2: It will not be affected in the DR.

K5-tu-35-1: Not true.

K5-tu-35-2: SV is only partially under neural control via CC, one of its importan t determinants.

K5-tu-35-3: We'll come back to this in a moment.

K5-tu-35-4: What othervariable is un der neural control?

K5-tu-39-3: LIKE CC!.

K5-st-40-1: TPR 0.

Example 5. More interesting analogies can be found in several sessions. Keyboard-to-keyboard session number sixty-four (K64) contains an analogy proposed by the student (st) between the heart and a traffic cop. The mapping between these analogs is not correct; the tutor (tu) proposes a more suitable analogy between the heart and a traffic jam. The structure mapping theory discussed in Gentner (1983, 1998), Goldblum (2001), Holyoak and Thagard (1995), and formalizes what the tutor is doing.

K64-st-54-1: Would it be a reasonable analogy to look at the heart like a traffic cop?

K64-st-54-2: If it slows down the rate of blood flow (lets fewer cars through) then there will be a

backup behind it (a backflow of blood prior to the heart, and therefore an increase in CVP) and fewer cars coming through (less blood coming out of the heart and therefore a decrease in MAP)

K64-tu-55-1: The analogy is OK.

K64-tu-55-2: But just as traffic jam does not occur because cars back up, the increase in CVP caused by a fall in CO is not the result of blood BACKING UP.

K64-tu-55-3: Everything soes in one direction.

K64-st-56-1: well, slowing down would be a better way to put it then

K64-tu-57-1: Yes.

K64-tu-57-2: A traffic jam caused by everybody piling into the same area at once.

Analogies in Human Tutoring Sessions

In the tutoring sessions that we have studied, we observe expert tutors taking steps to avoid misconceptions. They (Holyoak & Thagard, 1995):

- Make certain that students understand the system mapping.
- Use a variety of analogies.
- Inform students when an analogy is relevant and when it is not—point out the differences, as well as the similarities, between the known knowledge and the target.
- Correct misconceptions when they occur.

The outcomes of the analogies proposed by the tutor are shown in Table 1 (as discussed in Lulis & Evens, 2003; Lulis, Evens, & Michael, 2003). We summarize the analogies that we found in human tutoring sessions described here.

Table 1: Use of observed analogies proposed by tutors

Type	No. observed in corpus
no inference requested	5
successful mapping	4
failed mapping	1
inference requested	37
successful inference	15
failed inference	
success after repair	15
failure after repair	7
enhancement only	9
Total:	51

Out of the fifty-one analogies proposed by the tutors, nine were used after correct inferences and apparently intended to enhance the student's understanding of the material discussed and not to lead to further development. In forty-two cases, the tutor used analogies after the students made incorrect inferences. In five of the forty-two cases, the tutors

did not request inferences from the students. However, students did make correct inferences four out of the five times without prompting. In the remaining thirty-seven cases, an inference was requested after the analogy was proposed resulting in correct inferences being made by students fifteen times without repair to the analogy (to correct misunderstandings) and fifteen times with repair—81% success rate. In only seven of the thirty-seven cases—19% of the time—did the tutor abandon the use of analogy and opt for a different teaching strategy. In total, the use of analogy after an incorrect prediction was followed by a correct prediction in 34 out of the 42 times—81% success rate. The empirical evidence suggests that the use of analogy had positive affects on the students' ability to understand the material.

If we examine the different bases employed while tutoring using analogies—proposed by students and tutors—we find a wide range, as shown in Table 2. The analogy that was most often proposed by the tutors was another neural variable—twenty-nine times. In five of these cases, the tutors eventually gave up on the analogy and utilized a different approach to the material, but the other twenty-four were ultimately successful. There was one successful mapping without an attempt at an inference, twelve successful mappings with correct inferences, and four successful mappings with correct inferences after repairs. Other successful mappings occurred using in a wide variety of bases such as the heart as a balloon or pump, Ohm's law, airplane wings, bootstraps, a dimmer switch, traffic jams, and a black box. These bases were not observed as often,

Table 2: Bases present in the corpus

Base	No. observed in corpus
Airplane wing	1
Another algorithm	2
Another neural variable	29
Another procedure	3
Balloon	1
Balloon as a compliant structure	2
Black box	1
Bootstrap	1
Brake & accelerator	1
Compliant structure	3
Dimmer switch	1
Elastic reservoir	1
Flight or fight	1
Gravity	1
Last problem	1
Ohm's Law	2
Physician	1
Pump	1
Reflex	2
Sugar or glucose	1
Summation	1
Traffic jam	2

but made for extremely productive and interesting structural mappings resulting in correct inferences.

Gentner's (1983; Lowenstein, Thompson, & Gentner, 1999) work suggests that information from abstract and concrete bases may be processed differently. She has observed that children find it easier to understand analogies with concrete bases than with abstract ones. We hope to investigate this phenomenon using CIRCSIM-Tutor. In our data in Table 2, we see twenty-two different bases, twelve are concrete and ten are abstract (Table 3). The use of abstract bases are observed forty-four times in the corpus, while the concrete bases are used only fifteen times. Examination of the language used suggests another potentially useful classification—into analogies that remind students of earlier experience with another neural variable or another procedure and those that depend on a base from outside the immediate domain.

Table 3: Analogies with abstract and concrete bases

No.	Type of base	No. of times seen in the corpus
12	different concrete	15
10	different abstract	44

Implementation

Holyoak & Thagard (1995) identified the steps of analogical reasoning: the retrieval of possible analogs from memory, the mapping of these analogs to the new knowledge being learned, inferring something from the mapping, adjusting the new knowledge if necessary, and storing the new knowledge for future use. Computational models dealing with analogy address the first two steps—retrieval based on similarity and structural mapping. There are two dominating models for the retrieval step—case based reasoning (Birnbaum & Collins, 1989; Kass, 1990, 1994; Kolodner, 1984, 1993, 1994; Schank, 1982) and a model that emulates a document retrieval system, retrieving both relevant analogs and irrelevant ones. There are also two approaches to the mapping step. One makes inferences before the mappings—projection first—the other makes the mappings before the predictions—alignment first.

It is our goal to implement an analogy generating function in CIRCSIM-Tutor (Michael, Rovick, Glass, Zhou, & Evens, 2003). It has been decided that a document retrieval model coupled with an alignment-first mapping—MAC/FAC—(Gentner, 1998; Gentner & Markman, 1997; Forbus, Gentner, Everett, & Wu, 1997) was best suited for use when simulating human tutoring in CIRCSIM-Tutor System. MAC/FAC was chosen because we believe that it simulates how people process analogies and its implementation is very successful.

MAC/FAC

MAC/FAC (Many Are Called/Few Are Chosen) models Gentner's (1983) theory of structure mapping and simulates

the human propensity to favor relationships between bases and targets when comparisons are made and to favor superficial similarities and not retrieve the more profound analogical similarities while still, on occasion, retrieving relevant structural comparisons (Forbus, Gentner, & Law, 1995). Working memory consists of content vectors constructed from the structural representations of the bases. The MAC stage functions like a document retrieval system, searching working memory in a parallel manner seeking content vectors that are similar to the target. The dot product between each of the bases and the target is computed to determine the best and those within 10% of the best matches. Stage two, the FAC stage, utilizes the output from the MAC phase to do Gentner's (1983) structure mappings. The structure mapping engine (SME) selects the best mapping and all those within 10% of it.

Conclusion

Analogies are used by our human tutors infrequently; on the average, less than once a session. However, the human sessions have demonstrated that the use of analogies is extremely effective. We have observed tutors using analogy to tutor the topic at hand and to enhance existing knowledge. Misunderstandings were corrected and inappropriate analogies replaced with more suitable ones. The structure mappings between the analogs underlie what the tutor was doing.

Future research includes simulating the schemas observed in the corpus in our expert system CIRCSIM-Tutor (Michael et al., 2003). Many of the analogies observed can be implemented using structure mapping (Gentner, 1983, 1998; Goldblum, 2001; Holyoak & Thagard, 1995) to connect new knowledge to existing knowledge. We will attempt to simulate mutual alignment (Gentner, Loewenstein, & Thompson, 2003; Loewenstein, Thompson, & Gentner, 1999) for the most commonly found analogy in the corpus—another neurally controlled variable. The recommendations of Goldblum (2001), and Holyoak & Thagard (1995)—use more than one analog, detect and fix incorrect mappings, identify the analogical scope, and refine analogies—will also be attempted.

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