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ABSTRACT

Methods and approaches used by effective teachers are examined, and the set of goals and subgoals that guide these teachers, the set of specific strategies that they use to generate cases, questions, and comments for their pupils, and the control structure that they use to allocate their time between different goals are specified. The theory constructed from this analysis can be employed to educate effective teachers, and to build intelligent computer assisted instructional training systems for future use. (Author/MJB)

Goals and Strategies of Interactive Teachers

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The paper extends our earlier analysis of teaching to the analysis of the best teachers for whom we could obtain transcripts. The analysis attempts to specify the set of goals and subgoals that guide the teachers, the set of specific strategies that the teachers use to generate cases, questions, and comments for the students, and the control structure that the teachers use to allocate their time between different goals. The theory constructed from this analysis can be applied in educating teachers to be effective, and in building intelligent CAI systems of the future.

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Socratic tutoring, and to Natalie Dehn for recording Professor Roger Schank during one of his classes at Yale.

ABSTRACT

The paper extends our earlier analysis of teaching to the analysis of the best teachers for whom we could obtain transcripts. The analysis attempts to specify the set of goals and subgoals that guide the teachers, the set of specific strategies that the teachers use to generate cases, questions, and comments for the students, and the control structure that the teachers use to allocate their time between different goals. The theory constructed from this analysis can be applied in educating teachers to be effective, and in building intelligent CAI systems of the future.

INTRODUCTION

In previous work (Collins, 1977; Collins, Warnock, Aiello, and Miller, 1975a; Collins, Warnock and Passafiume, 1975b; Stevens and Collins, 1977) we have attempted to build formal process theories of the goals and strategies of human tutors. In this paper we attempt to analyze the strategies of the very best teachers for which we could obtain films or transcripts.

The teachers we analyzed have diverse teaching goals and strategies. Nevertheless we can abstract out common elements in their teaching, as well as reasons for the differences. All of the teachers use some version of the case, inquiry, or discovery method of teaching (Anderson and Faust, 1974; Sigel and Saunders, 1979). They do not simply teach facts, but rather they teach basic principles or basic problem solving strategies for approaching different kinds of problems. For example, one teacher we analyzed is particularly effective in teaching his students how to attack problems. His students end up using many of the same techniques he uses to approach novel problems. Such an outcome indicates that it is possible to teach problem solving strategies and that these techniques are sufficient to do so.

The theory of interactive teaching that we are constructing is cast in a framework similar to that used by Newell and Simon (1972) to describe human problem solving. It contains three parts:

1. The goals and subgoals of effective teachers.
2. The strategies used to realize different goals and subgoals.
3. The control structure for selecting and pursuing different goals and subgoals.

Teachers typically pursue several goals simultaneously. Each goal has associated with it a set of strategies for selecting cases, asking questions, and giving comments. These are represented in our theory as condition-action pairs (Collins, 1977). In pursuing goals simultaneously, teachers maintain an agenda (Collins, et al., 1975b; Stevens and Collins, 1977) which allows them to allocate their time among the various goals efficiently. The theory therefore encompasses goals, strategies, and control structure.

We see two kinds of uses for a formal theory of interactive teaching. Currently there is much active research to develop intelligent computer assisted instruction (ICAI) systems (e.g., Sleeman and Brown, 1979; Goldstein and Brown, 1979). To the degree we can develop precise theories of effective teaching strategies, these can be embedded in ICAI systems. Equally important are the implications for teacher education. We think we can make explicit the kinds of goals our best teachers pursue, and the specific strategies they use for dealing with different kinds of situations. In summary, we think it is possible to make the accumulated tacit knowledge of our best teachers explicit enough both for future teachers to learn and for ICAI systems to use.

Terminology used in the theory

Many of the teaching strategies we describe serve to communicate the teacher's understanding of the causal structure of a domain to a student. Thus, we need a way to notate a causal structure. One way of representing causal dependencies is in terms of an and/or graph (Stevens and Collins, 1980). Figure 1 shows such a graph for the causal dependencies derived by a student in a dialogue that one of us conducted on growing grain in different places (Collins, et al., 1975a). Each place that was discussed functioned as a case in the terminology of the theory. In the figure rice growing is the dependent variable, and is treated as a function having two possible values: either you can grow rice or you can't. In other sections of the dialogue wheat growing and corn growing were discussed as alternative dependent variables. Unlike grain growing, which the student treated as a threshold function, many dependent variables are treated as continuous functions (e.g. a place is colder or warmer), where there is a continuous range of values.

During the course of the dialogue the student identified four principal factors affecting rice growing: fresh water, a flat area, fertile soil, and warm temperature. These were configured as shown in the diagram. These factors (or independent variables) are linked to rice growing through chains with various intermediate steps. In fact any node in a chain can be considered as a factor affecting subsequent nodes. Figure 1 itself represents only a top-level description, since nodes or links in the diagram can be expanded to more detail (Stevens and Collins, 1977). Links expand into chains of links and nodes, so that for example "irrigation" can be considered an intermediate node on the chain from "river or lake" to "supply of fresh water".

Given a set of factors and a dependent variable, a rule (or hypothesis) is any function that relates values of one or more factors to values of the dependent variable. A rule can be more or less complete depending on the degree it takes into account all the relevant factors and the entire range of values of the dependent variable. For example a rule about rice growing might assert that growing rice depends on heavy rainfall and fertile soil. Such a rule is obviously incomplete with respect to the mini-theory shown in Figure 1. A theory specifies the causal structure interrelating different rules. In complex domains like rice growing and medicine, no theory is ever complete.

Insert Figure 1 here

Given the dependencies in the diagram, it is apparent that a factor like heavy rainfall is neither necessary nor sufficient for rice growing. It is not necessary because obtaining a supply of fresh water (which is a necessary factor) can also be satisfied by irrigation from a river or lake. It is not sufficient because other factors, such as a warm temperature, are required. When prior nodes are connected into a node by an "or", any of the prior nodes

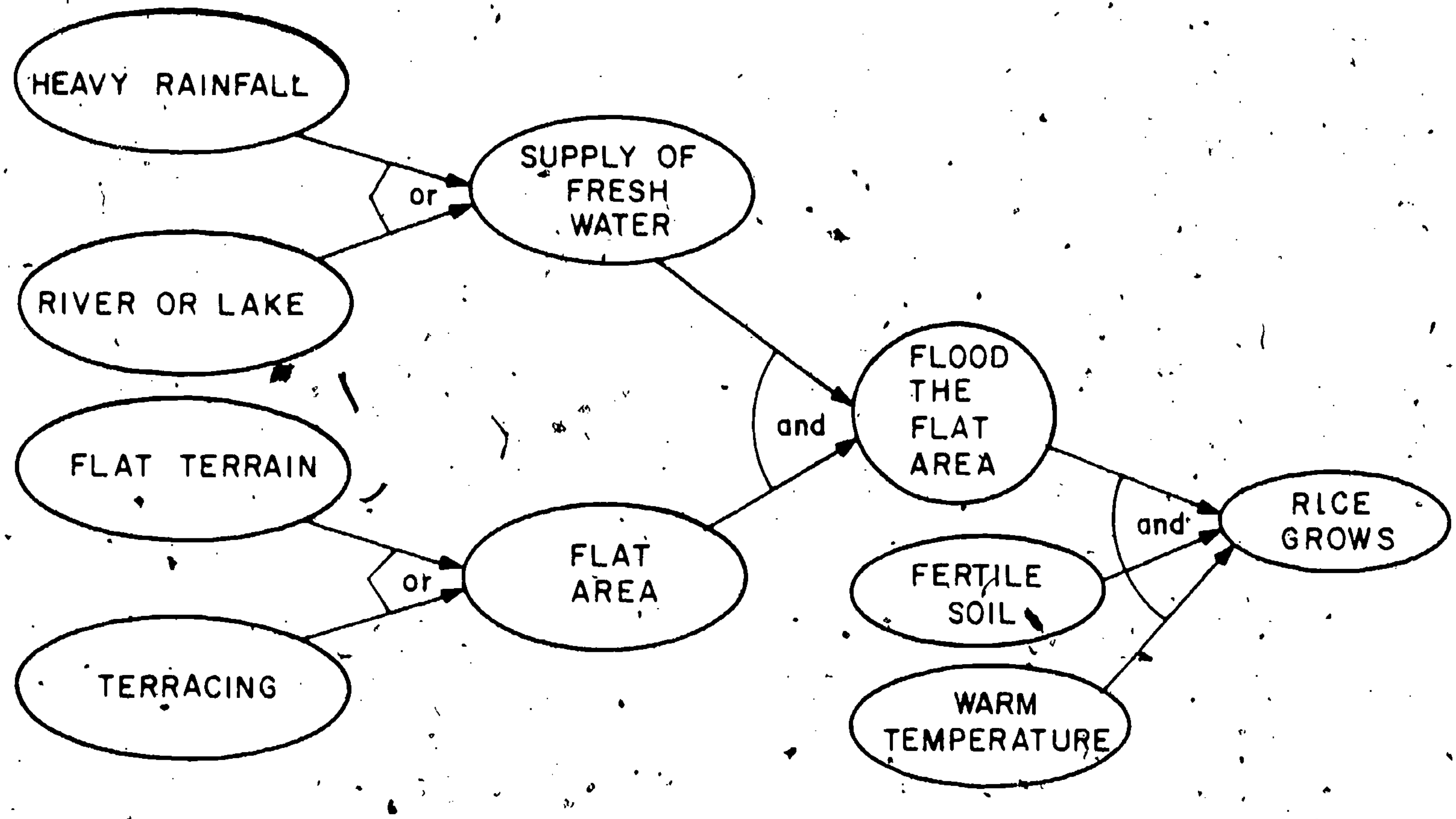

Figure 1. A student's analysis of the causal factors affecting rice growing.

is sufficient and none is necessary with respect to that node. For example, either heavy rainfall or a river or a lake is a sufficient source for fresh water, but none of these is necessary for fresh water. In contrast, when prior nodes are connected into a node by an "and", all of the prior nodes are necessary and none is sufficient with respect to that node. For example, fresh water is necessary to flood a flat area, but is not sufficient. Though heavy rainfall is sufficient as a source of fresh water, it is not sufficient for growing rice, because of the "ands" in the causal structure between rainfall and rice. Any variable not included as a factor in the diagram is effectively treated as <u>irrelevant</u> to the theory.

<u>Independent and Dependent Variables in Different Domains</u>

Table 1 illustrates how the terminology applies to teaching strategies in different domains. We believe that these teaching techniques can be applied to virtually any domain. In Table I we are not trying to list all possible independent and dependent variables, nor are we ruling out other possible assignments; these are merely meant to indicate the most common assignments that teachers make.

Insert Table 1 here

Let us briefly explain these examples:

1. In arithmetic, a student solves problems in order to learn how to handle different operations, numbers, variables, etc. Because of the procedural emphasis in arithmetic, it is the domain that fits our terminology least well.

2. In art history, the teacher attempts to teach students how techniques, uses of texture or color, structural interrelationships, etc., create certain effects on the viewer.

3. In law, historical cases are used to teach students how different variables (historical precedents, laws, aspects of the particular case, etc.) affect legal outcomes.

4. In medicine, the goal is to teach students how to diagnose different diseases, given patterns of symptoms, their course of development, and the patient's history and appearance.

5. In geography, most variables are treated both as independent and dependent variables on different occasions. For example, average temperature is a dependent variable with respect to the first-order factors, latitude and altitude, and general second-order factors, distance from the sea, wind and sea currents, tree and cloud cover, etc. But, in turn, temperature is a factor affecting dependent variables such as population density, products, land types, etc.

6. In moral education, teachers try to teach rules of moral behavior by considering different situations with respect to the actions and motives of the participants.
7. In botany, one learns what configurations of the shape, branches, leaves, etc., go with what tree and plant names.

Whether a variable is treated as a dependent or independent variable depends on what the teacher is trying to teach. It does not depend on the direction of causality. For example, in geography or law, the independent variables (e.g., amount of available water) are typically presented as causes of the dependent variables (e.g., population density). On the other hand, in electronics or medicine where the emphasis is on diagnosis, the independent variables (i.e., symptoms) are typically effects caused by the dependent variables (i.e., faults or diseases). In some domains, such as botany, there is no causality in either direction. What functions as a dependent variable is merely what one tries to make predictions about in the real world.

DATA ANALYZED

The dialogues we have analyzed range over a variety of domains and situations. Some are with individual students and some with groups of students. The students range in age from preschoolers to adults. In some cases the teacher has a well-worked out plan as to where the dialogue will go, whereas in others the teacher does not. We can illustrate the variety by describing briefly each of the dialogues we have analyzed.

Table 2 lists the dialogues we have analyzed most recently. The Meno dialogue by Plato (1924) operates as a case method on two levels. On one level Socrates tries to convince Meno that all ideas are innate by demonstrating that a slave boy "knows" a square with sides $\sqrt{2}$ units long is twice as large as a square with sides 1 unit long. On the second level Socrates gets the slave boy to figure out the area by considering different possible constructions. Socrates frequently uses entrapment strategies getting the slave boy to make a wrong hypothesis and then tracing the consequences of the hypothesis until the slave boy sees the contradiction. Socrates' purpose is not entirely pedagogical and therefore there is very little problem solving or discovery by Meno or the slave boy.

Insert Table 2 here

Another transcript is from a film series showing Max Beberman, a famous math teacher, teaching junior-high students. In the transcript Beberman starts out by giving students problems to work that involve a complicated procedure for computing the sum of real numbers. The procedure involves going right on a piece of graph paper the distance corresponding to any positive number being added, and left for any negative number. Students quickly start using a shortcut; they add the positive numbers together, the negative numbers together, and take the difference. That is they learn a generalized procedure for adding real numbers. Later Beberman tried to get the students to formulate the rules for addition of real

Table 2

Dialogues Analyzed with Cases,

Independent and Dependent Variables Specified

1. Socrates with slave boy in Meno dialogue

   (C=square with twice area; IV=length of sides and diagonal; DV=area of square)

2. Beberman with junior high students on addition of real numbers

   (C=problems; IV=numbers, directions; DV=answers)

3. Anderson with junior high girl on the distributive law in arithmetic

   (C=problems; IV=numbers, operators, order, sum; DV=answers)

4. Warman with pre-schoolers on who can play with blocks

   (C=situation; IV=girls and boys rights, actions, amount of playtime; DV=fairness)

5. Warman with pre-schoolers on morality of characters in Peter Pan

   (C=characters; IV=actions and motives of characters; DV=morality)

6. Schank with graduate students on planning (3 phases)

   (C=real world goals; IV=properties of actions and motives; DV=plans vs. nonplans)

   (C=same; IV=same; DV=primitive types of plans)

   (C=same; IV=primitive types of plans; DV=complicated plan) numbers as shown in this short excerpt: (The excerpts are annotated with the goals and strategies explained later.)

T: I want to state a rule here which would tell somebody how to add negative numbers if they didn't know how to do it before. Christine? (Ask for rule formulation.)

S: The absolute value--well--a plus b equals uh--negative--

T: Yes, what do we do when we try to do a problem like that? Christine is on the right track. (Reward rule formulation.) What do you actually do? Go ahead, Christine. (Ask for rule formulation.)

S: You add the numbers of arithmetic 5 and 7, and then you --

T: I add the numbers of arithmetic 5 and 7; but how do I get the numbers of arithmetic when I'm talking with pronumerals like this? (Ask for generalization of factors.)

S: Well, you can substitute.

T: But I don't want to talk about any special cases now; I want to talk about all the cases at once. (Ask for generalization of factors.)

What we see Beberman doing is creating a situation where students working problems will induce an abstract rule for addition of real numbers.

The third transcript we analyzed shows Professor Richard Anderson of the University of Illinois teaching a junior-high girl to induce the distributive law in arithmetic. It parallels the Beberman transcript in that a series of problems is given in order to get the student to induce a general rule. Anderson carefully selected problems to make the distributive law apparent. Some of this can be seen in the following excerpt from near the beginning of the dialogue: (numbers are written on the board)

T: OK. Close your eyes. 7 x 6 + 3 x 6 = . . Now. (Pick differentiation exemplar for first factor. Ask for prediction of dependent variable.)

S: 60.

T: OK. Close your eyes. 7 x 12 + 3 x 12 = . . Open 'em up. (Pick differentiation exemplar for first factor. Ask for prediction of dependent variable.)

S: (Goes off to side to work each part.)

T: Emmm.

S: No?

T: That's all right. You can do that. But you're still doing it the hard way, Margie. (Punish lack of rule formulation.)

S: 120.

T: Now look for a second at the problems that are up on the board. Don't say anything. But just look at all of the problems and the answers and see if you see anything interesting. Don't tell me if you do, but just look. (Suppress rule verbalization.) Look at the problems and the answers. (Ask for rule formulation.)

Anderson picked his cases so that the pattern was obvious; the numbers that are added sum to 10 so that the multiplicative factor (6 in the first case, 12 in the second) shows up as the significant digits in the answer. Anderson later varies the particular digits (6 + 4 instead of 7 + 3) and then their sum as well, until the student formulates the distributive law in its most general form. The dialogue mainly illustrates how case selection can be used to force generalization.

The two transcripts with Eloise Warman show how similar techniques can be applied to teaching moral education. Warman in the first dialogue tries to get a group of preschoolers to formulate a new rule in the classroom for allocating the toy blocks to the boys (B) and girls (G). In the second dialogue she tries to get the children to evaluate the morality of the different characters in the play, Peter Pan, which they just saw. Two excerpts, one from the very beginning of the first dialogue (which states the problem) and one from near the end (which gives the new rule), illustrate her techniques:

> T: The problem is that the girls say the boys never let them play with blocks. (Establish rule formulation goal. Subgoal have kids formulate rule. Point out insufficiency of factors in current rule.) But what do you think about this boys, that the girls play with legos and you can't play with legos? (Hypothetical case construction for insufficient factors. Ask if rule is correct or incorrect - i.e., fair or not.)

.....

> G: I think it should be the teachers.

T: But why just the teachers? (Ask for questioning of authority.) It doesn't seem to work. We had an idea. We've been trying. (Point out insufficiency of factors in rule.)

B: I've got one idea.

T: Oh, Gregg's got a good idea. (Reward rule formulation.)

B: The girls can play with the big blocks only on 2 days.

T: Hey, listen we come to school 4 days a week. If the girls play with the big blocks on 2 days that gives the boys 2 other days to play with blocks. Does that sound fair? (Restate rule. Ask if rule is correct or incorrect - i.e., fair or not.)

G: Yea! Yea!

The initial segment shows Warman's statement of her overall goal to formulate a new rule for allocating blocks. She then suggests the kind of hypothetical case she uses frequently where she proposes a situation with the opposite value as to who gets the advantage, and asks the group who had the advantage whether they think that is fair. The second segment illustrates how she encourages kids to verbalize their ideas and to question authority. She even manages to entice a fairer rule out of one of the boys in the class.

Another transcript we analyzed is based on a class in Artificial Intelligence taught by Professor Roger Schank at Yale. There were three phases to the class session: in the first phase the goal was to specify what features define a plan; in the second phase the goal was to define a taxonomy of basic plan types with respect to the definition in the first phase; in the third phase the goal was to analyze a real world plan in terms of the taxonomy. The excerpt below from the first phase illustrates the establishment of the initial goal and two of the definitions (i.e., rules in our terms) formulated by the students:

T: It's not an unreasonable question to ask how new plans might arise, but it's not the right time to ask it. The first thing to ask is what's a plan? (Establish goal: Identify factors necessary for something to be a plan. Strategy: Ask for rule formulation.)

S1: A means for getting to some desired state.

T: Anyone else? (Ask if rule is correct or incorrect or for formulation of another rule.)

S2: They're heuristics which people learn to use to deal with certain types of situations.

The two excerpts below from the second phase illustrate the establishment of the goal of characterizing different plan types and one of Schank's many attempts to get the students to question authority. In this phase the student's task is to form a disjoint set of basic plan types: in our terms this is a set of sufficient factors joined by "or" links.

T: I'm going to make you classify again. What kinds of plans are there? (Establish goal: Identify possible plan types. Strategy: Ask for sufficient factors.) Unless you would like to change the definition the only thing I'm going to let you answer is types of means. (Point out irrelevant factors.)

S2: Plans to establish social control over something.

T: The two of you are agreeing that everything from the book is gospel. (Point out factors are same as authority's.) It's all right. Give me something new -- I wrote those -- invent something. (Ask for questioning of authority. Ask for sufficient factors.)

S2: Plans to establish conversational offensive over one's dialogue.

T: Let's just call it conversation plans. (Restate factor.) OK? What else? (Ask for sufficient factors.)

S2: How about plans to manipulate objects?

S1: Plans to manipulate people.

Many of the individual strategies in the Schank dialogue, such as encouraging verbalization and questioning of authority, parallel the strategies in the Warman dialogues. This is probably because both place heavy emphasis on teaching the students to formulate their own rules or theories for dealing with novel problems.

Table 3 lists the dialogues that we analyzed in earlier papers (Collins, 1977; Stevens and Collins, 1977). These ranged across geography, medicine, moral education, and letter identification. The theory presented here incorporates the goals and strategies identified in these earlier analyses, though in some cases the names of specific strategies have been changed to fit the more general structure imposed upon the theory in this paper.

Insert Table 3 here

THE THEORY

Goals of Teachers

There is a progression shown in Table 4 among the goals that different teachers pursue. The first most basic goal is to teach students the facts and concepts that comprise a domain of knowledge. We analyzed dialogues of this kind in an earlier paper (Collins, et al. 1975b), but none of the dialogues discussed in this paper are of this kind. A second higher level goal is to teach students a particular rule or theory underlying a domain of facts and concepts. This kind of goal was evident in the Beberman, Anderson, Socrates, Stevens and Collins, and Swets and Feurzeig dialogues. The third and highest-level goal is to teach students how to derive a new theory for a domain of knowledge. This differs from the second goal in that the teacher has no a priori expectation of what the to-be-derived theory is, rather the teacher has an idea about what constraints the theory must satisfy. This kind of goal is evident in the Warman and Schank dialogues.

Insert Table 4 here

Table 3

Dialogues Analyzed Earlier with Cases, Independent and Dependent Variables Specified

1. Anderson with hypothetical college student on factors affecting temperature
   (C=places; IV=latitude, distance from sea; DV=temperature)
2. Anderson with hypothetical college student on morality of draft resistance
   (C=draft resistors and American revolutionaries; IV=acts, motives; DV=morality)
3. Stevens and Collins with secretaries and high school students on factors affecting rainfall
   (C=places; IV=currents, evaporation, cooling; DV=rainfall)
4. Collins with secretary and scientist on where different grains are grown
   (C=places; IV=climate, soil, water, terrain; DV=rice, wheat)
5. Collins with secretary and scientist on population density
   (C=places; IV=climate, products, transportation; DV=population density)
6. Swets and Feurzeig with hypothetical medical student on diagnosing disease
   (C=medical case; IV=symptoms, history; DV=disease)
7. Swets and Feurzeig with hypothetical student on identifying letters
   (C=letters; IV=letter features; DV=letter names)

Table 4

Goals of Teachers

1. Teach facts and concepts about a domain.
2. Teach a particular rule or theory for a domain.
    a. Derive correct rule or theory.
    b. Debug incorrect rules or theories.
    c. Learn to make predictions from the rule or theory.
3. Teach how to derive a rule or theory for a domain.
    a. Learn what questions to ask to construct a rule or theory.
    b. Learn the nature of a rule or theory.
    c. Learn how to test a rule or theory.

The goal of teaching a particular rule or theory has associated with it three basic subgoals:

1) The major subgoal is for the student to analyze different cases in order to derive the rule or theory that the teacher has in mind. For example, in arithmetic Beberman tried to get students to derive the rule for addition of real numbers, and Anderson the distributive law. In geography Anderson tried to get the student to understand how distance-from-ocean affects temperature, and Stevens and Collins tried to get students to build a first-order theory of the factors affecting rainfall. The case selection, questioning, and commenting strategies shown later in Tables 5 and 9, are the principal strategies used to teach a particular theory.
2) Along with trying to teach a particular rule or theory, teachers often try to elicit and "debug" incorrect rules or theories. The teachers want the student to confront incorrect hypotheses during learning, so that they won't fall into the same traps later. This kind of goal is evident in Socrates' dialogues where he often traces the consequences of his student's hypothesis down to a contradiction, and in Anderson's dialogues on geography and moral education where he entraps students into revealing their misconceptions. The entrapment, the counterexample, and the hypothetical case construction strategies shown in Tables 5 and 7 are particularly important to debugging incorrect hypotheses.

3) Another goal that frequently pairs with teaching a given rule or theory is teaching how to make novel predictions based on the rule or theory. Simply knowing the structure of a theory is not enough; one must be able to operate on the structure to deal with new problems. For example, Anderson in mathematics gives harder and harder problems for the student to predict the answer, Stevens and Collins in geography start with cases that exemplify first-order factors and gradually move to more difficult cases to predict, Warman tries to get her preschoolers to predict what will happen under different rules, and Swets and Feurzeig are trying to get students to diagnose novel cases. The case selection strategies and prediction strategies shown in Tables 5 and 9 are crucial to teaching students how to deal with new cases.

When teachers try to teach students how to derive a novel theory, there are again three kinds of subgoals that come into play:

1) The most important subgoal is to teach students what questions to ask in order to derive a new rule or theory on their own. For example, Warman teaches her students to evaluate any rule by how fair it is, Schank is trying to get students to construct a theory by asking particular kinds of questions in a specific order, and Swets and Feurzeig in medical diagnosis emphasize considering different diagnoses before reaching a conclusion. The suggestion strategies and the rule evaluation strategies in Table 9 are particularly relevant to these goals.

2) A second subgoal that probably underlies many of the dialogues, but which is most evident in Schank's dialogue, is to teach students what form a rule or theory should take. In Schank's case, the structure of a theory is a set of primitive elements, serving a role similar to the basic elements in chemistry. Beberman in the segment shown was teaching students the form of arithmetic rules, where variables replace numbers in order to be general. Stevens' and Collins' notion of a theory of rainfall was a hierarchically-organized, process theory. Individual strategies seem to be only rarely tied to this goal; rather, the principal method for obtaining this goal is to get the students to construct different rules or theories of the idealized type.

3) Occasionally in the dialogues the teachers pursue a goal of teaching students how to evaluate a rule or theory that has been constructed. For example, Anderson in teaching about the factors affecting temperature tried to get the student to learn how to control one factor while testing for another. Schank, after his students had specified a set of primitive plan types, tried to get them to test their theory by applying it to a real world plan (i.e., becoming president). The strategies teachers use are specific to the kind of evaluation methods being taught.

Finally, it was a clear goal of both Warman and Schank to get their students to verbalize and defend their rules or theories.

This goal is clearly at a different level from the other kinds of goals described, and operates concurrently with the other top-level goals. For example, it is clear why Warman's children were always interrupting to give their ideas: she was constantly encouraging and rewarding them for joining in. Similarly, Schank tries to get each student in the class to either offer their own ideas, adopt one of the other's ideas, criticize one of the other's ideas, etc. Both stress the questioning of authority in their dialogues as a means to push students to formulate their own ideas. The strategies for encouraging verbalization in Table 9 serve this goal.

These are the top-level goals and subgoals we have been able to identify so far. In pursuing these goals, teachers adopt lower-level subgoals of identifying particular omissions or misconceptions and debugging them (Stevens and Collins, 1977). Thus these top-level goals spawn lower-level subgoals that drive the dialogue more locally. This will be discussed more fully in the section on control structure.

Strategies for Selecting Cases, Questions and Comments

Looking at the fine structure of the dialogues one sees recurring patterns of strategies in selecting cases, asking questions, and making comments. We have tried to characterize the individual strategies that occur in terms of condition-action pairs or productions (Collins, 1977; Newell and Simon, 1972). To do so, we specify the conditions that trigger each strategy to be invoked, and the actions that the teacher takes when the strategy is invoked.

When the action taken is to ask a question or make a comment, the surface form of the question or comment can vary quite widely. For example, in asking for prior factors a teacher might say: "Why do they grow rice in Louisiana?" or "What makes it possible to grow rice there?" or simply "Why?", depending on the context. Despite the large number of possible surface forms, at a deeper level a single questioning strategy is being applied.

The condition-action pairs for each of the strategies, together with examples of each are shown in the Appendix. It is impossible to get a feel for the theory without wading through some portion of the Appendix.

Case Selection Strategies: Much of the art of effective teaching centers around the selection of the best cases. By looking at the various dialogues, we have formed an initial theory about the principles governing teachers' selection of cases.

Table 5 shows the different types of case selection strategies. There are four basic types: picking positive and negative exemplars for particular factors, picking comparison cases with respect to previous cases selected, picking counterexamples, and constructing hypothetical cases for particular types of misconceptions. We will describe each of the strategies with reference to an example.

Insert Table 5 here

Table 5

Different Types of Case Selection Strategies

Positive and Negative Exemplars

Pick a positive exemplar for a set of factors

Pick a negative exemplar for a set of factors

Pick a positive exemplar for a sufficient factor (a near hit)

Pick a negative exemplar for a necessary factor (a near miss)

Comparison Cases

Pick a generalization exemplar for a factor (a maximal pair)

Pick a differentiation exemplar for a factor (a minimal pair)

Pick an exemplar to show the variability of a factor

Pick an exemplar to show the variability of the dependent variable

Counterexamples

Pick a counterexample for insufficient factors

Pick a counterexample for unnecessary factors

Pick a counterexample for irrelevant factors

Pick a counterexample for incorrect values of factors

Hypothetical Cases

Construct a hypothetical case for insufficient factors

Construct a hypothetical case for unnecessary factors

Construct a hypothetical case for irrelevant factors

Construct a hypothetical case for incorrect values of factors

The first two case selection strategies involve the selection of paradigm cases to exemplify a set of factors. For example, if the teacher wants to illustrate the factors that lead to different amounts of rainfall in different places, he or she will start with "good" exemplars: either positive like the Amazon or Oregon, or negative like the Sahara Desert or Southern California. These are good exemplars because the values on all the relevant factors are consistent with the value on the dependent variable: i.e., the Amazon has all the factors that lead to heavy rainfall, and the Sahara all the factors that lead to little rainfall. Cases like the Eastern United States are not clear-cut, and are not chosen as paradigm cases.

The next two strategies also involve selection of positive or negative exemplars, but with respect to a single factor. They are used if the teacher wants to focus the student on a particular factor not yet identified. If the factor is sufficient (i.e., is "ored" with other factors) as irrigation is a sufficient source of water for growing rice, then the teacher would choose a positive exemplar. For example, to get a student to identify irrigation, as a factor, the teacher would choose a case like Egypt where irrigation is used for growing rice. If the factor is necessary (i.e., is "anded" with other factor) as is warm temperature for growing rice, then a negative exemplar would be chosen (this is the "near miss" strategy of Winston, 1973). For example, the teacher might choose Alaska as an exemplar in order to get the student to notice warm temperature is necessary for growing rice. Positive exemplars are used with sufficient factors because negative exemplars require that all the sufficient factors be missing, and so do not emphasize a particular factor. Similarly, negative exemplars are used with necessary factors, because positive exemplars require that all the necessary factors be present, and so do not emphasize a particular factor.

The second group of four strategies specify the selection of cases with respect to previous cases. These strategies are best understood in terms of a set of factors the teacher is focussing on and a set of other factors (often irrelevant factors) the teacher is not focussing on. In picking a generalization exemplar, the teacher holds constant the values of the dependent variable and of the factors in focus while varying as many other factors as possible. For example, if the teacher had chosen the Amazon as a positive exemplar for the factors leading to heavy rainfall, as a generalization the teacher might pick Oregon which varies a number of irrelevant factors (latitude, wind, direction) but holds the relevant factors constant. To pick a differentiation exemplar, the teacher tries to hold as many of the non-focused factors constant, while varying the values of focused factors and the dependent variable. For example, in order to teach the distributive law Anderson would hold all the other variables constant while he systematically varied the number that functioned as a multiplier (see p. 11) together with the answer. This latter strategy is the minimal pair strategy used in linguistics (e.g., Gleason 1965). In contrast the generalization strategy is a maximal pair strategy.

The next two strategies are used by teachers to illustrate to students the effects of varying the dependent variable or the factors that are in focus. In order to show the variability of a factor the strategy is to pick a case where the dependent variable (and other factors) are held constant while the factor in focus varies. For example, to show the effect of temperature on rice growing, a teacher might pick Japan after considering Java, because they show the range of temperature over which rice is grown. To show the variability of the dependent variable with respect to a particular factor the teacher will select a case where the factor in focus is held constant while other factors and the dependent variable vary. For example, to show the variance in temperature near the equator, the teacher might move from the Congolese jungle to the peak of Kilimanjaro. Picking cases to show the range of variability is important in domains, such as medicine, where students must learn to distinguish cases that initially appear the same and group cases that initially appear different.

There are four types of counterexample strategies: counterexamples for insufficient factors, counterexamples for unnecessary factors, counterexamples for irrelevant factors, and counterexamples for the wrong value of a factor. We can give examples for each of the four counterexample strategies. If a student says they grow rice in Louisiana because there is lots of rain (which is insufficient), one can pick Oregon where there is lots of rain but no rice. If a student says they don't grow rice in Oregon because it lacks a flat terrain (which is unnecessary), one can pick Japan which is also mountainous, but produces rice. If a student asserts rice is grown in Japan because they are Oriental (which is irrelevant by the theory in Fig. 1), one can pick Mongolia or Louisiana as counterexamples. If a student asserts that a cool climate is needed for rice growing (which is the wrong value), one can pick Java and Alaska as counterexamples.

The hypothetical case construction strategies are triggered by the same four situations as the counterexamples. If a student thought rice couldn't be grown in Wyoming because it is too dry (which is insufficient because it is also too cold), the teacher could ask "Suppose that it rained a lot in Wyoming, do you think they could grow rice then?" If a student said they grow rice in Louisiana because it rains a lot (which is unnecessary since they could use the Mississippi River for irrigation), one could ask if they could still grow rice if it did not rain a lot. Similar kinds of cases can be constructed if the student gives an irrelevant factor or the wrong value for a factor by presupposing what is not true to be true.

Insert Table 6 here

Table 6 illustrates what the condition-action pair looks like for one of the case-selection strategies: in particular, the counterexample for insufficient factors. There are three conditions where the rule might be triggered: (1) the student proposes a rule

Table 6

A Condition-Action Pair for a Case Selection Strategy

Counterexample for Insufficient Factors

If (1) a student proposes a rule or makes a prediction based on one or more factors that are insufficient, or

(2) is entrapped by a rule based on one or more factors that are insufficient,

then (3) pick a case that has the values specified on the insufficient factors, but not the values specified on the dependent variable.

EXAMPLE (from Collins on factors affecting grain growing)

T. Why? (i.e., why do they grow rice in Louisiana)

S. Places where there is a lot of water. I think rice requires the ability to selectively flood fields.

T. OK. Do you think there's a lot of rice in say Washington and Oregon? (T selects a case where there is a lot of water but no rice; this counterexample then led the student to consider climate and terrain).

based on insufficient factors, (2) makes a prediction based on insufficient factors, or (3) is entrapped by a rule based on insufficient factors (see Table 7). If any of these conditions is met, a new case can be selected (if there is one) that has the conditions specified in the "then" statement. The example shown is from an actual dialogue on grain-growing (Collins, 1977).

Entrapment Strategies. Teachers use a variety of strategies to entrap students into revealing their misconceptions about a domain. Some of these misconceptions exist prior to the teacher's inquiry, but some are in fact provoked by the inquiry. Bringing out the misconceptions allows teachers to correct them directly. In this way teachers can act to prevent misconceptions from arising in future situations where the student is on his own. Some teachers shy away from using entrapment strategies, perhaps for fear of forcing students into mistakes they might not otherwise make. But if there's no stigma attached to making mistakes, then bringing latent misconceptions into the open can provide a much deeper understanding of the domain.

The entrapment strategies form a two dimensional space shown in Table 7. Like the counterexample strategies, there are four kinds of entrapment with respect to (1) insufficient factors, (2) unnecessary factors, (3) irrelevant factors, and (4) incorrect values of factors. Orthogonal to this breakdown are the entrapments formed by proposing a rule, by proposing a prediction about the dependent variable, or by proposing a set of factors. We will give examples to illustrate the different types of entrapment strategies.

Insert Table 7 here

Entrapment rules are formed when the teacher proposes a general rule based on some set of factors. For example, an entrapment rule for insufficient factors occurs if a student thinks they grow rice in Louisiana because it rains a lot and the teacher suggests "Can you grow rice anywhere there is a lot of rain?" An entrapment rule for unnecessary factors occurs if the teacher suggests "Do you always need a lot of rain to grow rice?" General rules of either of these kinds can also be constructed if the student mentions an irrelevant factor or gives an incorrect value for a factor.

Entrapment into a prediction occurs when the teacher asks for a prediction based on factors that are likely to lead to an incorrect prediction. For example, the teacher might elicit a prediction based on insufficient factors that they grow rice in Southern Florida because it is warm and moist (even though it doesn't produce rice). The teacher might elicit a prediction based on unnecessary factors that they do not grow rice in Egypt because it is quite dry (even though it does produce rice). Similarly incorrect predictions of either type can be elicited for irrelevant factors or incorrect values of factors.

Entrapment based on factors occurs when the teacher asks if particular values of factors are consistent with or support a particular value of the dependent variable. For example, entrapment

Table 7

Different Types of Entrapment Strategies

Entrapment on Rules

Rule based on insufficient factors

Rule based on unnecessary factors

Rule based on irrelevant factors

Rule based on incorrect values of factors

Entrapment on Predictions

Prediction based on insufficient factors

Prediction based on unnecessary factors.

Prediction based on irrelevant factors

Prediction based on incorrect values of factors

Entrapment on Factors

Entrapment based on insufficient factors

Entrapment based on unnecessary factors

Entrapment based on irrelevant factors

Entrapment based on incorrect values of factors on insufficient factors might occur if a teacher asks whether the warm climate and flat terrain in Florida accounts for their failure to grow rice there. Entrapment on unnecessary factors might occur if a teacher asks whether the lack of rainfall is consistent with their growing rice in Egypt. Similar kinds of entrapments can be constructed for irrelevant factors and incorrect values of factors.

Insert Table 8 about here

Table 8 shows the condition-action pair for an entrapment based on irrelevant factors. There are two conditions together that trigger the use of such a strategy: if a particular value of the dependent variable is being considered, and there are irrelevant factors that the student might consider relevant. The action taken is to question whether the irrelevant factors are consistent with or support the particular value of the dependent variable being considered. The example shown is from a medical dialogue given in Swets and Feurzeig (1965).

Identification and Evaluation Strategies. There is a large variety of strategies for trying to get students to identify and evaluate different cases, factors, rules, and predictions. We have identified a dimensionalized space of strategies teachers use for questioning students and commenting on their answers. Our proposed space of strategies is shown in Table 9.

Table 8

A Condition-Action Pair for an Entrapment Strategy

Entrapment based on irrelevant factors

If (1) a particular value of the dependent variable is being considered for a case, and

(2) there are one or more irrelevant factors that a student might consider relevant,

then (3) ask if the values of the irrelevant factors are consistent with the value of the dependent variable.

EXAMPLE (from Swets and Feurzeig on medical diagnosis)

T. Pleural pain, dyspnea, fever, and the physical exam signs are certainly consistent with pulmonary infarction. (Point out correct values of factors) Do you think that shaking chills and the presence of rusty sputum further supports this diagnosis? (Entrapment based on irrelevant factors)

S. No. (Student resists entrapment)

T. Right.

Insert Table 9 about here

The two major dimensions in Table 9 are the type of strategy (identification strategies vs. evaluation strategies) and the object the strategy is applied to (either a dependent variable, rule, factor, or case). The table collapses three different kinds of identification and evaluation strategies:

1. Questioning strategies: Ask for or Ask if.
2. Suggesting strategies: Suggest
3. Commenting strategies: Point out.

The table is presented in terms of the questioning strategies: i.e., ask for or ask if. But each rule in Table 9 can occur in the two other forms obtained by replacing Ask by Suggest or Point out. The suggestion form of each rule occurs when the teacher does not try to elicit the information from the student, but instead proposes a factor or a value of the dependent variable for the student to consider, without telling the student whether the proposed information is correct or not. The comment form of each rule occurs when the teacher simply tells the student what the correct information is. In inquiry dialogues the question form of each rule is most common, but the other two forms do occur sometimes: the suggestion form when the teacher wants students to think hypothetically, and the comment form when the teacher doesn't think the student can generate the information.

Table 9

Identification Strategies	Evaluation Strategies
Dependent Variables	
Ask for value of dependent variable	Ask if a value of dependent variable is correct or incorrect
Rules	
Ask for the formulation of a rule	Ask if a rule is correct or incorrect
Ask for the formulation of an alternative rule	Ask if a rule is the same or different from another rule
Factors	
Ask for sufficient factors	Ask if factors are sufficient or insufficient
Ask for necessary factors	Ask if factors are necessary or unnecessary
Ask for relevant factors	Ask if factors are relevant or irrelevant
Ask for values of factors	Ask if the values of factors are correct or incorrect
Ask for prior steps	Ask if a step is a prior step
Ask for intermediate steps	Ask if a step is an intermediate step
Ask for subsequent steps	Ask if a step is a subsequent step

Ask for similarities in factors for similar cases

Ask for differences in factors for similar cases

Ask for similarities in factors for dissimilar cases

Ask for differences in factors for dissimilar cases

Ask if similar cases are the same on given factors

Ask if similar cases are different on given factors

Ask if dissimilar cases are the same on given factors

Ask if dissimilar cases are different on given factors

Cases

Ask for a case with a given value on the dependent variable

Ask for a case with given values on some factors

Ask for a case with given values on some factors and on the dependent variable

In dialogues where the teachers are trying to encourage verbalization, such as those of Warman and Schank, two other forms of the identification rules occur: rewarding strategies and reformulating strategies. There is frequently a rewarding of the student when they formulate a rule, identify a factor or case, or make a correct prediction about the dependent variable. In Warman's case she rewards the students by telling them they have has a good idea, and then either repeating or reformulating what they said. Reformulation also occurs in situations where the student's statement is underspecified; e.g., the values of factors are implicit rather than explicit. In one case, we have seen a teacher use a negative reward strategy, by pointing out that the student was failing to formulate a general rule. But much more commonly the teachers stayed with positive rewards and reformulations.

Within the object dimension there are a number of subclassifications we will describe. In identifying and evaluating different factors, there are three different subgroups. The first subgroup repeats the pattern found among the counterexample and entrapment strategies: i.e., there are questions about sufficient factors, necessary factors, relevant factors and the values of factors. This pattern reflects the logical relations among different factors.

The second subgroup derives from the structure of logical chains (see Figure 1). Questions can be posed to elicit steps prior to some node in the chain, steps intermediate between two nodes, and steps subsequent to some node in the chain. These strategies usually occur when the teacher is probing for a causal chain linking together different factors, but can occur when a teacher, such as Socrates, traces a logical chain to the point where the students see a contradiction between the implications of what they said and what they believe.

The third subgroup of strategies arises out of situations where the teacher has selected two cases and asks for a comparison of factors. These strategies correspond to the case comparison strategies in Table 5. If the two cases have the same value on the dependent variable, then asking for similarities forces the student to abstract the sufficient factors leading to the value of the dependent variable (i.e., generalization). Asking for differences in this situation forces the student to notice what factors do not change with the dependent variable (i.e., are unnecessary). If the two cases differ on the dependent variable, asking for differences forces the student to abstract the necessary factors that lead to changes in the dependent variable (i.e.,differentiation). Asking for similarities in this situation forces the student to notice what factors do not change given a change in the dependent variable (i.e., are insufficient). Thus these strategies allow the teacher to focus the student on different necessary and sufficient factors.

There are three different strategies for asking the student to identify a given case. These derive from distinctions between the dependent variables, the factors, and the rules relating factors to the dependent variable. Thus you can ask a student to identify a case with a given value of the dependent variable, a case with given values of particular factors, or a case with given values both for particular factors and the dependent variable. There are no evaluation stragegies corresponding to the identification strategies for cases. This is because they are redundant with other evaluation strategies. For example, the evaluation strategy that would correspond to the first case identification strategy is the same as the evaluation strategy "Ask if a value of the dependent variable is correct or incorrect". The redundancy occurs because the strategies for dependent variables, rules and factors all assume a case has been specified.

Insert Table 10 about here

Tables 10 and 11 show the condition-action pairs for two of the strategies in Table 9. The first shows an identification strategy, "Ask for intermediate steps". This can be elicited whenever a student specifies two non-adjacent steps in a causal chain. In the question form of the rule the teacher then asks for the intermediate steps, but alternatively the teacher might suggest or point out the intermediate step. The example shown is from Stevens and Collins (1977) where the tutor was teaching the factors that lead to heavy rainfall in Oregon and the student left out an intermediate step in the tutor's causal model.

Table 10

A Condition-Action Pair for an Identification Strategy

Ask for intermediate steps

If (1) two steps in a causal chain or procedure that are not adjacent have been identified,

then (2) ask the student to identify the intermediate steps.

EXAMPLE (from Stevens and Collins on causes of rainfall)

S. When the moisture laden air reaches the mountains it is forced to rise and consequently the air cools? causing rainfall, no?

T. Why does cooling cause rainfall? (Ask for intermediate steps)

Insert Table 11 here

Table 11 shows the commenting version of the evaluation strategy, "Ask if a set of factors is sufficient or insufficient". This variant can be triggered either by the student making a prediction based on insufficient factors or by asserting that a set of factors is sufficient. In this variant the teacher points out that the set of factors is insufficient. The example shown is from Swets and Feurzeig (1965) where the student's task was to identify a letter from a set of features. When the student made a prediction based on insufficient data, the tutor pointed out the insufficiency.

Tables 5, 7 and 9 then summarize the set of strategies (155 in total counting all the variants) that follow from the structure we have developed. But these do not cover what teachers do exhaustively. They cover about 80% to 90% of the teacher's statements in the dialogues we have analyzed. There are other things that teachers do, such as getting students to test hypotheses, or to question authority, that are not incorporated in this space of strategies. Nevertheless, this taxonomy captures a very large part of what the teachers we have studied are doing at the local level in order to carry on a dialogue with their students.

Dialogue Control Structure

The control structure that the teacher uses to allocate time between different goals and subgoals may be the most crucial aspect

Table 11

A Condition-Action Pair for an Evaluation Strategy

Point out factors are insufficient

If (1) a student makes a prediction about the value of the dependent variable based on a set of factors that are insufficient, or

(2) asserts that a set of insufficient factors is sufficient,

then (3) point out that the set of factors is insufficient.

EXAMPLE (from Swets and Feurzeig on identifying a letter)

T. Start when ready. (The student must guess a letter from its features.)

S. Curves?

T. One.

S. Loose ends?

T. Two.

S. Obliques?

T. Zero.

S. C.

T. You don't have enough information yet to get the right answer. (Point out a set of factors is insufficient) How do you know it isn't J, for example? (Suggest a value of the dependent variable) of effective teaching. An earlier attempt at a theory of the control structure was developed in Stevens and Collins (1977). That theory was based on protocols taken from teachers while they were teaching over linked computer terminals. The four basic parts of the control-structure theory are: (1) an agenda for keeping track of different goals and subgoals, (2) a set of priority rules for adding goals and subgoals to the agenda, (3) a set of strategies for selecting cases with respect to the high-level goals, and (4) the teacher's model of the student.

The Agenda. As we have argued elsewhere (Collins, Warnock and Passafiume, 1975b), the agenda that guides teachers in their selection of topics is not prespecified, except in terms of a few global goals. For the most part the agenda is constructed as the dialogue progresses on the basis of the responses of the student, the high-level goals of the teachers, and the previous topics discussed in the dialogue. We will try to describe briefly how this complex interweaving occurs, though it is described in more detail in the earlier paper.

The high-level goals of the teacher are the topics specified on the agenda before any dialogue occurs. In Schank's dialogue, there appear to be three top-level goals which manifest themselves as phases of the dialogues: to define what a plan is, to specify the primitive types of possible plans in terms of the definition, and to analyze cases of planning in terms of the primitive types. These three goals in turn derive from Schank's top-level goal of teaching students how to construct theories: they are the subgoals instrumental to that goal. A similar agenda occurs in the Anderson dialogue on factors affecting average temperature: the first phase of the dialogue was directed toward getting the student to form the hypothesis that distance-from-the-ocean affects temperature, and the second phase related to how the student could test the hypothesis. Similarly these two goals derive from Anderson's top-level goal to teach theory construction. In many of the dialogues there is only one phase (as in the Warman dialogues or the Stevens and Collins dialogues), but there is always some high-level goal driving the dialogue.

These high-level goals guide the selection of cases (see section below on global strategies for case selection) and the generation of specific questions to probe for predictions, factors, and rules (usually in that order) about the cases selected. Students' responses to these questions in turn spawn local subgoals to diagnose and correct the misconceptions and omissions revealed by them (Stevens and Collins, 1977). These subgoals are then added to the agenda according to a set of priorities given in the next section.

We can illustrate the way the agenda works most clearly with reference to a dialogue given in the Stevens and Collins paper. The dialogue was on the subject of what factors lead to rainfall in different places, and the case selected was a paradigm case of heavy rainfall, namely the Oregon coast. The teacher first asked for the student's prediction, and went on to ask about the causal factors leading to heavy rainfall in Oregon. In one response the student made a guess based on what she had learned about the Amazon, "Does the air (moist air) from the ocean somehow get blown over Oregon and encounter a block of some sort which causes it to rise and cool?". The teacher commented off-line that the student's answer was missing three basic steps in the teacher's first-order theory of the factors leading to rainfall: (1) why the air is moist, (2) why it is blown over Oregon, and (3) why cooling results in rain. Then the teacher asked about the first of these steps "Why is the air so moist?", and held the other two on his agenda. The discussion of this topic continued for 14 interchanges, with additional subtopics added to the agenda during the discussion, before the teacher returned to the second missing step (i.e., why the air is blown over Oregon) on the agenda. The third step was raised shortly thereafter.

Our analyses indicate that the agenda is an ordered list of goals which are held until they are satisfied. When a goal is satisfied, it is removed from the agenda and the next goal is pursued. New goals can be inserted at arbitrary places in the agenda and it can be reordered. However, we expect that manipulations other than pushing new goals on to the beginning and popping them off of the beginning require extra efforts on the part of the teacher and therefore the tendency is to treat the agenda as a push-down stack, pushing and popping goals off of the top.

This pattern of pushing and popping of different goals is evident in almost all conversation (Collins, et al., 1975b; Grosz, 1977; Levin and Moore, 1977; Reichman, 1978). When pop-ups occur they are often signalled by various clue words such as "Okay", "Now", or "Anyway" (Collins et al., 1975b; Reichman, 1978). There is some suggestive evidence that well-prepared teachers come in with a highly-structured theory of the domain they are teaching, and frequently select new topics from the agenda to cover different aspects of the theory, rather than following topics associatively from one to the other, as do less well-prepared teachers (Collins et al., 1975b).

Priorities for adding goals to the agenda. In adding goals to the agenda, there must be a set of priorities. Often a single question, as in the example above, uncovers several misconceptions or omissions that the teacher may want to pursue. In such circumstances, the teacher must decide which to pursue first. But even when goals are added to the agenda at different times, it is essential to decide which should be pursued first; that is to say the teacher may want to pursue a new goal being added before some other goal already on the agenda. Or the teacher may want to drop some previous goal in favor of some more important goal he identifies during the dialogue. For all these reasons, there must be a set of priorities for ordering goals on the agenda.

In Stevens and Collins (1977) we identified four priorities that occurred among the teachers' comments on why they were asking each question. In the dialogues with groups of students a fifth priority for allocating time between different students became apparent. We list the priorities below roughly in the order of highest priority first, but we think they are weighed together in making a decision about which goal to pursue first.

1. Errors before omissions. Teachers correct any errors they diagnose before they deal with omissions in their theory. This is because errors have more devastating consequences; they can interfere with learning other information correctly. This priority is sometimes violated when the teacher is trying to lead the student to discover his or her own error by an extended dialogue, during which more immediate goals arise.

2. Shorter fixes before longer fixes. Teachers typically will correct errors or omissions that can be taken care of quickly, before taking on more extensive problems. For example, teachers will often deal with errors about facts or about principles outside the domain being taught, by simply telling the student the correct answer (Stevens and Collins, 1977). This is done quickly, so it tends to take highest priority. But shorter fixes do not always take precedence; for example in the dialogue on rain in Oregon, the second and third steps were dealt with much more quickly than the first step, which took precedence because of priority 3.

3. Prior steps before later steps. Teachers often take up steps in causal chains in the order of occurrence, so that the discussion moves in the order of temporal or causal sequence. This is what the teacher did in the Oregon example when he identified three missing steps

in his causal theory, and then asked about the first missing step. This may often be violated where branching structures occur in the theory, or the student brings up a causal factor somewhere in the middle or at the end of the chain.

4. Low-order factors before high-order factors. Teachers select more important (i.e., low-order) information before less important (i.e., high-order) information, particularly when a pop-up occurs and they have to select a new branch of a causal structure to pursue. This priority is violated frequently in that teachers pursue branches or subparts of a causal model in detail before taking up other branches. This occurred in the Oregon dialogue where the teacher went into a fair amount of detail about currents and evaporation in pursuing the first missing step, before taking up the second and third missing steps.

5. Students who haven't spoken for awhile before students who have. This is most noticeable in the Schank and Beberman dialogues where the teacher is trying to get all the students to participate and verbalize their theories. It is violated when the teacher is pursuing a particular line of inquiry with one or another student.

These five principles are the ones we have been able to identify in the dialogues, but there may be other principles that are also contributing to the order in which goals are added to the agenda.

Case selection with respect to high-level goals. Given a set of high-level goals, the teacher selects cases that optimize the ability of the student to master those goals. There appear to be several overall strategies that teachers apply in selecting cases:

1. Select cases that illustrate lower-order factors before higher-order factors. For example, in teaching about rainfall, Collins and Stevens move from cases like the Amazon and Ireland that exemplify a first-order theory to cases like Eastern America or Patagonia where the factors are more complex. In teaching the distributive law, Anderson chose cases that systematically isolated one factor after another.
2. Select more salient or more frequent cases before less salient or less frequent cases. Other things being equal, a South American geography teacher will select cases like Brazil and Argentina rather than Paraguay and Guyana. A medical professor will select the most frequent diseases and the ones that are most important to diagnose.
3. Select cases such that a generalization will make prediction easier or less tedious. This is most evident in the Beberman and Anderson transcripts where

they present a series of math problems that are rather tedious to work until you see the short cut (see Neches and Hayes, 1978 for a discussion of strategy modification) that leads to a significant generalization, in one case the rules for addition of real numbers, in the other the distributive law. This case selection strategy has its analog in non-procedural domains when the teacher selects a set of cases that have some generalization that makes prediction easier. For example, in the domain of factors affecting rainfall the teacher might select a set of cases like Southern California, Northern Africa, Northern Chile, Western Australia, and Namibia in order to lead the student to induce the generalization that any place on the western side of a continent in the latitude of 20 to 30 degrees will have little rainfall.

4. Select well-known cases that arise in the student's experience. This strategy is most evident in the Warman dialogues with preschoolers, where she selects cases that arise in the course of school (concerning a problem about playing with blocks or a movie they saw) to get the children to generalize about moral actions. This same strategy is apparent in the selection of well-known cases by Schank, Anderson, and Collins. Because students have more knowledge in these cases, they are better able to consider all the relevant factors and to abstract rules relating the factors to the dependent variable.

The student model. The teacher's model of the individual student guides the selection of which parts of the domain to discuss, which parts to skip over because they will be too difficult for the student to assimilate, and which parts to assume the student knows (Collins, et al., 1975). It also guides the teacher in attempting to diagnose the student's misconceptions about the domain (Stevens, Collins, and Goldin, 1979; Stevens and Collins, in press).

We assume that the teacher has two types of a priori information that are used in constructing models of individual students: (1) a structured theory of the domain and attached to each element in the theory (i.e., each node or link) the relative likelihood that any student will know about that element, and (2) a set of underlying misconceptions (alternative rules or theories) that different students might have. We will discuss in turn how these two kinds of information guide the selection of goals to pursue.

When we say that the teacher has a notion of the relative likelihood that any student will know a given element, we do not mean that the teacher thinks there's a 30% chance student A will know one element and a 20% chance another element. Rather we assume only a partial ordering on the elements, reflecting perhaps when the teacher learned each element. This partial ordering corresponds to the notion of first-order to nth-order factors in a theory. For example, the factors affecting temperature of a place might be partially ordered as follows: latitude, altitude, ocean currents, distance from the ocean, cloud and tree cover. The teacher's assumption is that students learn the elements in approximately this same order. Therefore it is possible to gauge what the student will know or not know based on a few correct and incorrect responses. These responses are used to determine the criterion point in the partial ordering above which the student is likely to know any element and below which the student is unlikely to know any element.

In our earlier work (Collins, et al., 1975b) we noted four levels of elements with respect to this criterion point in the partial ordering that determine the goals the teacher will pursue. We repeat those here in terms of our current framework:

1. Elements the teacher can assume the student knows, and hence need not pursue.
2. Elements the student may know, and so the teacher asks the student to provide them (i.e., give predictions, factors, etc.) These include all the elements just above and below the criterion point.
3. Elements the student will not be able to figure out, and so the teacher will tell the student if they come up in the dialogue.
4. Elements so far beyond the student's current level that they can not be assimilated until the student has more information. These elements are not mentioned by the teacher.

Thus these levels determine what goals will be added to the agenda (i.e., goals will be added for teaching elements at levels 2 and 3) and whether these will be pursued with questions (level 2) or comments (level 3).

The experienced teacher also accumulates a large amount of knowledge about the possible misconceptions students may have. In the domain of rainfall, we (Stevens, et al., 1979) have identified sixteen basic misconceptions students have, based on systematic questioning of eight high school students. In arithmetic Brown and Burton (1978) have identified the 50 most common procedural errors that primary students have, based on data from 1300 Nicaraguan children. Depending on the question or the problem, a particular misconception can appear in many different forms, so that a teacher must recognize a variety of manifestations for each possible misconception.

We think that teachers store many of the misconceptions they see as perturbations of subparts of the knowledge structure they are trying to teach. When a student makes a misstatement, the teacher may recognize it as a manifestation of one of the possible misconceptions. If the teacher can not identify the misconception underlying the error, or if there is a pattern of misconceptions that frequently occur together (Stevens et al, 1979), the teacher will ask questions to identify what the underlying misconceptions are. In order to correct any misconceptions there are a variety of actions the teacher may take (Stevens and Collins, 1977). The teacher may simply inform the student of the correct answer, or if the teacher thinks the student won't get further confused, counterexamples, hypothetical cases, or tracing consequences may be used to encourage the student to debug his or her own misconception.

CONCLUSION

This summarizes what we think are the most important elements of effective teaching. By turning teaching into problem-solving in this way, by selecting cases that optimize the abilities the teacher is trying to teach, by making students grapple with counterexamples and entrapments, the students are challenged more than by any other teaching method. Because of the experience they are able to attack novel problems by applying these strategies themselves.

Appendix

TEACHING STRATEGIES IN THE THEORY

Case Selection Strategies

CSS1: Positive paradigm exemplar for factors

If (1) a student has not identified many of the factors that are relevant to a particular value on the dependent variable,

then (2) pick a case where as many as possible of the values on the factors are consistent with the particular value on the dependent variable.

EXAMPLE

If a student is being taught the factors affecting whether a place has heavy rainfall or not, pick a case like the Amazon or Oregon where all the factors have values that lead to heavy rainfall.

CSS2: Negative paradigm exemplar for factors

If (1) a student has not identified many of the factors that are relevant to a particular value on the dependent variable,

then (2) pick a case where as many as possible of the values on the factors are inconsistent with the particular value on the dependent variable.

EXAMPLE

If a student is being taught the factors affecting whether a place has heavy rainfall or not, pick a case like the Sahara or Southern California where all the factors have values that lead to little rainfall.

CSS3: Positive exemplar for a sufficient factor (Near hit)

If (1) a student has not identified a factor that is sufficient for a particular value on the dependent variable,

then (2) pick a case where the factor is predominant, the value of the factor is consistent with the given value of the dependent variable, the values of the other sufficient factors are inconsistent with the given value of the dependent variable, and the dependent variable has the given value.

EXAMPLE

Suppose a teacher wants a student to see that you don't need rainfall for growing rice. Then the teacher might choose Egypt which has little rainfall, but does grow rice by using irrigation from the Nile.

CSS4: Negative exemplar for a necessary factor (Near miss)

If (1) a student has not identified a factor that is necessary for a particular value on the dependent variable,

then (2) pick a case where the factor is predominant, the value of the factor is inconsistent with the given value of the dependent variable, the values of the other factors are consistent with the given value of the dependent variable, and the dependent variable has the opposite value.

EXAMPLE (from Collins on factors affecting population density)

T. (In discussing population density, the student had not identified climate as a factor.) OK. Now do you think it's very dense in Alaska? (CSS4: Pick a negative exemplar for a necessary factor)

S. No.

T. Why? (IS6: Ask for relevant factors.)

S. I would imagine because of the cold?

CSS5: <u>Generalization exemplar for factors</u> (Maximal pair)

If (1) a student has not identified one or more factors that are relevant to a particular value on the dependent variable, and (2) there is a case identified that is a positive or negative exemplar for those factors,

then (3) pick a case that has the same or similar values as the previous case on the given factors, that has as different a value as possible on other factors, and that has the same or a similar value on the dependent variable.

EXAMPLE (from Stevens and Collins on causes of rainfall)

T. The current is called the Japanese current and it comes from the Equator along the coast of Japan and across to Canada and Oregon. (IS8b: Point out prior steps) Is there another current you know about with the same pattern? (CSS5: Pick a generalization exemplar for a set of factors) (ES14: Ask for a case with given values on a set of factors)

S. I don't know what you mean - the equatorial current?

T. I meant the Gulf stream. (IS16b: Point out a case with given values on a set of factors) I wanted you to see the general pattern of currents in the world. (IS11b: Point out similarity in factors between similar cases)

CSS6: Differentiation exemplar for factors (Minimal pair)

If (1) a student has not identified one or more factors that are relevant to a particular value on the dependent variable, and (2) there is a case identified that is a positive or negative exemplar for those factors,

then (3) pick a case that has a different value from the previous case on the given factors, that has the same or similar values on other factors, and that has a different value on the dependent variable.

EXAMPLE (from Collins on the factors affecting population density)

T. OK. Why do you suppose Java has a high population density and some of the other Indonesian islands have low population density? (IS14: Ask for differences in factors between different cases)

S. There's so many of them.

T. Sumatra. (CSS6: Pick a differentiation exemplar for factors) (Sumatra is chosen because it's like Java in most respects, e.g., climate, location, but has a different value on the dependent variable. This forces the student to pay attention to the factors, such as terrain, that differentiate Java and Sumatra).

CSS7: Exemplar to show variability of a factor

If (1) a student has identified a factor that is relevant to a particular value of the dependent variable, and
(2) there is a case identified that has a particular value on that factor,
then (3) pick a case that has the same value on the dependent variable, that has as different a value as possible on the particular factor, and that has as similar values as possible on the other factors.

EXAMPLE

Suppose Java has been identified as a place that is warm enough to grow rice, then pick a case like Japan which is much cooler but still grows rice.

CSS8: Exemplar to show variability of the dependent variable

If (1) a student has identified one or more factors that are relevant to a particular value of the dependent variable, and
(2) there is a case identified that has a particular value on the dependent variable,
then (3) pick a case that has the same values on the factors, and that has as different a value as possible on the dependent variable.

EXAMPLE

Suppose the Congo jungle has been identified as a place near the equator where the average temperature is 85 degrees to 90 degrees. Then pick a case like the top of Mt. Kilimanjaro, which is also near the equator, but the average temperature is much colder (<32 degrees).

CSS9: <u>Counterexample for insufficient factors</u>

If (1) a student proposes a rule or makes a prediction based on one or more factors that are insufficient, or

(2) is entrapped by a rule (ENS 1 or ENS 9) based on one or more factors that are insufficient,

then (3) pick a case that has the values specified on the insufficient factors, but not the value specified on the dependent variable.

EXAMPLE (from Collins on factors affecting grain growing)

T. Why? (i.e. why do they grow rice in Louisiana) (IS5: Ask for relevant factors)

S. Places where there is a lot of water. I think rice requires the ability to selectively flood fields.

T. OK. Do you think there's a lot of rice in say Washington and Oregon? (CSS9: Pick a counterexample for an insufficient factor) (IS1: Ask for the value of the dependent variable) (T selects a case where there is a lot of water but no rice; this counterexample then led the student to consider climate and terrain).

CSS10: Counterexample for unnecessary factors

If (1) a student proposes a rule or makes a prediction based on one or more factors that are unnecessary, or

(2) is entrapped by a rule (ENS 2 or ENS 10) based on one or more factors that are unnecessary,

then (3) pick a case that does not have the values specified on the unnecessary factors, but does have the value specified on the dependent variable.

EXAMPLE (from Collins on factors affecting grain growing)

S. (In response to why they can not grow rice in Oregon) I don't think the land is flat enough. You've got to have flat land so you can flood a lot of it.

T. What about Japan? (CSS10: Pick a counterexample for an unnecessary factor) (IS1: Ask for the value of the dependent variable) (Japan grows rice but does not have much flat land.)

CSS11: Counterexample for an irrelevant factor

If (1) a student proposes a rule or makes a prediction based on one or more factors that are irrelevant, or

(2) is entrapped by a rule (ENS 3 or ENS 11) based on one or more factors that are irrelevant,

then (3) pick a case that has the values specified on the irrelevant factors, but does not have the value specified on the dependent variable, or

(4) pick a case that does not have the values specified on the irrelevant factors but does have the value specified on the dependent variable.

EXAMPLE

Suppose a student proposed that having high humidity was necessary for growing rice or predicts that Java grows rice because of the high humidity, then the teacher can ask about Egypt where the humidity is low but rice is grown, or the Congo where humidity is high but no rice is grown.

CSS12: Counterexample for an incorrect value on a factor

If (1) a student proposes a rule or makes a prediction based on one or more values of factors that are incorrect, or

(2) a student is entrapped by a rule (ENS 4 or ENS 12) based on one or more values of factors that are incorrect,

then (3) pick a case that has the values specified on the factors, but does not have the value specified on the dependent variable, or

(4) pick a case that does not have the values specified on the factors, but does have the value specified on the dependent variable.

EXAMPLE

Suppose a student proposed that having a cool temperature is necessary for growing rice or predicts that Japan grows rice because it is cool, then the teacher can ask about Java where the temperature is quite warm all year around and they grow rice, or about Oregon which is cool but where no rice is grown.

CSS13: Construct a hypothetical case for insufficient factors

If (1) a student proposes a rule or makes a prediction based on one or more factors that are insufficient, or

(2) is entrapped by a rule (ENS1 or ENS9) based on one or more factors that are insufficient,

then (3) construct a case that has the values specified on the insufficient factors, but not the values specified on the dependent variable.

EXAMPLE

Suppose a student suggests they don't grow rice in British Columbia because it is too mountainous, ask the student "If British Columbia were flat could they grow rice then?". The answer is that they could not, because of the cold temperature.

CSS14: Construct a hypothetical case for unnecessary factors

If (1) a student proposes a rule or makes a prediction based on one or more factors that are unnecessary, or

(2) is entrapped by a rule (ENS2 or ENS10) based on one or more factors that are unnecessary,

then (3) construct a case that does not have the values specified on the unnecessary factors, but does have the value specified on the dependent variable.

EXAMPLE

Suppose a student suggests they grow rice in Louisiana because it rains a lot there, then the teacher might ask "If it didn't rain a lot in Louisiana, could they still grow rice there?". The answer is they could by irrigating the rice paddies from the Mississippi River.

CSS15: <u>Construct a hypothetical case for irrelevant factors</u>

If (1) a student proposes a rule or makes a prediction based on one or more factors that are irrelevant, or

(2) is entrapped by a rule (ENS3 or ENS11) based on one or more factors that are irrelevant,

then (3) construct a case that has the values specified on the irrelevant factors, but does not have the value specified on the dependent variable, or

(4) construct a case that does not have the values specified on the irrelevant factors, but does have the value specified on the dependent variable.

EXAMPLE

Suppose a child asserts that John's tripping of Sam was bad because Sam broke his leg, then the teacher might ask whether John was bad even if Sam didn't hurt himself at all, or even if Sam had accidentally tripped over John and broke his leg.

CSS16: <u>Construct a hypothetical case for incorrect values of factors</u>

If (1) a student proposes a rule or makes a prediction based on one or more values of factors that are incorrect, or

(2) a student is entrapped by a rule (ENS4 or ENS12) based on one or more values of factors that are incorrect,

then (3) construct a case that has the values specified on the factors, but does not have the value specified on the dependent variable, or

(4) construct a case that does not have the values specified on the factors, but does have the value specified on the dependent variable.

EXAMPLE (from Warman on who can play with blocks)

S. How about no girls play with anything and boys play with everything. (This is one boy's proposal for a fair rule.)

T. Ok. Let's take a vote. Boys, how about if you don't play with any toys here in school? (CSS16: Construct a hypothetical case for an incorrect value on a factor) (ES2: Ask if rule is correct or incorrect)

Entrapment Strategies

ENS1: Rule based on insufficient factors

If (1) a student explains the value of the dependent variable based on one or more factors that are not sufficient, or

(2) makes a prediction based on one or more factors that are not sufficient,

then (3) ask if it is a general rule that the dependent variable must have the value specified given the values of the insufficient factors.

EXAMPLE (from Anderson on factors affecting temperature)

S. (In response to a question about why he predicted Newfoundland was colder in winter than Montana) Newfoundland is further north.

T. Yes, Newfoundland is further north than Montana. (ES6b: Point out correct value of a factor) Are you arguing then, that if you take any two places in the Northern Hemisphere, the one which is further north will have the lower average winter temperature? (ENS1: Entrapment rule based on an insufficient factor)

ENS2: Rule based on unnecessary factors

If (1) a student explains the value of the dependent variable based on one or more factors that are not necessary, or

(2) makes a prediction based on one or more factors that are not necessary,

then (3) ask if it is a general rule that the unnecessary factors must have the values specified given the value of the dependent variable.

EXAMPLE

Suppose a student says lots of rainfall is a reason for growing rice, or predicts that a place with heavy rainfall grows rice, then ask "Do you think it is necessary to have heavy rainfall to grow rice?"

ENS3: Rule based on irrelevant factors

If (1) a student explains the value of the dependent variable based on one or more factors that are irrelevant, or

(2) makes a prediction based on one or more factors that are irrelevant,

then (3) ask if it is a general rule that the dependent variable must have the value specified given the values of the irrelevant factors.

EXAMPLE

Suppose a student says they grow rice in China because of their oriental nature, or predicts they grow rice in Mongolia because of their oriental nature, ask if it is general rule that people with an oriental nature grow rice.

ENS4: Rule based on incorrect values of factors

If (1) a student explains the value of the dependent variable based on one or more incorrect values of factors, or

(2) makes a prediction based on one or more incorrect values of factors,

then (3) ask if it is a general rule that the dependent variable must have the value specified given the incorrect values of the factors.

EXAMPLE

Suppose a student suggests that a place grows rice because it has a dry climate, ask if generally a place must have a dry climate to grow rice.

ENS5: Prediction based on insufficient factors

If (1) a case is selected where the value of the dependent variable is inconsistent with the value of one or more factors that are not sufficient, and

(2) the value of the dependent variable has not been specified,

then (3) ask if the dependent variable has the value that is consistent with the values of the insufficient factors, or

(4) ask the student to make a prediction based on the insufficient factors.

EXAMPLE (from Collins on factors affecting average temperature)

T. Is it very hot along the coast here? (points to Peruvian coast near the equator, where the effect of latitude is overridden by ocean currents.) (ENS5: Entrapment into prediction based on insufficient factors)

S. I don't remember

T. No. It turns out there's a very cold current coming up the coast, and it bumps against Peru, and tends to make the coastal area cooler, although it's near the equator. (IS7b: Point out values of factors) (IS1b: Point out value of the dependent variable)

ENS6: Prediction based on unnecessary factors

If (1) a case is selected where the value of the dependent variable is inconsistent with a value of one or more factors that are not necessary, and

(2) the value of the dependent variable has not been specified,

then (3) ask if the dependent variable has the value that is consistent with the values of the unnecessary factors, or

(4) ask the student to make a prediction based on the necessary factors.

EXAMPLE

Suppose Egypt has been selected to discuss rice growing, then the teacher can ask if the student thinks they can not grow rice there given there is little rain, or whether the student thinks they could grow rice or not.

ENS7: Prediction based on irrelevant factors

If (1) a case is selected where the value of the dependent variable is inconsistent with what the student would predict given the values of one or more irrelevant factors, and

(2) the value of the dependent variable has not been specified,

then (3) ask if the dependent variable has the value that the student thinks is consistent with the values of the irrelevant factors, or

(4) ask the student to make a prediction based on the irrelevant factors.

EXAMPLE

Suppose a student thinks an Oriental nature is necessary for growing rice, then ask "Do they grow rice in Mongolia, since they have an Oriental nature?" or "Do you think they grow rice or not in Mongolia?"

ENS8: Prediction based on incorrect values of factors

If (1) a case is selected where the value of the dependent variable is inconsistent with what the student would predict given the values of one or more factors for which the student's rule is incorrect, and

(2) the value of the dependent variable has not been specified,

then (3) ask if the dependent variable has the value that the student thinks is consistent with the values of the factors, or

(4) ask the student to make a prediction based on the incorrect value of the factor.

EXAMPLE

Suppose a student thinks a dry climate is necessary for growing rice, then ask if they grow rice in Arizona since it has a dry climate, or ask whether they can grow rice in Arizona.

ENS9: Entrapment based on insufficient factors

If (1) a particular value of the dependent variable is being considered for a case, and

(2) there are one or more insufficient factors that have values inconsistent with that value of the dependent variable,

then (3) ask if the values of the insufficient factors are consistent with that value of the dependent variable.

EXAMPLE

Suppose a student is considering whether they grow rice in Florida, ask if the warm climate would account for the inability to grow rice there.

ENS10: Entrapment based on unnecessary factors

If (1) a particular value of the dependent variable is being considered for a case, and

(2) there are one or more unnecessary factors that have values inconsistent with that value of the dependent variable,

then (3) ask if the values of the unnecessary factors are consistent with the value of the dependent variable.

EXAMPLE

Suppose a student is considering whether they grow rice in Egypt, ask if the lack of rainfall would make him think they grow rice there.

ENS11: Entrapment based on irrelevant factors

If (1) a particular value of the dependent variable is being considered for a case, and

(2) there are one or more irrelevant factors that a student might consider relevant,

then (3) ask if the values of the irrelevant factors are consistent with that value of the dependent variable.

EXAMPLE (from Swets and Feurzeig on medical diagnosis)

T. Pleural pain, dyspnea, fever, and the physical exam signs are certainly consistent with pulmonary infarction. (ES7b: Point out values of factors are correct) Do you think that shaking chills and the presence of rusty sputum further supports this diagnosis? (ENS11: Entrapment based on irrelevant factors)

S. No.

T. Right.

ENS12: Entrapment based on incorrect values of factors

If (1) a particular value of the dependent variable is being considered for a case, and

(2) there are values of one or more factors that are inconsistent with that value of the dependent variable,

then (3) ask if the values of the factors are consistent with the value of the dependent variable.

EXAMPLE

Suppose a student is considering a diagnosis of pulmonary infarction for a case with a low white blood count, the teacher might ask if the low white blood count is consistent with pulmonary infarction. In fact a high white blood count is consistent with pulmonary infarction.

Identification Strategies

IS1: Ask for value of the dependent variable

If (1) a case has been selected, and

(2) the value of the dependent variable has not been specified;

then (3) ask the student to identify the value of the dependent variable.

IS1a: Suggest a value of the dependent variable

If (1) a case has been selected, and

(2) the student doesn't know the value of the dependent variable,

then (3) suggest a possible value of the dependent variable for the student to consider.

IS1b: Point out the value of the dependent variable

If (1) a case has been selected, and

(2) the student is mistaken about or doesn't know the value of the dependent variable,

then (3) tell the student the correct value of the dependent variable.

EXAMPLE (from Stevens and Collins on the causes of rainfall)

T. Do you think it rains much in Oregon? (IS1: Ask for value of the dependent variable)

S. No.

T. Why do you think it doesn't rain much in Oregon? (IS6: Ask for relevant factors)

S. I'm not exactly sure - just hypothesizing - it seems to me that the surrounding states have a rather dry climate, but I really don't know anything about the geography of Oregon.

T. It does in fact rain a lot in Oregon. (IS1b: Point out value of dependent variable) Can you guess what causes the rain there? (IS6: Ask for relevant factors)

IS2: Ask for the formulation of a rule

If (1) one or more factors have been identified,
then (2) ask how the values of the factors are related to the value of the dependent variable.

EXAMPLE (from Anderson on factors affecting temperature)

T. Please try to be more precise (e.g., with respect to the effect of latitude on temperature). Would you, for instance, say that if you take any two places in the Northern Hemisphere, the one furthest south has the colder winter temperatures? (IS2a: Suggest the formulation of a rule)

IS3: Ask for the formulation of an alternative rule

If (1) an incorrect rule has been specified relating the values of one or more factors with a particular value of the dependent variable,
then (2) ask for the formulation of an alternative rule.

EXAMPLE (from Anderson on factors affecting temperature)

S. (In response to question under IS2 above) No I wouldn't say that.

T. What would you say? (IS3: Ask for the formulation of an alternative rule.)

IS4: Ask for sufficient factors

If (1) there are one or more sufficient factors that have not been identified,

then (2) ask the student to identify those factors.

EXAMPLE

Suppose a student has not identified irrigation or a means of obtaining enough water to grow rice, the teacher might ask "Is there any way to obtain enough water to grow rice other than from rainfall?".

IS5: Ask for necessary factors

If (1) there are one or more necessary factors that have not been identified,

then (2) ask the student to identify those factors.

EXAMPLE

Suppose a student has not identified any factors that affect whether a place has heavy rainfall, a teacher might ask "What is necessary to have heavy rainfall in a place?"

IS6: Ask for relevant factors

If (1) there are either necessary or sufficient factors that have not been identified,

then (2) ask the student for any relevant factors.

EXAMPLE (from Anderson on factors affecting temperature)

T. Which is likely to have the coldest winter days, Newfoundland or Montana? (ENS5: Entrapment into prediction based on insufficient factors) (In this case a secondary factor overrides a primary factor.)

S. Newfoundland.

T. Please give your reasons for answering Newfoundland. (IS6: Ask for relevant factors)

IS7: Ask for values of factors

If (1) there are relevant factors that have been identified for a particular case, but

(2) the values of the factors have not been identified for that case,

then (3) ask the student for the values of the factors.

EXAMPLE (from Collins on factors affecting grain growing)

S. I suppose there are places, like Nigeria is pretty darn fertile.

T. OK. It's fertile, but what other qualities (IS6: Ask for relevant factors) Is the temperature warm or cold?

(IS5a: Suggest a necessary factor) (IS7: Ask for the value of a factor)

IS8: Ask for prior steps

If (1) a particular step in a causal chain or procedure has been identified, and

(2) there are prior steps that have not been identified,

then (3) ask the student to identify the prior steps.

EXAMPLE (from Stevens and Collins on causes of rainfall)

T. Where does the moisture in the air come from? (IS8: Ask for prior steps)

S. Help.

T. The moisture evaporates from the ocean. (IS8b: Point out prior steps) Why do you think a lot of moisture evaporates? (IS8: Ask for prior steps)

IS9: Ask for intermediate steps

If (1) two steps in a causal chain or procedure that are not adjacent have been identified,

then (2) ask the student to identify the intermediate steps.

EXAMPLE (from Stevens and Collins on causes of rainfall)

S. When the moisture laden air reaches the mountains it is forced to rise and consequently the air cools? causing rainfall, no?

T. Why does cooling cause rainfall? (IS9: Ask for intermediate steps.)

IS10: Ask for subsequent steps

If (1) a particular step in a causal chain or procedure has been identified, and

(2) there are subsequent steps that have not been identified,

then (3) ask the student to identify the subsequent steps

EXAMPLE: (from Anderson on morality of draft resistors)

S. You just can't have individuals deciding which laws they are going to obey.

T. So, you would say the American revolutionaries should have followed the law. (CSS9: Pick a counterexample for an insufficient factor)

S. Yes, I guess so.

T. If they had obediently followed all the laws we might not have had the American revolution (IS10a: Suggest a subsequent step)

IS11: Ask for similarities in factors between similar cases

If (1) two or more cases have been identified that have similar values on the dependent variable,

then (2) ask the student to identify any factors on which the cases have similar values.

EXAMPLE (from Warman on morality of characters in Peter Pan)

T. What makes those characters good? (referring to Peter Pan, Tinkerbell, and Wendy) (IS11: Ask for similarities in factors between similar cases)

IS12: Ask for differences in factors between similar cases

If (1) two or more cases have been identified that have similar values on the dependent variable,

then (2) ask the student to identify any factors on which the cases have different values.

EXAMPLE

Suppose that both Japan and Java have been identified as producing rice, the teacher could ask the student for any differences in factors between the two cases. In fact Japan is colder and much more mountainous. This indicates that flat land and a tropical climate are not necessary factors.

IS13: Ask for similarities in factors between different cases

If (1) two or more cases have been identified that have different values on the dependent variable,

then (2) ask the student to identify any factors on which the cases have similar values.

EXAMPLE

Suppose that Oregon has been identified as having a lot of rain, and Baja California as having little rain, then the teacher might ask what factors they have in common. Since they are both on the western coast of the continent, that means that that factor doesn't determine the amount of rainfall.

IS14: Ask for differences in factors between different cases

If (1) two or more cases have been identified that have different values on the dependent variable,

then (2) ask the student to identify any factors on which the cases have different values.

EXAMPLE (from Anderson on factors affecting temperature)

S. Some other factor besides north-south distance must also affect temperature.

T. Yes. Right. What could this factor be? (IS5: Ask for necessary factors)

S. I don't have any idea.

T. Why don't you look at your map of North America. Do you see any differences between Montana and Newfoundland? (IS14: Ask for differences in factors between different cases)

IS15: Ask for a case with a given value on the dependent variable

If (1) there is no case currently being considered, and

(2) there is a particular value of the dependent variable to be considered,

then (3) ask the student to pick a case that has that value on the dependent variable.

EXAMPLE (from Collins on factors affecting grain growing)

T. Where in North America do you think rice might be grown?
(IS15: Ask for a case with a given value on the dependent variable)

S. Louisiana

IS16: Ask for a case with given values on some factors

If (1) there is no case currently being considered, and
(2) there are particular values of some set of factors to be considered,
then (3) ask the student for a case that has the given values on the set of factors.

EXAMPLE

Given a discussion of rice growing, the teacher might ask a student if he knows a place where there is a lot of rainfall but it is rather cold (e.g., Oregon).

IS17: Ask for a case with given values on some factors and the dependent variable

If (1) there is no case currently being considered, and
(2) there is some pairing of values on particular factors and on the dependent variable to be considered,
then (3) ask the student for a case that has the given values on the factors and on the dependent variable.

EXAMPLE

Given a discussion of rice growing, the teacher might ask a student if he knows a place where there is a lot of rainfall, but no rice is grown (e.g., Oregon).

Evaluation Strategies

ES1: <u>Ask if the value of the dependent variable is correct or incorrect</u>

If (1) a value has been suggested for the dependent variable in a particular case,

then (2) ask the student if that value is correct or incorrect.

EXAMPLE (from Collins on factors affecting grain growing)

T. What do you think they live on in West Africa? (IS1: Ask for value of the dependent variable)

S. I guess they grow some kind of grain in West Africa.

T. What kind is most likely? (IS1: Ask for value of the dependent variable)

S. Wheat.

T. You think wheat is the most likely grain? (ES1: Ask if the value of the dependent variable is correct or not)

ES2: <u>Ask if a rule is correct or incorrect</u>

If (1) a rule has been suggested relating a set of factors to the dependent variable,

then (2) ask the student if the rule is correct or incorrect.

EXAMPLE (from Warman on who can play with blocks)

T. How about if we had boys could play with everything but blocks? (CSS13: Construct a hypothetical case for insufficient factors) (ES2: Ask if rule is correct or incorrect) (Warman treats fairness as the dependent variable, and here suggests a rule derived by constructing a hypothetical case for insufficient factors.)

ES3: Ask if a rule is the same as or different from another rule

If (1) a rule has been suggested which appears similar to another rule,

then (2) ask if the rule is the same as or different from the other rule.

EXAMPLE (from Warman on who can play with blocks)

S1. I've got a good idea. Everybody play with blocks..

T. What do you think about that? (ES2: Ask if a rule is correct or incorrect)

S2. Rats.

T. Isn't that the rule we have now? (ES3: Ask if a rule is the same or different from another rule)

ES4: Ask if factors are sufficient or insufficient

If (1) one or more factors have been identified with respect to a particular value of the dependent variable,

then (2) ask the student if the factors are sufficient or insufficient to determine the value of the dependent variable.

EXAMPLE (from Swets and Feurzeig on identifying letters)

T. Start when ready (The student must guess a letter from its features)

S. Curves?

T. One.

S. Loose ends?

T. Two.

S. Obliques?

T. Zero.

S. C.

T. You don't have enough information yet to get the right answer. (ES4b: Point out that factors are insufficient) How do you know it isn't J, for example? (IS1a: Suggest a value of the dependent variable)

ES5: <u>Ask if factors are necessary or unnecessary</u>

If (1) one or more factors have been identified with respect to a particular value of the dependent variable,

then (2) ask the student if the factors are necessary or unnecessary to determine the value of the dependent variable.

EXAMPLE

Suppose a student suggests that places with a lot of rain can grow rice, the teacher might ask "Do you have to have a lot of rain in order to grow rice?"

ES6: <u>Ask if factors are relevant or irrelevant</u>

If (1) one or more factors have been identified with respect to a particular value of the dependent variable, then (2) ask the student if the factors are relevant or irrelevant to the value of the dependent variable.

EXAMPLE (from Warman on who can play with blocks)

S. How about all the boys take all the blocks and put them outside and the blocks stay outside the building.

T. So we have the blocks outside the building. (Restate rule) Then do we still have the problem? (ES6: Ask if a factor is relevant or irrelevant) (Warman is asking whether having the blocks outside is relevant to fairness.)

ES7: <u>Ask if the values of factors are correct or incorrect</u>

If (1) the values of one or more factors have been identified with respect to a particular value of the dependent variable,

then (2) ask the student if the values of the factors are correct or incorrect with respect to the value of the dependent variable.

EXAMPLE (from Swets and Feurzeig on medical diagnosis)

T. In that case I'd like to talk about viral pneumonia. (IS1a: Suggest a value of the dependent variable) The tachycardia, high WBC, elevated respiratory rate, shaking chills, bloody sputum, and severe pleural pain all lend weight to that diagnosis - right? (ES7: Ask if the values of factors are correct or incorrect)

ES8: Ask if a step is a prior step

If (1) there are two steps identified in a causal chain or procedure,

then (2) ask the student if one step is prior to the other step or not.

EXAMPLE

In discussing what causes rainfall, the student might mention the air cooling and rising. The teacher might then ask the student if the air cools before it rises.

ES9: Ask if a step is an intermediate step

If (1) a given step in a causal chain or procedure has been identified with respect to two other steps,

then (2) ask the student if the step is intermediate between the other two steps.

EXAMPLE

Suppose a student is learning about evaporation processes, the teacher might ask whether clouds form after vaporization takes place, but before condensation occurs. Cloud formation is in fact caused by condensation.

ES10: Ask if a step is a subsequent step

If (1) a given step in a causal chain or procedure has been identified with respect to another step, then (2) ask the student if the step is subsequent to the other step.

EXAMPLE

Suppose a student is learning the distributive law in arithmetic (as in one of the Anderson dialogues), then with respect to the problem 7 X 12 + 3 X 12 = ?, the teacher might ask if you multiply by the 12 after adding the 7 and 3.

ES11: <u>Ask if similar cases are the same on given factors</u>

If (1) two or more cases have been identified that have the same value on the dependent variable, and

(2) there are one or more factors for which the cases have the same values,

then (3) ask the student if the cases have the same or different values on the given factors.

EXAMPLE

Suppose the student is learning about the causes of rainfall, and the student notices that Baja California and Northern Chile have little rainfall, the teacher might ask if they have the same latitude (which they do).

ES12: <u>Ask if similar cases are different on given factors</u>

If (1) two or more cases have been identified that have the same value on the dependent variable, and

(2) there are one or more factors for which the cases have different values,

then (3) ask the student if the cases have the same or different values on the given factors.

EXAMPLE

Suppose a student has identified the Amazon and Oregon as having a lot of rainfall, then the teacher could ask if they have the same or different values on latitude and altitude (they differ on both).

ES13: Ask if dissimilar cases are the same on given factors

If (1) two or more cases have been identified that have different values on the dependent variable, and

(2) there are one or more factors for which the cases have the same values,

then (3) ask the student if the cases have the same or different values on the given factors.

EXAMPLE (from Anderson on morality of draft resistors)

T. You are saying that what the draft resistors did was wrong because they broke the law. The American revolutionaries broke the laws too. (CSS9: Pick a counterexample for an insufficient factor) (ES13b: Point out that two dissimilar cases are the same on a given factor) Therefore to be consistent, you would have to say that what they did was wrong. (IS1a: Suggest a value of the dependent variable)

ES14: <u>Ask if dissimilar cases are different on given factors</u>

If (1) two or more cases have been identified that have different values on the dependent variable, and

(2) there are one or more factors for which the cases have different values,

then (3) ask the student if the cases have the same or different values on the given factors.

EXAMPLE

Suppose a student has identified Sumatra and Java as having different population densities, the teacher might ask if they have the same terrain.

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