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DIAGNOSING STUDENTS' MISCONCEPTIONS IN CAUSAL MODELS.(U)

JUN 78 A L STEVENS, A COLLINS, S GOLDIN N00014-76-C-0083

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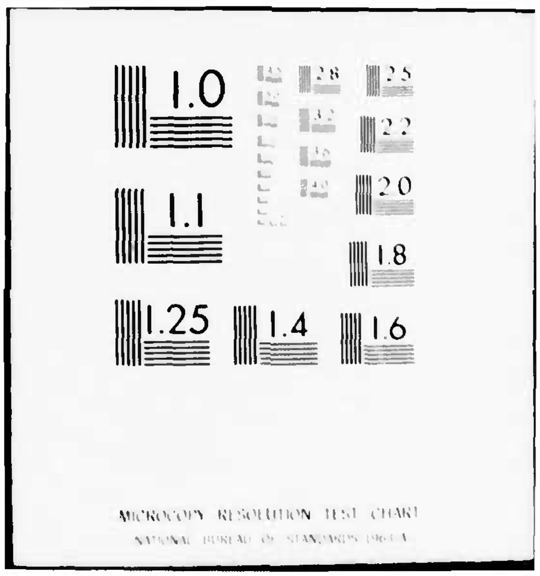
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LEVEL II

Report No. 3786

Diagnosing Students' Misconceptions in Causal Models

Albert L. Stevens, Allan Collins, and Sally Goldin

June 1978

Prepared for:
Office of Naval Research
Advanced Research Projects Agency

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DIAGNOSING STUDENTS' MISCONCEPTIONS IN CAUSAL MODELS

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Contract No. N00014-76-C-0083, effective September 15, 1975.
Expiration Date: September 30, 1978
Total Amount of Contract - $337,000
Principal Investigator, Allan M. Collins (617) 491-1850

Sponsored by:
Office of Naval Research
Contract Authority No. NR 154-379
Scientific Officers: Dr. Marshall Farr and
Dr. Henry Halff

and

Advanced Research Projects Agency
ARPA Order No. 2284, Amendment 4
Program Code No. 61101E

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Technical Report No. 4	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	9
4. TITLE (and Subtitle): 6 Diagnosing Students' Misconceptions in Causal Models.	5. TYPE OF REPORT & PERIOD COVERED: Semi-Annual Technical Report, 30 Sep [redacted]77-1 Mar [redacted]78
	6. PERFORMING ORG. REPORT NUMBER: BBN [redacted]o. -3786
7. AUTHOR(s): 10 Albert L. Stevens, Sally Goldin, Allan Collins	8. CONTRACT OR GRANT NUMBER(s): 15 N00014-76-C-0083
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Bolt Beranek and Newman Inc. 50 Moulton St., Cambridge, MA 02138	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61153N 16 RR042 04 01 NR154-379
11. CONTROLLING OFFICE NAME AND ADDRESS: Personnel and Training Research Programs, Office of Naval Research (Code 458), Arlington, VA 22217	11 12. REPORT DATE: Jun[redacted]78
	13. NUMBER OF PAGES: 31
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 17 RR04204O1	15. SECURITY CLASS. (of this report): UNCLASSIFIED 12 36p.
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

To appear in R. Snow, P. Federico and W. Montague (Eds.), Aptitude, Learning and Instruction: Cognition Process Analysis.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Education, Tutoring, Computer-Assisted Instruction, Learning, Teaching, Educational Psychology.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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Diagnosing Students' Misconceptions in Causal Models

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This research was sponsored by the personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-76-C-0083, Contract Authority Identification Number, NR 154-379.

Abstract

Tutorial dialogues can be analyzed as an interaction in which a tutor "debugs" a student's knowledge representation by diagnosing and correcting conceptual misunderstandings. In this paper, we outline some tentative steps toward a theory which describes tutorial interactions. We outline the goal structure of a tutor, describe types of conceptual bugs that students have in their understanding of physical processes and discuss some of the representational viewpoints necessary to diagnose and correct these bugs.

Diagnosing Students' Misconceptions in Causal Models

Albert Stevens

Allan Collins

Sally Goldin

We are building a computer aided instructional system which tutors students to reason about and understand physical processes. In order to build such a system, we have been forced to confront several fundamental issues about the tutorial process:

(1) What is the goal structure that governs a tutor's selection of examples, questions and statements at different points in the dialogue?

(2) What are the types of misconceptions that students have and how do tutors diagnose misconceptions from errors students make?

(3) What are the abstractions and viewpoints that tutors use to explain physical processes?

We believe we are taking tentative steps toward a theory which addresses these issues. Our approach is to work out a theory based on analyses of tutoring dialogues and experiments and then build a system based on that theory. Building the system reveals points where the theory is inadequate or wrong. In subsequent iterations of this process, we concentrate on these weak points. In this paper, we will describe the first version of our system, its weak points and the steps in analysis and theory development we are taking to remedy these weak points.

The WHY System

The first version of our system, called the WHY system, can carry on a simple teaching dialogue about the causes of rainfall. The theory on which the WHY system is based is formalized as a set of production rules representing teaching strategies (Collins, 1977) and a script-like knowledge structure (Schank & Abelson, 1977). The script structure represents the different temporal and causal steps in processes that affect rainfall. Many scripts in the system can be decomposed into more detailed subscripts. The resulting embedded structure is used to represent levels of detail of knowledge about different processes.

Figure 1 illustrates these aspects of knowledge organization. It shows the top-level script for heavy rainfall which consists of four steps: Evaporation, movement of the air mass, cooling and precipitation. The subscript for the first step is also shown and consists of a more detailed breakdown of the steps involved in evaporation.

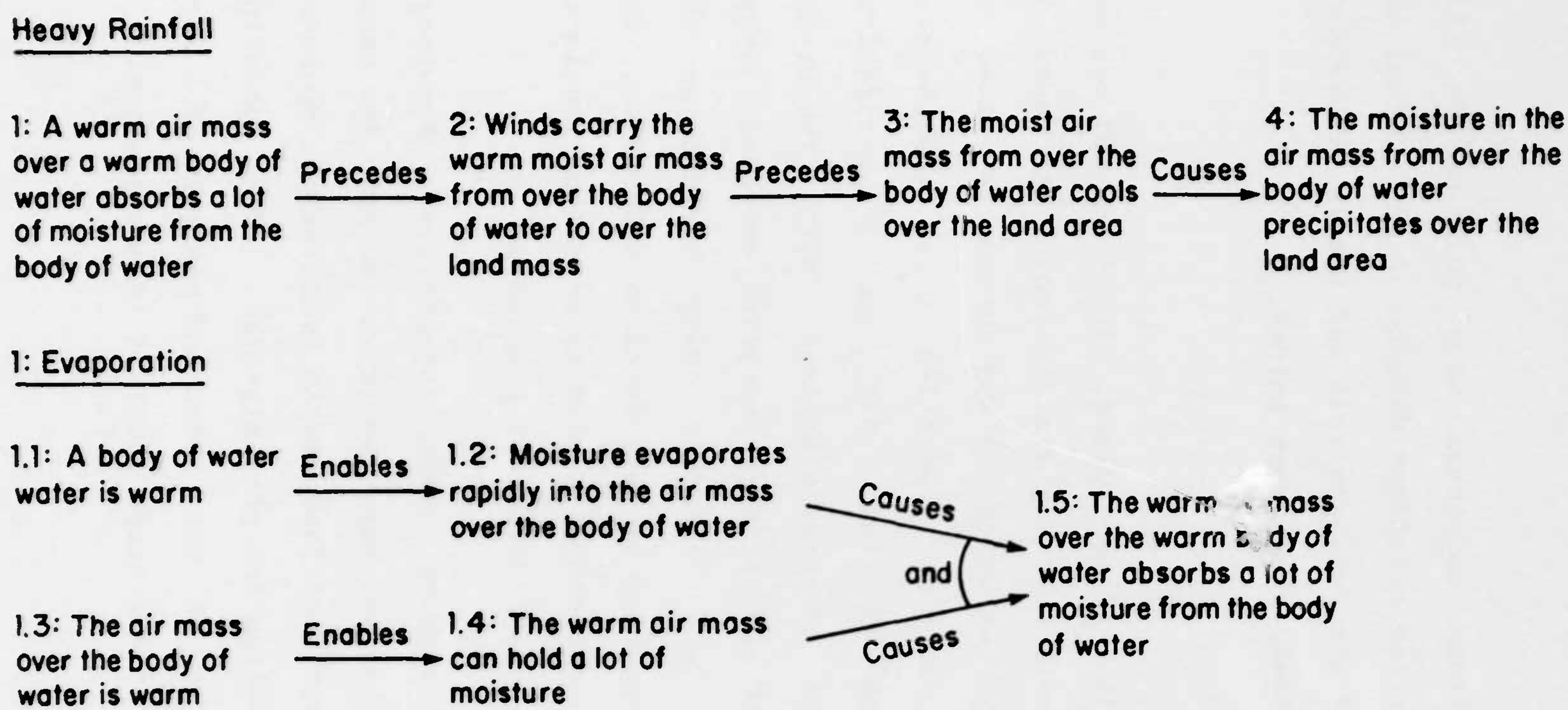

FIGURE 1. The script for heavy rainfall and the subscript for evaporation in the first version of the Why system.

The teaching strategy rules are stated in terms of a conditional test of the student's response to a question paired with an action to perform if the test is true. Example rules are:

(1) If the student gives as an explanation a factor that is not an immediate cause in the causal chain,
then ask for the intermediate steps.

(2) If the student gives as an explanation one or more factors that are not necessary,
then formulate a general rule by asserting that the factor is necessary and ask the student if the rule is true.

The theory in Collins (1976) consists of twenty-four rules. The first version of the Why system contains seven rules which test for missing script steps, ask students questions and present information.

Problems With the Current System

The current WHY system is able to carry on simple tutoring dialogues about the causes of rainfall. It can ask questions about places where heavy rainfall occurs, diagnose missing steps in the student's knowledge and inform the student about the correct steps. A bit of interaction with the system reveals several problems: (1) It has little global perspective about the dialogue and thus bases its questions and responses almost exclusively on local context. (2) It is sensitive to student errors, but typically misses the cause of these errors, correcting the surface error but failing to diagnose the underlying misconception that the error reflects. (3) There are many important aspects of physical processes and many important ways of describing physical processes that the WHY system fails to use.

These problems parallel the issues listed earlier. The lack of global perspective in the current system arises because there is no coherent goal structure. The teaching-strategy rules we originally developed are based on the students' immediate responses and have no way to establish and be influenced by higher level goals.

The types of misconceptions in students' knowledge that a system can diagnose are heavily dependent on the knowledge represented in the system. The script structures in the current WHY system are able to represent misconceptions which result because of missing substeps or extra substeps in the various scripts. These are only two of several types of misconceptions that occur. We will discuss others below.

The problems of failing to discuss important aspects of physical processes and failing to use important ways of describing physical processes arise because the script-subscript formalism is limited. We believe that representing knowledge about physical processes requires multiple "representational viewpoints." Our script structures provide one of those, the viewpoint of a sequence of temporally ordered processes, some causally related to others, and some subprocesses of others. This representational viewpoint is important, but equally important is the "functional viewpoint" which emphasizes the functional relationships among attributes of the various objects involved in different processes.

In the following sections, we will discuss each of these problems and provide some initial ideas about a theory necessary to deal with them. It will be apparent that they are all intimately interrelated and that a key element necessary for their solution is an adequate formalism for representing the knowledge taught.

Some Proposed Solutions

Goal Structure. One of the major constraints on a theory of tutoring is that it should adequately describe the structure of tutorial dialogues. Our analyses of tutorial dialogues reveals a general structure that follows from the script structure of the knowledge base. Tutors discuss topics in a rational order, typically following the discussion of one process with discussion of a temporally or causally adjacent process or with a discussion of component subprocesses.

Detailed dialogue structure is much more problematical. Close examination of tutorial dialogues reveal that the tutor probes the student about many different aspects of the knowledge. When the student makes an error, the tutor will sometimes correct it immediately, but in many cases will ask other questions until the misconception underlying the error is isolated. The treatment of the misconception may then require a number of interchanges during which the tutor tests the student's knowledge and supplies the relevant information. We believe that a powerful perspective from which to view this more detailed structure of tutorial dialogues is that of the tutor as a "debugger." Much of the detailed structure of a dialogue results from the tutor using various strategies to diagnose students' misconceptions, or "bugs," and then applying strategies to correct them.

In order to investigate this perspective of tutors as debuggers, we have conducted dialogues where the questions and responses were communicated over linked terminals and where the tutors verbally commented on two aspects of the dialogue as they proceeded. The two aspects were: (1) What they thought the student knew or didn't know, based on the student's response, and (2) why they responded to the student in the way they did. This technique supplies data normally unavailable for a dialogue analysis, providing insights into how the tutor develops a model of the student, how the tutor organizes the knowledge being taught and how these two factors influence the tutors choice of questions and responses to the student.

Using this data, we developed the outlines of a theory of tutors' goal structures. The goal structure we derived is summarized in Table 1. The top level goals are (1) refine the student's causal model and (2) refine the student's procedures for applying the model. These directly govern the selection of cases. As the student's knowledge becomes more refined, moving from an understanding of first-order factors to higher-order factors, cases are selected which are exemplary of the factors the tutor is trying to teach. As the student's predictive ability becomes refined, cases are selected which are progressively more novel and complex, taxing the student's predictive ability more and more.

The process of achieving these top-level goals involves two types of subgoals: diagnosis and correction. Both of these subgoals govern the selection of basic strategies.

The purpose of diagnosis is to discover gaps and misconceptions in the student's knowledge. This generally requires that the tutor probe the student by asking for relevant factors, by requiring the student to make

Table 1

Outline of a Socratic Tutor's Goal Structure. The manifestations refer to the rules described in Collins (1976) and Stevens and Collins (1977).

Goals	Manifestation
Refine the student's causal model moving from 1st to nth order factors.	Case selection rules: Select cases that are exemplary of the relevent factor.
Refine the student's procedures for applying the causal model to novel cases.	Case selection rules: Select less familiar cases, exemplary of new factors.
Subgoals	
Diagnose the student's "bugs", (i.e. the difference between the student's knowledge and the tutor's knowledge.)	Ask-for-factor rules. Prediction rules. Entrapment rules. Probe-reasoning-strategy rules
Correct the diagnosed bugs	Inform-student rules Missing-factor rules Forming hypotheses rules Testing hypotheses rules Information-collection rules

predictions about carefully selected cases, and by trying to entrap the student into making incorrect predictions. It is clear from our analysis of human dialogues that diagnosis cannot be completely characterized in terms of a simple mapping between students' errors and their conceptual bugs. Rather the process involves sophisticated use of a student model and knowledge about common bugs in order to simulate the student's reasoning processes and pinpoint the underlying conceptual errors or missing information. In some cases, a single answer may reveal a whole set of bugs, while in other cases, the tutor must carefully probe the student, testing alternative hypothesized bugs to reveal the misconception.

Typically, when a conceptual bug is diagnosed, the tutor attempts to correct it. This may require a single statement for simple factual errors or an extended dialogue to correct problems in the student's causal model. In Stevens and Collins (1977) we illustrate the application of this goal structure model by analyzing a tutorial dialogue.

Our outline of goal structure is relatively general and probably can be applied to many different knowledge domains and tutorial interactions. However, in order to specify it in detail, we need to know what the bugs are, how they can be represented, how they are diagnosed from errors and how they can be corrected.

Types of bugs in understanding rainfall. Our analyses of dialogues show that tutors spend a good part of their time diagnosing conceptual bugs from errors manifested in the dialogue. We believe that one of the major skills a teacher possesses is knowledge about the types of conceptual bugs students are likely to have, the manifestations of these bugs and methods for correcting them. It is thus clear that an important component of any teaching system is a method for representing, diagnosing and correcting bugs.

To examine the types of bugs that occur in students' understanding of rainfall, we carried out a simple experiment. We compiled a systematic test about the causes of heavy rainfall by generating questions for all major script nodes in the current WHY system representation of rainfall. This included, for each node, a question which queried prior script steps and questions which queried subsequent script steps. These questions were presented to subjects on a questionnaire. At the top of the questionnaire was a context-setting paragraph which explained that all questions were to be interpreted as referring to areas of the world where heavy rainfall occurs and described what we meant by heavy rainfall. Some typical questions from this test are:

"How is the moisture content of the air related to heavy rainfall?"

"What role does rising air play in causing rainfall?"

"What causes evaporation?"

There were a total of 32 questions. The questions were initially randomized and each subject received them in the same random order. The questionnaire also included two questions, one which asked the subjects to name areas of the world which have heavy rainfall and the other areas which have little rainfall.

The instructions emphasized that even if the subjects felt they did not know an answer, they should try to answer the question. We adopted these instructions, because the typical response given by subjects when confronted with this test was "I don't know anything about rainfall." Subsequent probing revealed that they often knew a good deal more than they thought. The test was administered to subjects individually and typically was completed in about 30 minutes.

The experiment provided us with a substantial body of data on errors and misconceptions. In order to analyze the responses in detail, all answers that were judged incorrect were tabulated under the appropriate questions. We then analyzed these errors by developing a basic set of conceptual bugs and classifying the errors according to this set. This analysis revealed two points of major interest:

(1) A particular conceptual bug is often shared by many students.

(2) A particular conceptual bug is often manifested in many different ways.

For example, a bug we call the Cooling-by-contact bug is very common, occurring for 6 of the 8 subjects. Some verbatim examples of manifestations of this bug are:

(1) "Cold air masses cool warm air masses when they collide."

(2) "Winds cause air to cool."

(3) "Mountains cause condensation because cold land touching warm air causes condensation."

(4) "Cold fronts, wind, snow and rain cause air to cool."

(5) "Cold air masses cool the clouds so the rain falls."

None of the above types of cooling are of any consequence in causing heavy rainfall. The type of cooling necessary occurs when an air mass is forced to rise. The rising results in expansion and energy loss.

We identified a total of sixteen different bugs from this experiment. They are shown in order of frequency in Table 2. Using these sixteen bugs, we were able to account for 58% of the answers originally judged to be incorrect or omitted. (By ignoring omissions, we were able account for 72%.) We are being conservative in this accounting. For many of the remaining errors and omissions, one can make a plausible argument that these bugs could lead to that error. Many statements that we did not account for were factual errors, for example, "Heavy rainfall occurs only in warm areas." (Heavy rainfall occurs in many cool and cold areas of the world.) Others were naming errors. For example, "When water evaporates, it turns to steam." (The standard term in meteorology for the product of evaporation is water vapor.)

Many of the bugs we observed are specific to the domain of rainfall. This should be neither surprising nor disturbing. One of the skills a good teacher must possess is knowledge of the types of misconceptions that arise in the domain taught. It is likely that there are other bugs which occur in students' knowledge about rainfall, but it will surprise us if this number is unmanageably large.

Table 2. The set of observed misconceptions.

	Misconception	Number of Subjects	Example
(1)	Cooling-by-contact	6	"Mountains cause condensation because cold land touching air causes condensation."
(2)	Heating-by-radiation	6	"The sun warms the air."
(3)	Small-moisture-source	5	"A 12 by 12 by 10 foot pond is enough to cause rainfall."
(4)	Rising-causes-increased-pressure	3	"Rising air makes the moist air rise, pressure increases ..."
(5)	Absorbtion-by-expansion	3	"...decrease in pressure causes water molecules to expand, causes evaporation."
(6)	Heating-by-contact	3	"...land warms the air at night."
(7)	Squeezing-causes-condensation	2	"Putting pressure on air masses causes condensation."
(8)	Temperature-of-water-irrelevant-for-evaporation	2	"Temperature of water is unrelated to evaporation."
(9)	Temperature-differential-causes-evaporation	2	"Air has to be cooler than the body of water for evaporation to occur."
(10)	Insufficient-warming-of-water	2	"A current can be warm because it comes from a warm source of water--for example, a lake which is warm."
(11)	Heating-causes-condensation	1	"Air warming up causes rainfall."
(12)	Winds-cause-pressure-increases	1	"Winds are forceful and cause various air pressures."
(13)	Cooling-causes-evaporation	1	"When a body of water is cold, it evaporates."
(14)	Rising-results-in pressure-equalization	1	"Air that is warmer is expanded and has less pressure. It rises until its pressure is equal to surrounding air."
(15)	Cooling-cause-air to-rise	1	"Cooling causes air to rise."
(16)	Evaporation-causes-air-to-rise	1	"Evaporation causes air to rise."

To represent these bugs in a way that makes it possible for a teaching system with a diagnose-and-correct goal structure to use them is an important step. In principle, the current script-like formalism could be used. In practice, such things as incorrect functional relationship (e.g. the Heating-causes-condensation bug) or incorrect attributes (e.g. the temperature of mountains in the Cooling-by-contact bug) seem to require a different representational viewpoint than those provided by script structures. We will provide some steps toward a solution below in the section on representation.

Explaining physical processes. The third problem we described in the introduction is the nature of the abstractions and viewpoints that tutors use to describe physical processes. The teaching dialogues we have examined require a multi-leveled structure, with script-like knowledge necessary to support some parts of the discussions and relatively low-level detailed knowledge about physical principles necessary to support other parts. More interestingly, to adequately support the dialogues requires that the knowledge be factorable in several ways. Tutors discuss far more than causal and temporal linkages between steps in a script structure. They probe and discuss information about attributes of the actors that are important, the results of processes and the form of the functional relationship which holds between the attributes of actors and the results of processes.

Some examples of tutors' statements and questions are shown in Table 3. In each case, the question or statement refers to one of the specific aspects of the knowledge we just described. A cursory examination of our dialogues suggest that a large percentage of tutors' statements and questions fall into these categories. For example, in a representative dialogue which consisted of 41 exchanges between the tutor and student, four of the tutor's statements were about attributes of actors, four were about results of processes and seven were about functional relationships. This accounting includes 15 of the tutor's statements. Of the remaining 26, eight are references to prior, intermediate or subsequent processes at a level of abstraction that can be handled by script structures. The remainder, which we do not have good ideas about, include references to the spatial structure of the processes, descriptions of physical principles and explication of a metaphor.

Representing the knowledge domain

For each of the three problems we have discussed, a key element necessary for its solution is an adequate formalism for representing the knowledge taught. To specify the goal

Table 3. Example statements for each part of the representation.

Factors (Attributes of Actors)

"Do you think the amount of moisture in the air affects the amount of rainfall?"

"Does the temperature of water affect evaporation?"

Results of Processes

"Condensation is the process by which moisture in the air becomes liquid water again."

"Evaporation is the process by which water in the ocean becomes moisture in the air."

Functional Relations

"What happens to the temperature of the air as it rises?"

"Do you remember how temperature affects evaporation?"

structure of a tutor in detail requires specifying misconceptions and methods for correcting them. Specifying misconceptions and the proper abstractions and viewpoints from which to diagnose and correct them requires a detailed formalism for representing the knowledge taught. Script structures can be used to represent ordered causal and temporal processes, but this handles only a small number of bug representations and viewpoints from which to discuss them. In this section, we will describe one additional representational viewpoint that seems important for a tutorial system.

A representation of functional relationships. The basic unit of our representation for functional relationships is a description of some process such as cooling or evaporation. An example is shown in Figure 2. This represents the process of evaporation as it occurs in the rainfall domain. Its parts are:

(1) A set of actors each with a role in the overall process. For example, the ocean plays the role of moisture source.

(2) A set of factors which affect the process. The factors are all attributes of actors. For example, the temperature of the source body-of-water is a factor in evaporation.

Figure 2. A functional representation for evaporation.

EVAPORATION

<u>Actors</u>

Source: Large-body-of-water

Destination: Air-mass

<u>Factors</u>

Temperature(Source)

Temperature(Destination)

Proximity(Source, Destination)

<u>Functional-relationship</u>

Positive(Temperature(Source))

Positive(Temperature(Destination))

Positive(Proximity(Source, Destination))

<u>Result</u>

Increase(Humidity(Destination))

(3) A description of the result of the process. The result is always a change of an attribute of one of the actors. For example, the result of evaporation is to increase the humidity of the destination air mass.

(4) A description of the functional relationship which holds among the factors and the result. We believe there is room for complexity and subtlety in the description of functional relations, but we currently use a simple descriptive scheme which allows positive and inverse relationships. For example, in evaporation there is a positive relationship between the temperature of the moisture source and the resulting humidity of the air mass.

This representation is general in two ways. It can be partially specified by assigning values to the actor attributes. For example, representing an instance of a large amount of evaporation requires assigning values like "warm" to the temperatures of source and destination and a value like "adjacent" to the proximity relationship. Inference rules which make use of the information about relevant attributes and functional relationships can be constructed to check (at some level of approximation) if the assigned values of factors and result are consistent.

The second way that this representation can be further specified is by instantiating the actors. For example, in the case of rainfall over Ireland, the source is the Gulf Stream.

Thus, the information in this representation provides a way for generating representations of different amounts of evaporation and for representing these different amounts with different actors. This representation provides an additional representational viewpoint that is missing from script structures.

Representing Bugs. In addition to representing knowledge that is correct, it must be possible to represent misconceptions. One constraint on a knowledge representation used for teaching is to represent misconceptions as meaningful transformations of the basic knowledge representations (Brown and Burton, 1978). For example, consider the representation for the Absorption-by-expansion bug shown in Figure 3. The key part is highlighted. It consists principally of a substitution of pressure for temperature as the relevant attribute of the destination in the normal representation for evaporation. Representing bugs in the same format as the correct knowledge makes differential diagnosis possible. In trying to decide whether a student has the cooling-by-contact bug,

Figure 3. The Absorption-by-expansion bug.

Evaporation under the Absorption-by-expansion bug

Actors

Source: Large-body-of-water

Destination: Air-mass

Factors

Pressure(Destination)

Proximity(Source, Destination)

Functional-relationship

Inverse(Pressure(Destination))

Positive(Proximity(Source, Destination))

Result

Increase(Humidity(Destination))

asking the student what actors are involved will not provide any relevant information. Either winds, mountains or cold air masses will still be mentioned as important. It is the role or attributes of these actors that supplies the leverage. However, in the Small-moisture-source bug, the actor itself supplies the diagnostic leverage point.

Bugs show up in all parts of the representation. For example, the Cooling-by-contact bug is represented as a difference in the role of the object, or as a difference in the relevant attribute of the object. The Heating-causes-condensation bug is represented as a difference in functional relationship. The Small-moisture-source bug is represented as a difference of actor in the source role.

Remaining Problems

In the previous sections, we outlined some tentative steps toward solving the problems of goal structure, representing misconceptions, and providing the additional representational viewpoint of a set of functionally related processes. We believe the heart of these problems lies in the representation of knowledge. Our tentative steps toward representing knowledge and misconceptions about physical processes extend the script-like representation we have been using, but we believe we are still just scratching the surface.

Adding this one viewpoint has given us more windows into problems that were opaque using our previous notation. In the remainder of this paper, we will point out the nature of some of the problems that we can now see.

Interacting Bugs. In most cases, a single bug accounts for each error, but there are cases where bugs interact to produce a single misconception. Brown and Burton (1978) have shown that in arithmetic, students often have a set of bugs that interact to produce non-obvious patterns of errors. The observations from our experiment suggest that similar things happen in the rainfall domain. For example, one subject said in response to a question about the role of cold air masses:

> "Cold air masses hitting warm air masses cause condensation."

Since she mentioned contact and not rising, the most straightforward diagnosis from this statement is that she has a Cooling-by-contact bug. However, the problem really seems to be due to two interacting bugs: the Heating-by-contact bug and the Heating-causes-condensation bug. Two of this student's responses to other questions were:

"Air warming up causes rainfall."

"Tropical winds warm air."

Thus, her description of condensation caused by cold air masses hitting warm air masses is most likely due to these bugs interacting to produce a model in which the cold air is warmed up from contact with the warm air (the Heating-by-contact bug) and this warming causes rainfall (the Heating-causes-condensation bug).

The existence of interactions imply that the mapping from errors to bugs is not one-to-one. We suspect that there are many cases where the relationship between a set of errors and the underlying bugs may be quite subtle. The existence of non-obvious interactions may account for our inability to classify many of the errors we observed.

Where do bugs come from? Having looked at the bugs we have isolated, we now believe that they still are relatively shallow, reflecting even deeper levels of misconceptions in knowledge. The major reason for believing this is that bugs themselves seem to form patterns. The patterns seem best explained as the result of deeper problems in the student's knowledge. Sometimes these deeper problems are due to the application of an incorrect metaphor in understanding a process; other times the patterns reflect incorrect or missing general relationships between process, like the notion of inverse, or positive feedback.

An example of a pattern that reflects an incorrect application of a metaphor is the "sponge pattern". It includes two bugs: the Absorption-by-expansion bug and the Squeezing-causes-condensation bug. In effect, the student views the air mass as a giant sponge, expanding to absorb moisture and later having it squeezed out. Tutors typically deal with this deep-level misconception by using a "container" analogy for the air mass, identifying the capacity of the container with air temperature rather than size.

A second type of pattern is that which arises because of missing generalizations about process relationships. For example, the pattern which includes the Heating-causes-condensation bug but which also includes the correct functional relationship between heating and evaporation seems to reflect the student's lack of understanding that condensation and evaporation are inverse processes. Tutors deal with this bug by informing the student that the two processes are inverses and explaining the sense in which they are inverses.

These processes of understanding draw on a large set of real-world knowledge that students have built up over their lifetime. The bugs often seem to depend on the student's failure to understand some deep physical principles that support the correct model. In order for tutors to deal with conceptual bugs, they must recognize this mode of understanding and attempt to discover what models the student applies to understand the processes taught.

Other representational viewpoints. The existence of patterns of bugs implies that that there are still other representational viewpoints necessary to deal completely with physical processes. The analogical use of the "sponge" concept implies that a complete analysis will require techniques for representing and modifying models drawn from other domains. The process-relationship example implies that representation of general process relationships like "inverse processes", "feedback system", and "cyclical process" will have to be included. There also seem to be multiple ways of describing what appears to be essentially the same information. These different ways may be generative in nature, but they emphasize different aspects of the processes. For example, there is the energy viewpoint from which various processes appear to add or remove types of energy to different actors. There is the change-of-state viewpoint, from which various actors appear to change form and location as time progresses. These multiple representational viewpoints are different but must interact in order to provide a complete representation of a physical process. We believe that defining them will provide additional insights into the nature of tutorial skill.

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