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K A VANLEHN 13 AUG 85 ISL-11 N00014-82-C-0067

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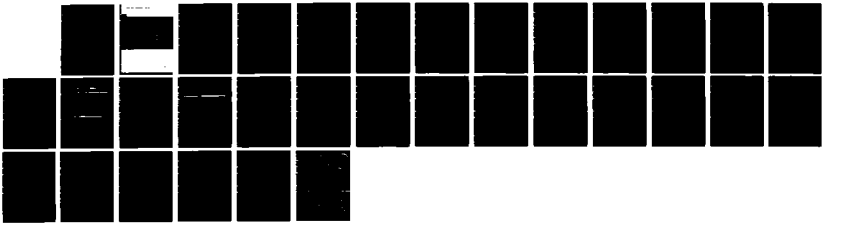

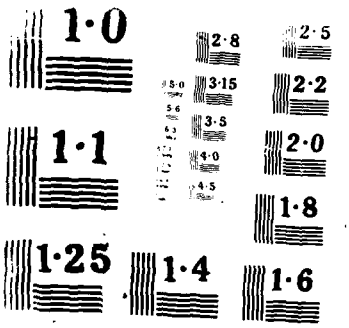
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Theory Reform Caused by an Argumentation Tool

Kurt VanLehn

XEROX

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

A169358

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): ISL-11	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Xerox Palo Alto Research Center; 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION: Personnel and Training Research Program Office of Naval Research
6c ADDRESS (City, State, and ZIP Code): 3333 Coyote Hill Road, Palo Alto, CA 94304	7b ADDRESS (City, State, and ZIP Code): Arlington, VA 22217
8a NAME OF FUNDING/SPONSORING ORGANIZATION; 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N00014-82C-0067
8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO 61153N; PROJECT NO RR042-06; TASK NO RR042-06-0A; WORK UNIT ACCESSION NO NR667-477

11 TITLE (Include Security Classification): Theory Reform Caused by an Argumentation Tool

12 PERSONAL AUTHOR(S): VanLehn, Kurt Alan

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Technical	FROM 1/1/82 TO 6/15/85	August 13, 1985	29

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Linked text systems, Notecards, argumentation

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Recently, software aids have been developed for formulating and managing arguments. Most of these programs are combinations of text editors and databases. This paper concerns one such system, called NoteCards. The paper discusses two incidents where using the system uncovered major flaws in the arguments. These discoveries were quite unexpected. This paper discusses these two incidents and tries to ascertain why a such a simple tool had such a profound impact and what the tool's future might be

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Mike Shafto	22b TELEPHONE (Include Area Code): (202) 696-4322; 22c OFFICE SYMBOL: 4 42 PT

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE: Unclassified

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ISL-11 July 1985 [P85-00102]

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Theory Reform Caused by an Argumentation Tool

Kurt VanLehn

Abstract

Recently, software aids have been developed for formulating and managing arguments. Most of these programs are combinations of text editors and databases. This paper concerns one such system, called NoteCards. The paper discusses two incidents where using the system uncovered major flaws in the arguments. These discoveries were quite unexpected. This paper discusses these two incidents and trys to ascertain why a such a simple tool had such a profound impact and what the tool's future might be.

Theory reformulation caused by an argumentation tool

Kurt VanLehn

There are many projects whose goal is to produce a network of well-reasoned arguments in support of some assertions. Examples of such networks are a legal brief, a market analysis or a scientific theory. Until recently, computer technology for developing such networks was concerned mostly with the acquisition of information to feed into the arguments. Information retrieval systems help the lawyer find precedents. Survey instruments and statistical packages help the market analyst quantify market forces. Computer-driven instruments line the benches of the physical scientist's laboratory. Such tools help find the facts upon which the arguments rest, but they don't help the reasoner invent, record, manage or modify the arguments themselves. For manipulating arguments, these professionals have had to rely on paper technologies, such as index cards and file folders, or their electronic analogs, text editors and file systems.

Recently, software aids have been developed for formulating and managing arguments. Most of these programs are combinations of text editors and databases. This paper concerns one such system, called NoteCards, which is being developed at Xerox's Intelligent Systems Laboratory. The paper reports the authors's experience in using the system. It discusses two incidents where using the system uncovered major flaws in the arguments. These discoveries were quite unexpected. The expectation had been that NoteCards would make argumentation easier, but not that it would change its quality.

This paper discusses these two incidents and trys to ascertain why a such a simple tool had such a profound impact and what the tool's future might be. The discussion and analysis is necessarily informal and even anecdotal at times. Such a treatment cannot, of course, substitute for careful experimentation. However, it seems worth reporting these incidents now because they raise certain interesting, non-obvious issues. This informal presentation of the issues may lay the groundwork for more formal studies.

The two incidents occurred a month apart. The second one is simpler to describe, so it will be presented first. Before that, a little background on my project is necesary.

Background

The project is to develop a psychological theory of how people learn procedures, such as arithmetic procedures, clerical procedures, or procedures for analyzing electronic circuits (see VanLehn, 1983a, for a synopsis). The main data are a large collection of systematic errors (called bugs) that were observed in

the behavior of 1147 elementary school students who were learning arithmetic. Most bugs can be explained more than one way depending on what hypotheses one makes about the learning process. The main job of argumentation is to contrast the explanatory power of various sets of hypotheses. Metaphorically speaking, the theorist takes several sets of hypotheses and sees how many bugs each can explain.

In practice, the argumentation does not contrast multiple *sets* of hypotheses. Instead, a divide and conquer strategy is used. The overall question — how are procedures learned? — is divided into a set of *issues*. Each issue has several alternative hypotheses to explain it. One starts with very general issues, such as "Do students learn from worked example exercises, or from analogies to familiar procedures, or from written descriptions of the procedure, or what?" Depending on which hypothesis wins the argument, more specific issues are formulated, e.g., "Given that students learn procedures from worked examples, how do they learn conditional branches?" (A conditional branch is a chunk of procedure of the form: If such-and-such then do X else do Y.) The relationship between issues, hypotheses and subissues will be discussed later in detail. The point here is only that instead of formulating a huge argument that contrasts whole sets of hypotheses, one considers a set of issues and for each issue, formulates an argument contrasting several individual hypotheses.

The two incidents of NoteCard-induced theory reformulation are complementary. One incident concerns the structure of *intra*-issue reasoning, and the other incident concerns the structure of *inter*-issue reasoning. To put it differently, the first incident concerns the structure of an argument about a single issue, i.e., how to compare several hypotheses and choose a winner. The second incident concerns representing the relationships between issues.

Intra-issue argumentation

NoteCards deliberately does not force an argument structure on the user. In this respect, it differs from ThinkTank and other outlining tools which force the user to employ a tree structure. This extra flexibility allows users to use multiple argument structures and to change their arguments from one structure to another. The incident to be described in this section was precipitated when the theory's arguments were converted from one format (a tree structure) to another (a matrix structure).

The NoteCards system is based on a simple idea: an electronic 3-by-5 card. The database is a set of "notecards." Figure 1 shows several notecards as the user normally sees them on the screen. A notecard has a title, which shows in the dark bar on the top of the card. The body of a notecard is text and/or graphics. All the notecards shown in figure 1 have textual bodies. A notecard's body may contain pointers. In the middle card of figure 1, there are four pointers. Pointers have labels. The label of the first pointer is "Remark," and the label of the second pointer is "Rebuttal." The other two pointers are labelled as well, but the user has chosen a display format for these pointers that does not show the labels. There are no contraints on the vocabulary of pointer labels: the user may create new labels at will. The destination of a pointer is another card. The destination of the first pointer in the middle card is the top card. The destination of the other three pointers is the bottom card. There are no constraints on the topology of pointers. A card can point to itself or any other card.

Insert figure 1 about here.

Each card is an instance of a WYSIWYG editor (what you see is what you get) that uses a mouse as a pointing device. When the user points at a pointer and clicks the mouse button, the card that is the destination of the pointer is fetched from the notecard database and displayed on the screen. This allows one to flip quickly through cards. Many other facilities are provided by NoteCards, but the preceding brief introduction will suffice for now.

As mentioned earlier, a change in the format of arguments led to uncovering flaws in the theory. The old format was a tree. Figure 2 displays such a tree as a schematic outline. This tree structure reflects a standard rhetorical structure. The format has the advantage that breadth-first traversal of the tree is an expositional sequence that makes sense. In fact, the original NoteCards database was constructed from a 328-page document (VanLehn, 1983b) whose expositional structure was a breadth-first traversal of the argument trees. That is, each chapter was a discussion of a single issue. A chapter began with a statement of the issue and a list of the competing hypotheses. Each of the remaining sections of the chapter discussed a single hypothesis, giving the arguments for and against it. The document had about 20 chapters, with three to seven hypotheses per chapter. Because the document was carefully structured and the NoteCards format was chosen to reflect this structure, it was easy to convert the document into a NoteCards database. It took only ten days.

Insert figure 2 about here.

The incident occurred while new hypotheses were being added to the theory. A certain issue already had four hypotheses. Three more hypotheses had been invented. Their empirical implications looked promising, although a little confusing. Putting the new hypotheses into the NoteCards system should have clarified which of the seven hypotheses was the best. However, the resulting tree structure did not make it much easier to tell which hypothesis was the winner. The actual empirical facts (i.e., bugs) dangled off the leaves of a bushy tree of notecards. A summary card was needed that would show the hypotheses and facts in a compact way. For each fact and each hypothesis, it should show whether the fact supported the hypothesis or not. The obvious organization was a Cartesian product (see Figure 3).

Insert figure 3 about here.

When the issue card mentioned above was converted to this matrix format, each of the seven hypotheses had its own row. There were six columns, one for each of the facts. However, not all the cells of the matrix were filled in. I had neglected to evaluate some of the hypotheses against some of the facts. The old tree structure made it easy to overlook such mistakes. The matrix format made them stick out as blank cells in the matrix. Not much research was needed to provide the needed evaluations and fill in

the blank cells, and yet, the results were quite surprising. All three of the new hypotheses turned out poorly. Of the four old hypotheses, the one that was thought best actually turned out quite badly. A previously rejected hypothesis turned out best. In short, sloppy reasoning, abetted by a poor rhetorical organization, allowed the suppression of a winning hypothesis. The new matrix organization uncovered the mistakes, leading to an improved theory.

This incident was not unique. Several reversals of the same kind occurred as the rest of the arguments were converted to matrix format. That these errors could remain undetected for several years is even more amazing when one considers how many people had read or listened to the arguments. The implications of this incident will be discussed after the second incident has been described.

Inter-issue argumentation

A common device in the argumentation is to use an independently motivated hypothesis to help defend one of the hypotheses under discussion. For instance, if A and B are competing hypotheses, and X is the winning hypothesis of some other issue's competition, one argues "X and A together predict F, whereas X and B predict not-F. Since F is empirically true, A is a better hypothesis than B." The argument for A assumes X. This is one kind of inter-argument relationship, the most common one. This inter-issue relationship was represented in NoteCards by having the argument cards for A and B have a pointer to X labelled "premise."

Explicitly representing inter-issue relationships was a major reason for converting the document to NoteCards. As the theory changed, it was important to know which arguments depended on which hypotheses. For instance, if hypothesis X is refuted by new evidence, then one must retract the arguments that have X as a premise. This was difficult given just the document. Although one could open the document to the section that describes hypothesis X in order to see the arguments for and against it, the document was not cross-indexed in such a way that one could find all the arguments that depended on X. NoteCards automatically provides such a cross-index. Attached to the card for X is a list of all the pointers that point to X. This cross-index makes it easier to revise the theory.

After a few weeks of theory revision, it seemed likely that these inter-issue pointers could provide a nice geometric summary of the theory as a whole. NoteCards can automatically construct, layout, and display a directed graph whose nodes are card titles and whose links correspond to pointers running between a pair of cards. This facility is called a *browser*. Similar facilities in programming environments have been found to be extremely useful in summarizing complex programs. It seemed likely that browsing the NoteCards database using the premise pointers would yield a helpful overview of the theory.

When an attempt was made to browse the database, an unexpected property of the argumentation was discovered: the graph created by the browser was disconnected. There were sets of issues that were totally unrelated to other sets. Intuitively, this shouldn't be so. Because the issues are all part of the same theory, they must relate somehow. The browser revealed that some essential inter-issue relationships had not been made explicit.

This touched off a examination of the epistemology of inter-issue relationships. It was discovered that important assumptions had been made without mentioning them anywhere. The assumptions were all of a certain kind: a large issue was decomposed into smaller issues. For example, the large issue "what is the student's mental representation of the skill they are learning," was decomposed into three smaller issues:

1. What is the representation of perceptual knowledge about the skill's environment, e.g.,
   - For the subtraction skill, a grammar for the multicolumn notation.
   - For algebra equation solving, a grammar for algebraic equations.
2. What is the representation of procedural knowledge, e.g.,
   - For subtraction, a procedure for writing and scratching out digits.
   - For algebra, a procedure for selecting algebraic transformations.
3. What is the representation of factual knowledge, e.g.,
   - For subtraction, a table of number facts such as 7-5 = 2.
   - For algebra, a table of facts such as "- is the opposite sign of +".

The division of task-specific knowledge into notational, procedural and factual knowledge was never mentioned explicity in the document. There were several such decompositions, none of which had been recognized in the document. The NoteCards system browser revealed that these decompositions were needed in order to complete the argumentation.

The obvious cure was to add a new type of notecard, called a decomposition, to describe the division. When this was done, it became clear that these decompositions were doing almost as much 'work' as the hypotheses. At that time, there were 36 issues; seven were handled by decomposition and 29 were handled by competitive argumentation among hypotheses. Clearly, these decompositions needed to be subjected to closer scrutiney. The best way would be to hold competitions among alternative decompositions. It didn't take long to figure out alternative decompositions to the seven original ones (which is significant in itself).

One of the new, alternative decompositions turns out to have very interesting properties. It is an alternative to the decomposition mentioned above. This decompostion is called the annotated grammars decomposition because it replaces two knowledge representations — the notational grammar and the procedure, which are parts 1 and 2 in the list above — with a unified representation called an annotated grammar. Whereas grammars, procedures and tables of facts are common representations in computer scince, annotated grammars are new. Although it is not worth explaining the techical details in this paper, it seems now that annotated grammars are a much better model of student's knowledge structures, even for the supposedly "procedural" skills of arithmetic! The annotated grammars decomposition is a major, and welcome, revision to the theory.

The discovery of the annotated grammars decomposition was provoked by an observed incompleteness in the argument structure of the theory. NoteCards made observing this incompleteness easy, and perhaps even inevitable. By the way, once the seven new decomposition issues were added to provide a home for the new decomposition competitions, the browser created a connected graph (see figure 4).

The titles with a "<" suffix label the decomposition issues. Without them, the graph would be quite disconnected.

Insert figure 4 about here.

Discussion

Paper note cards have been used for decades for organizing arguments, although I did not happen to use them in developing my theory. Although NoteCards may be faster and more convenient than paper note cards, but is there any reason to believe that NoteCards encourage better quality argumentation than paper note cards? That is, would the incidents just described have happened if I had used paper note cards instead of NoteCards? There are several reasons to doubt that they would have. First, because paper note cards are three-dimensional objects, the easiest way to implement scratch organizations of paper note cards is to arrange them spatially. However, when there are more than about 100 note cards, this gets cumbersome. (Incidently, there are about 800 NoteCards in my database.) When there are many paper note cards, it is inevitable that they are arranged spatially along their thinest dimension: they are filed in a file box. The most complex topology that can fit in a single dimension is a tree. Paper note cards encourage dendralic organizations, unless the person is working with a small number of cards. In short, when one is fooling around with various scratch organizations, paper note cards don't encourage one to search the whole space of possible organizations. To put it more parochially, I doubt that I would have tried a matrix format for arguments if I had been using paper note cards. Consequently, the theory would still contain many flawed arguments.

There is no doubt that NoteCards encourages one to "fool around with scratch organizations." Is this good? I will argue that it is, by using an analogy to text editing. One often-heard complaint about modern text editors is that they encourage writers to fool around with the format of the text, and thus slow the document preparation process down. That is, writers get too engaged in making their document look pretty. Not only that, many writers are bad at it. Their documents are uglier and harder to understand than documents that are professionally typeset. The complaint goes on to suggest that writers should either be trained in how format text quickly and effectively, or they should leave text formatting to those who are trained at it. Superficially, there seems to be a analogy here to NoteCards, which encourages thinkers to explore organizations of their arguments. The analogy says that fooling with argument organizations will just waste the thinker's time. Someone else should do it. However, there is no cadre of professional argument-organizers who are the analogs of printers and graphics designers. Nor can there be such a cadre. The organization of arguments is too strongly coupled to their content. In contrast, the format of text is weakly coupled, so professional text formatters can and do exist.

Put another way, argumentation has an organization whether one likes it or not. (Likewise, text has a format, like it or not.) Someone has to give the arguments a good organization. And that

someone must be the thinker who is responsible for the argument's content. In short, exploring argument organizations is a necessary activity, not a waste of the thinker's time.

Notecards encourages a particular kind of exploration. To see this, let's compare the process of organizing arguments using NoteCards with the same process using paper note cards. With paper note cards, a spatial organization is external to the content of the note cards. You don't have to change what the card says in order to move it from one file to another. On the other hand NoteCards' browser is driven by the *content* of the cards, namely the pointers that are part of their texts. To reorganize a browser, you must change the cards' content. To put it differently, NoteCards' organizations are *emergent properties of the content of the arguments*; they are not imposed from the outside. In retrospect, both the tree organization that I used for my arguments in the document and the list-like chapter structure were external organizations. They were so decoupled from the content of the arguments that I was able to fool myself (and the readers!) into believing that more was shown than actually was shown. Notecards' emphasis on emergent organizations makes it harder to fool oneself.

Perhaps the hardest job that a theorist has is to discover the assumptions that he or she is making. Goodman (1955) has pointed out, in connection with his famous Grue-Bleen example, that important scientific assumptions may hide in the very vocabulary one uses to think about the theory. Uncovering such assumptions is so difficult that any aid, even indirect aid, would be welcome. NoteCards seems to provide such aid. At least, it helped me uncover a class of assumptions, namely the decomposition issues, that lay deeply buried in the technical vocabulary of computer science and mathematics. The discovery of the annotated grammars decomposition is a case in point.

What happens to a NoteCards database eventually? *Mine is too big to publish, even as a book.* One wonders if it is worth the effort to type in all those NoteCards when all one can hope to gain is a better theory (as if that weren't enough!). There are several answers, ranging from mundane to futuristic. First, it isn't all that much typing. It took only ten days to get my database started. Second, NoteCards has facilities for stringing together cards into a single document. Thus, with a little extra effort, one can obtain a rough draft of a paper, or perhaps several papers.

On a more personal note, I find that NoteCards falls into a natural nitch that is midway between publications and lab notes. Publications have to be carefully worked over to be both an accurate, consistent presentation of the theory *and* an understandable one. On the other hand, lab notes are private memoranda, where ideas are worked out in rough. One's recent lab notes are often based on assumptions that contradict earlier lab notes, reflecting the process of theory revision. As a whole, lab notes are inconsistent and sometimes vague, and lack the expositional "sugar" of publications. The NoteCards database is an accurate, consistent presentation of the theory, but a private one that need not have expositional sugar. Metaphorically speaking, it represents the integral over time of the lab notes. All the contradictions, reversals, and dead ends are removed.

To see why this is important, consider an analogy. Suppose a computer scientist builds a program and a mathematician builds a proof. Both the program and the proof can be accurately represented in writing. However, the typical publication doesn't print the program or proof, but only the key ideas and a discussion. Nonetheless, constructing the program or proof is a methodological necessity because it

allows one to clarify the ideas and make them rigorous. On a deeper level, it may be important to have a concrete embodiment (i.e., a written one) of the program or proof as an aid to thinking about it. Now for the analogy. A theorist builds a theory, and the publications discuss it, just as a computer scientist builds a program and the publications discuss it, or the mathematician builds a proof and the publications discuss it. But unlike programs or proofs, a theory usually has no accurate, written representation. That is, until NoteCards and its ilk were developed. The NoteCards database is about as close as any written artifact can get to expressing a whole theory. If the analogy holds, then we can expect NoteCards to help theorists clarify their ideas and make them rigorous. Moreover, the NoteCards database should serve as a concrete embodiment of the theory. This last feature seems particularly important to me. Nowadays, I view my work as building a NoteCards database *qua* theory. To theorize without building a NoteCards database seems like programming without building a program. One can do it, but it's harder.

Because NoteCards databases are accurate representations of theories, they have excellent potential as vehicles for collaboration. Moreover, because the user interface lies somewhere between a blackboard and a text editor, NoteCards may augment or replace them as the customary focus of a collaborative theory-development effort. It is easy to imagine two people in different cities both editing the same NoteCards screen while the talking over the phone.

Being halfway between lab notes and journal articles may also make NoteCards a unique aid to graduate-level teaching. A Notecard database would allow young theorists to crawl around inside a classic theory, getting to understand it more deeply than they could from journal articles. Incidentally, this is one answer to what could happen to NoteCard databases after their active development ceases. They might rest in graduate schools, embalmed in computational display cases for students to dissect.

The last comment should be that NoteCards is only a beginning. One can imagine many facilities that could be added to it to make theory development even better. For instance, a truth maintenance system (de Kleer, in preparation; Doyle, 1979; McDermott, 1983) would make it easier to revise the theory. When a hypothesis changes from winning to losing, the TMS would automatically retract all the arguments that depend on it. That may, in turn, cause other hypotheses to lose their support and become losers. Currently, such propagation is done by hand. Adding a TMS to NoteCards is just one example of how automatic inferencing techniques could be imported from Artificial Intelligence. NoteCards is a first step on the path towards a theoretician's workbench that is a synergistic combination of hypermedia and artificial intelligence.

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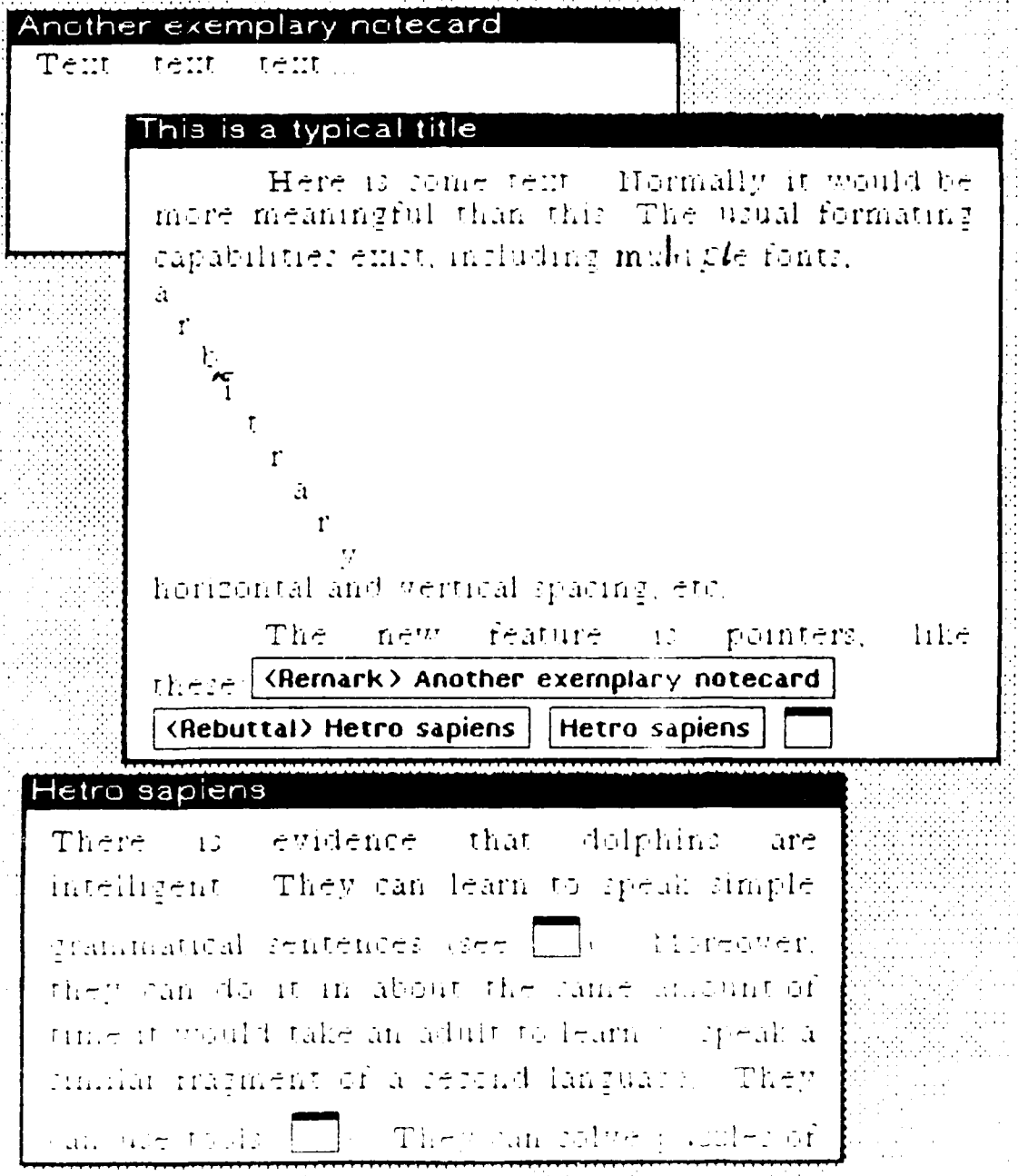

Figure 1

Examples of notecards

I. An issue: something that the theory must take a stand on
    A. Hypothesis 1
        1. Pro
            a. an argument in favor of the hypothesis 1
                i. an empirical fact used in the argument
                ii. another fact...
            b. another argument in favor of hypothesis 1
                i. an empirical fact...
        2. Con
            a. an argument against hypothesis 1
                i. an empirical fact used in the argument
                ii. another fact...
            b. another argument against hypothesis 1
            c. another...
        3. Moot
            a. an argument that bears on hypothesis 1, but is not decisive
            b. another such argument
    B. Hypothesis 2
        1. Pro
            a. an argument in favor of the hypothesis 2
            b. another argument in favor of the hypothesis 2
        2. Con
            a. an argument against hypothesis 2
            b. another...
        3. Moot
            a. an argument that bears on the hypothesis 2, but is not decisive
            b. another such argument
II. Another issue....

Figure 2
An argument tree, displayed as an outline.

There is one notecard for each issue, one for each hypothesis, one for each argument, and one for each empirical fact. The issue notecard points to the relevant hypothesis notecards (e.g., for the above tree, card I would point to cards A and B). Each hypothesis notecard points to the argument notecards that concern it. An argument notecard points to the facts that it references.

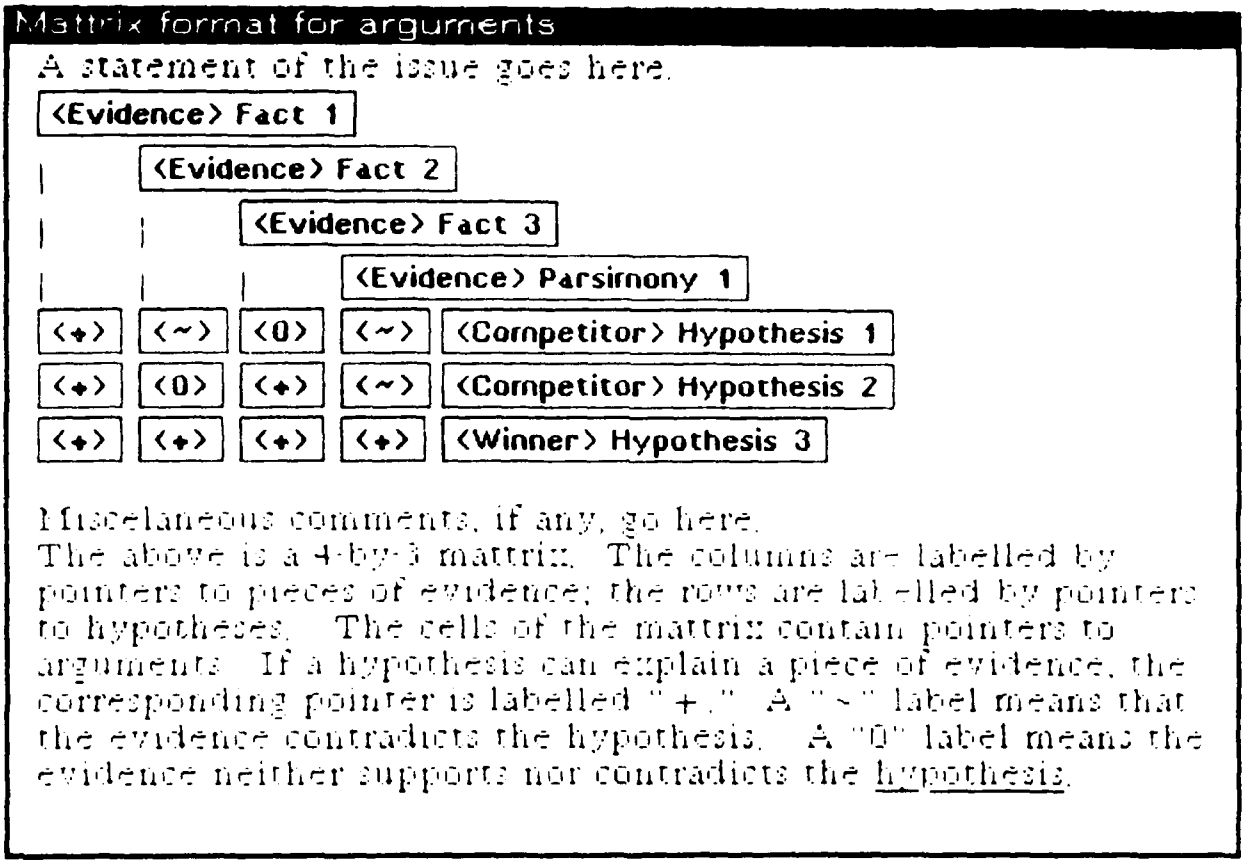

Figure 3

A Cartesian product notecard

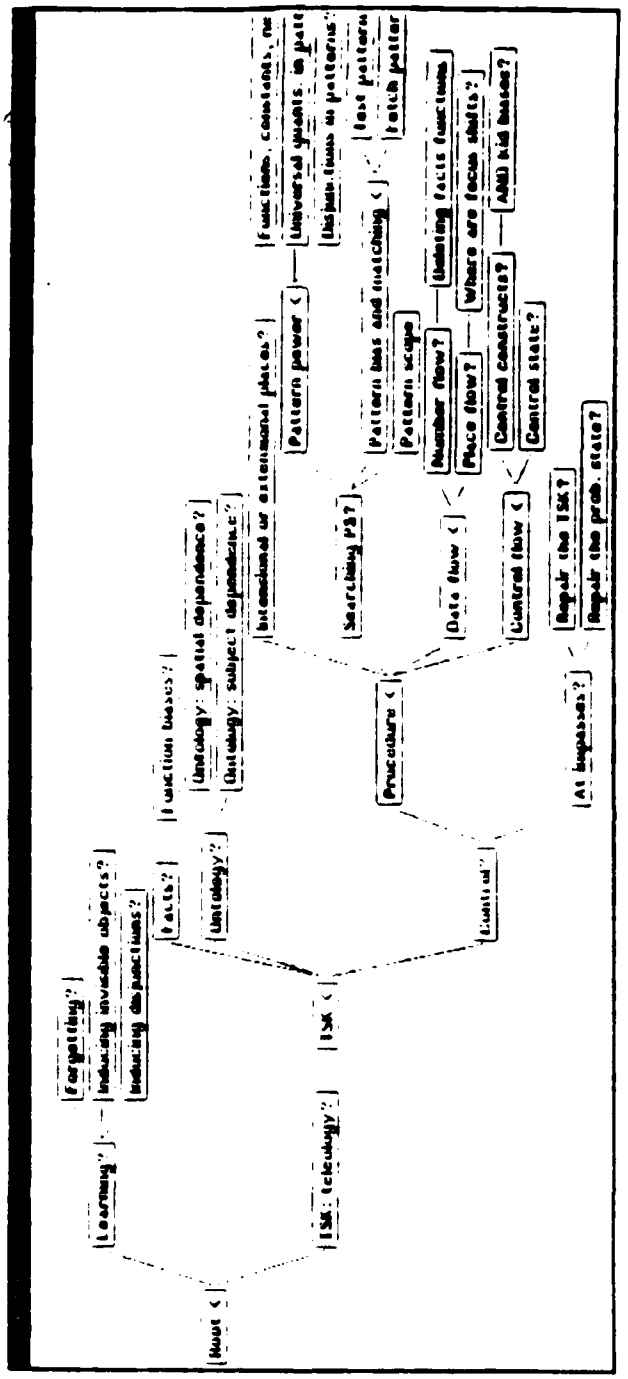

Figure 4

A browser notecard

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