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ABSTRACT

A 2-year study of optimal structures for multimedia instruction is being conducted to provide experimentally validated guidelines for the design of computer-based instruction generation systems and for human instruction in a multimedia setting. In order to obtain for analysis a significant range of the possible discourse structures that occur in instruction, the project's first phase elicited explanations of a demonstration device from experienced community college engineering instructors. The outcome of this phase was a set of variables and a set of hypotheses about relationships among variables that lead to effective instruction. The project's second phase will test these hypotheses on groups of students. Four major results were achieved in the first phase: (1) the development of a framework for discussing optimal discourse structures and/or visual presentations in multimedia instruction, based on the notion of a mapping between semiotic systems; (2) the discovery that the command and control speech act chain is used in "hands-on" instruction; (3) the development of a rich set of experimental hypotheses; and (4) a demonstration of the viability of a methodology combining linguistic analysis with experimental research. This report describes the first year's work, with sections on discourse analysis, semiotics, other analytic concepts, and project variables and hypotheses. Also presented are appendices on project methodology and the grammar of the command and control speech act chain, a 34-item bibliography, and a report distribution list. (ESR)

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# OPTIMAL STRUCTURES FOR MULTIMEDIA INSTRUCTION

Annual Technical Report

January 1984

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The aim of this project is to provide experimentally validated guidelines both for the design of computer-based instruction generation systems, and for human instruction in a multimedia setting. Potential applications for this research include multimedia output capability (e.g., graphics output plus audio, using speech technology) for automatic instructional systems and for onboard fault diagnosis systems, as well as the improvement of traditional classroom instruction.

Four major results have been achieved so far: (1) a framework for discussing optimal discourse structures and/or visual presentations in multimedia instruction, based upon the notion of a mapping between semiotic systems, as discussed in Section 3.4; (2) the discovery that the command and control speech act chain is used in "hand-on" instruction (our structure theory of this discourse type is given in Appendix II); (3) a rich set of experimental hypotheses, given in Section 6; and (4) a demonstration of the viability of a methodology combining linguistic analysis with experimental research.

# Table of Contents

# List of Figures

# Optimal Structures for Multimedia Instruction[1]

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SRI International and Structural Semantics

## 1 Introduction

This report describes the first year's work in a two year study of optimal structures for multimedia instruction. The project has two phases. The first phase elicits experienced instructors' explanations of a demonstration device, in order to obtain for analysis a significant range of the possible discourse structures that occur in instruction. The outcome of this phase is a set of variables, and a set of hypotheses about relationships among them that lead to effective instruction. The second phase will test these hypotheses on groups of students.

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[1]We would like to thank Marshall Farr and Henry Halff, of the Office of Naval Research, for helping to conceptualize and focus this project, and our consultants Tora Bikson and James Weiner for their suggestions and help throughout the work.

### 1.1 Method

This research concerns instruction, particularly mixed media explanation, involving for example, language, diagrams, and demonstration equipment. The approach draws from linguistics (specifically, discourse analysis), experimental psychology, and philosophy (specifically, semiotics). The purpose of this subsection is to provide enough information on what we are doing so that the reader can follow the explanations and examples below. Most of this subsection concerns the Phase I experiments already completed. See Section 4.1 and Appendix I for some further details, especially regarding our Phase I pilot experiments and our plans for the rest of the project.

#### 1.1.1 Task

Instructors are given a "logic box" having four lights and two switches (see Figure 1). Each light realizes a different logical function of the two switches. (Note that there are sixteen such functions, of which just four are realized in the actual box.) Instructors are also given a blackboard with colored chalk. Their task is to explain to students how to use the logic box; students are to set the switches so as to achieve some given configuration of lights. After several trials, we developed the following approach: Students are told that they are being trained to control an irrigation system producing a continuous flow of fertilized water, and that each light indicates whether or not a certain fertilizer is being mixed into the current product. Their job will be to set the switches, upon receiving a telephone call describing the desired mixture.

The explanations elicited from instructors in this way are then subjected to formal linguistic analysis, to identify significant variables and to formulate interesting hypotheses about the relations between the form of the instruction and subsequent performance by students. The most suitable of these hypotheses will be tested in Phase II to determine which instructional structures have the most favorable effects on learners' performance.

This task was chosen because it can be presented by instructors using a wide variety of media mixtures (e.g., spoken language and written language; charts, equations and diagrams on the blackboard; and direct use of the demonstration device) at several different cognitive levels (including concrete operational and abstract Boolean algebra; see Section 4.1). Moreover, it is fairly easy to design and score instruments to test the effectiveness of a given instructional

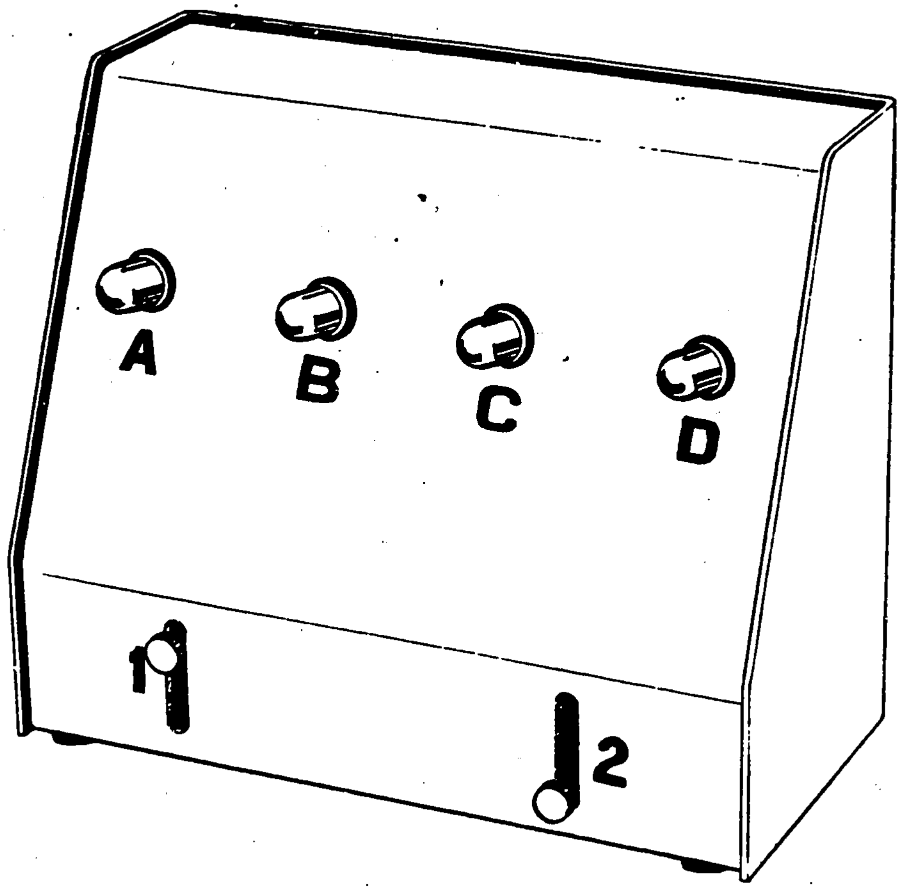


**Figure 1:** The Logic Box

technique using student comprehension as a dependent measure. Although the task that we have chosen may seem relatively simple, in fact instructors exhibited surprising variability in its performance; in addition, it is typical of subtasks of larger instructional tasks, and we believe that the results obtained from its analysis will generalize to far more complex situations.

### 1.1.2 Procedures

Subjects were instructors from the Engineering Department of a local community college. Before the instructional session began, one of the experimenters presented the logic box instruction task to the instructor; the logic box itself was explained to instructors using a circuit diagram, with the remark that this would probably not be an appropriate explanation for students. This leaves the instructor free to determine a more concrete level of description for the students. In the first two experiments, the instructor had an audience of community college students with little or no previous exposure to engineering subjects. (This population is similar in background and age to most novices entering technical training programs, such as in the Armed Forces.) The experimenters played the role of students in subsequent experiments, since the students' questions proved to be insufficiently focussed to elicit the desired range of responses.

Five instructors were used as subjects in six experiments. This series of experiments increasingly refined our experimental technique. All experiments were recorded on audio tape and then transcribed, yielding a total of 124 pages of transcript for the instructor briefing and subsequent instructional session. (There are also debriefings for students and/or instructors for some sessions.) Each such session lasted between one-half and one hour. The first two experiments used the same instructor, and also used groups of community college students as an audience, 4 students in the first and 5 in the second.

### 1.1.3 Results

Analysis of this corpus resulted in the theory given in Section 4, the variables given in Section 5, and the hypotheses given in Section 6. In addition, we discovered that our theory of the command and control speech act chain [Structural Semantics 83] was directly applicable to the structure of hands-on instruction; see Section 2.6 and Appendix II. Finally, we became convinced of the necessity to study the visual component (as discussed in Section 1.2) and were inspired to begin a systematic study of optimal representations based on semiotics (see Section 3.)

## 1.2 The Visual Component of Explananation

Our research to date, and indeed most research on explanation, has concentrated on the analysis of the verbal component, since this appears to be the dominant component, controlling many aspects of those other modalities that may be present. However, we have now found that it is necessary to analyze the visual component as well as the verbal. This subsection discusses some reasons for this, and some probable practical results.

### 1.2.1 Indications of the Necessity for Study of the Visual Modality

We had initially decided not to use video in these experiments, since it is well known that video analysis is a difficult and lengthy process. However, our pilot experiments have made it clear that some of the most theoretically interesting and practically important issues, such as the interaction between linguistic and visual modalities and the reasons why some visual materials are more effective than others, can only be studied using video-taped data.

1. **The Ubiquity of Diagrams.** In our instructions to instructors, we indicated that if they wished, they could use the blackboard. All five instructors made significant use of both the blackboard and the demonstration device, and also employed a variety of referring expressions in oral explanations, such as **it, this one, that one** [illegible] **the bottom case** (referring to the last row of a table). It is difficult or impossible to understand the meaning of such expressions without video.
2. **Visual Deixis.** One of the most important problems in linguistic theory is reference and the accomplishment of reference. This problem becomes additionally complicated when reference can be accomplished not only with referring expressions, but also by means of visual deixis -- pointing, gaze direction, etc. In a subject domain in which a considerable amount of the material to be conveyed is in visual form, visual deixis becomes so important a form of reference that it must be studied in order to understand the mechanisms of communication.
3. **Anomalies in the Visual Modality.** Our current research has revealed a number of interesting anomalies or errors in the construction of diagrams. One such anomaly is the case of a subject who made visual reference to parts of the diagram by pointing to its parts, *before* he drew the diagram on the board. (Our experience of lectures, classroom explanations, etc, indicates that this practice is more common than might be believed.) Another interesting case is that in which the diagram differs from the verbal explanation -- either because the diagram is incorrect, or because the explanation is incorrect. It seems clear that these unfortunately fairly common types of error must have a considerable effect on learning. In addition to this fairly obvious hypotheses, it would also be of great interest to see whether these types of error are themselves dependent on some other variables in the communication situation.

### 1.2.2 Practical Reasons to Study the Visual Modality

In addition to these considerations from the experiments already performed, there are also strong practical reasons for studying the visual modality. The first is that the relation between the verbal material and the visual models should yield a number of hypotheses which would be easy to test, and which would be rather general in scope. In addition, such hypotheses should lead to valuable suggestions for training in multimedia instruction, since it is known that most people, including most instructors, receive no training in the production and use of effective diagrams, visual models, etc.

### 1.2.3 Theoretical Basis of the Study of the Visual Modality

Linguistics provides a wealth of techniques for the analysis of spoken language, but unfortunately there is no comparable body of theory for the analysis of graphical or mixed media data. We found that, while semiotics does provide a good starting point, it lacks a theoretical framework for describing systematic ways of representing signs from one sign system with signs from another system (e.g., representing states of the logic box by rows of a table on a blackboard). This led us to develop the notion of a "semiotic morphism" described in Section 3.4. Now that this theory is available, we are able to design experiments especially suitable for collecting video data, and in Phase II, we will perform at least two such experiments before moving on to testing hypotheses about which representations and structures have the most favorable effects on learners' performance. The experiments of Phase II will involve showing instructional videotapes constructed according to specific principles to groups of experimental subjects, and then administering a single post-instructional instrument.

## 1.3 Related Research

The present study has connections with many other projects in cognitive science, psychology, and artificial intelligence. Part of our analysis is to understand the conceptual structure of the task and the task domain. This is similar to [Stevens & Steinberg 81, Stevens & Collins 80, Gentner & Gentner 82], which provide conceptual models for complex knowledge domains and the possible explanations that can be given of them. Similarly, [Kieras 82, Kieras & Bovair 83] study the organization of knowledge schemas for electronic devices and the effects of different mental models on how to operate such devices. An early important study in this area is [Grosz 77], which established the hierarchical nature of peoples' knowledge of task domain structure for problems like water pump repair.

The present study differs from these preceding studies in emphasizing structural analysis of both the semantics and the syntax of interaction, particularly explanation. We find that complex communicative situations involving multiple semiotic systems cannot be analysed intuitively or on the basis of our knowledge as members of the culture; thus formal, theoretically-based analysis is required.

Many additional references are given in the body of this report in connection with specific topics such as semiotics.

## 2 Discourse Analysis

This section reviews some of the concepts, theories, and techniques from linguistics that are used to analyze the explanations elicited, in order to provide specifiable and quantifiable data for further research. We first discuss the basic notions of discourse unit and discourse type, and the kinds of rules that apply to them, and then discuss the known discourse types found in our data, mentioning some particularities that these discourse types exhibit in instructional discourse. Many of our examples are taken from the study of aircrew communication [Structural Semantics 83] since the complete range of examples is not yet available for instructional discourse at the present stage of research.

### 2.1 Discourse Unit and Discourse Type

Discourse analysis, the study of linguistic units larger than the sentence, is used in this study because it appears that the discourse unit, rather than the sentence, the word, etc., is the linguistic level of greatest significance in effective instruction. Specifically, we have found that reasoning, pseudonarrative, and the command and control speech act chain are the most relevant discourse types in our data. These are respectively discussed in Sections 2.3, 2.4 and 2.5 below.

A **discourse unit** is a segment of spoken language, composed of one or more sentence, having socially recognized initial and final boundaries, and a formally definable internal structure. (This definition generalizes the criteria given by [Labov 72] for the narrative of personal experience.) Other discourse units that have been studied include pseudonarratives, specifically spatial descriptions [Linde 74, Linde & Labov 75], plans [Linde & Goguen 78], jokes, and explanations [Weiner 79, Goguen, Weiner & Linde 81]. It is rare that an entire discourse unit consists of a single sentence; more often, it appears as a several sentences, a question-answer pair, a question-answer-evaluation triple, etc. A **discourse type** is a *theory* of the structure of a class of discourse units, that is, it provides a way of recognizing whether or not a given segment of language is an instance of the type. Thus, we can think of a discourse type as the class of discourse units that satisfy a given theory. This corresponds to the familiar distinction between type and token.

Discourse analysis studies the structure of discourse types. In order to apply it to the question of how people actually use discourse units, there are a number of further requirements on how the research should be conducted, and in particular, on the descriptions to be used for the discourse units involved. First, the work must based upon a careful empirical analysis of actual human discourse in natural situations. This means in particular that we cannot use invented examples to develop our theory (although such examples could be used to illustrate it). Secondly, it is necessary to have a mathematically precise description of the discourse structures of interest. Without this, we cannot properly test hypotheses involving variables that refer to discourse structure. Third, a suitable theory must also provide a simple and natural taxonomy of the parts that can occur in a given type of discourse, and of how these parts relate to one another. Each of the discourse types that has been studied has certain characteristic parts, and also certain characteristic relationships of subordination among these parts.

For example in reasoning, one statement may be subordinate to another statement by the relationship of providing a supporting REASON, as in the following example, where the second statement supports the first.

(1a) If your memory is short, the best thing to do is to construct a table

(1b) so that you know exactly what what the output would be.

Other kinds of subordination that can occur in reasoning include a subordinate statement serving as an EXAMPLE (i.e., an instance) of a statement, and several statements serving in conjunction or disjunction, supporting the same statement. There is also ALT subordination, indicating that two subtrees represent alternate possible worlds.

Such an organization of discourse units into parts that are connected by relationships of subordination is easily and naturally represented by a **tree structure**. This offers a convenient, graphically suggestive, and mathematically precise way to represent hierarchical subordination. In this representation, the top node represents the whole discourse, and its immediate subordinates represent the first subdivision into parts. For example, in reasoning the top node is a STATEMENT/REASON node indicating a division into two major parts, the first a statement of the proposition to be established, and the second a structure of propositions supporting this statement. Labels on nodes distinguish the different kinds of subordination that occur; these labels are called **subordinators**. Such a labelled tree structure closely resembles the tree structure of a mathematical proof of the assertion at the STATEMENT subtree of the root.

A fourth feature of discourse that an adequate theory should model is the construction of discourse units in *real time*. For this purpose, it is necessary to have a notion of the present focus of attention, in order to be able to indicate to what previous part a new part is to be subordinated, as discussed in the next subsection.

### 2.2 Transformation and Focus of Attention

The real time aspect of discourse is especially important for any study of the interactive *use* of language. The process of discourse construction is modelled by **transformations** on the tree structure that represents the discourse structure. Such transformations can add, delete, or alter a discourse part. It is particularly important within the instructional context to have a formal description of such processes, since they represent important variables of instructor-student interaction and of instructor self-correction.

For example, Figure 2 shows the transformation that constructs a tree representing a text of the form `S1 since S2` as in Example (1a-b) above. It begins with S1, **`If your memory is short, the best thing to do is to construct a table`** which is then subordinated by a STMT/RSN node as the transformation adds the statement S2, **`so that you know exactly what what the output would be`** supporting S1.

Transformations are very familiar in the literature of linguistics [Chomsky 65]. However, they are most commonly applied to the structure of sentences, rather than to larger discourse structures. Also, such transformations have not been used to model the real time construction

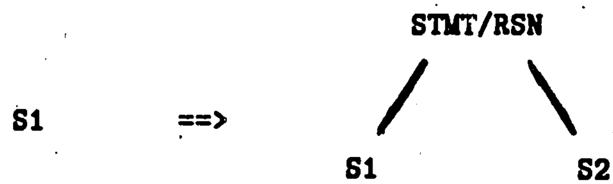


**Figure 2:** A Simple Transformation

of syntactic structures, but rather have been postulated as part of an abstract mechanism for generating syntactic structures.

The **focus** of a discourse represents the presumed focus of attention of the participants at a given point in a discourse; it might be described intuitively as "where we are now." Graphically, we represent the current focus as a "*" at a particular node on the tree.[2] [Grosz 77] discusses a notion of focus that is primarily semantic and is useful for resolving pronoun references; it involves a hierarchical structure of "focus spaces" that is similar to the use of embedded pointers in our theory.

There is one very important connection between focus and transformations, a constraint on how discourse structure can be built up in real time: a transformation can be applied *only* at the node currently in focus. This constraint on the application of transformations corresponds to speaker's and hearer's expectations about what will occur next. In particular, a transformation cannot be applied to a part of the tree developed earlier without first moving the pointer back to the appropriate subtree. Some transformations, in fact, only accomplish pointer movement, i.e., they just change the focus of attention, and thus do not add any semantic content to the tree.

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[2]Actually, more than one pointer is needed for some transformations [Goguen, Weiner & Linde 81]. We have found constructions in explanation much like those called "parallelism" in classical rhetoric, where there is not only an active node of focus, but also a passive node; in these constructions, some transformations reverse the active and passive nodes, so that addition can proceed alternately among two subtrees. Markers such as "on the other hand" are used to switch to the other subtree. There are even cases where more than two pointers are needed; for example, if one parallel construction is embedded within another. However, such constructions can be quite difficult to understand, and we have not found them in instructional discourse.

This general theory of the structure of discourse types is the basis for the particular theories of reasoning, pseudonarrative, and command and control speech act chain present in our data. We now turn to the first of these.

**2.3 Reasoning**

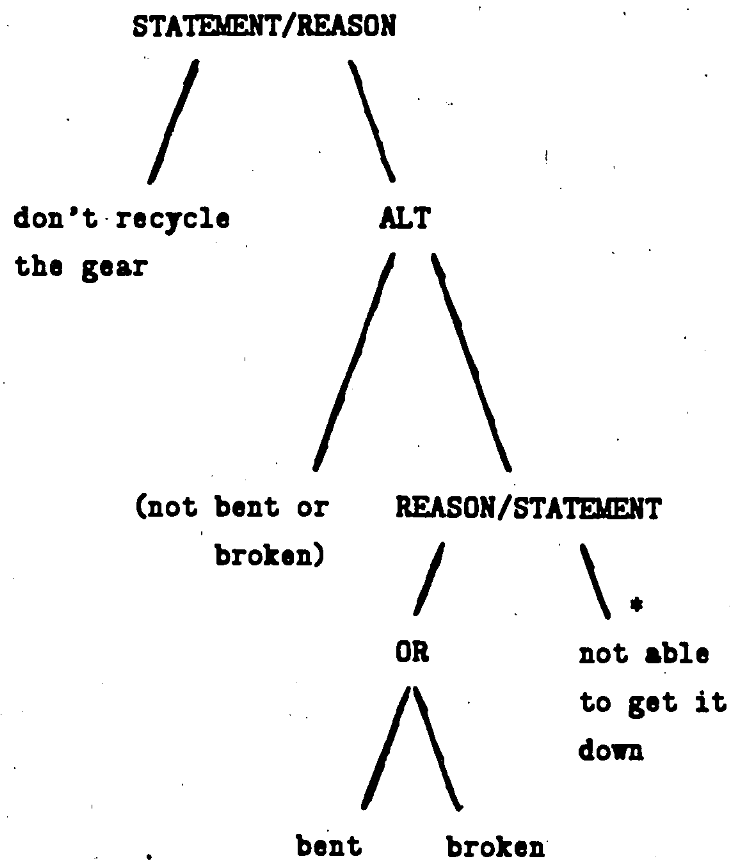
Reasoning (called explanation in some previous studies) is the most frequent discourse type found in instructional discourse, and has been studied previously using accounts of income tax decisions, career choice, and the probable effect of taking certain political decisions [Weiner 79, Goguen, Weiner & Linde 81] as data. In the current study, we call this discourse type **reasoning** and reserve the term **explanation** for a broader social function. This social function of explanation can be accomplished by many discourse types including reasoning, narrative, pseudonarrative, and planning. For example, a question like **Why are we learning this?** might be answered with a pseudonarrative about the mixtures of fertilizer, or with a reasoning structure to show that a correct approach is being taken. Either of these could function as an explanation.

Figure 3 shows an analysis of a simple instance of reasoning from the domain of aircrew communication in which the flight engineer reports his justification to ground control of the decision not to recycle the landing gear after an initial attempt to bring the landing gear down has failed.

The most important relationship of subordination in reasoning is indicated by the STATEMENT/REASON node. In the reasoning structure displayed in Figure 3, the main STATEMENT is **Don't recycle the gear**. Everything that follows is a REASON supporting this. The ALT node represents the speaker's postulation of two alternate worlds, differing by whether or not the landing gear is broken. This ALT node is established by the underlined portion of (2). (The number in parentheses refers to the time in the flight recorder transcription of the United Airlines flight 173 crash near Portland Oregon on December 28, 1978; this convention is also used in subsequent examples taken from the same flight.)

> (2) **...we're reluctant to recycle the gear for fear something is bent or broken.** (1752:16)

The phrase **for fear** indicates indicates both the uncertainty about whether the gear is bent, and the decision to treat the alternate world in which it is bent as the one on which attention




... we're reluctant to recycle the gear for fear something is bent or broken, and we won't be able to get it down
(1751:16)

**Figure 3:** A Reasoning Tree

is focussed; in fact, the world in which the gear is *not* bent or broken is only implicit in the text of this example.

Figure 4 shows the node types found in reasoning, including EXAMPLE, which is not present in the example of Figure 3. An EXAMPLE node takes as its subordinates one or more examples of a statement.

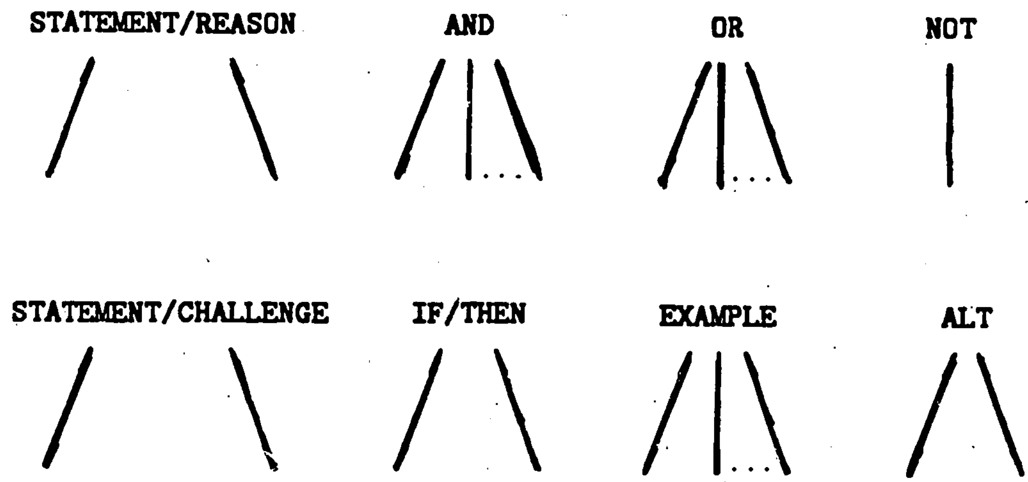



**Figure 4:** The Subordinators Found in Reasoning

### 2.3.1 Summary Nodes in Reasoning

Although we found that the theory of reasoning structure developed in [Goguen, Weiner & Linde 81] applies to the units of reasoning in the current dataset of instructional discourse, we also made one addition that is very helpful. This is a new branch type, called SUMMARY, that subordinates capsule descriptions or summaries; the symbol $\Sigma$, Greek sigma, is used to label these branches. Nodes that involve this new kind of branch include $\Sigma$/STATEMENT, STATEMENT/$\Sigma$, $\Sigma$/STATEMENT/$\Sigma$, STATEMENT/REASON/$\Sigma$, and $\Sigma$/REASON/STATEMENT. Some hypotheses concerning the placement and structure of summary branches are given in Section 6. (3) is a typical example of reasoning, and contains several summaries. It is a response to a student's complaint that previously given explanations were too simple.[3]

(3) You can get a little more complicated. Like you can think about what the individual lights do. One of the interesting things with this one, it doesn't depend upon this switch at all. Like to see [inaudible] Switch Two. So if it's off when

[3] The reader unfamiliar with transcriptions of spoken language may find (3) incomprehensible. It is, however quite characteristic of spoken data. It is immediately comprehensible when heard on the tape; with practice, the written version of such data becomes familiar and accessible.

> **Switch Two is down, it's on when Switch Two is up, independent of what happens with Switch One. So, Switch Two controls light C. You know, let's see, what's another one? I think D says that the two switches are the same ... so if they're both down or both up, D is on, but, if they're different, D is off. I think A, if I remember right, A is, is th-, no B is that they're both down. Uh, in any other position B is off. And then there's a more complicated one. What was that? If A's, A says that it's not anything other than One up or Two down, then it's on. Then that's off. It gets a little bit more complicated when you explain it that way.**

The structure of this reasoning unit is shown in Figure 5. Notice that two nodes of this structure have summary branches; the top (root) node actually has two summary branches, one given before the body of the explanation and the other given after it. The body of this reasoning unit consists of an AND that subordinates four reasoning sub-trees, one for each light on the box. A summary is given after the first of these sub-trees. It is interesting to notice that the order in which the lights are considered is here not their physical order on the box (which would be A, B, C, D, going left to right); rather, the lights are discussed in order of increasing psychological complexity (although not based on any firm evidence, this order appears to be C, D, B, A; using the convention that Sn is the predicate "switch n is up," C is just "S2", D is "S1=S2", B is "(not S1) and (not S2)," and A is "S1 or not S2."). Two semiotic systems that are involved here are (1) the system of things that are observable about the lights, and (2) the discourse system in which these observations are explained. This example is suggestive for Hypothesis 6 in Section 6, that optimally comprehensible explanations do not preserve relations (such as ordering by complexity) at the expense of basic constructors (in this case, the physical placement of lights). Discourse elements are ordered by the time of their production; and the lights can be ordered either by the complexity of their logical functions, or by their physical placement. The explanation would have been more comprehensible if the physical ordering had been used.

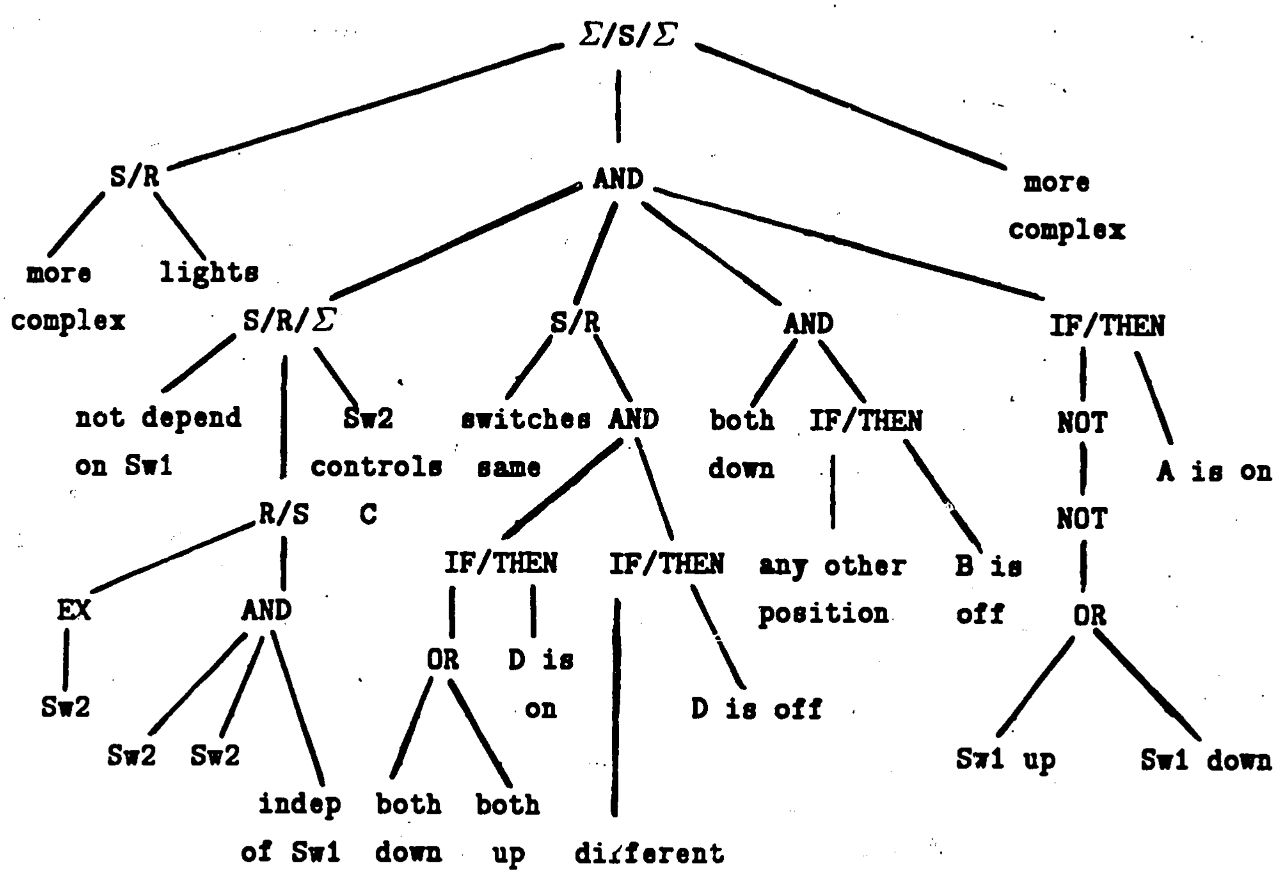



**Figure 5:** Structure Tree for an Instance of Reasoning

### 2.4 Pseudonarrative

In addition to reasoning, instructional discourse also contains a number of instances of pseudonarrative. Pseudonarrative is a discourse type having some but not all of the characteristics of spontaneous oral stories, the discourse type of which is called **narrative**. Like narrative, pseudonarrative relies on the **narrative presupposition**, the rule of interpretation stating that the order of main clauses is to be taken as the order of the events that they describe. Also like narrative, The pseudonarrative type permits optional initial summaries, closing evaluations, and end markers. The difference is that narrative consists of past tense main clauses, referring to actions understood as actually having happened, whereas **pseudonarrative** refers to hypothetical, potential, or habitual actions. (4) is a pseudonarrative from the data of the current study. The reader may be note a lack of redundancy in this example; however, some redundancy is provided by the preresence of a diagram on the blackboard summarizing the same material.

> (4) **We'll go through it again slowly. O.K. In one position of these two switches, where One is up and Two is down, all these lights are off. We take Switch One and move it to its other position, three of the lights come on. We reverse this combination and make them both go up, we got again three of the lights are on but a different three lights. And, if we move em till both down, again, we got three lights on but these two lights are changed over.**

Note the narrative structure imposed by the use of the personal pronoun **we** and the active verbs **go, take, move, make**, indicating actions rather than states.

Pseudonarrative has previously been studied in the domain of apartment layout descriptions [Linde 74, Linde & Labov 75]. In this domain, speakers commonly use pseudonarrative structure to convert spatial organization to temporal organization. It was found that they used a spatial organization far more frequently than a temporal organization, and made far fewer errors in the temporally organized descriptions, suggesting that the pseudonarrative organization is easier to produce and understand.

In the present domain, pseudonarrative offers a considerably simpler alternative structure to that of reasoning. Structurally, this simplicity is reflected in the fact that pseudonarrative has a broad tree structure rather than a deep one; i.e., it has fewer complex subtrees. The choice between pseudonarrative and reasoning yields the general hypothesis that broad trees are more comprehensible than deep trees, since the load on memory is less [Yngve 60], and the specific hypothesis that pseudonarrative is simpler for novices than reasoning structure, since the discourse organization will be more familiar.

## 2.5 Command and Control Speech Act Chains

The command and control speech act chain provides the simplest way of accomplishing several important forms of complex social action, and is important in the study of instruction discourse, since any sequence in which an instructor requests a student to do anything and then receives a response from the student constitutes a command and control speech act chain. Such sequences are thus the basic discourse type for hands-on instruction.

We define a **speech act chain** to be a maxmal sequence of speech acts, each of which has the same major propositional content. (This discussion relies on [Searle 69] in its use of the terms "speech act" and "propositional content.") One specific form of speech act chain constitutes the command and control speech act chain, which has been studed as the basic discourse type for aircrew discourse [Structural Semantics 83]. Appendix II gives a technical discussion of such command and control speech act chains, including the categories of utterance, the subordinators that are used, and the rules that govern sequencing.

Example (5) illustrates the use of the command and control speech act chain in an instructional context.

(5a) Instructor: And if you had a question, now you could ask a question.

(5b) Student: Um-

(5c) Instructor: You could say what, what kinda controls *do* I have. What *can* I do with that box.

(5d) Student: How come when you've got both of the switches off, you have some lights on?

(5e) Instructor: Both of the switches off?

(5f) Student: See you've got them off.

(5g) Instructor: Okay well that isn't necessarily off, that's just down. It, maybe you really wouldn't wanna say up and down rather than on and off, might be a better way of saying it. Does that make sense? ...

(5h) Student: Mmm-hmm. Yeah.

(GS, p.10)

In this example, (5a) and (5c) are requests for action, (5d) and (5e) are requests for information, (5f) is a challenge, (5g) is a statement followed by a request for information, and (5h) is an acknowledgement (italics indicate emphasis).

The study of speech act chains in an instructional context is of general interest in understanding classroom discourse [Griffin & Mehan 81, Sinclair & Coulthard 75], and is of particular importance in the understanding of hands-on instruction.

### 3 Semiotics

This section presents our preliminary investigations into semiotics. The present project is concerned with optimal structures for multimedia instruction; semiotics is a natural theoretical framework for such an investigation, since it attempts a general theory of all sign systems, including language, diagram, gesture, etc. As this work is inspired by our experimental program rather than by philosophical analysis, it has a preliminary character, and we expect that there will be reformulations as our experimental hypotheses are tested and refined.

We begin with a short introduction to semiotics based on the thought of Charles Saunders Peirce, followed by a short discussion of the relation between semiotics and linguistics that includes a review of Saussure, a founding figure with Peirce in the study of semiotics. We next formulate precise notions of "semiotic system" and "sign system." The main concept then follows, that of a "semiotic morphism," which is a translation from signs in one system to signs (i.e., representations) in another. Finally, we consider what makes some translations better than others.

These ideas should be applicable to many aspects of instruction as well as to other areas of communication; some instances include generating appropriate explanations, determining good representations ("icons") for computer graphics, measuring the quality of analogies, and choosing good names for files in a directory. There is a very large literature that is relevant to problems like these; however, all studies that we know are restricted to particular a semiotic system (such as natural language) and/or a particular semantic domain, or else lack the precision of the theoretical model that we will present. Some recent research, however, is fairly close to ours in spirit; in particular, the last two problems listed above have been studied by [Gentner 83], [Gentner & Gentner 82] and [Carroll 82], respectively, who reach conclusions compatible with ours; in particular, they emphasize the importance of structure as opposed to content. However, their theoretical framework is less rich than ours, which includes hierarchical levels and constructor functions, as well as objects and relations.

### 3.1 Peirce

This subsection briefly reviews some ideas from Peirce's approach to semiotics [Peirce 65], since our approach is partially based upon his ideas. We try to use Peirce's original terminology and definitions since his work is often superior to later popularizations and extensions. On the other hand, his exposition is difficult and his work has not yet been thoroughly assimilated into current philosophical thought; furthermore, the insights of modern linguistics and our research on multimedia instruction have suggested certain additions and reformulations that we do not attempt to distinguish from Peirce's original concepts.

A basic concept in Peirce's semiotics is **semiosis**, an instance of signification, which is a situation involving the following three main components:

1. a **sign**, "something which stands to somebody for something in some respect or capacity;"
2. an **object**, that for which the sign stands; and
3. an **interpretant**, which is another sign, raised by the original sign in the mind of the interpreter, which is "directly applicable to self-control," i.e., to its pragmatic use.

Peirce's original terminology, apparently based on the Medieval *trivium*, was "pure grammar," "logic proper," and "pure rhetoric." These concerned respectively: necessary conditions for meaningfulness, necessary conditions for truth, and "the laws by which ... one sign gives birth to another, and especially one thought brings forth another" [Peirce 65].

Peirce calls the "logical interpretant" of a sign (as opposed to its "emotional" interpretant) the **meaning** of the sign. This notion suggests the modern concepts of "knowledge representation;" similarly, his "pure rhetoric" strikingly resembles the concerns of modern "knowledge engineering" and expert systems. The following quotation might almost be a modern computer scientist (rather than a "pragmaticist"[4]) discussing requirements for the knowledge representation system of a robot:

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[4]Peirce introduced the term "pragmaticism" in the hope that it would be so awkward that no one would copy it, as William James had his earlier term "pragmatism."

> The rational meaning of every proposition [which is a well-formed complex of signs] lies in the future. How so? The meaning [i.e., the logical interpretant] of a proposition is itself a proposition. Indeed, it is a translation of it. But of the myriads of forms into which a proposition may be translated, which is that one which is to be called its very meaning? It is, according to the pragmaticist, that form which is most directly applicable to self-control under every situation and to every purpose.

Certainly Peirce did not have in mind the fruits of modern cognitive and computer science, such as semantic networks, relational databases, non-monotonic logic and rule-based systems. But these appear to be consistent extensions of Peirce's thought in the direction of further precision, applicability and effective computability; in any case, we shall ourselves move in this direction. We note that it is the goal-directed content or application of such structures that is particularly relevant here.

Some further comments on the notions of sign and object are in order. Peirce's "objects" are not limited to physical objects, but also include relations and properties as possible designations for signs. In considering computer generated instruction, we shall probably also want to use less traditional and more complex entities from the ontology of modern computer science, such as "continuations" and procedures or algorithms.

Peirce had a good deal to say about the nature of signs, much of it very relevant to our study of multimedia instruction. Let us first consider his influential threefold division of signs into icons, symbols and indices, according to the manner in which they signify. Peirce defines an **icon** as a "sign which refers to the Object that it denotes merely by virtue of characters of its own," "such as lead-pencil streak as representing a geometrical line." A sign $x$ is an **index** for an object $y$ if $x$ and $y$ are regularly correlated, in the sense "that always or usually when there is an $x$, there is also a $y$ in some more or less exactly specifiable spatiotemporal relation to the $x$ in question" [Alston 67]. "Such, for instance, is a piece of mould with a bullet-hole in it as sign of a shot" [Peirce 65]. Finally, Peirce defines a **symbol** as a "sign which is constituted a sign merely or mainly by the fact that it is used and understood as such."

Peirce did not finally believe that the best interpretant of a given sign is necessarily another sign. The argument goes as follows: Any given sign can always be "further developed" into another sign that is its interpretant. This leads to an infinite sequence of signs. If at some point the next interpretant in this sequence is the same as the previous one, then we may regard the sequence as finite. But in some cases it is genuinely infinite, and there is no final interpretant. Instead, Peirce (sometimes) took what he called **habit**, the "readiness to act in a certain way under some circumstances and when actuated by a given motive" as "the veritable and final logical interpretant." Since this is not a sign, it need not be further interpreted. Notice that this formulation is also quite consistent with modern procedural approaches to knowledge representation.

### 3.2 Semiotics and Linguistics

Although semiotics is intended to be the general study of all sign systems, almost all studies of semiotics have taken language as the primary semiotic system. There are several reasons for this. First, the units of language are both familiar and easy to discern. Letters, words, and parts of speech have been known and analyzed as formal units at least since Aristotle, and the additional units added by modern linguistics are relatively well agreed upon. In contrast, kinesics, or body language, after more than forty years of study, still shows no agreement on what its units are, or whether or not the system is independent of parallel activity in the linguistic system. Second, of known semiotic systems, language appears to have the greatest number of hierarchical levels, with the greatest number of units instantiating each level, and also the fullest body of theory and of methods for studying the chosen domain. Therefore, many studies of other semiotic systems and many theoretical formulations of semiotics as a meta-theory take linguistics as a model. For example, see [Worth & Adair 73] and [Carroll 80] studying the semiotic system of film, and [Barthes 57] studying cultural systems, such as the meaning of steak in French cuisine.

#### 3.2.1 Saussure and Peirce

Most work in semiotics derives from either Saussure or Peirce. A major difference in their approach [Eco 79] is that Saussure gives a two category account of semiosis, involving only signs and meanings, while Peirce gives the three category account discussed above. Their work also differs greatly in emphasis: as a linguist with a background in historical linguistics, Saussure focusses on the paradigmatic relations of signs within sign systems; while Peirce, as a logician and philosopher interested in pragmatics, considers signification, interpretation, and the combination of signs in syntagmatic relations. A **paradigmatic** organization of signs is composed of all the signs of a given class in relation to one another. Paradigmatic sign systems include, for example, the paradigm consisting of all case markings possible for a noun of a given class, the paradigm of all relative pronouns, and the paradigm of all Boolean functions. In contrast, the **syntagmatic** plane of organization consists of the actual order of signs as they are used in real time, for example, the order and syntactic organization of words in a sentence, or of symbols in a logical proof. Clearly, both planes of organization are necessary to understand a sign system.

Perhaps the most characteristic of Saussures's contributions to the study of semiotics is an emphasis on and extension of the notion of the arbitariness of the sign [Saussure 74]. Traditionally in linguistics, arbitrariness has meant the absence of a necessary connection between sound and meaning. That is, the sound sequences 'arrow' or 'fleche' or 'pfeil' can all express the meaning '→'; there is no necessary connection between the sound and the meaning. However, Saussure's work shows that although the sound/meaning connection is arbitrary (with the minor exception of onomatopoiea), the range of meaning of a given sign is not arbitrary, but rather is constrained by the meanings of all related words. For example, the set of color terms in a given language forms a mutually constraining semiotic system within the lexicon. Therefore, it is not possible to give the meaning of an individual color term in isolation. Thus we cannot understand the full range of the English term 'brown' from just a definition and examples of brown. We must also know what it is *not*, and so must also understand red, black, yellow, and all the other terms in the same system with which brown contrasts.

These notions of the arbitrariness and mutual constraint of paradigm members will become important when we study particular multi-media semiotic systems, since they can help to answer questions about the boundaries of a given system, their degree of arbitrariness, etc.

### 3.3 Semiotic Systems

This subsection gives our notion of semiotic system, inspired by Peirce's formulation of semiosis; it will be seen that most of our discussion concerns the structure of complex signs. Our exposition is gradual, and is finally summarized by a reasonably precise definition of semiotic system. Some formalization of the structure of a system of related signs is needed in order to study what makes one representation of a given sign better than another. This is because it is necessary to consider how related (but significantly different) signs will be represented in order to avoid confusion and ambiguity; and it is necessary to consider what attributes of signs should be given priority in constructing their representations. (These issues of representation are not explicitly addressed until Section 3.4.)

In all but the simplest sign systems, individual signs are organized into compound signs; for example, sentences are made of words. This is a fundamental strategy for rendering the complexity of non-trivial communication more manageable. One may iterate this strategy, by regarding complex signs at one level of analysis as individual signs at a higher level, and then forming compound signs from these as well, which leads to a multilevel hierarchy of sign structure. For example, linguistics recognizes the following levels: phonological (the sounds of a given language); morphological (the smallest repeated compounds of phonemes with a stable meaning); lexical (words); syntactic (phrases and sentences); and discourse (multisentential) units. It is important to note that this is a "whole/part" hierarchy, in which items at each level are composed from components from the next lower level. Such a hierarchy is therefore quite different from Peirce's three-fold division of semiosis, which focusses on the meaning of signs at a given level.

Sometimes there may be one or more **basic** levels, which are somehow most important or characteristic of a given semiotic system. In the case of natural language, for the last thwnty five years, it has been supposed that the sentential level is basic, although more recent research is inclined to regard the discourse level as at least as important. More generally, there may be a partial ordering relation upon the levels of a semiotic system, such that some levels are more basic than others.

The whole/part hierarchical organization of complex signs requires that signs be considered not only individually but in their context. The immediate context of a sign consists of those other signs that surround it, in space and/or time, and that together with it form a complex sign at the next higher level. In numerous linguistic studies, it has been found that the context and speaker of a given sentence in a story are at least as important for determining its meaning as are the words that comprise it. (For an extreme example, the sentence "Yes" could mean almost anything if given an appropriate context.) Generalizing this, we may say that it is more useful to view meaning as being produced "top-down" than "bottom-up." (An example of the utilitiy of this view is found in artificial intelligence research, where contextual cues have been found to be essential in recognizing and disambiguating signs; this has particularly been the true for speech understanding and machine vision projects.)

It is a common approach to take individual signs as the basic meaning bearing units; however, Peirce gave that role to **propositions**, which are well-formed complexes of individual signs[5]. This has the important advantage that the well-known dependence of sign meaning upon the context in which the sign occurs is not a strange phenomenon that needs to be explained, but instead follows directly from the way that things are defined, since meaning lies in the context rather than in the individual sign. (Notice that this phenomenon can be iterated over several hierarchical levels of sign structure.)

An important aspect of semiosis is the particular sensory means by which a sign is expressed. Possible senses include visual, auditory, and kinesic. For convenience, we will also include mental events as sensory events; some such move is clearly needed to handle many important examples, such as inferring a proposition from one or more others. Of course, a sign may involve more than one sensory modality. For example, a telephone conversation involves the auditory modality, while a television program involves an audio-visual mix.

For a given sensory mix, a very large number of different signs may be possible; and it may also be possible to organize these signs (or subsets of them) in a wide variety of different ways. Within a given sensory mix, a given choice of signs and way of organizing them may characterize a particular semiotic system (there are, of course, other factors, such as the objects and interpretants involved). Notice that a sign that is meaningful in one semiotic system may not be in another. For example, different alphabets (such as Roman, Greek and Cyrillic) involve different letters, although a given form for a letter may be used in more than one alphabet.

### 3.3.1 A Formalization of Semiotic Systems

Having considered the three aspects of semiosis, and the whole/part hierarchy of levels, we now consider the structure of entities at a given level. Some of this discussion may be familiar from formalisms used in linguistics, but our purpose here is to give a formalism that is applicable to any semiotic system whatever.

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[5] Of course, a proposition is also a sign; and in some cases, an individual sign is also a proposition.

We have already noted that entities at level n are constructed from entities at level n-1 (and other entities at level n that are already so constructed). A given semiotic system admits only a certain limited number of ways to put parts together at a given level n; we will refer to these as its **constructors** at level n. In general, there is a classification scheme for the entities at a given level (e.g., the parts of speech are such a scheme for the syntactic level of a natural language semiotic system), and the constructors at that level can be seen as *rules* for combining entities of these various **classes** to get a new entity of another certain class. Such rules may be written in the form

r: <c1>...<cn> → <c> ,

where <c> is the result class, r is the constructor, and <c1>,...,<cn> are the classes of the parts that r puts together. Thus, e=r(e1,...,en) is the entity (of class <c>) resulting from applying r to entities e1,...,en of classes <c1>,...,<cn>, respectively. (Incidentally, the <ci> may be classes of entities either from level n or level n-1.)

A familiar special case is that of a formal context-free grammar, where each <ci> is a syntactic class (or "part of speech"), the entities are words, and each rule r is of the form

e=w0 e1 w1 e2 w2 ... en wn ,

where w0,...,wn are fixed words (or strings of words, possibly the empty string); this is more conventionally written in the form

<c> → w0 <c1> w1 <c2> w2...<cn> wn .

A familiar special case of such a string is

S → NP VP

for which <c>=S, n=2, w0=w1=w2= the empty string, <c1>=NP and <c2>=VP.

However, a grammatical formalism that is based on strings cannot be used conveniently for applications like two-dimensional graphical displays, or multi-media presentations such as audio-visual animations. This is because string formalisms are not only inherently one dimensional[6] but are also inherently limited to *discrete* phenomena, as opposed to phenomena that are more naturally viewed as involving *continuous* variables. Some examples of continuous variables would be pitch and volume in an auditory semiotic system, or size and

[6] Although two or more dimensions can in principle be encoded in such a formalism, it is unnatural and inconvenient to do so, since no special formal support is provided for this.

placement in a graphics system. This is why we have chosen the more general functional notation e=r(e1,...,en).

Three slight additions to this basic formalism seem useful; there may well be others that we have not discovered. First, a given constructor (or rule) r may have, in addition to its formal arguments e1,...en which are entities, some number of **parameters** p1,...pk, chosen from fixed sets of parameter values <p1>,...,<pk>. Thus, we might write

$$r : <p1>,...,<pk>,<c1>,...,<cn> \rightarrow <c>$$

and

$$e = r_{p1,...,pk}(e1,...,en).$$

For an example of parameters, consider the location of the upper-lefthand corner, and the size of a graphic entity, say a cat, to be displayed on a graphics terminal; depending on the values of these parameters, the cat will have a different location and size, but will still be recognizably the same cat.

The second addition is that there may be a **priority ordering** on these constructor functions. Under such an ordering, there may be a **primary constructor**, which has greater priority than any other constructor; there may also be one or more **secondary** constructors, each having less priority than the primary constructor and greater priority than any non-primary and non-secondary constructor, with none of these having priority over any other; similarly, there may be one or more **tertiary** constructors, etc. Notice that what we have here is a **partial** ordering rather than a total ordering, since given two distinct constructors r1 and r2, it is not necessary that either one has priority over the other.

The level of discourse types in the English natural language semiotic system provides some nice examples of primary constructors. For example, explanation [Goguen, Weiner & Linde 81] has a primary constructor, AND, which serves to conjoin a number of reasons for the same statement. The argument that AND is a primary constructor is simply that it is so basic to the explanation discourse type that explicit textual markers for it can often be omitted without obscuring the meaning. Several other discourse types are also known to have such "default" constructors [Linde & Goguen 80]; thus, these also have primary constructors.

The third addition is that of **context conditions**[7] on rules. These are conditions (i.e., predicates) that limit the applicability of a rule to certain particular contexts, namely those where the predicate is true; these predicates may involve the arguments e1,...,en and also the parameters p1,...,pk. Context conditions often express constraints that arise as a result of structure at higher levels of the hierarchy, and are a feature of many recent grammatical formalisms [Kaplan & Bresnan 82], [Wasow *et al.* 82].

The predicates that can be used for expressing constraints are also a significant part of a semiotic system. At a given level, there will be only a finite number of basic predicates; others can be formed as simple logical combinations of these. (Here we will rely on the conventions of ordinary logic, instead of creating a special grammar of predicates for a given semiotic system; but note that higher order logic, and other extensions of first order logic, may be needed.) For example, in a semiotic system for graphics, we may have predicates like RED and SQUARE. Note that predicates can also be constructed using **functions** like COLOR, SIZE and BRIGHTNESS. These associated predicates and functions express basic **properties** of entities at a given level of the semiotic hierarchy. Like constructor functions, their arguments may be restricted to particular classes of entities at their level. We will use the notation

p: <c1>...<cn>

to indicate that p is a predicate having n arguments, where the $i^{th}$ argument must lie in class <ci>. p(e1,...,en) is thus either true, false, or undefined, and is well-formed only if ei is of class <ci> for i=1,...,n. Functions may also have their arguments restricted to particular classes in the same way.

It should be noted that there is a standard way to reduce functions to relations. For example, we may represent a real-valued function f(e1,e2) as a relation

F: <c1><c2><real>

where <c1>, <c2> refer to the classes of e1, e2 respectively. Then f(e1,e2)=r if and only if F(e1,e2,r)=true. We can also consider arguments and/or values that are not necessarily entities; non-entity arguments correspond to parameters, and may be restricted to specific parameter sets. For example, g(p1,p2,e1,e2) corresponds to the relation

[7] This is a limited and technical sense of "context." A broader sense has been given earlier; a still broader sense would take account of pragmatics.

G: <p1><p2><c1><c2><real>

where <p1>, <p2> refer to the parameter sets of p1, p2, and <c1>, <c2> refer to the classes of e1, e2 respectively. Then g(p1,p2,e1,e2)=r if and only if G(p1,p2,e1,e2,r)=true. Also note that higher order relations can play a significant role in some cases; in fact, the priority ordering on constructors is such a higher order relation.

The systematic construction of new entities from parts, either at the same level or at the next lower level, provides another kind of hierarchical structure, that of entities at a given level. From another perspective, one may speak of analyzing a given entity in terms of other entities at the same or lower levels. A familiar example from high school English is diagramming the syntactic structure of a sentence. Such a diagram shows the division of a sentence into parts, called "phrases," and moreover explicitly shows the relationships of subordination among these phrases; that is, it shows which phrases are sub-phrases of other phrases, and also what class they belong to. (Examples of classes are "noun," "verb phrase," "prepositional phrase," etc.)

There are many different systems of notation for the analysis of sentence structure and for similar structured entities in other semiotic systems, most of which rely upon special conventions suited to the case at hand. Our intention here is to give a uniform tree notation that applies to any semiotic system having constructor functions as described above. If e=r(e1,...,en), then we shall represent e as a tree with root node labelled r, where r has n branches corresponding to e1,...,en, each of which is either a subtree (constructed in the same way recursively) or else is an entity of the next lower level. In some cases, it may also be helpful to label edges with the classes to which they correspond, e.g., the label of the edge from the root to ei might be labelled <ci>. For example, the sentence "The light on the left comes on" can be diagrammed as in Figure 6. Such diagrams can also be decorated with parameters as subscripts to node names (or in parentheses after node names). We note again that the purpose of such diagrams is to show the internal part/subpart structure of a given entity at a given level within a given semiotic system. It is also worth noting that such an abstract "parse tree" of a sign gives an ordering to the entities which comprise it, namely the left-to-right ordering of the "frontier" (i.e., the leaf nodes) of the tree. We call this ordering the **intrinstic** ordering of these parts.

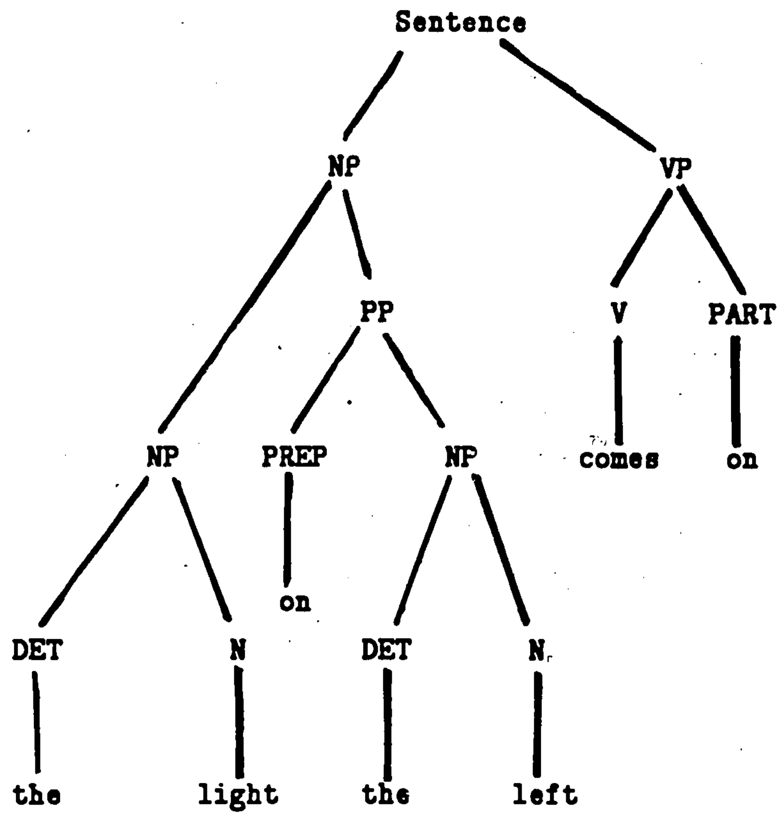


**Figure 6:** Part/Subpart Hierarchy for a Compound Sign

Many aspects of this approach to the structure of signs seem to be present or implicit in Peirce's treatment of the semiotics of propositions. But, as far as we can tell, these considerations were never explicitly assembled into a single definition. Our purpose in doing so below is to make as precise and explicit as possible what is involved in constructing (or in attempting to construct) optimal explanations or other representations of instructional material. (This application is considered in more detail in the Section 3.4.)

The basic insight underlying this definition of semiotic system is that semiotic events are not isolated phenomena, but rather occur in systems: there are common rules relating to the recognition, construction, denotation and interpretation of such a collection of signs. Moreover, semiotics as a subject is (or *should* be) more concerned with such rules than with the comparative study of individual signs and the settings in which they are found. (This distinction is like the distinction between descriptive biology and modern biology that is based on biochemistry and molecular biology.) We repeat that Definition 1 merely embodies our current understanding of the structural elements that are involved in semiotics and can be expected to change as that understanding improves.

**Definition 1:** A **semiotic system** consists of four classes of entities:

1. Signs,
2. Objects, and
3. Interpretants,

such that each class of entities (except the first) is divided into **levels** (not necessarily disjoint), some of which may be more **basic** than others, such that entities at level n+1 are constructed from entities at level n (and other entities at level n+1) by use of a fixed set of **constructor functions** (which may also have parameters and context conditions). In addition, there may be a **priority** (partial) **ordering** on these functions at each level. Finally, there may be predicates, relations and functions expressing properties of entities at each level of each stage. []

We may illustrate the concepts in this definition with examples from the semiotic system of spoken English. The underlying medium is sound, that is, physical vibrations. The signs are classed into the usual levels of spoken English, phonemes, morphemes, words, phrases, sentences, and discourse units. Constructors at the sentence level are given by rules, as previously described. Objects and interpretants are more problematic; it seems fair to say that it is the objective of current research in Cognitive Science and Artificial Intelligence to construct suitable entities for these classes, and to write programs for processing them.

The purpose of this definition is to explicitly describe the *structure* of a system of related signs, in order to facilitate the construction of good representations of signs from one system by signs from another system. The next subsection addresses such representations.

### 3.4 Semiotic Morphisms

This subsection focusses on our primary concern in semiotics, which is the *translation* of signs in one system to signs in another system. It is our intention to provide the theoretical background for a general theory of the construction and interpretation of signs. For example, generating an optimal (or at least reasonably good) explanation, generating appropriate graphical icons, choosing a good file name, choosing a good analogy, and understanding texts and/or graphics, can all be seen as problems of translating signs from one sign system into another. Notice that the problem of choosing an optimal mix of media also falls in this framework, since we can regard the signs of each media mixture as forming a subsystem of the total sign system within which we must choose representations. This subsection addresses general questions about the nature of translations between sign systems, and the reasons for preferring one translation to another. In order to formulate such questions with sufficient generality, we first introduce another basic concept, that of a sign system.

**Definition 2:** A **sign system** is a class of entities, called **signs**, divided into a set of **levels** (numbered 1 to N and not necessarily disjoint), some of which may be more **basic** than others, such that entities at level i+1 (for $1 \leq i < N$) are constructed from entities at level i (and other entities at level i+1) by use of a fixed set of **constructor functions** (these may also have parameters and context conditions). In addition, there may be a **priority** (partial) **ordering** on these constructors at each level. Finally, for each level, there may be predicates, relations and functions expressing properties of signs at that level. []

Artificial systems often exhibit the structures in this definition in a very natural way. For example, let us consider a simple line-oriented editor for a standard 24 line by 80 character screen. The lowest hierarchical level is that of characters, the second that of lines, the third that of screenfulls, and the last that of sequences of screens; thus, entities at the second level consist of strings of 80 or fewer characters, and entities at the third level consist of strings of 24 or fewer lines. We can see this simple system as having just one constructor at each level greater than 1, namely string-of(a1, ..., aN, N) with parameter N, which "strings together" N entities at the next lower level. The second level has the context condition $0 \leq N \leq 80$, and the third $0 \leq N \leq 24$. Since there is at most one constructor at each level, the priority ordering is trivial. However, there are some interesting predicates and functions, such as the LINELENGTH function for lines, and the ALPHANUMERIC predicate for characters.

A more sophisticated editor, specifically oriented toward text editing, might have character, word, sentence, and paragraph among its levels. It might have one sentence level constructor for each possible final punctuation, e.g., SENT.(a1, ..., aN, N), SENT?(a1, ..., aN, N), SENT!(a1, ..., aN, N), each with parameter N and context condition $N \leq 0$. Here SENT. clearly has priority over SENT? and SENT!. (Note that many editors in current use provide both line-oriented and sentence-oriented commands.)

We can also illustrate Definition 2 in the domain of computer graphics. Example entities are lines, characters, circles and squares. Levels might consist of pixels (individual "dots" on the screen), lines, simple figures, and windows (consisting of arbitrary "scenes," collections of entities at lower levels, plus other windows); each entity at each level must also have associated attributes for location on the screen, and size; there may also be attributes for color and intensity. The most interesting constructor here is WINDOW, which can encapsulate any collection of entities from any levels.

The classes of signs, objects and interpretants involved in a semiotic system each form a sign system, as follows directly by comparing the above definition with that of semiotic system.

Now the main concept of this section, which is intended to capture the notion of mapping signs from one system to representations as signs in another system. Such a mapping may or may not preserve the structure of a sign system. The degree to which it does so affects the quality of its representations, as made precise in Definition 4 below.

**Definition 3:** Let *S1* and *S2* be sign systems. Then a **(semiotic) morphism** M: *S1* → *S2*, from *S1* to *S2*, consists of the following partial functions (all denoted M):

1. Entities of *S1* → Entities of *S2*,
2. Levels of *S1* → Levels of *S2*,
3. Classes of *S1* at Level i → Classes of *S2* at Level M(i),
4. Constructors of *S1* at Level i → Constructors of *S2* at Level M(i), and
5. Property Predicates and Functions of *S1* at Level i → Property Predicates and Functions of *S2* at Level M(i),

such that

1. if $i<j$ (for $1 \leq i,j \leq N$, where N is the number of levels of *S1*) then $M(i) \leq M(j)$,
2. if r: <c1>...<cn> → <c> is a constructor at level i of *S1*, then M(r): M(<c1>)...M(<cn>) → M(<c>) is a constructor at level M(i) of *S2* (if it is defined), and
3. if p: <c1>...<cn> is a predicate at level i of *S1*, then M(p): M(<c1>)...M(<cn>) is a predicate at level M(i) of *S2* (if it is defined)[8].

[8]As in the previous subsection, by translating functions to relations, this condition applies to property functions as well, and a slight generalization also permits translating arguments and/or values that are not entities.

We will say that M **preserves entity** e **at level** i (for $1 \leq i \leq N$, where N is the number of levels of *S*1) if M(i) is defined and M(e) is at level M(i) in *S*2. Then M **preserves level** i if M preserves all entities at level i (for which it is defined), and M is **level preserving** if it preserves all levels of *S*1 (for which it is defined).

We say that M **preserves constructor** r: <c1>...<cn> → <c> (at level i) **for entities** e1,...,en if r(e1,...,en) is defined, if M(r)(M(e1),...,M(en)) is defined, and if it equals M(r(e1,...,en)). Then M **preserves constructor** r if it preserves r at all entities for which r is defined; and M **preserves constructors** (at level i) if it preserves all constructors (at level i for which it is defined) of *S*1.

If r and r′ are constructor functions of *S* and $r > r'$ (r has priority r′) in *S*1, then we say that M **preserves the priority** of r over r′ if $M(r) > M(r')$ in *S*2, provided that M(r) and M(r′) are defined. M is **priority preserving** if it preserves all priorities in *S*1 (for entities where it is defined).

Next, we say that M **preserves a property** relation p: <c1>...<cn> of *S*1 provided that M(p) is defined and M(p)(M(e1),...,M(en)) holds whenever p(e1,...,en) holds, for ei of class <ci> in *S*1[9]. Also, M is **property preserving** if it preserves all properties of *S*1 (for which it is defined).

Finally, we say that M is **structure preserving** if it is level preserving, constructor preserving, priority preserving, and property preserving. []

These careful distinctions about what kind of structure might be preserved by sign representations from one system with signs from another will be used in Section 6 to formulate precise experimental hypotheses about the quality of representations.

It is important to notice that semiotic morphisms need not be totally defined; that is, each of the functions denoted M can be undefined on some of what is in *S*1. For example, there need not be any representation in *S*2 for some entities in *S*1; in particular, some components of M could even be totally undefined, i.e., the empty function.

An example of a semiotic morphism is the correspondance between the physical order of lights on the box, and the order in which clauses are given to describe the lights (narrative order).

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[9] This extends to functions and to non-entity arguments and/or values as be...

The processes of signification and interpretation (i.e., of constructing objects and interpretants within a semiotic system) might be viewed in the light of semiotic morphisms, since the entities that they map from and to are both sign systems. This only makes sense because semiotic morphisms can be partial functions. For example, it is often the case that low level signs in complex systems, such as phonemes in the English natural language semiotic system, seem not to have either denotations or interpretations. Moreover, there is very little structure other than sequential succession to preserve at these levels.

It seems clear that a structure preserving semiotic morphism M: $S1 \rightarrow S2$ will faithfully represent all of the semiotic structure of $S1$ in terms of that available in $S2$. This would seem to be desirable for an optimal representaton; however, if the resulting structures in $S1$ are too complex, then they may be hard for human beings to understand, and thus not really optimal. For example, if $S1$ consists of parse trees for English sentences and $S2$ consists of the usual "printed page" text format, then it is possible to translate all the syntactic information that is available in $S1$ into structures in $S2$ with so-called "phrase structure" notation, which uses brackets to delimit phrases and uses subscripts on brackets to indicate the class of phrase is involved. For example, the sentence given previously would be represented by something like

$$[[[[\text{the}]_{Det}\ [\text{light}]_N]_{NP}[[\text{on}]_{Prep}[[\text{the}]_{Det}[\text{left}]_N]_{NP}]_{PP}]_{NP}[[\text{comes}]_V[\text{on}]_{Part}]_{VP}]_{Sentence}$$

in this notation. This may be useful for some purposes, but it is clearly not optimal for all purposes. The point to be noted is that there is some kind of a trade-off between the degree of structure preservation and the degree of complexity of the resulting representations.

We now turn to the rather delicate issue of determining whether one representation (i.e., semiotic morphism) is better than another. One evident consideration is whether it preserves more structure than the other (of course, this will make it better only if the complexity of its representations are not too great).

**Definition 4:** Let M′ and M be morphisms from sign system $S1$ to sign system $S2$. Then M′ **preserves more structure** than M does, provided that:

1. if M preserves an entity e at level i, then so does M′;
2. if M preserves a constructor r at entities e1,...,en, then so does M′;
3. if M preserves a priority r>r,′ then so does M′; and
4. if M preserves a property p, then so does M′. []

The real difficulties arise in trying to compare morphisms M and M′ such that neither preserves strictly more structure than the other, or for which one preserves more structure but also produces more complex representations. For example, M might preserve more levels than M′, whereas M′ preserves more properties than M. It is for unclear cases such as this that our future experimental results will be especially interesting. The framework that we have developed suggests that preserving levels is more basic than preserving priorities, which is more basic than preserving properties. It is not difficult to formulate a number of specific experimental hypotheses that will test these suggestions, and we hope this will eventually lead to a workable notion of what it means to be a good representation. "Workable" here means that it will be possible to effectively determine of a given representation whether or not it is adequate to the task in hand. More optimistically, given sign systems *S*1 and *S*2, where *S*1 contains abstract forms of the information to be conveyed, it may be possible to discover (to "compute" even) a semiotic morphism M from *S*1 to *S*2 that will give adequate representations in *S*2 for entities from *S*1. For example, *S*1 might contain instructions for repairing some piece of equipment, and *S*2 might be a color graphics terminal. The problem is then to generate displays that utilize the capabilities of that particular terminal reasonably well.

Similar considerations arise in [Gentner 83]'s discussion of successful and unsuccessful natural language analogies. We now quote from the summary of that paper:

> The *structure-mapping theory* describes the implicit interpretation rules of analogy. The central claims of the theory are that analogy is characterized by the mapping of relations between objects, rather than attributes of objects, from base to target; and, further, that the particular relations mapped are those that are dominated by higher-order relations that belong to the mapping (the *systematicity* claim). These rules have the desirable property that they depend only on syntactic properties of the knowledge representation, and not on the specific content of the domain.

Our approach introduces a finer structure on the source and target domains, and thus permits finer hypotheses about what makes analogies good. In addition, our approach is not limited to natural language as the target sign system, and considers representations other than analogies.

We now introduce the notion of a subsystem of a sign system. This notion has already been used informally in the discussion of choice of media mix at the beginning of this subsection, and will be used again in the next subsection.

**Definition 5:** Given sign systems *S* and *S'*, we will say that *S'* is a **subsystem** of *S* provided that: every level of *S'* is also a level of *S*; every entity of *S'* is also an entity of *S* and entities in *S'* have the same level in *S'* as they do in *S*; every property function and predicate in *S'* is also one in *S*, and has the same values in *S'* as in *S*; every constructor function of *S'* is also a construtor of *S*, and constructors in *S'* yield the same results in *S'* as they do in *S*, and also have the same parameters and context conditions; and finally, the ordering on the constructors of *S'* is the same as that on those constructors in *S*. []

Now suppose that we are given sign systems *S*1 and *S*2 and a semiotic morphism M from *S*1 to *S*2. Then the set of entities M(e) in *S*2 for which M is defined for some entity e in *S*1 has: a set of levels, inherited from those of *S*2; a set of constructors, also inherited from those of *S*2 (but they will have to be undefined whenever combining entities of the form M(e) fails to yield another of the same form in *S*2); a priority ordering on these constructor functions, namely the same one that *S*2 has; and also the functions and predicates from *S*2, now thought of as expressing properties of entities of the form M(e) for e in *S*1. In short, the entities of the form M(e) form a subsystem of the sign system *S*2; we call it the **image** subsystem of the semiotic morphism M.

### 3.4.1 Iconicity and Naturalness

As discussed in Section 3.1, semiotics distinguishes three types of sign -- the index, the icon, and the symbol. The symbol is fully arbitrary, in the Saussurean sense. The index as signifier is a necessary (or probable) concomittant of the signified -- smoke as an index of fire. It is the icon which poses the most interesting questions for the relation of signifier and signified. The accepted definition of the icon is that it involves an actual resemblance between signifier and signified; a portrait signifies its subject by resemblance, not by convention. (Compare, for example, a highly conventionalized political caricature.)

This definition implies a specific directionality to the relation between signifier (*S*2 in Definitions 3 and 4) and signified (*S*1), in which the signified is more *natural* or *basic* than the signifier in some sense. Thus, it is often assumed that a diagram, drawing, or visual icon is more basic, easier to comprehend, and freer of the arbitrary conventions of language. (We find a folk theory of iconicity in the proverb: "A picture is worth a thousand words.")

However, it is important to note that pictures, diagrams, etc., are only partially iconic in this sense, and also contain a component of conventional representation that must be learned. For example, Venn diagrams may appear fully iconic of boolean relations to someone accustomed to using them; but to someone who has not learned the aspect of convention in this only partially iconic semiotic system, a Venn diagram may be iconic only of a pretzel or symbolic of a brand of beer.

In terms of the theoretical apparatus introduced in Section 3.4, the problem of generating an iconic representation is one of constructing a semiotic morphism from one sign system to another. The considerations of the above paragraph suggest that the set of all representations that are so generated, viewed as a sign system (this is the image subsystem of the full system of possible representing signs) should be in some sense simpler, more natural, or more basic (to humans) than the original set of signs. It is hoped that experimental explorations along these lines will lead to a deeper understanding of iconicity.

## 4 Some Further Analytic Concepts

We now consider some additional concepts used to formulate the variables and hypotheses in Sections 5 and 6. We begin with the possible cognitive structures of the task domain, and then consider some linguistic issues, including syntactic placement and strength, focus, and indexing .

### 4.1 Cognitive Structure of the Task Domain

The task of explaining the logic box (Figure 1), can be fulfilled by accounts based on at least five different ways of understanding the task domain:

1. **Behavioral.** This is a simple, unanalyzed description that matches a pattern of lights to corresponding switch positions. Loosely speaking, an account at this level sounds like a description rather than an explanation.
2. **Combinatorial.** An account at this level considers the possible patterns of lights as an aggregate. This might be displayed in a table, such as a truth table of the relation of switch positions and lights. An optional addition at this level explains that only four combinations of switch position are possible, by simple multiplication of two switches times two switch positions.
3. **Logical.** Such an account would indicate the Boolean functions of the switch positions represented by each light, using primitive functions like AND, OR, and IF. Depending

on the background of the audience, accounts at this level would differ in how full an explanation of logical functions is required.

4. **Electronic.** An account at this level might use a circuit diagram to indicate how the relation between switch position and light patterns is accomplished.
5. **Physical.** An account at this level would utilize the principles of physics and chemistry underlying the previous level of electronics.

The first three of these form a hierarchy by levels of abstraction, while the first, fourth and fifth form a hierarchy by levels of reduction. We have found instances of the first three of these levels in instructors' explanations, and the fourth in their briefings and debriefings; the fifth was included for completeness.

This categorization of possible cognitive organizations of the task domain relates to work by a number of researchers on the cognitive organization of explanations. For example, [Kieras 82] distinguishes knowledge of what a device is for, how to operate it, and how it works. The first two levels of description of our task correspond to varying degrees of knowledge of the first type: how to operate the device. The third, fourth, and fifth levels correspond to varying degrees of knowledge of how the device works. We note that a description at any of these five levels may function as an explanation, depending on the purpose of the description and the existing level of understanding of the audience. Similarly, in a study of Navy instruction manuals, [Stevens & Steinberg 81] provide a typology of explanations beginning at the behavioral level and proceeding to more abstract forms of explanations. (No exact correspondence between the higher levels of their taxonomy and ours is possible, since ours is a simple, non-branching tree structure, while theirs is a matrix of four two-way distinctions.

The first round of experiments gave instructors highly nondirective instructions, telling them to teach students how to check whether the device was doing what it was supposed to. This produced explanations of types one and two. Interestingly, although the audience was a group of community college students having no background in mathematics or electronics, many students found these explanations unsatisfactory, and in the subsequent debriefing session requested further information. Examples of such comments are:

(6) The thing is so easy to understand. I mean, it's, that we
look for the complications, you know, we're trying to
look for something that you know, what is, what's there.

**and we have to really explain it and you haveta get into ...**

(7) **I know. It's hard to explain because it's so easy.**

These comments strongly suggest that the cognitive structure underlying an explanation is an important variable for comprehension. Our later experiments elicited explanations at other cognitive levels, by asking the instructor to present the device as the control panel of a set of sluices, where switches controlling gates, and the lights indicating whether or not the sluices are open; this required students to understand not only the current relations but the basis underlying any possible set of relations.

In our first set of pilot experiments, the comprehension task (for the audience) was to write an explanation of the box, on the basis of the explanation given by the instructor. A similar procedure can be used to test comprehension of any of the cognitive organizations listed above (of course, the writing skills of the subjects will also effect such a measure). Our Phase II experiments will use more focused test questions to probe particular cognitive organizations. Thus, a question such as **Can all four lights be on at once?** can be answered from simple observation at the behavioral level. In contrast, a question like **Does any light correspond to the logical function ((not Switch 1) or (not Switch 2))?** requires some comprehension at the third level, that of Boolean functions.

### 4.2 Sentential Syntax

A number of issues at the syntactic and lexical levels appear to affect the comprehensibility of explanations. These include the syntactic placement of information and the strength of structural markers. Variables at this level may not be highly trainable for a human instructor delivering a non-scripted explanation, but may be extremely valuable in scripting computer produced or videotaped explanations.

#### 4.2.1 Syntactic Placement of Information

In a semantically restricted domain like that of the present study, it is possible to examine the syntactic placement of information quite precisely. This is valuable because syntactic placement is an important organizational device for discourse that allows the analyst to determine what information is given major importance and what information is given minor importance. Our task domain involves three basic types of information: information about the switches, information about the lights, and information about relations between the two.

Linguistic research has shown that there is a continuum of syntactic constituents ranging from the maximally sentence-like on downward. It has been further shown that more important information is, the more it is likely to be placed in sentence-like syntactic constituents [Linde 74, Ross 73]. To aid comprehensibility, it appears that important information should be placed in syntactically heavy constituents, that is, in constituents that are quite sentence-like. Similarly, semantically parallel information should be placed in syntactically parallel units.

#### 4.2.2 Strength of Structural Markers

Structural markers are pieces of text that invoke internal nodes of the discourse structure tree, such as STATEMENT/REASON, IF/THEN, and EXAMPLE, or that indicate movement in the tree. Our formal theory of discourse structure states that the first of these indicates relations between pieces of information, while the second type indicates change of focus of attention. Text invoking these markers may do so with varying degrees of strength. There are a number of dimensions that combine to produce strength of markers, including weight of the syntactic placement of the marker, degree of semantic ambiguity or univocality, and length in words.

### 4.3 Focus

To describe the semantics of these explanations, the additional notion of **focus** is required. The logic box employed in our explanation task has both lights and switches, and the patterns of each may vary. A coherent description must focus on one of these, describing the other in terms of the item in focus. (8) shows a focus on lights, while (9) shows a focus on switches.

(8) **What happens is each of those lights is a logical function, which means you know, true and false, or yes and no, of the two switches. So, for instance, this light C is on, just depends on Switch Two. Now whenever Two is up, C is on. It doesn't matter what One is on.**

(9) **We'll go through it again slowly. O.K. In one position of these two switches, where One is up and**

Two is down, all these lights are off. We take
Switch One and move it to its other position, three
of the lights come on. We reverse this combination
and make them both go up, we got again three
of the lights are on but a different three lights.
And, if we move em till both down, again,
we got three lights on but these two lights are
are changed over.

Issues involving focus include the question of whether there is an optimal focus for a given task, and the effects of maintaining or switching focus. Preliminary results suggest that changes of focus are confusing and that poor placement within the explanation structure can make them even more confusing; (10) is an example of such a change.

(10) So, in a condition where they're all off, this switch, Two, is down, and this switch, One, is up, and if we change the position of just one switch, we'll change the condition of the lights. So we'll go from all off to three of these lights going on and the three lights that come on are A, B, and D. If we go back to this situation which is where we started, they'll all go back off again.

This explanation begins with a focus on the switches and changes in the middle to a focus on the lights.

The taxonomy of explanation types given in [Stevens & Steinberg 81] contains a number of distinctions that correspond to this notion of focus; these are distinctions at the same level of abstraction, such as a "stuff-state-attribute" description of a physical system, versus a "stuff-as-a-transport medium" description of the same system.

### 4.4 Prior Text Reference

To understand explanations (or indeed any discourse type) we must take account not only of the linguistic form of the explanation and its semantic structure, but also of the knowledge shared by its speaker and addressees. In recent years, the fields of cognitive science, linguistics, and artifical intelligence have all been concerned with the effects of shared knowledge on linguistic and cognitive structures. The present discussion is concerned with the linguistic forms that speakers use to indicate that a particular body of shared knowledge is relevant or necessary in order to understand a given explanation.

As we define it, a **prior text reference** is a pointer in a given text to some body of information not present in that text, or to some prior text that speaker and audience are presumed to share. This definition derives from the discussion in [Becker 81] of what they term **indexing** of prior text. We have changed the term to avoid confusion with Peirce's related but different sense of the term index. Prior text reference can be accomplished explicitly, as in **As we were discussing last week about circuits**, and it may can accomplished implicitly, as in **Does this have to do with circuitese?** For a given prior text reference to succeed, it must indicate a body of knowledge or a prior text that the audience actually has mastered. Thus, the reference **If you remember the commutative law from high school algebra** will succeed only if the audience remembers the commutative law from high school algebra. Another example from our data is the statement that the operation of the logic box is **like a set of traffic lights**. This will succeed only if the audience does in fact know enough about how traffic lights work. Section 6.1 gives hypotheses about prior text reference.

## 5 Variables of Interest

This section discusses some variables applicable to our data that appear to be important for the comprehensibility of instruction; these variables are used in the hypotheses of the following section. We expect that further variables will be found as the research progresses.

### 5.1 Discourse Level Semantic Variables

#### 5.1.1 Cognitive Structure of the Task Domain

As discussed in Section 4.1, explanations can be based five different cognitive organizations of the task domain: behavioral, combinatorial, logical, electronic, or physical. Similarly, the comprehension task can probe any of these.

### 5.1.2 Focus

An explanation can be based either on the condition of the lights or on the positions of the switches, treating the other as functionally dependent on the one chosen as basic. Similarly, the comprehension task can be based either on the lights or on the switches.

### 5.1.3 Prior Text Reference

Prior text reference, as defined in Section 4.4, may be present or absent in any given part of an explanation.

### 5.1.4 Form of Prior Text Reference

Prior text reference may be either explicit or inferential. **Boolean algebra tells us** ... is an explicit prior reference. **Is that circuitese?** is inferential.

## 5.2 Variables of Discourse Structure

This subsection uses the distinction between discourse type and discourse unit introduced in Section 2.1.

### 5.2.1 Discourse Type

An explanation may consist of any of several discourse types, including reasoning, narrative, and pseudonarrative.

### 5.2.2 Number of Discourse Units

An explanation may contain one or more instances of each of its discourse types, and it may consist of several different discourse types. For example, a single explanation may consist of three reasoning units, it may consist of one reasoning unit and two pseudonarrative units, etc.

### 5.2.3 Presence or Absence of Discourse Summary

Any of the discourse types that have been found to perform the function of explanation may have as part of their structure an optional summary, giving an overview of the entire explanation, or of some part of it.

#### 5.2.4 Placement of Summary

Within a given discourse unit, a summary may be placed at the beginning, at the end, or may be embedded within the discourse unit. (This distinction between an initial and a final summary is related to the distinction commonly made in rhetoric between deductive and inductive paragraph structure. A deductive structure places the topic sentence at the beginning of the paragraph and follows it with supporting material; an inductive structure begins with cases or examples building up to a final general statement.)

#### 5.2.5 Presence or Absence of Explicit Structural Markers

In the construction of discourse structure trees, transformations can establish internal nodes in the tree, and can also alter the focus of attention within the tree. These functions may be accomplished explicitly, by separate pieces of text, or they may be accomplished implicitly, as part of the semantics of text primarily devoted to content. Such implicit markers depend on the fact that each discourse type has a characteristic default node type. For example, in a narrative, the default node type is SEQ, corresponding to the narrative presupposition, the rule of interpretation stating that events are assumed to have occurred in the same order as the main clauses that refer to them. Thus, in a narrative, it is sufficient to say `He moved the second switch. Two lights went out`. It is possible, but not necessary to add a marker such as `and then`, getting `He moved the second switch and then two lights went out`.

#### 5.2.6 Strength of Marker

In the case where an explicit structural marker is present, we may ask how strongly the marker is indicated. Strength of indication depends on a number of factors:

1. Syntactic heaviness of the marker, i.e., whether it is a single conjunction, a phrase, a dependent clause, or a sentence.
2. Length in words of the marker. (This is related but not identical to 1.)
3. Explicitness of the marker. For example, a marker like `so` is quite inexplicit, and may indicate causality, simple sequence, resumption of a previous topic, etc. In contrast, a marker like `because of that` indicates causality explicitly and unambigously.
4. Position in the sentence. A position at the beginning of the sentence is heavier than a later one; there are a number of syntactic devices in English that can move a constituent to front position.

### 5.2.7 Penetrance of Discourse Tree

Different choices of node type and different orderings of subordinate nodes (which correspond to different embeddings of clauses) can lead to a variety of different tree shapes. In general, discourse trees can be described as fundamentally deep structures, or broad structures. A relevant variable, related to a quantity called **penetrance** in artifical intelligence [Nilsson 71], is the ratio of the average path length A to the total number N of nodes. Thus, $P = A/N = \Sigma_{i=1}^{T} L_i/TN$, where T is the number of paths and $L_i$ is the length of the i<u>th</u> path, since $A = \Sigma_{i=1}^{T} L_i/T$. P is larger for deep trees and smaller for broad or shallow trees.

### 5.2.8 Explicit Establishment of the Basis of Parallel Structure

Many of the explanations in our data contain parallel structures. For example, there may be four subtrees correponding to the four lights. Or, in a differently organized explanation, there may be four subtrees corresponding to the four possible switch positions. A variable of interest is whether or not the basis of this parallel structure is made explicit. This could be done by a reference to the existence of the four lights in the first case, or to the simple computation of two switches times two switch positions in the second. Because of the existence of the demonstration prop, if the focus is on the lights, the explicit establishment of the four lights can be accomplished simply by directing attention to the box itself. It seems important that parallel structures in the text be ordered in a way that clearly corresponds to the geometry of the physical world in such a case. Such an iconicity between visual and linguistic representations would be particularly important in generating graphics in computer aided instruction.

## 5.3 Sentential Level Variables

### 5.3.1 Syntactic Placement of Information

As discussed in Section 4.2, the syntactic form of the constituent in which information is placed is one indication of its presumed importance. This variable appears in a number of hypotheses.

## 6 Hypotheses

As already noted, Phase II of this project will test the most interesting hypotheses suggested during the analysis of Phase I data, by presenting experimentally varied explanations (of the logic box task) to learners. Once the hypotheses have been selected and the test explanations constructed, we will develop suitable dependent measures of comprehension (verbal and/or behavioral). Subjects will be randomly assigned to experimental conditions so that, although subject knowledge and education may have some influence, it will not be specific to any condition. Thus, hypotheses about explanation effectiveness can be tested in terms of student comprehension.

This section gives some candidate hypotheses found so far. We expect that the statement of these hypotheses will be refined during the process of testing; i.e., that many of these hypotheses will not be tested in exactly the form given here, and some will not be tested at all. However, they all seem to represent reasonable intuitions about instructional processes and valuable directions for further investigation. The hypotheses to be tested will be selected according to the following criteria:

1. Potential application of the hypothesis to the improvement of human or computer based instruction.
2. Possibility of incorporating and varying the variables of interest in instructional discourse.
3. Possibility of accurate measurement of the degree of variation.
4. Possibility of holding other variables constant.

Notice that dependent measures can be constructed in at least three ways: (1) performance on physical tasks involving actual use of the logic box; (2) performance on comprehension tasks, such as multiple choice questions; and (3) performance on the task of generating an explanation based on that given by the instructor. Tasks of type (2) and (3) can be aimed at any of the five levels given in Section 4.1, but tasks of type (3) would be difficult to score. Now the hypotheses, subdivided into three main categories.

### 6.1 Discourse Level Semantic Hypotheses

1. Explanations at the combinatorial and logical levels will result in superior comprehension. (Explanations at the behavioral level will result in inferior comprehension because their cognitive structure is relatively simple and therefore they must rely on rote memory; explanations at the electronic or physical levels will result in inferior comprehension because they are too abstract for most learners. Note that this assumes dependent measures based on performance of tasks at the intermediate levels, since explanations whose cognitive level matches that of the comprehension instrument will get the best scores.)
2. Comprehension will be impaired if the focus changes among the direct subordinates of an AND, OR or SEQ node.
3. Comprehension will be assisted if the focus of a summary corresponds to the focus of the nodes that are being summarized.
4. Explanations based on semiotic morphisms that preserve the level structure, especially the basic levels (if there are any), will result in superior performance to morphisms that do not.
5. Explanations based on semiotic morphisms that preserve primary constructors (if there are any) will result in superior performance to explanations based on morphisms that do not.
6. Explanations based on semiotic morphisms that preserve properties at the expense of basic levels or primary constructors will produce inferior performance to explanations based on morphisms that preserve basic levels or primary constructors at the expense of properties.
7. Comprehension will be assisted by the presence of prior text reference.

### 6.2 Hypotheses at the Level of Discourse Structure

8. Comprehension will be assisted by the inclusion of summaries.
9. Comprehension will be assisted more by initial placement of summaries than by medial or final placement.
10. Comprehension will be assisted more by a broad tree than by a deep tree. A more precise formulation of this hypothesis is that structures with larger penetrance will be more easily comprehended than structures with small penetrance.
11. Comprehension will be assisted by explicit markers of discourse structure; these may be either verbal or visual.
12. Comprehension will be hampered by interruption of parallel structures, even if the interruption represents a summary.

13. Complexity of linguistic structure and strength of marking tend to attenuate within a parallel structure, and the greater the number of parallel items, the greater the degree of attenuation. Comprehension will by assisted by or unaffected by such attenuation of structural marking if the basis of the parallelism has been comprehended by the audience.
14. For novices comprehension will be superior with pseudonarrative structure rather than reasoning structure. (Note that all of the subjects will be novices.)
15. Comprehension will be superior if the focus and level of a summary correspond to the focus and level of the structure being summarized.

### 6.3 Hypotheses at the Sentential Level

16. Comprehension will be assisted if the strength of a POP marker is proportional to the size of the movement in the tree that it accomplishes.
17. Comprehension will be assisted by parallel syntactic placement of semantically parallel information units.
18. Comprehension will be assisted if information that is structurally important is placed in syntactically heavy constituents.

# I. Method

This appendix brings together various discussions from the main text on the methodology of Phase I of the project, including the order of experimental tasks, selection of subjects, and experimental procedures employed, and also outlines the methodology of Phase II.

## I.1 The Order of Experimental Tasks

### I.1.1 Phase I

The first series of project activities has been directed toward the design of explanatory protocols for experimental test in Phase II.

1. A circuit diagnosis problem (see below) was presented to individuals whose teaching should benefit from the proposed improved instructional paradigms. We used faculty in engineering and electronics at a local community college as instructors, and community college students with no background in engineering or mathematics as subjects. The instructors were briefed on the problem, and then asked to present material to prepare students to perform the indicated task. A variety of briefings were tested before a suitable one was determined. The first presented the logic box as a piece of equipment coming off an assembly line which was to be tested by the student. This briefing proved to be unsatisfactory because it elicited only explanations at the behavioral level, and could not be used to elicit any of the more complex cognitive levels. The second form of briefing presented the box as the control device of a set of sluices, and the final version elaborated this to a control device for an irrigation system providing varying mixtures of fertilizer and water.
2. Five instructors were used as subjects in six experiments. All experiments were recorded on audio tape and then transcribed, yielding a total of 124 pages of transcript for the instructor briefing and subsequent instructional session. (There are also debriefings for students and/or instructors for some sessions.) Each such session lasted between one-half and one hour. The first two experiments used the same instructor, and also used groups of community college students as an audience, 4 students in the first and 5 in the second. Instructors' presentations were recorded on audio tape.
3. Following elicitation and transcription, we then analyzed the structure of the explanations obtained using current linguistic theory. This required studying linguistic strategies at the levels of the sentence and the discourse unit, and also studying the effect of different kinds of questions asked by students on the elicited explanation structure. This analysis makes use of the mathematical theory of discourse structure.

This analysis was used to identify significant variables and to formulate hypotheses about relations between linguistic form and task performance. These hypotheses are presented in Section 6.

4. The last step in Phase I was the preliminary selection of the most interesting hypotheses for experimental testing in Phase II. Selection is based on the following criteria: likelihood that the hypothesis will have significant effects on learning; possibility of incorporating and varying the variable of interest in a natural discourse; possibility of accurate measurement of the variable of interest; and possibility of holding the other variables present constant.

### I.1.2 Phase II

In this phase of the project, we will first collect and analyze video-taped versions of our explanation task, since the analysis of the audio-taped experiments of Phase I indicated that some of the most theoretically interesting and practically important issues of multimedia instruction can only be studied using video data. We will then refine the hypotheses in the light of this data, and subject the most promising hypotheses to experimental validation. The tasks of this phase are the following:

5. We will perform at least two video-taped sessions of the instructional task, and will analyze the forms of multimedia instruction using the theory of semiotic morphisms already developed.
6. Based on the results of the Phase I, and task 4, we will make a final selection of the most promising hypotheses for testing.
7. To test these hypotheses, standard variations of explanations of the circuit diagnosis problem will be administered to groups of learners. These may be given by actors, via videotape, or by computer. While the cell design depends on the nature and number of independent explanation variables that emerge from Phase I, enough subjects will be tested to enable statistical generalization (e.g., at least 30 per cell of the design).
8. If the results suggest it, follow up trials will be conducted with promising combinations of variables or setting (e.g., with vs. without interactive discussion; with vs. without diagrammatic aids).
9. Dependent measures of effect (including both test and task performance) collected from learners will be examined by analysis of variance. In addition, effects will be assessed to determine the contribution (if any) of exogeneous variables such as age, education level, and previous work history on learners' response variables.
10. Learning data will be examined primarily by means of analysis of variance where alternative explanatory approaches serve as independent variables and test (verbal) and

task (behavioral) outcomes serve as dependent variables. Associations among background variables and dependent measures will be assessed correlationally; exogeneous variables that importantly influence outcomes can be incorporated into major analyses as covariates. Results of these analyses are expected to contribute both to basic understanding of the effectiveness of alternative explanation approaches and to provide a foundation for recommendations addressed to the design of an automatic explanation generator, and to the improvement of instructional discourse.

## I.2 Procedures

The task for both the elicited explanations and the learning trials makes use of the logic box of Figure 1. This box has two switches and four lights, each light being a logical function of the positions of the two switches. In Phase I, instructors were shown the box and how it works; they were then requested, in a nondirective manner, to provide an explanation of how it works to a "typical" group of students.

In the second part of Phase II, groups of students will be presented with instructions about how the logic box works. Then each will be tested, both verbally and behaviorally, for comprehension. Phase I procedures have been administered to subjects (instructors) individually, while Phase II procedures apply to groups. Data from Phase I consists of verbatim protocols for linguistic analysis, while data from Phase II will consist primarily of standardized test and task scores for statistical analysis.

## I.3 Subjects

Subjects for Phase I procedures were community college instructors who are accustomed to giving explanations of circuit logic. Elicitation continued until a variety of patterns had been observed and replicated.

Subjects for Phase II will be individuals (male and female) aged about 17 to 25 who are not specially trained or experienced in circuit logic. The N will be determined by the cells of the design for testing hypotheses generated in Phase I efforts. A minimum of 250 and a maximum of 550 subjects are anticipated.

# II. Grammar of the Command and Control Speech Act Chain

## II.1 Categories of the Grammar

This appendix discusses the command and control speech act chain, a specific kind of speech act chain which is the most typical discourse type for aviation discourse. In the most general sense, these rules can serve as an example of how any speech act chain can be analyzed. More specifically, we have found that the command and control speech act chains characteristic of aviation discourse are formally identical to the speech act chains of instructional discourse, in the sense that the same formal grammar describes them.

In the aviation context, operationally relevant speech act chains typically concern possible actions or actions that have already been performed. According to the usual definition [Searle 69, Searle 71], speech acts can also be seen as linguistic acts that alter the perceived state of the world. This subsection presents a category system that includes both linguistic and physical acts; this is necessary for the formal description of the command and control speech act chains.

The most general category is **acts**. This includes **physical acts**, **command and control speech acts**, and **acknowledgements** of such speech acts. A more specific category is **speech acts**, the basic category of interest for command and control. This category includes **requests**, **reports**, and **declarations**.

Additional utterance categories of interest for the command and control speech act chain are plans and explanations, which may be embedded within a command and control speech act chain. (Plans and explanations as they occur in the command and control speech act chain are the same discourse types discussed in Section 2.1.)

## II.2 Subordination

This subsection discusses the elements used to construct command and control speech act chains. These elements are of two types: the speech acts used in command and control; and the subordinators that indicate the relationships among them. The present discussion focusses on how these categories function within the formal grammar of command and control speech act chains. An abbreviation for use in graphical representations is given for each subordinator; these abbreviation use "square brackets," i.e., [...].

1. **CHAIN:** This node type is the top level subordinator for a sequence of command and control speech acts having the same major propositional content and constituting a command and control speech act chain. This node therefore marks the fact that a sequence of utterances is indeed a speech act chain; it is not usually indicated explicitly in the actual sequence of utterances. The abbreviation is simply [CHAIN].
2. **REQUEST:** Requests are the most typical command and control speech acts. They include questions, commands and suggestions. (A command can be viewed as a request that has been ratified by the speaker with relevant authority.) In the formal grammar, a request must have the form of a request node subordinating a single subtree, which is the act that is requested. (Searle's taxonomy calls these "directives.") The abbreviation is [REQ].
3. **REPORT:** A report is an indication of some state of the world. The abbreviation is [REP]. In the formal grammar, reports have the form of a [REP] node subordinating a single subtree giving the act or state reported. (11b) is an example.

    **(11a) CAM-2 Ah, what's the fuel show now buddy?**

    **(11b) CAM-3 Five**

    **(11c) CAM-2 Five**

    **(1748:54)**

4. **ACKNOWLEDGE:** A command and control speech act (e.g., a request or declaration) can be acknowledged; but challenges, supports, and other acknowledgements cannot be acknowledged. (This is the kind of constraint on sequencing that the rules below are intended to capture.) For example, (11b) is an acknowledgement. The abbreviation is [ACK]. An [ACK] node indicates the subordination of an acknowledgement to the speech act that it acknowledges.

    **(12a) C-1 You gotta keep em running, Frostie**

    **(12b) C-3 Yes, sir**

    **(1808:42)**

    Two interesting further points about [ACK] nodes are: (1) the speaker of an acknowledgement must be among the addressees of the request or report that it acknowledges; and (2) more than one addressee may produce an acknowledgement of the same speech act.
5. **STATEMENT/REASON:** Subordinates a request or report on the left, and a reason supporting it on the right. It is abbreviated [ST/RSN]. It may also occur in the opposite order, abbreviated [RSN/ST].

6. **STATEMENT/CHALLENGE:** Subordinates a request or report on the left, and a challenge to it on the right. It is abbreviated [ST/CH]. It may also occur in the opposite order, abbreviated [CH/ST].
7. **GOAL/PLAN:** Subordinates a goal on the left, and a plan to achieve it on the right. Abbreviated simply [GOAL/PLAN]. It may also occur in the opposite order, abbreviated [PLAN/GOAL].

## II.3 Rules

This subsection gives the rules of the grammar for command and control speech act chains in simple English, and also in a graphical form in Figure II-1. This grammar expresses how these speech act chains are constructed in real time. It thus defines the sequences of operationally relevant speech acts that are possible in command and control discourse, and indicates some (but not all) of the sequences that are not possible. It should be noted that this is a grammar of social force rather than of linguistic form; that is, the rules apply to the social interpretations of utterances, rather than to the utterances themselves, or to the sequences of words or sentences that comprise them.

In this grammar, nodes that must subordinate other nodes have "square brackets," e.g., [ACK], and nodes that indicate categories that will later be filled have "pointed brackets," e.g., <REPORT>. The first two rules simply define subcategories of given categories. They are

1. A command and control speech act, abbreviated <SPACT>, may be a request, a report, or a declaration, abbreviated <REQ>, <REPORT> and <DECL> respectively.
2. An act, abbreviated <ACT>, may be a <SPACT>, an acknowledgement, or a physical act, abbreviated <ACK> and <PHACT> respectively.

The basic entity being formalized, the command and control speech act chain, is indicated by a [CHAIN] node; all the speech acts that constitute a given chain will be subordinated to one such node. The beginning of the production of a command and control speech act chain is a single [CHAIN] node with two subordinate <SPACT> nodes; the fact that there are two such nodes expresses the fact that there must be at least two speech acts in a command and control speech act chain. The basic rule of development for command and control speech act chains is simply:

3. A [CHAIN] node with n descendent nodes can be elaborated into a [CHAIN] node with n+1 descendents. This expresses the fact that a command and control speech act chain may be of any length; that is, it may contain any number of speech acts.

The next two rules are basically parallel; they indicate how <REQ> and <REPORT> nodes can be elaborated:

4. A <REQ> node can be expanded into a [REQ] node subordinating an <ACT> node. This means that any request is a request for an action, either a physical action or a speech act.
5. A <REPORT> node can be expanded into a [REPORT] node subordinating an <ACT> node. This means that any report is a report of an action, either a physical or a speech act or of a state of the world.

Next is a set of three rules that may be applied to any node [XX] that is either a [REQ] or a [REPORT] node subordinating an arbitrary subtree:

6. An [XX] node subordinating a subtree may be replaced by an [ACK] node subordinating [XX] with its subtree on the left, and an <ACK> node on the right. This means that any report or request may be acknowledged.
7. An [XX] node subordinating a subtree may be replaced by either: a [ST/RSN] node subordinating the [XX] node with its subtree on the left, and subordinating an <EXPL> node on the right; or a [RSN/ST] node with the same subordinate subtrees in the opposite order. This rule means that any report or request may be supported by giving a reason (RSN), having the formal structure of an explanation.
8. An [XX] node subordinating a subtree may be replaced by either: a [ST/CH] node subordinating the [XX] node with its subtree on the left, and an <EXPL> node on the right; or else a [CH/ST] node with the same subordinates in the opposite order. This rule means that any report or request may be challenged by a speaker giving an explanation of why it is a bad idea.

The final rule permits the introduction of planning.

9. A [REQ] node subordinating an arbitrary subtree may be replaced by a [GOAL/PLAN] node subordinating the [REQ] node with its subtree on the right, and a <PLAN> node on the left. This means that any request may be incorporated as part of a plan; that is, the simple process of requesting an act can be elaborated into the process of planning.

These rules are all given graphically in Figure II-1; graphical indications of focus of attention are also given there. An extended example is given in the following subsection, illustrating how these rules are used to analyze an actual command and control speech act chain.

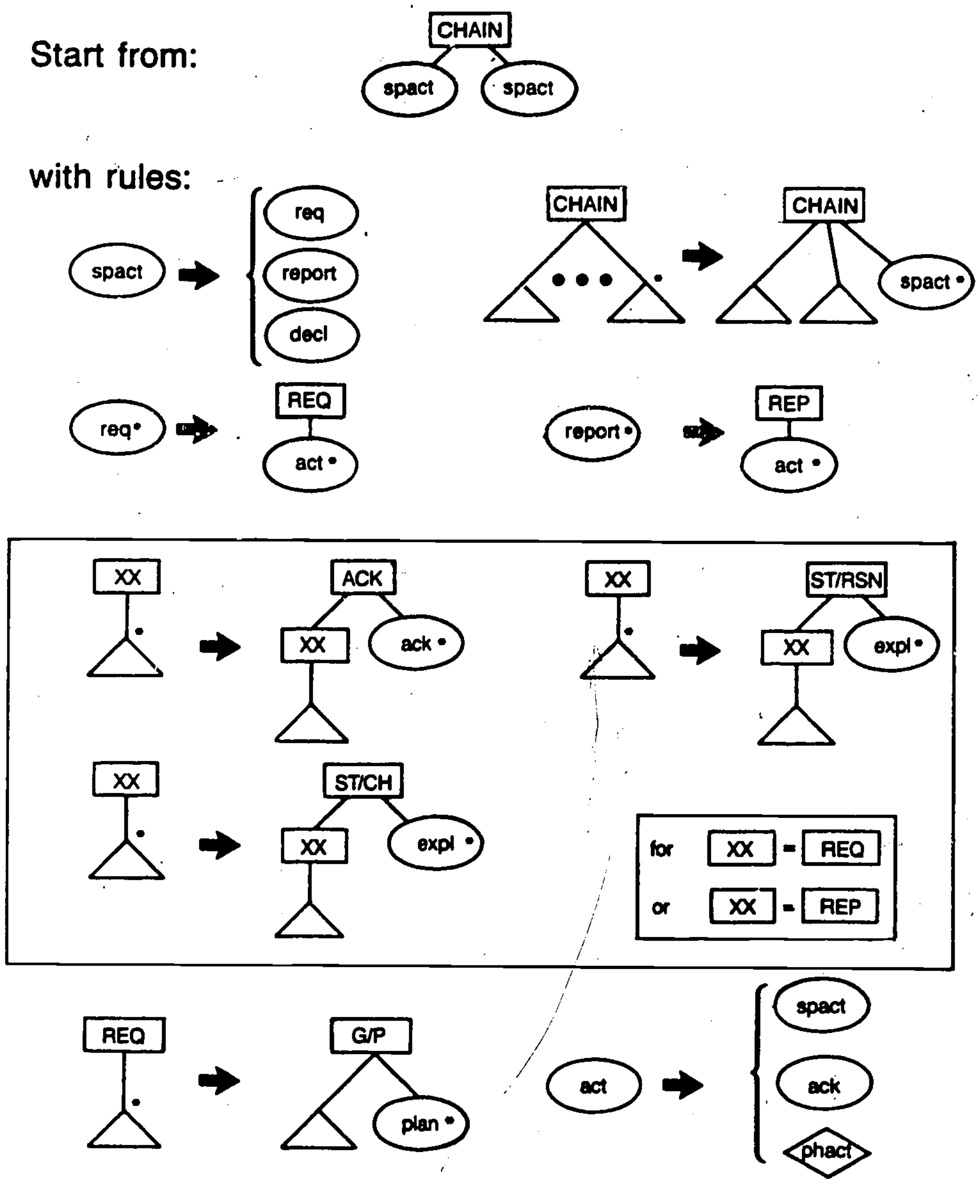


Figure II-1: Graphical Presentation of Command and Control Rules

## II.4 An Example of a Command and Control Speech Act Chain

The purpose of the preceding discussion has been to describe some constraints on command and control speech act chains, and in particular, to indicate some possible and impossible embeddings of social force. That is, we have attempted to specify what sequences of speech acts form command and control speech act chains, and what sequences do not. For example, an acknowledgement of a support of a request for an act A should not occur, although an acknowledgement of a request for an act A and a request for a support of a request for an act A may occur.

To illustrate this kind of sequencing, let us consider the data in example (13):

```
(13a)  CAM-1  Hey Frostie
(13b)  CAM-3  Yes sir
(13c)  CAM-1  Give us a current card on weight figure about another
                 fifteen minutes
(13d)  CAM-3  Fifteen minutes?
(13e)  CAM-1  Yeah give us three or four thousand pounds on top
                 of zero fuel weight
(13f)  CAM-3  Not enough
(13g)  CAM-3  Fifteen minutes is gonna really run us low on fuel here
(13h)  CAM-?  Right
                                                          (1750)
```

First of all, (13a) and (13b) form what is termed a "call-response" pair, that is, a call for attention followed by an acknowledgement that the addressee is attending. Using the concepts of this study, this can be seen as a request having empty propositional content, followed by an acknowledgement; it cannot be seen as a command and control speech act chain, because chains must have more than one subordinate node. Thus the pair (13a-b) is indicated as shown in Figure II-1, where Ø indicates empty propositional content. Adding (13c-d) to this yields the tree shown in Figure II-3, where **c** denotes the propositional content of (13c) and **d** that of (13d).

(13e) refines this propositional content to say that there will be three or four thousand pounds in fifteen minutes, denoted here as **e**. This is followed by an unusually strong challenge in (13f), the propositional content of which, **Not enough**, is indicated by **f** in Figure II-4. Rather

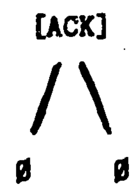


**Figure II-2:** A Call-Response Pair

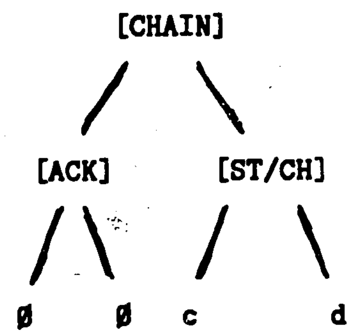


**Figure II-3:** A Challenge

than repeating the two subtrees of Figure II-3, we here denote them as **t1** and **t2**, respectively.

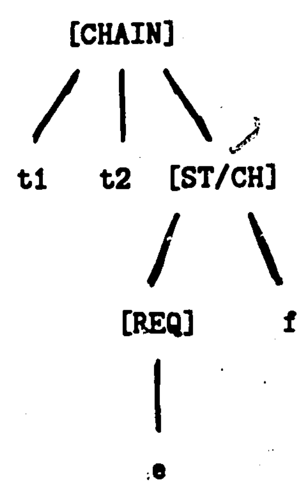


**Figure II-4:** A Further Challenge

Finally, (13g) is a supporting explanation of (13f), and (13h) is a support of (13g), and thus of (13f). Thus, the social force of this whole sequence could be notated as in Figure II-5, where **g** is the propositional content of (13g) and **h** that of (13h).

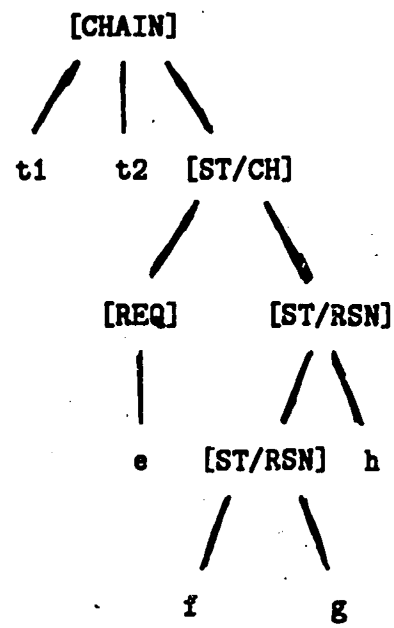


**Figure II-5:** A Complete Command and Control Speech Act Chain

## References


[Alston 67] Alston, William P.
Sign and Symbol.
In Paul Edwards (editor), *Encyclopaedia of Philosophy*, , pages 437-441. Macmilan & Free Press, 1967.
8 volumes; republished 1972 in 4 books.

[Barthes 57] Barthes, Roland.
*Mythologies.*
Seuil, 1957.

[Becker 81] Becker, Judith and Alton.
A Musical Icon: Power and Meaning in Javanese Gamelan Music.
In Steiner, Wendy (editor), *The Sign in Music and Literature*, . University of Texas Press, 1981.

[Carroll 80] Carroll, John M.
*Toward a Structural Psychology of Cinema.*
Mouton, 1980.

[Carroll 82] Carroll, John M.
Learning, Using, and Designing Filenames and Command Paradigms.
*Behavior and Information Techlogy* 1(4):327-246, 1982.

[Chomsky 65] Chomsky, Noam.
*Aspects of the Theory of Syntax.*
MIT Press, 1965.

[Eco 79] Eco, Umberto.
*A Theory of Semiotics.*
Indiana University Press, 1979.

[Gentner 83] Gentner, Deidre.
Structure-Mapping: A Theoretical Framework for Analogy.
*Cognitive Science* 7(2):155-170, 1983.

[Gentner & Gentner 82]
Gentner, Dedre and Gentner, Donald R.
*Flowing Water or Teeming Crowds: Mental Models of Electricity.*
Technical Report, Bolt, Beranek and Newman, 1982.

[Goguen, Weiner & Linde 81]
Goguen, Joseph, Weiner, James and Linde, Charlotte.
*Reasoning and Natural Explanation.*
Technical Report, Structural Semantics, 1981.
To appear in *International Journal of Man-Machine Studies.*

[Griffin & Mehan 81]
Griffin, Peg and Mehan, Hugh.
Sense and Ritual in Classroom Discourse.
In Coulmas, Florian (editor), *Conversational Routine: Explorations in Standardized Communication Situations and Prepatterned Speech*, . Mouton Publishers, 1981.

[Grosz 77] Grosz, Barbara J.
*The Representation and Use of Focus in Dialogue Understanding.*
Technical Report, SRI International, 1977.
Artificial Intelligence Center Technical Note 151.

[Kaplan & Bresnan 82]
Kaplan, Ronald and Bresnan, Joan.
Lexical-Functional Grammar: A Formal System for Grammatical Representation.
In Bresnan, Joan (editor), *The Mental Representation of Grammatical Relations*, . The MIT Press, 1982.

[Kieras 82] Kieras, David.
*What People Know about Electronic Devices: A Descriptive Study.*
Technical Report, University of Arizona, 1982.

[Kieras & Bovair 83]
Kieras, David E. and Bovair, Susan.
*The Role of a Mental Model in Learning to Operate a Device.*
Technical Report, University of Arizona, 1983.

[Labov 72] Labov, William.
The Transformation of Experience into Narrative Syntax.
In *Language in the Inner City*, . University of Pennsylvania Press, Philadelphia, 1972.

[Linde 74] Linde, Charlotte.
*The Linguistic Encoding of Spatial Information.*
PhD thesis, Columbia University, 1974.

[Linde & Goguen 78]
Linde, Charlotte and Goguen, Joseph.
The Structure of Planning Discourse.
*Journal of Social and Biological Structures* 1:219-251, 1978.

[Linde & Goguen 80]
Linde, Charlotte and Goguen, Joseph.
On the Independence of Discourse Structure and Semantic Domain.
*Proceedings, 18th Annual Meeting of the Association for Computational Linguistics, Parasession on Topics in Interactive Discourse* :35-37, 1980.

[Linde & Labov 75]
Linde, Charlotte and Labov, William.
Spatial Networks as a Site for the Study of Language and Thought.
*Language* 51, 1975.

[Nilsson 71]
Nilsson, N.
*Problem-Solving Methods in Artificial Intelligence.*
McGraw-Hill, 1971.

[Peirce 65]
Peirce, Charles Saunders.
*Collected Papers.*
Harvard University Press, 1965.
6 volumes; See especially Volume 2: Elements of Logic.

[Ross 73]
Ross, John Robert.
A Fake NP Squish.
In Bailey, Charles-James N., and Shuy, Roger (editor), *New Ways of Analyzing Variation in English*, . Georgetown University Press, 1973.

[Saussure 74]
Baskin, Wade (editor).
*Course in General Linguistics.*
Fontana, 1974.

[Searle 69]
Searle, J. R.
*Speech Acts.*
Cambridge University Press, 1969.

[Searle 71]
Searle, John.
What Is a Speech Act?
In Searle, John (editor), *The Philosophy of Language*, . Oxford University Press, 1971.

[Sinclair & Coulthard 75]
Sinclair, J. McH. and Coulthard, R. M.
*Towards an Analysis of Discourse.*
Oxford University Press, 1975.

[Stevens & Collins 80]
Stevens, Albert and Collins, Allan.
Multiple Conceptual Models of a Complex System.
In Snow, Richard E., Federico, Pat-Anthony, and Montague, William E (editor), *Aptitude, Learning, and Instruction, Volume 2: Cognitive Process Analyses of Learning and Problem Solving*, . Lawrence Erlbaum Associates, 1980.

[Stevens & Steinberg 81]
Stevens, Albert and Steinberg, Cindy.
*A Typology of Explanations and Its Application to Intelligent Computer Aided Instruction.*
Technical Report, Bolt, Beranek, and Newman Inc, 1981.

[Structural Semantics 83]
Goguen, Joseph and Linde, Charlotte.
*Linguistic Methodology for the Analysis of Aviation Accidents.*
Technical Report, Structural Semantics, 1983.
Report NAS-3, to NASA, Ames Research Center.

[Wasow *et al.* 82]
Gawron, J.M., J.J. King, J. Lamping, E.E. Loebner, E.A. Paulson, G.K. Pullum, I.A. Sag and T.A. Wasow.
Processing English with a Generalized Phrase Structure Grammar.
In *Proceedings, Twentieth Annual Meeting of the Association for Computational Linguistics*, , pages 74-81. ACL, 1982.

[Weiner 79] Weiner, James L.
*The Structure of Natural Explanation: Theory and Application.*
PhD thesis, UCLA, Computer Science Department, 1979.
Also published as Report SP-4035, Systen Development Corporation, Santa Monica, CA, October 1979.

[Worth & Adair 73]
Worth, Sol and Adair, John.
*Through Navajo Eyes: An Exploration in Film Communication.*
Indiana University Press, 1973.

[Yngve 60] Yngve, Victor H.
A Model and an Hypothesis for a Language Structure.
*Proceedings of the American Philosophical Society* CIV(5):444-446, October, 1960.

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