A Computational Neurolinguistic Approach to Processing Models of Sentence Comprehension

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ABSTRACT

HOPE, a first pass version of a simulation model of natural language processing which is simultaneously a modelling tool is described.

The multidisciplinary approach to its design and implementation which emphasizes behavioral evidence reported in the neurolinguistic literature is discussed. The critical processing constraint of "lesionability": that processing must continue in the lesion state without redesign or reprogramming, albeit in a degraded fashion, is discussed in the context of clinical studies. Psychological validity claims of current artificial intelligence models are shown to be inadequate under the "lesionability" criteria applied to HOPE.

The assumptions of the model are described and justified within the disciplines of neurolinguistics (including clinical aphasiology), linguistics, psycholinguistics, and artificial intelligence.

Serial and parallel computations within the model, in conjunction with the use of a cooperative-competitive control paradigm as found in neural network perception models is discussed. Memory management that is crucial to the control paradigm includes use of spreading activation and automatic decay.

Finally, simulation runs of a test model defined within HOPE are presented. Using a single sentence from a cover set of sentences defined for the test model, a normal and simulated "lesion" run are described and discussed with respect to their possible clinical interpretations. Validation techniques are suggested to demonstrate how a model such as HOPE will continue to evolve.

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> Pandora was sent in good faith, by Jupiter, to bless man. She was furnished with a box, containing her marriage presents, into which every god had put some blessing. She opened the box incautiously and the blessings all escaped, HOPE only excepted (Bullfinch, 1894, pg. 20).

1. Introduction

In a paper entitled "Neurolinguistics Must Be Computational" (Arbib and Caplan, 1979) the authors advocated adoption of a computational approach to the study of aphasiology. They further suggested that the computational model be designed using a control strategy based on interaction among knowledge representations similar to that demonstrated in models of neural network decision processes (Amari and Arbib, 1977; Anderson, Silverstein, Ritz, and Jones, 1977; Reiss, 1962). Their claim was that new insights and dimensions in understanding how the brain processes language could evolve by adopting such an approach. This paper will discuss the underlying issues in defining a computational model as suggested and will describe HOPE, a version of such a model, including its theoretical linguistic, neurolinguistic, psycholinguistic, and computational claims.

The challenge of adopting an interactive control strategy using an Artificial Intelligence (AI) approach to the problem is better stated as several issues:

1. Can human behavior be adequately defined to build a computerized model of it?
2. Do the studies of neurolinguistics, psycholinguistics, and psychology provide the "right kind" of information to develop such a model or are different techniques necessary to obtain better data?

Building an AI model requires explicit definition of representations of all relevant factors in the behavior being modelled. A rich literature of relevant empirical evidence exists in studies of psycholinguistics, neurolinguistics, and aphasiology. For this reason applying AI methodology to develop the suggested model seemed plausible.

Furthermore, a goal in designing and developing such a model is to determine if the assumed representation and processing hypotheses used in it can aid in sharpening our concepts of the processes underlying the behavior. In other words, can computational design decisions find a counterpart in the modelled behavior, enhancing our understanding of the behavior?

Questions raised by researchers in aphasiology, neurolinguistics, psycholinguistics, and psychology with respect to language behavior provided additional inspiration to design and implement the model. Hypothesized interactions among knowledge shown to be relevant can not be empirically tested. With pencil and paper, computations factors--such as timing synchrony of interaction--can not easily be studied. A computer model designed to include facility to vary timing control during processing can perform the computations consistently and provide a valuable tool for analyzing possible effects of such factors on processing.

Models such as HOPE are dynamic not only in their processing design, but also in their modifiability. As more knowledge is gained regarding cognitive representations, it can be incorporated into the model. Assumptions about representations shown to be critical in the process itself can be empirically validated using psycholinguistic or neurolinguistic tests. Discrepancies can be used to better refine the model definition. The process of validation can also contribute to defining new methodologies in clinical experimental testing procedures. HOPE is intended to be used in both ways.

In summary, the following statement from Jenkins, Jeminez-Pabon, Shaw, and Sefer (1975; pg. 69) expresses the goals of implementation and design of the model as well as the criteria to be aimed for in a unified theory of aphasia:

1. a general description of the nature of multilevel support for the normal process (the standard), and
2. a description of the functional organization of the system which when negated by fault propagation results in the observed positive and negative symptoms.

1.1 The Problem

Can the variability of linguistic performance demonstrated by normals and present within clinically classified groups of aphasics be modelled in a computer? What knowledge structures and representations are critical in normal language processing and how are they affected by brain lesion?

One way of studying these questions is to develop a modelling tool which permits explicit definition of hypothesized representations and defines interactions among them in a modifiable way. To develop such a tool, one must assess potential representations and hypothesize their interactions. A suggested approach to determining potential representations and interactions is to use empirical evidence which is already available. An abundance of such evidence exists but is reported in studies within frameworks of several related but distinct disciplines. For this reason, the interdisciplinary premises of HOPE are derived from conjoint consideration of aspects of language processing as seen within the distinct disciplines of linguistics, neurolinguistics (including aphasiology) and computer science.

1.1.1 Interdisciplinary Approaches -

Each discipline approaches the study of natural language within differing basic assumptions. Results of studies conducted within each discipline are reported within their "model" of what constitutes natural language and how to characterize it. One of the difficulties in designing an interdisciplinary model is to reconcile these results. A brief introduction to the bases of each approach will illustrate the nature of the problem of integrating these different perspectives.

Linguistics provides a theoretical approach to natural language. Studies are based on Chomskian transformational approaches to language or on semantically related approaches within a Chomskian framework (cf. Chomsky, 1957; Chomsky, 1965; for a description of the basic transformational--generative--theory of language). A multitude of competing theoretical frameworks have been proposed since 1965, and Chomsky's current proposals are very different from those of his earlier work (cf. Chomsky, 1980; and Chomsky, 1982).

Basic assumptions within the transformational theory include separate components for phonology, syntax, and deep structure. Base Phrase Structure Rules, Lexical Insertion Rules, and Transformations constitute the syntax; Interpretive Rules relate syntactic structures to semantic and phonological representations. The goal of linguistics is to explain language within the formal system established among these components.

Neurolinguistics includes the study of aphasia from both a theoretical linguistic perspective (competence approach) and a clinical performance perspective (performance approach) (Goodglass, 1978; Preface). Neither approach specifically addresses issues of how language is achieved. Competence based approaches relate observed pathological language behaviors to the linguistically posited components of language representations and their transformational structure. These studies of aphasia assume representations at the levels of phonology, syntax, and deep structure with associated transformations as do the linguists. The exact role of semantics in neurolinguistic studies is not clearly elaborated.

In contrast to the competency based approach, performance based approaches study language behavior as an artifact of lesion. Models assumed within aphasiological studies seek to define the breadth and kind of representations available in pathology. They test under the assumption that there is multimodal sensory access and representation of meaning in the brain. (For an elaboration of the underlying assumptions within performance based approaches, see Goodglass and Kaplan, 1972; Jenkins, Jiminez-Pabon, Shaw, and Sefer, 1975; and Kertesz, 1979.) These studies report on meaning associates, sensory feature availability, picturability of words and whether words represent objects, actions and their level of abstractness. Other performance studies assess the similarity of and use of structural (syntactic) and semantic cues. As in the linguistic and competence based studies, performance based studies are not concerned with process, but with characterizing the phenomena.

Computer scientists approach natural language processing within the study of Artificial Intelligence (AI). AI characterizes specific instances of input and the "typical" human response under a specific (adequately constrained) task based on that input. The development and evolution of the underlying program to effectively "compute" the appropriate output from a given input is the goal of the study. Often additional computational constraints ("real" time, memory size) or theoretical constraints (linguistic, psychological) are included in the overall task. Here the "discovery" of an effective process between assumed representations is the focus of the study.

Also within the realm of computer science, and related to the problem of behaviorally defining a process model, is the study of neural modelling (or brain theory). In these computer studies, mathematically constrained systems are developed and their dynamics studied to determine the scope of functions that they can subserve in processing. These studies are similar to analyzing the scope of functions a selected group of computer components can accommodate. Another aspect of neural modelling is developing mathematically constrained models which exhibit a specific "neural" behavior such as hysteresis or pattern classification. The pattern classification models also involve associative learning and tuning procedures to effectively develop the models so that they adequately perform selected discriminations. These models are intimately concerned with process subserving a function. They use a vector representation of ones and zeroes for input and output and are not immediately concerned with how such a representation might occur in the physical system being modelled. The design within these models often relies on physiological data and neuroanatomical evidence of processing (within lower vertebrates).

The challenge of developing a neurolinguistically based process model of language comprehension included integrating aspects of all of these levels of modelling. Assumptions of representations in the current model, such as phonology, syntax, and semantics, were included because of personally observed aphasic performance and reported theoretical and performance based neurolinguistic evidence. The linguistic assumption of transformational characterization is not ignored, but is not assumed to define the processing strategy between representations. Rather the process is orthogonal to linguistic theory, and applies neural modelling approaches to processing as its basis. In this sense it is like an AI model, developing a program to perform an effective mapping. However, the control strategy, based on neural modelling, introduces a neurologically plausible processing strategy which ideally can evolve to enhance our understanding of linguistic process by neural mechanisms.

Transformations in the linguistic sense are not the goal of this evolution. Rather, the goal is an understanding of processes which might be characterized by suitable transformations. Process modelling, based on linguistically assumed, clinically observed characterizations defines these characterizations explicitly and attempts to discover the nature and mechanisms that effect their "transformations."

In addition to constraints adopted from the above disciplines, HOPE incorporates two basic assumptions:

1. Language processing can be modelled in a cooperative-competitive manner by using interacting knowledge representations, and
2. The working model of the parsing process in normals can be so designed that aphasic language processing deficits can be produced by systematic degradation of the models. This assumes that aphasic processing is a degradation of normal processing.

To obtain the implemented version of the model of normal processing several sub-problems required solution:

1. Demonstration that it was possible to maintain processing control of the natural language parsing model within the interacting modules, rather than by using an external source of control (cf. Bobrow, 1978; Bobrow and Webber, 1980; Cullingford, 1981; Erman, et al, 1980; Marcus, 1978; Riesbeck, 1975; Rieger, 1978; Robinson, 1982; Schank, 1975; Woods, et al, 1976; and Small, 1980).

2. Modular design and inplementation of the interacting knowledge representations to permit subsequent experimentation using either different processing strategies or different representation schemas, or both.

3. Definition of a fragment of English sufficiently robust to include processing that would provide simulated performance evidence to be correlated with actual linguistic performance, specifically of agrammatic aphasics, but which would not prohibit correlation with other clinical aphasic types. At the same time, the fragment had to be linguistically concise and theoretically substantiated.

4. Specification of a grammar that was flexible in its prediction of constituent structure so that the interaction among the competing knowledge structures, both syntactic and semantic, could inherently resolve ambiguities, and at the same time adequately constrain the search space.

1.1.2 Neurolinguistic Hypotheses and the Model -

A critical observation in aphasiology research is that the observed behavior is the artifact of processes which are no longer intact. Processing in aphasia does not cease; rather, it is changed and results in observable modification of language behavior. This fact is the most critical constraint placed on the model. The model must be designed to process language in a manner considered to be "normal;" it must contain in its design means to simulate hypothesized lesions, and without redesign or reprogramming be able to produce some observable result.

To design simulation models of aphasic performance one must assess possible lesion simulations to be included and specify how they can be effected. Based on clinical observation of aphasic patients, and evidence as presented in neurolinguistic studies and standardized tests (cf. Bradley, Garrett, and Zurif, 1980; Brookshire, 1978; Caplan, Matthei, and Gigley, 1981; Duffy, 1979; Geschwind, 1965; Goodglass and Kaplan, 1972; Kolk, 1977; Lesser, 1978; Jenkins, Jiminez-Pabon, Shaw, and Sefer, 1975) possible hypotheses of underlying causes of the observed performance deficits include:

1. Degradation of knowledge representation, such as elimination of elements of grammatical structure;

2. Inability to access knowledge; and

3. Memory limitations during comprehension processing.

Drawing on evidence of timing constraints in neural modelling and the importance of timing in aphasic performance (Brookshire, 1971; Katz, Blumstein, Goodglass, and Shrier, 1981; Laskey, Weidner, and Johnson, 1976; Liles and Brookshire, 1975), a fourth hypothesis was formulated:

4. Timing coordination between types of information that interact during processing is a relevant factor in comprehension.

Within simulation contexts defined by the manipulation of the hypothesized lesion effectors, the model will make predictions of certain subtle processing deficits which can be utilized as the basis for the design of psycholinguistic studies to be conducted with clinically classified aphasic patients for verification or falsification. Results of these studies will be used to modify the model, make additional predictions, and suggest subsequent clinical studies.

1.2 Summary

HOPE, the model to be described, is a first pass version of an AI simulation model of natural language comprehension using a cooperative computation control strategy for studying degraded comprehension performance based on evidence from aphasia. It is also an experimental tool. As such, HOPE defines a set of simulation models. It will require extensive validation. The example model that is used the following discussions processes simple declarative sentences with either an intransitive verb or transitive verb with direct object.

The scope of linguistic structures which can be processed in HOPE will be experimentally determined. In designing the model many assumptions are known to be too simplistic. One obvious case is failure to take word usage frequency into account in processing. It will be interesting to see where the lack of this information becomes critical in expanding the linguistic structures which the model processes.

The model is designed with many "stubs," places where characterizations are known to be inadequate; but in a first pass some things had to be ignored. These stubs provide links to additional processing considerations and additional definition of knowledge representation.

As an experimental tool, HOPE permits redefinition of the lexicon, the grammar, interpretation functions, and case-control-information. It allows the experimenter to simulate lesions based on knowledge representation degradation, change in the effectiveness of propagation, modification of timing synchrony of interaction, or timing of new word introduction, alone and in combination.

The validity of the model as an experimental tool will be determined by relating its performance to the performance of aphasic patients on language comprehension tasks. Any discrepancies will be used to refine the model.

It is to be expected that this first model will undoubtedly make many false predictions because of the numerous intermediate and interactive hypotheses at every level, from the categorization of particular words and the form and content of knowledge representations to the nature of the parsing process. Whether any direct correlation with aphasic lesion data can be found is an indeterminable question at this time. However, a better determination of clinically observable phenomena should result. The intended value of the work lies not so much in the specifics of each possible hypothesis instantiated in the model, but rather in the demonstration of the utility of such a model for testing and refining hypotheses in a domain where complex interactions of subsystems whose effects are not independently observable makes testing by simple inspection of the fit of the data to the theory impossible.

The remainder of this paper includes background discussions of various aspects of the problem definition and provides examples of processing interactions of the model. Section 2 discusses our current understanding of the comprehension abilities of aphasics. Section 3 discusses AI models of natural language comprehension as possible neurolinguistic models. Section 4 describes HOPE's control strategy and contains an example of a cooperative computation. In Section 5 the linguistic assumptions of HOPE are discussed. Section 6 describes a "normal" model, as defined within HOPE. Section 7 includes examples of normal processing and a sample lesion experiment on the defined model. Concluding remarks are found in Section 8.

2. Comprehension and Aphasia

Many studies of aphasia attempt to distinguish different behavioral characteristics and to relate such characteristics to the site of lesion. Clinical classification of aphasia tends to emphasize the language production performance of patients. For example, using the Boston Diagnostic Aphasia Examination's patient profile characterizations (Goodglass and Kaplan, 1972), based on a running sample of free speech, the factors defining classification are:

> melodic line (intonational pattern), phrase length (longest utterance in free speech which may occasionally be produced), articulatory agility (ease of articulation), grammatical form (variety in types of sentences produced), paraphasia in running speech (semantically inserted erroneous words or neologistic paraphasias during free speech), and word finding (based on the informational content of speech). In addition a scale of auditory comprehension is determined by finding the z-score of the average of four auditory comprehension subtasks within the exam (word discrimination, body-part identification, commands, and complex ideational material, i.e. ability to agree or disagree with verbally presented stimuli such as "Will a board sink in water?"). All scores are interpreted within another evaluation based on the severity of deficit (a measure of the patient's ability to communicate, from 0 for no communicative ability, to 5 for no perceptible handicap). (Goodglass and Kaplan, 1972; pp. 25-29) .

Until recently, parallel communicative facility in production and comprehension performance was assumed (Kertesz, 1979; pg. 3) The validity of this assumption has been questioned in light of recent evidence that comprehension and production are not necessarily equally affected in any clinical group (to be discussed below). Furthermore, evidence that the production based clinical classes may be heterogeneous in comprehension characteristics has led to more detailed studies of the relationship between production and comprehension abilities.

Studies of comprehension are based on theoretical linguistic assumptions or psychological assumptions, or are carried on under the auspices of aphasiologists concerned with sensory modality related processing and characterization of same as related to clinical classification. The appraoches are not as distinct as suggested by the above labelling. There is great overlap in test methodology, borrowed from psychology, and characterization of basic components of language, such as phonology, syntax, and semantics from linguistic theory. The remainder of this section presents an overview of our current understanding of comprehension ability in aphasics as characterized by the literature from the various approaches.

The studies of aspects of comprehension which are assumed to be distinctive in processing and assumed to characterize a particular clinical class, provide the basis for representational constraints and suggested processing interactions in the current version of HOPE.

2.1 An Historical Perspective on Aphasic Language Comprehension

The general nature of comprehension disturbance in aphasia has been classified as good or poor and related to anterior or posterior left hemisphere lesion site since these correlations were first recorded. Early analyses of language pathology were documented as isolated cases correlated with primitive autopsy analyses. These original relations have continuted to influence the study and analyses of pathological performance.

Broca in 1861 reported that patients having a left hemisphere anterior lesion had good comprehension even though they were unable to verbally express their intent or show their comprehension. Wernicke, based on his observations in 1874, reported that patients with localized lesions in the posterior portion of the left hemisphere had poor comprehension. These views no longer are viable, as sufficient evidence exists that demonstrates that Broca's aphasics usually <u>do</u> have comprehension problems and that only temporal, posterior lesions produce the associated poor comprehension ability while other posterior lesions present different comprehension patterns which can be relatively mild. (Cf. Arbib and Caplan, 1979 for a brief discussion of the neurological based models and empirical support.)

Two competing theories of brain organization that developed based on the reported general performance attributes, and labeled "localizationist" vs. "connectionist," were summarized by Geschwind (1965) in his introduction to "Disconnection Syndromes in Animals and Man."

> Starting from the picture of the brain as a collection of sets of more or less specialized groups of cells connected by relatively discrete fiber pathways, these classical neurologists deduced a series of symptom complexes. On the basis of this model clinical syndromes could be divided into those resulting from lesions of grey matter and those which resulted from lesions of the matter interconnecting specialized regions (Geschwind, 1965; pg. 239).

In a process model these issues are not critical, because our present level of neuroanatomical sophistication prohibits any correlation with aspects of the grossly defined representations and assumptions employed in HOPE.

Leaving aside issues of specific neuroanatomical involvement, using only gross neuroanatomical correlations, aphasiology has begun to address the problem of determining the extent of linguistic and cognitive capacity associated with particular clinically interpreted syndromes. Since approximately 1958 (Goodglass, 1976; pg. 242), controlled experiments have provided evidence that relates stimulus to response. Goodglass warns, however, of the complexity and difficulty of the task of designing controlled experiments and the subsequent interpretation of what is observed.

> Two types of variables need to be brought under control. By manipulating the stimulus variable, it is possible to define more precisely exactly what causes the patient to fail and what permits him to succeed. This approach can be applied to the study in depth of individuals or of small collections of individuals who appear to resemble each other clinically....
>
> On the other hand, manipulation of subject variables is equally important. It is not sufficient to demonstrate grammatical failures by experiments on patients who are clinically agrammatic. It is possible that under similar test conditions, failures would be observed in individuals whose spontaneous and reactive speech is grammatically intact.... A patient's performance under test conditions may bear little resemblance to what he produces in free conversation (Goodglass, 1976; pg. 242).

Neurolinguistics, employing linguistic theory as the interpretation paradigm for clinical observations under controlled experimental conditions, has provided more detailed hypotheses of cognitive representation and function. These hypotheses and the results of such studies must be reconciled with those from the studies of aphasiologists to determine our understanding of comprehension processing in aphasia.

Keeping in mind the cautionary note of Goodglass (1976), we now turn to a discussion of these recent studies of aphasic comprehension. First we will review the studies related to competency issues within linguistic theory, then the linguistically prompted studies that additionally address some reference to physical parameters of processing, and finally, those studies which are based on a multi-modality specific performance characterization of natural language.

2.2 Recent Studies of Aphasic Comprehension

The complexity of language comprehension is reflected in the breadth of comprehension studies reported in the literature. In addition to determining severity of comprehension deficits, controlled studies have begun to analyze specific aspects of the comprehension process.

For historical reasons, studies for determining the critical factors in comprehension (both competency based and performance based) simultaneously attempt to relate the findings to currently accepted clinical evaluation and classification, or attempt to better define classification methodology among the aphasic syndromes.

Studies of auditory comprehension ability in aphasics have attempted to determine factors that are critical in both on-line sentence comprehension processing and during off-line lexical comprehension processing. Attempts have been made to determine the relationship between these two levels of processing ability. Studies of factors considered significant during on-line auditory comprehension processing, the effect of vocabulary and syntactic complexity, are reported in Parisi and Pizzamiglio, (1970); Pastouriaux and Brownell, (1981); Pizzamiglio and Appicciafuoro, (1971); Samuels and Benson, (1979); Schuell and Jenkins, (1961); Schwartz, Saffran, and Marin, (1980); Zurif and Caramazza, (1976); and Zurif, Caramazza, Myerson, and Galvin, (1974).

Parisi and Pizzamiglio (1970; pg. 206) studied syntactic abilities of clinically classified patients on

a) grammatical units such as prepositions,

b) order properties of words in sentences, and

c) bound morphemes and other syntactic devices

using a picture selection task. Rank ordering of difficulty of syntactic constructions for sentences designed to test one syntactic aspect showed no overall differentiation characteristic for aphasic type, Broca's, Wernicke's, and a combined group of mixed and global. Of interest in the results was the overall difficulty for all types in processing word-order related contrasts such as subject-object, active-passive voice, and direct-indirect object. Selective difficulty for certain prepositional relationships was also found, although prepositional contrasts were the easiest to comprehend in rank order of ability. Morphological contrasts of singular-plural and masculine-feminine were next easiest (Parisi and Pizzamiglio, 1970; pg. 211).

A study by Goodglass, Gleason, and Hyde (1970) assessed four factors assumed to be critical in auditory aphasic language comprehension to determine if they were characteristic for different aphasic groups. Factors studied included vocabulary, auditory memory retention span, interpretation of directional prepositions, and recognition of correct grammatical usage. Evidence was found that Broca's aphasics could comprehend prepositions. This study showed that for the clinical groups studied (classified predominantly by production ability), distinguishing patterns of comprehension abilities for each clinical group could be found with respect to the four factors studied. They also found, however, that the patterns of the distinguishing abilities were not sufficiently distinct (i.e. statistically significant) to be useable to clinically discriminate. Furthermore, the study concluded, "a patient's ability to comprehend a language feature presented orally was not necessarily related to his ability to produce that feature in his spoken language" (Goodglass, Gleason, and Hyde, 1970; pg. 606) in accordance with a conclusion reached by Shewan and Canter (1971; pg. 221).

Shewan and Canter (1971) addressed issues of vocabulary difficulty based on word frequency, syntactic complexity, and sentence length. There was no conclusive evidence relating sentence length, as measured by digit span recall, to comprehension difficulty in this study. The interpretation of this result was that the processing deficits were not caused by problems of short-term-memory capacity. The complexity of the syntax exerted the most influence on comprehension performance when controlling vocabulary and sentence length. In contrast to the Goodglass, Gleason, and Hyde (1970) study, but in agreement with Parisi and Pizzamiglio (1970), they found there was no evidence that an aphasic's expressive language deficits were good predictors of a patient's receptive abilities. There were no group defined differences in qualitative measures of comprehension (patterns of correct responses). The difference in performance between groups was noted in quantitative measures, such as the numbers of each syntactic sentence type correct.

Working within neurolinguistic assumptions, several studies have addressed the relationship of linguistic complexity and comprehension (Caramazza and Zurif, 1978; Kean, 1978; Scholes, 1978; Schwartz, Saffran, and Marin, 1980; and Zurif and Caramazza, 1976). These studies have centered around the use of articles as markers of syntactic disambiguation. Syntax is assumed autonomous. The role of semantics is acknowledged but not explicitly described.

Using center embedded sentences such as "The apple that the boy is eating is red.", Caramazza and Zurif (1978) reported that the most difficult sentences to comprehend for all groups--Broca's, conduction, and Wernicke's--were the subject-object reversal sentences. These are sentences such as "The boy that the girl is chasing is tall.", where "is tall" can be semantically related to either the subject, boy, or the object, girl. Broca's subjects had more difficulty when semantic constraints were not available, as in the reversible sentence. (This result received support from the study by Schwartz, Saffran, and Marin, 1980.) Caramazza and Zurif (1978, pg. 159) further claimed that there was no dissociation between the processing in production and comprehension for Broca's and conduction aphasics. For Wernicke's the results of this study were uninterpretable.

The use of semantic relationships in comprehension by Broca's aphasics as demonstrated by Zurif and Caramazza (1976), Caramazza and Zurif (1978), Schwartz, et al (1980), received additional support in the reading comprehension studies of Samuels and Benson (1979). Semantic weighting of the relations of the sentence constituents during reading was an important factor of comprehension for anterior aphasics. For posterior aphasics semantic bias made no difference in demonstrated comprehension ability regardless of mode of presentation.

Kean (1978) claimed that a theoretical phonological interpretation (a non-syntactic interpretation) explained the observed comprehension deficits of Broca's aphasics as previously discussed. She described the pattern of deficit for Broca's aphasics:

> Major lexical items which carry word stress typically are fully attended to, but function words and bound inflectional morphemes which occur phonologically as clitics on major lexical items and which do not carry stress are ignored.

She further claimed,

> that the only systematic characterization of the agrammatism, dysprosody, etc. of Broca's aphasia is solely in terms of phonological structure (Kean, 1978; pg. 128).

Schwartz, Saffran, and Marin (1980) provided counter evidence to the phonological theory in their study of comprehension. They demonstrated that syntactic functor marking was not sufficient to characterize the observed difficulty in Broca's aphasic's comprehension. In reversible sentences, if the phonological theory was adequate, then a simple word order analysis of the sentence should result. Contrary to this, they found that when verbs were neutral with respect to subject-object determination the word order hypothesis broke down. Verb control seemed to be critical as a semantic determiner during comprehension. Incorporating this evidence with that of a previous study (cf. Schwartz, Saffran, and Marin, 1978), they concluded that the linguistic deficit was in part syntactic, that a major factor in comprehension of grammatical morphemes was the function each served in the utterance.

Confirming support for this interpretation can be found in the study by Zurif, Green, Caramazza, and Goodenough (1976) on aphasic patients' sensitivity to functors (cf. Goodglass, Gleason, Bernholtz, and Hyde, 1970). This study reported that only those aphasics with good comprehension had the functional aspect of functors available. The same group was able to understand prepositions, an ability not available to those with poor comprehension.

Determination of the availability of information contained in articles during comprehension was carried out by Goodenough, Zurif, and Weintraub (1977). The test used a pointing response to the correct one of three pictured objects to demonstrate comprehension of spoken phrases which included "critical" determiner markers, such as "a black one" vs. "the black one." They found evidence that Broca's aphasics were unable to use articles to assign appropriate reference. Anomic aphasics in this study showed that in addition to longer response time, they attended to the content of the article in determining reference based on feature matching in a pragmatic way. If they were shown a black circle, a white circle, and a black square and told to point to "the black one," they pointed to the black circle, i.e. the black one of two circles. Broca's aphasics gave no indication of processing the article at all. There was no change in their latencies whether the article named was appropriate for the set of pictured objects or not (Zurif and Blumstein, 1978; pg.235).

Studies by Kolk (1978) and Caplan, Matthei, and Gigley (1981) have shown that the comprehension deficits in Broca's aphasia are the result of more than a deficit in functor usage. Kolk used a grouping task of the words of a declarative sentence which had adjective-noun vs. determiner-noun noun phrase definition as subjects and objects. Example sentences for each type respectively, are "Little girls eat sweet cookies." and "My dog chased their cat." (Kolk, 1978; pg. 620). He was able to show that, for aphasics, not only functors, but the adjectives were not grouped by surface constituent relations as they were by normals. His finding provided additional evidence that the phonological interpretation was not valid, as adjectives (content words) in his study were grouped in the same way as unstressed morphemes. He also noted a relationship between degree of severity and performance on the judgmental classification, distinguishing a high comprehension group and a low comprehension group across his clinically classified subjects.

A similar finding of two performance subgroups that cut across clinical classification occurred in the Caplan, Matthei, and Gigley (1981) study. One group of subjects was able to use grammatical relationships in comprehension. For the other group, the results indicated that the inablilty to use functor information was inadequate to describe the observed behavior.

In the Caplan, et al (1981) study, the phonological theory of bound morphemes was also demonstrated to be inadequate based on evidence using adjective adverb pairs that differed only in the bound morpheme. Regardless of the adjectival or adverbial context, the syntactic class of the following gerund was not appropriately influenced in a consistent manner. Rather, a more pragmatic strategy in determining the relationships in a sentence seemed to be used.

A recent study by Pastouriaux and Brownell (1981) further corroborates the fact that observed behavior deficits for Broca's aphasics are the result of more than inabilty to use functors. They reported on the significance of verb meaning in the comprehension process, specifically with respect to passive sentence comprehension by Broca's aphasics. They claimed that the number of thematic relations involved in the verb action of a sentence was relevant to the degree of comprehension of the sentence. The types of relations specified by the verb, such as spatial relations, and applied force that produced direct physical change were also significant factors in the degree of comprehension obtained when using different groups of verbs. It is interesting to note that Schank (1975) posited similar types of verbal relations as the "primitives" for semantic decomposition of verb meanings.

Previously discussed studies were based entirely on generative linguistic models of language stressing the definition of linguistic competency. They were not studies of process but instead hypothesized characterizations of representations and transformations on those representations that were consistent with current linguistic theory, and which could be inferred from the results of testing. Scholes (1978) reanalyzed the results of the above reported studies and other psycholinguistic studies to develop an alternative competency based model of sentence processing. His model was performance motivated, rather than within the motivational framework of generative linguistics. The model included syntactic and semantic aspects in parallel. He conjectured two parallel processes, one syntactic, that utilized inference rules to determine a deep structure representation, and the other lexical, using projection rules of semantic prediction to derive a deep structure representation in parallel. One important consideration omitted from the discussion of his parallel model was synchronization of the interaction of the parallel processes. Synchronization is critical if this model is to be considered as a process model. Scholes validated his model with additional clinical studies which demonstrated the inability of Broca's and conduction aphasics to use functor information. Within his studies, Wernicke's aphasics seemed to have a lexical problem; there appeared no way to determine if their syntactic processing were intact. These results supported those of Caramazza and Zurif (1978) and Schwartz, et al (1980).

Several neurolinguistic studies of aphasic performance have dealt with aspects of the processing of language. In attempting to explain the noted functor deficit during processing reported for Broca's aphasics, Bradley, Garrett, and Zurif (1980) reported evidence that differences existed in the accessing of closed class vs. open class (content) words. They were able to demonstrate that response latencies for Broca's aphasics did not show the same patterns for these two classes of words as they did for normals. The interpretation was that there were two access mechanisms available for normals (one for open class words and one for closed class words), but for aphasics only one (the open class access pathway). This single access facility was suggested as a possible cause for the functor deficit in processing.

The reported results of this study have been shown to be in error due to lack of control between the frequency of usage in the two classes of words (Gordon and Caramazza, 1980). Gordon and Caramazza demonstrated that the latency differences for the two classes of words in normals did not exist, and furthermore, that the relationship was non-linear above certain word frequencies, a factor not considered in the original analysis. This suggests that, if the functor deficit is a major factor in Broca's comprehension, it is not due to inability to access the closed class words in a normal manner, but instead is due to other aspects of closed class word processing.

Phonological discrimination and its role in the comprehension deficit was studied by Blumstein, Baker, and Goodglass (1977). They demonstrated that for Wernicke's aphasics, phonological discrimination was the same as for Broca's and that the problem in comprehension was not caused at the phonological level. It was hypothesized that for Wernicke's aphasics the problem was in relating the phonological representation to a meaning.

A more recent study by Katz, Blumstein, Goodglass, and Shrier (1981) investigated the effect of timing of auditory presentation on sentence comprehension by different clinically classified aphasics. For Broca's, conduction, and global aphasics, slowing of the input during auditory processing, for word recognition, and in normal continuous speech had statistically insignificant, although different quantifiable effects for each clinical group. Broca's comprehension decreased with increased between-word pauses; for conduction aphasics, comprehension increased for vowel elongation, and decreased in the same way as Broca's for between-word pauses; and for global aphasics, increased very slightly for all four timing modification conditions. Wernicke's aphasics demonstrated the only statistically significant increase in ability to comprehend sentences and only for increased silence at phrase boundaries. The study concluded that time effects in comprehension were not sole critical factors in performance deficits but rather that "it was the way in which the structural properties or cues used to gain meaning to a particular sentence were enhanced -- either syntactically or phonologically" (Katz, et al, 1981; pg. 11).

A similar study of the effects of rate of sentence presentation and syntactic complexity on sentence comprehension was reported in Lasky, Weidner, and Johnson (1976). They found that sentence complexity of the following types affected the degree of comprehension: 1. active-affirmative, 2. passive-affirmative, and 3. active-negative. Active-affirmatvie sentences were easier to comprehend across their aphasic population than were passive-affirmative, than were active-negative. They also demonstrated that the speed of presentation was a significant factor in comprehension ability. Comprehension was improved at a lower rate of speech. Additionally, interphrase pauses for both rates of speech employed in the study produced significant increases in comprehension ability. The results suggested that the effect of rate of speech and interphrase pause time might be additive, although it was not demonstrated by this study (Lasky, Weidner, and Johnson, 1976; pp. 391-392). (Cf. Brookshire, 1971, and Liles and Brookshire, 1975, for additional evidence that increased pause time has positive effects on the comprehension ability of aphasic individuals.)

That these studies measuring effect of time on processing are not in complete accordance can be due to differences in rate of slow down included in the studies, as well as the patient populations studied. The Lasky, Weidner, and Johnson study (1976) did not look at specific clinical types to determine more precisely which patients contributed to their overall observations and in what ways. (A similar problem is found in the studies of Brookshire, 1971; and Liles and Brookshire, 1975.) It was not clear that they used a homogeneous clinical group in their study which makes adequate comparison with the Katz, et al (1981) study impossible.

Finally, within the assumptions of performance based appraoches to aphasia, studies have addressed related issues to those already presented, but which concentrate more on the breadth and nature of the representations available for processing. Here the critical assumption becomes that of multi-modal representations underlying meaning.

To determine aspects of comprehension deficits, naming tasks, using selective stimuli presentation, provide clues to the accessibility of an internal representation via different sensory pathways (cf. Gardner, 1973; Goodglass and Baker, 1976; Goodglass, Barton, and Kaplan, 1978; Goodglass, Gleason, and Hyde, 1970; Goodglass, Klein, Carey, and Jones, 1966; and Mills, Knox, Juola, and Salmon, 1979).

For patients with known comprehension deficits, these studies attempt to determine whether the deficit is related to perceptual or conceptual processes, or whether it is stimuli specific, i.e. dependent on auditory, tactile, or visual input. Testing assumes there is a

> complex interaction between sensory-motor skills, symbolic associations, and habituated syntactic patterns, all at the speaker's intent to communicate, and subject to the intellectual capacity which he brings to the task of manipulating them so as to carry out his intent (Goodglass and Kaplan, 1972; pg.5).

The Token Test (DeRenzi and Vignolo, 1962) provides an example of the multimodal aspects used in standardized auditory comprehension testing. The test requires ability to associate spoken words with objects, to discriminate between objects and among objects using specific color, shape, and size attributes and, as the complexity increases, to further discriminate using stated positional relationships expressed by prepositions.

In attempting to determine critical factors of verbal association during lexical (off-line) processing (assuming words are representations of multimodal associates), studies have analyzed the availability of semantic feature attributes for spoken words and have assessed semantic relatedness judgements in contrast to those of normals (Goodglass, and Baker, 1976; Zurif, Caramazza, Myerson, and Galvin, 1974).

Goodglass and Baker (1976) studied the possibility of dissociation between the denotation of a referent and a spoken word. Using controlled semantic field definitions, the study employed the naming task as a measure of integrity of semantic field for the subject. They assumed that there were two types of semantic association based on investigations of word association in normals. These associations were based on single word verbal responses to a spoken word or sentence completion based on semantic prediction. The task measured associations within the following: supraordinate class, semantic attributes, contrast coordinate class (another name within the same supraordinate class), associated function of the object, context of function of the object, homonyms, and identity, by presenting an actual object in each class associated to the target by the assumed association relation. In the analysis, homonymity was ignored, as the intended association was not noticed by aphasics or by normals.

The study reported that the intactness of semantic field associations of nouns was affected selectively in aphasic subjects. For normal and high comprehension aphasics, a claim was made for a hierarchy of associations: identity, supraordinate association relation, attribute, and situational contiguity (functional context). These were followed by, in increasing distance of association relation, objects of the same category and verbs denoting characteristic actions carried out or demonstrating the target stimulus (function associations). Severe comprehension deficits showed a marked increase in difficulty in recognition of function associates (verbs) and an increase in difficulty for the functional context.

Supporting evidence for the use of specific attributes by Broca's aphasics in semantic association as opposed to supraordinate association by normals is described in the study by Zurif, Caramazza, Myerson, and Galvin (1974). Using cluster analysis techniques, they demonstrated that aphasics grouped words on specific attributes more readily than on class inclusion attributes, and that the groupings were characteristic within aphasic clinical class.

Summarizing, studies of comprehension in aphasics have concentrated on relating deficits in comprehension to classification based on performance. Analysis of specific hypothesized functor, or phonological characterizations of comprehension deficits were described. Effects of rate of presentation on comprehension ability have been studied.

Controversy as to the findings exists. Broca's aphasics do seem to have more ability than mere stringing together of words (Cooper and Zurif, to appear). However, the use of word order in processing was an acknowledged deficit for Broca's aphasics as was the use of semantic processes to define sentential relationships. For all aphasic groups, semantic feature associations for words were found to be different than in normals. Finally, little about comprehension processing for Wernicke's aphasics is interpretable beyond their ability to phonologically discriminate.

Although much of the evidence is controversial, it provides a first approximation to factors critical in language processing. Determining the relationships among the differentiated factors is a goal shared by the clinicians, the neurolinguists, and the designers of the model.

Much of the controversy stems from inadequately defined models within which the studies were conducted. Theories of transformational grammar do not include such aspects as explicitly stated assumptions about the lexicon, its representation, its function in the process of language. Likewise, the aphasiological theories do not precisely elaborate the model of what is assumed as a process underlying their statistically reported characterizations. These assumptions <u>must</u> be explicitly defined in a computational model. Even if the assumptions and definitions are incorrect, by explicitly defining them, one has concretely stated hypotheses in a manner which allows explicit validation or refutation.

HOPE employs the linguistically based components studied in the literature as its representations. It assumes a multi-modal representation underlying meaning, although not presently implemented within the model. It does not assume, as do the neurolinguists, a transformational processing model with separate syntactic and semantic analyses. Rather it attempts to provide a methodology for integrated syntactic/semantic processing in parallel that is time-coordinated and effected in a cooperative manner achieved through the assumed interconnected representations which achieves multiple access and multiple effect.

The question of whether the data is useful in the design of a process model has both "yes" and "no" answers. Clinical studies seek answers to questions that are relevant to designing a process model. However, the manner of reporting the results of the studies, as described above, provides inappropriate data for the design. Nevertheless, the studies do demonstrate aspects of the process which need to be distinguished, such as phonological versus syntactic, versus semantic, versus lexical, versus time related process.

The critical data that need to be used in model design, beyond the differentiated aspects of representation, are the error data. Only through careful analysis of the errors produced by patients can one begin to infer the interactions which might occur in the normal state. Knowing that a group of 10 patients of a particular clinical aphasic group has better performance under a certain type of condition does not indicate the role of that condition in the process. Looking at the explicit changes in processing performance attributed to the condition does provide the necessary information. This is not necessarily a quantized result, but rather a defined pattern of interaction where the relation of the inputs to the outputs provides the clues to process. The goal is to discover the process in an evolutionary way. This goal is similar to the AI approaches to natural language comprehension.

AI studies tend to concentrate on the input/output relationships observed in the human process, while simultaneously ignoring the human process which produces them. The developed and implemented program that effectively computes the "human-like" relationships between input and output is the AI theory of language processing. It is an alternative representation to transformations.

In the past, AI has sometimes included linguistic transformations and assumptions in the design of these programs. However, there has been no intent in AI models to simulate the human process which "computes" the input/output relationships, but rather to express a characterization of it. In this sense, HOPE goes beyond other AI models by including constraints of simulating human processing within the program design, a point which will be discussed at the end of the next section.

3. AI Models of Sentence Comprehension

In this section, a sample selection of AI models of language comprehension are reviewed in the light of the special considerations required for models which can be tested for neurological validity. One must keep in mind that previous AI models were not intended to be simulation models of language, as is intended in HOPE. AI models which claim psychological validity approach process simulation by including psychologically reported process constraints, such as number of buffers used, and short term memory limitations. However, as will be demonstrated, they are inadequate as simulation models because they fail to simultaneously account for processing variability of normal performance and degradation as evidenced in aphasic performance.

Depending on the scope of comprehension included in AI models, different types of knowledge, representations, and procedures are hypothesized. In discourse analysis more complicated inference methodologies are necessary for such problems as anaphoric reference (pronoun reference) than in single sentence, question answer models (Hirst, 1981; Robinson, 1982; Webber, 1978). HOPE presently falls within the latter group of comprehension models.

The following descriptions of several existing AI models include assessment of their design and implementation based on considerations found to be necessary in designing a model of normal processing meeting assumed "minimal criteria" for neurolinguistic validity (continued processing without redesign, or restructuring, with incomplete or missing knowledge, and with timing-coordination modifiability). Of particular concern is the inclusion of facilities to simulate lesions with the model consistent with hypothesized causes of aphasic comprehension problems as reported in the literature.

Models which stressed the role of syntactic processing include Thorne, Bratley, and Dewar (1968), Woods (1970), Marcus (1978), and Woods (1980). Other approaches eliminated syntax, solely employing semantic analysis. These include models by Rieger (1975) and Riesbeck (1975); Schank (1973); Schank (1975); Simmons (1973); and Small (1980) and embodied the claim that no syntax was necessary to determine the contextually appropriate meaning of words within sentences. Meaning for these models was independent of syntax.

Winograd's model (1972) was the first to demonstrate the need for interactive use of syntax and semantics in conjunction with inference mechanisms using a pragmatic model and world knowledge. His system used a Halliday systemic grammar (Winograd, 1972; pg. 3). The grammar included syntactic function definition with associated semantic markers that were used by interpretation processes during input analysis. Syntactic constituent well-formedness was preliminary to semantic and pragmatic processing in his procedural based model. Errors in parsing or interpretation were noted and affected subsequent action of the model. His model was the first to demonstrate that context was necessary for understanding.

The HEARSAY-II (Erman, et al 1980), HWIM (Woods, et al 1976), and HARPY (Newell, 1978) systems interleaved semantics in a structural way by including enumerated word class combinations that could occur in the input specific to suitably constructed databases of inquiry. Semantic interpretation in the final implementation occurred after the determination of the "best" representation of the syntactic structure for an entire utterance.

Bobrow and Webber (1980) and Robinson (1982) have developed comprehension models which were specifically designed as interfaces for database inquiry. They included discourse level analysis and utilized interaction between syntax and semantics, testing semantic compatibility of constituents to eliminate interpretations which were impossible in the context of the utterance. Constituent structure provided the requisite minimal analyzed syntactic form preliminary to semantic interpretation.

None of the previously mentioned models addressed issues of simulating "normal" or "lesioned" comprehension processing. They all claimed to meet the "Turing test criteria" for some narrowly defined aspect of comprehension performance (usually constrained by semantic content and specific vocabulary). They did not use evidence from observed behavior as a basis for their design specification, but often relied on introspection, machine processing constraints, or linguistic theory to aid in limiting the model specification, and to simultaneously reduce the mapping considerations necessary to produce the desired result.

3.1 AI Models and Psychological Validity

In the past, AI models claiming psychological validity have ignored the performance evidence of neurolinguistics. The degradation of linguistic ability is a real phenomena following selected brain lesion, and in the future, should be as mandatory a part of the psychological validity claim as the "normal" criteria have been in the past.

Most AI claims of psychological validity have centered on the length of short-term buffer size, the number of buffers, whether on-line processing is deterministic, the derivational theory of complexity and its relation to computational processing time, and the role of semantics in comprehension (i.e. is syntax really necessary?) (Cf. Charniak, 1981; Marcus, 1978; Milne, 1980; Schank, 1975; and Small, 1980 for discussions of their processing strategies and claims relevant to aspects of psycholinguistic evidence.)

None of these models claimed to simulate natural language processing. None of these models considered neurolinguistic evidence in their design or implementation strategies. To this end, none are "lesionable" in a neurolinguistically plausible sense; none are psychologically valid. Because of the pattern matching, explicitly enumerated control decisions encoded in these models, the variability of normal performance and the complexity of pathological performance cannot be demonstrated. Both criteria are necessary in processing models which intend to claim psychological validity.

As an illustration of one aspect of degraded processing hypothesized to exist in pathology, which should be possible in any AI model claiming psychological validity, consider removal of closed class words (determiners, prepositions, etc.) at some level of the processing implementation. The functional aspect of closed class words which is affected by lesion is variable across patient populations and within a given clinical classification (cf. discussion of Comprehension and Aphasia in Section 2.0).

The syntactically based systems (Bobrow, 1978; Bobrow and Webber, 1980; Marcus, 1978; Winograd, 1972; Woods, 1970; Woods, 1980) minimally require a complete constituent structure before any interpretation can occur. There is no facility for partial constituent "understanding." They do not include any means of semantic interaction during constituent analysis to redirect the comprehension process when syntactic problems, such as "no correct constituent analysis," occur. This type of incomplete or incorrect syntax does occur during speech and hence is processed during normal comprehension, and is suggested to represent an aspect of the aphasic performance problem, even for well-formed utterances. For these systems, redesign would be necessary to meet the "Turing criterion" with respect to such performance.

Marcus (1982) has demonstrated that redesign would be necessary to analyze his parser, PARSIFAL, in a lesioned state. He considered the resulting performance degradation based on "damage" (removal in his case) of a particular part of the parsing mechanism, "rendering the parsing unable to recognize the closed class words of the language." (Marcus, 1982; pg. 123). At the same time, he encoded the closed class lexicon in a manner he claimed was consistent with the evidence for the lexical access of closed class words by Broca's aphasics as reported in Bradley, et al, 1980 (see Section 2). This "lesion" will form the basis of comparison for conjectured "lesion" state performance throughout the remainder of this section, even though it has been shown to be statistically invalid.

In the paper, Marcus described one suggested redesign of PARSIFAL to be able to function in this single lesion condition and discussed the results with respect to clinical interpretations of possible partial syntactic structures obtained during parsing.

The role of semantics in the process was suggested. Without actual implementation and actual results from the model, any comparison with clinical performance remains at best conjecture. Many questions of the effects of his modifications on his overall parsing theory were briefly mentioned. However, in the scope of the paper they were insufficiently discussed and should be carefully examined.

Each possible lesion condition in models such as PARSIFAL would require additional redesign. This fact is inconsistent with processing in the brain. One might conjecture that redesign and recoding as described for PARSIFAL could be related to recovery. However, after initial lesion, the brain continues to function, albeit in a degraded state, which PARSIFAL cannot do without redesign (Marcus, 1982; pp. 121-125).

The strictly semantic models (Rieger, 1975; Riesbeck, 1975; Schank, 1975; and Small, 1980) were not dependent on syntax at all. They were able to process incomplete input. The effect of the elimination of closed class words at any level or levels in these models should be negligible. Processing should produce semantically plausible interpretations of interrelations of the content words, even though the input is not well formed. The results would be entirely dependent on word order analysis (a demonstrated problem for "agrammatic" aphasics in reversible sentences, see Section 2) and would not necessarily coincide with the clinical data (although it would be very interesting to compare).

Only in Small's semantically based model (1980) can the effect of closed class words be noted. As they were encoded to enter a concept entity construction state, (Small, 1980; pp. 61 and 66) their exclusion would tend to produce verb meaning preference for all ambiguous content words.

The semantically based systems would necessarily have to include the "definition" of the lesion state such as the level of processing affected by elimination of the information being lesioned as discussed by Marcus (to appear). Merely eliminating the closed class words from the input does not reflect the processing level difficulties exhibited by the aphasic population (see Section 2.0). Recoding and redesign of the basic models would need to be undertaken to fully study different aspects of closed class word interaction with such systems.

Winograd's system, based on interactions among syntactic, semantic, and inference procedures, would also require redesign for elimination of normal access to the closed class lexicon. The effect such elimination would produce is not clear from the discussion of SHRDLU in Winograd (1972). Analyzing the effect of determiners within noun group (NG) processes in SHRDLU, it seems that an NG would still be recognizable. However, during interpretation procedures, the features specified by the determiner would not be appropriately available to the semantic process. In forming an NG, the determiner was structurally optional and was interpreted last during the semantic processing of the entire NG (Winograd, 1972; pg. 129). As an NG could still be recognized, the problem of the missing determiner could produce a "random" semantic choice. This result could be interpreted as reflecting the findings of functor use reported in Goodenough, Zurif, and Weintraub (1977) as described in Section 2.0.

The impact of the access to closed class words on sentences of sufficient syntactic complexity to mirror the aphasic data, however, is not clear. As previously stated for the syntactically based models, different lesion conditions for SHRDLU would require reanalysis and redesign.

HARPY (Newell, 1978), HEARSAY-II (Erman, et al 1980), and HWIM (Woods, et al 1976) did address some of the difficulties encountered in discretely discriminating and recognizing the small words in the input. These systems, faced with incompletely determined, uncertain "word" input, were forced to rely heavily on the most reliable portions of the input and to infer the surrounding linguistic structures. The level of difficulty in lexical access in these systems is more similar to that of the hearing impaired, rather than at the level of lexical difficulty hypothesized by Marcus (1982) and evident in aphasic persons.

Another aspect of the closed class word problem which current AI models can not handle is the evidence of different levels of representation and access during processing. Some patients can hear a word but don't process it in understanding. Others do not say the word during repetition, but comprehend the word, demonstrating that they heard and processed it. These combinations of neurological processing deficits cannot be handled by any of the AI models discussed. The types of information encoded and control strategies of implementation in previous AI models were not concerned either with behaviorally demonstrated representation levels or possible degradations of performance.

AI model development, if it claimed psychological validity, attempted to use psycholinguistically reported limitations such as buffer restrictions and derivational theory of complexity in conjunction with accepted linguistic theoretical interpretations to constrain the design. It is not surprising that the models are successful as they often demonstrate the computational counterpart of an algorithmically defined theory.

Finally, none of these briefly discussed models considered timing relationships of information flow to be important in comprehension, although in the aphasiology literature and in models of neural network decision processes, the connections and coordination of information interaction were shown to have critical effects.

Human processing performance as a basis for constraining the design decisions has not been previously considered in AI models. Instead the models tend to make arbitrary representation determinations, select a control strategy based on issues such as length of processing time or memory limitation criteria, and map a normally occuring input into an observable, verifiable output.

3.2 HOPE and Psychological Validity

Chief concerns in psycholinguistically/neurolinguistically valid models of comprehension processing center on the representations of knowledge AND their processing. Means of further elaborating knowledge structures and processing interactions based on additional behavioral evidence is a concern of the design and implementation of such systems.

The current version of HOPE makes extensive use of psychological and neurological evidence to define types of information relevant to the comprehension process. Assuming that neurological evidence is a window on degraded performance, careful analysis of processing deficits provides clues as to how different types of information interact during a given task. (Cf. Goodglass and Kaplan, 1972; Jenkins, Jiminez-Pabon, Shaw, and Sefer, 1975; Wepman, Jones, Bock, and Van Pelt, 1960.) In the design of HOPE, these studies were used to determine which aspects of representation need to be distinct and how these aspects can work cooperatively during processing.

Variability in individual performance as a basis of design contributed significantly to the decision to use the cooperative computation paradigm of neural network decision processes (discussed in the next section). Addressing the variability issue required a different problem decomposition from that currently found in AI studies. One must consider types of information that can interact rather than specific instantiations (patterns) of information that can interact. Using the cooperative control strategy eliminated the necessity of attempting to enumerate, a priori, all possible combinations of information state which affect any computation. One of the goals in designing the model was to use the computer to begin enumerating these states to aid in understanding aphasic performance better.

The cooperative decision strategy, in addition to having neurologically plausible processing attributes, also permitted the definition of the process in a way that was orthogonal to the models previously described. As different humans are able to analyze the same phenomena in different equally valid ways, the processing underlying language behavior needs to be equally interpretable within the alternatively derived theories developed within the different approaches, linguistic, neurolinguistic, psychological, apahasiological, and within computer science. The neural-like control strategy makes this possible.

HOPE is deterministic. The control strategy delays commitment to any specific facet of any representation until sufficient information has confirmed its selection. This eliminates considerations of backtracking and the associated bookkeeping that have constrained many AI models in the past.

Psycholinguistic evidence of buffer size limitations (short-term memory effects) are included when defining the bottom of the range of activity-value for information which is considered to be active. HOPE presently contains the equivalent of two buffers, the two memory states of all active information (Short-Term-State and Post-Refractory-State). It should be noted that these buffers are not lists with built-in size constraints, as in other AI models. The observed changes in information in these states during processing will be useful in determining a bound on activity value range that is consistent with the seven ± two claim (Miller, 1956) and will possibly provide a process mechanism that offers an explanation for the phenomenon.

Finally, the model can serve as a prototype of a tool for the study of the effect of a given knowledge representation definition, and its interaction on process time and performance. It can simultaneoulsy aid in developing more relevant clinical testing paradigms that will both provide the kind of information necessary to define processing models and that will also further our understanding of the clinical problem (cf. Cullingford, 1981; pg. 60).

4. The Control Strategy

4.1 An Example

A cooperative computation is a decision process whose outcome is effected by intercommunication among a suitable number of relevant facts. The number of facts relevant is dependent on the context in which the decision process occurs. Communication is achieved by either independent reinforcement or inhibition attributable to an external source, or by interrelated reinforcement or inhibition which results when one fact is internally linked to another fact.

An hypothetical example will best illustrate the paradigm. Assumptions underlying this illustration are only used to constrain the example in a perspicuous way. Facts within the example can be considered as confidence or activity values associated with semantic features of concepts. Useful facts for a concept are variable and depend on the context in which the concept occurs. Whenever sufficient confirmation, i.e. reaching a threshold, of a sufficient number of facts is realized, the concept is recognized and the result passed to subsequent processes.

In the following example, visual and auditory perceptual processing into semantic features is assumed to map into a confidence or activation value associated with the value of a feature. (Cf. Quillian, 1980; pg. 242 for further elaboration of features, feature values, and associated activity values of concepts.) In the concept of bear, the semantic feature, color, has a feature value, dark, which can be activated with an activity value via perception or via interrelated activation.

Values of features that are interrelated can be semantic opposites or directly related associates. An example of an "opposite" interrelation is seen in the height feature of the concepts for bear and mountain lion. Visual input, confirming something as tall, will inversely affect the confidence that something is short by simultaneously raising the activity value associated with the feature value tall and lowering the activity value associated with the feature value short. Directly related associations are illustrated in the interpretation of "rustling" as support for all types of movement used in the example by increasing all associated activity levels.

Suppose that in a hunting episode the concepts bear, mountain lion, and hunter can each be characterized by the following sets of features (NOTE: the features visual-motion and sound-motion each have two feature values for the mountain lion and hunter concepts; "-" indicates no contextually relevant feature value exists.):

	bear	mountain lion	hunter
height:	tall	short	tall
color:	dark	-	bright
noise:	growl	cry	chatter
visual-motion:	lumbering movement	fast movement stealthy	running walking
sound-motion:	lumbering movement	fast movement stealthy	running walking

To understand the cooperative computation example, the three characterizations need to be considered as intersecting sets of features. This means that any activity value for a feature value is shared across all concepts that include that specific feature value for that feature, i.e. for the feature color, all concepts having feature value red have the same associated activity value for red, regardless of the feature class red occurs in.

Consider the following situation: a lone hunter is on a tree-covered mountainside hunting bear. He hears rustling in the brush to his right. The rustling noise will activate the hunter's sense of motion of the anticipated corresponding feature values for sound-motion: stealthy, fast movement; and lumbering movement: walking, and running. These feature values are simultaneously activated for visual-motion because they belong to the intersection of the two feature specifications although there is no overt visual-motion input at this time. This is an example of interrelated reinforcement connections.

Additional concentration on the auditory input will continually reinforce or inhibit the activity levels on these feature values. Perhaps additional auditory perception will bias the activity levels to favor one value over another.

Within moments, the hunter sees a tall, dark shadow in the brush. This will activate the tall value for the height feature and dark value for the color feature. If any activity were associated with a short value for height, because of the inverse semantic relationship between tall and short, it would be inhibited. This is an example of inversely related interaction or inhibition.

At this state of the situation the involved concepts can be analyzed as intersecting sets of features. Each set of features defines one of the previously named concepts for the given context. As a set the features define the competing interpretations for the sensed movement in the brush. Higher activity values indicate higher confidence in a feature value. Absence of an activity value indicates the feature value has received no data to support or refute it. A zero or near zero activity value indicates the feature value has highly disconfirming data.

The competing concepts, based on visual and auditory percepts are reflected in the activity levels over all semantic feature values associated with each concept. For bear, in the example, the confidence measure can be considered as some computed value based on the activity levels of tall, dark, and lumbering movement. When the confidence value computed over a set of features that constitute a concept reaches or surpasses a threshold value, such as 100, the decision process is considered terminated and the outcome, i.e. concept having the value at or above threshold, at this time can activate subsequent activity values in other processes.

Now back to the situation...

Suddenly the hunter sees a bright orange object where the dark shadow was. Attention immediately raises the confidence value of the color feature, bright, to a very high value, near threshold. Simultaneously, the dark value for color is reduced.

The high value of the bright color feature in combination with the high activity values on the features for movement is sufficient to confirm the concept of hunter.

The lone hunter quickly recognizes that the rustling was caused by a fellow hunter and lowers his gun.

There is no overt computation based on seeking values for a specifically enumerated set of feature values in a pattern matching sense. There is no criterion used to select input from one stimulus over another at any moment in the computation. Visual and auditory inputs in this example contribute simultaneously by sending confidence levels to expected features and sometimes to unexpected features based on the context of the episode. Additional inputs over the same stimulus pathways raise and lower values for the associated features until a sufficient level of confidence across a set of features reaches a threshold value and disambiguates which of the possible characterizations best fits the context.

The decision is controlled by propagation of confidence or activity levels. The levels are initialized and subsequently reinforced or inhibited by external stimuli. Activity levels interact via explicit propagation paths to converge to a final state where one of the competing concepts has a sufficient degree of confidence. The result of the decision is the reported concept. The control assumes that information propagates whenever it is sufficiently confirmed. Information representations are passive receivers of confirmed stimuli interpretations as reflected in activity levels associated with the values of features used to represent a concept. Control of information flow assumes hierarchical levels of representation. There is no requirement in the control that information flow depends on complete definition within one level of the hierarchy before other levels can be affected.

The cooperative computation control strategy uses distributed representations of knowledge. Depending on the connections among the representations, the control can be shown to support both serial and parallel computation. It is in this dual control representation that the value of the paradigm is found for the design of the model of aphasic sentence comprehension.

4.2 The Cooperative-Computation Paradigm for HOPE

The cooperative-computation paradigm was suggested as a control strategy after studying the behavioral aspects of the problem. Simple serial control is not sufficient to capture the generality of the deficits observed during comprehension processing of aphasics (cf. Lashley, 1967). The individual variability within a clinically classified group, the combinations of observed deficits that commonly occur, the hypothesis that disturbance of synchronization of control could be an underlying cause of the observed performance all contributed to the decision to use the neural network decision paradigm as the control strategy for the model.

Knowledge representations hypothesized on linguistic grounds and supported by clinical studies to be distinct levels in processing, could be distributed in a manner consistent with this control strategy. Dynamics of interaction could be implemented by including a local interaction specification in one of the knowledge structures. The complexity of timing interactions could be maintained using a computed control. In maintaining the control within the paradigm, with explicit links between knowledge types, but having different effects depending on the global context of the model it was felt that a useful tool to study underlying causes for observable behavior could be developed.

HOPE can be interpreted to be using two types of spreading activation (cf. Anderson, 1976; pp. 122-123; Collins and Loftus, 1975). One is fixed-time propagation and activates aspects of the meanings of words; the other is determined by context and threshold values and is variable in its effect. The knowledge activated is locally defined in the grammar. The grammar can be experimentally modified for experimental purposes (cf. "Using HOPE: Neurolinguistic Simulation Investigation, Gigley, to appear). The effect of activation depends on the type and status of the information being activated. In some cases activation results in execution of a process, in others it reflects a change in the state of information or an activation of another aspect of the meaning of a word.

The paradigm utilizes feedforward and feedback interconnections of activity value (or firing frequency) propagations among knowledge representations, to converge to different recognized concepts (Anderson, Silverstein, Ritz, and Jones, 1977; Dean, 1980; Gordon, 1982: Reiss, 1962; Wood, C. C., 1978; Wood, C. C., 1980; Wood, C. C., 1982).

Locally constrained activity can propagate and produce global effects over time. A specific local constraint has different global effects depending on the context of its application. Evidence of this is presented in the description of the model and is particularly evident during lesion simulation. (See Sections 6 and 7.)

Modification of activity values during processing, via the interconnections among knowledge representations and due to the effect of the introduction of new information, achieves an overall interactive control structure of the parsing and interpretation process which is dynamic, varying with the global context of the model. The variability and dynamics of this control structure best fit the behaviors reported in the aphasiology literature, observable in work with patients and discussed with speech pathologists. Use of this control strategy allows definition of appropriate knowledge representations and modification of timing synchrony to provide a suitable environment to study the effects of simulated lesions.

5. The Linguistic Basis of the Model

Using the guidelines of cooperative computation with control manifest in the intercommunication of the knowledge representations requires that problem decomposition include specification of types and representations of knowledge in a manner that permits multiple access and multiple effects. By distributing knowledge representations and creating dynamic communication links the same representations can be accessed by different processes producing different results depending on the overall context in which they occur. The present model includes representations based on theoretical linguistic descriptions of the lexicon (which is distributed), the grammar, and a pragmatic space, which currently serves as an interface with an investigator's world knowledge representation.

In the design, a grammar representation had to be defined that included flexibility in its predictions and concurrently specified structural and semantic compositional aspects of comprehension. Fodor (1977; pg. 4) states that

> The meaning of a sentence is a function of the morphemes it contains and the way in which those morphemes are syntactically combined. Clearly, then, sentence meanings must be correlated by the rules of the grammar with sentence structure and lexical content.

A categorial grammar specification (Ajdukiewicz, 1935; Bar-Hillel, 1964; Lewis, 1972) was selected because it provides a computational structure that permits such correlation, and does so in a way that includes the necessary processing flexibility to simulate "lesion" conditions.

A categorial grammar is based on semantic category types. Precisely defined:

> The word or expression A, taken in sense x, and the word or expression B, taken in sense y, belong to the same semantic category if and only if there is a sentence (or sentential function) Sa, in which A occurs with meaning x, and which has the property that if Sa is transformed into Sb upon replacing A by B (with meaning y), then Sb is also a sentence (or sentential function). (It is understood that in this process the other words and the structure of Sa remain the same.) (Ajdukiewicz, 1935; pp. 208).

A categorial grammar expresses the conditions under which "a word pattern, constituted of meaningful words, forms an expression which itself has a unified meaning (constituted, to be sure, by the meaning of the single words belonging to it)" and is called syntactically connected (Adjukiewicz, 1935; pp. 207).

This grammatical form is employed in a locally specific way, spanning syntactic and semantic knowledge representations, that constrains the convergence process by affecting propagation throughout the model over time.

A categorial grammar is weakly equivalent to a context-free phrase structure grammar (Bar-Hillel, 1964). It has

1. A small number of basic categories, and

2. Infinitely many derived categories.

Derivation rules use concatenation and can be described for a derived category as:
derived-category := C/Ci,

where the derived-category concatenates with the Ci category to produce a category of type C, (cf. Lewis, 1972).

Categories in addition to being basic or derived (functor) may contain lexical items (words). These are the lexical categories.

A composite category is a category which results from the application of a derivation rule of syntactic connection (Adjukiewicz, 1935; pp. 210) and is a category type associated with a pragmatic interpretation within the model. A composite category type can also be a lexical category type.

A categorial grammar is a structural description of parallel syntactic and semantic composition. It characterizes the well-formed syntactic structures used in interpretation, and simultaneously defines the well-formed compositional structure of the meanings. The parallelism implicit in its definition is critical to the control within the model.

A categorial grammar is used here to locally predict in a "top-down" sense the category types of words in the incoming sentence. It also controls semantic interpretation in the pragmatic space of syntactically disambiguated word meanings. This occurs "bottom-up" in a manner procedurally related to the composition of types described by Adjukiewicz as a derivation of syntactic connection (Adjukiewicz, 1935; pp. 215-216). (Cf. Bach, 1980a; Bach, 1980b; Bach, 1981; Montague, 1974; Ades and Steedman, 1979 for additional discussions of categorial grammars and their application in the determination of the meaning of sentences.)

Interpretation of the "heard" utterance is represented as a linked network in the pragmatic space. During the interpretation process, category type determines the general interpretative procedure followed for any specific word meaning . The noun interpretation of "run" is computed differently from the intransitive verb interpretation. However, all noun interpretations are computed the same way, as are all intransitive verb interpretations. Each grammatical class of words has a distinctive interpretation procedure that functionally utilizes the meaning of any particular word to which it is applied.

5.1 A Simple Representation of "Meaning"

In clinical testing, aphasic comprehension performance is often measured on sentences spoken in isolation. Representation of the sentence to be interpreted as a string of phonetically encoded words introduced input to the system similar to that of a spoken utterance but without the added problems of defining the phonological perception process (cf. Blumstein, 1973; Klatt, 1979a; Liberman, A., 1977; and Liberman, A. and Studdert-Kennedy, 1978).

Mapping of the phonological representation of a word to a meaning required several decisions.

1. How was the meaning to be defined?
2. How was "a" meaning to be related with a given phonetic representation of a word?; and
3. Could more than one meaning be associated with a phonetically "heard" word?

There is much psycholinguistic, philosophic, and AI literature addressing the meaning of a word and how it is encoded (cf. Brachman, 1979; Johnson-Laird, 1977; Johnson-Laird, 1979; Miller, 1978; Quine, 1960; Winograd, 1976). The two central issues debated are whether meaning is best expressed as representation or procedure. Can a sufficient set of features be associated with a given word to completely define its meaning? Is there a procedural decision process to determine a particular meaning of a word that is computed with each reference?

These questions underlie the issue of whether the meaning of a word can be statically represented. To circumvent the manifest problems in selecting one approach, or a combination of both approaches to meaning, it was decided to substitute the orthographic spelling of the word and its grammatical category for an artificial representation of meaning.

Multiple meanings of the same phonetic word having the same orthography and grammatical category are numbered. An example is for the word [p-l-ey-n] (using the phonetic representation of Klatt, 1979b): where meanings, plane1 (airplane) and plane2 (carpenter's tool) are both noun categories. This particular facet is strictly for the sake of "computation" and has no linguistic or neurological foundation.

Associational meaning relationships based on morphology are included and used in interpretational aspects of the model. These are specified during model definition and can include any relationships that the investigator decides are important. The defined model used in the examples includes aspects such as singular/plural relationships for nouns and stem/ending relationships for verbs.

Verbs have an additional aspect of meaning. Case-control information is required for all verbs defined for any explicit model definition within HOPE. This information is defined for a specified base form of each verb. The base form is designated explicitly during model definition or via a morphological relationship as previously mentioned.

One category type, an intrinsic part of the meaning of a word, is statically specified for each orthographically encoded meaning. This permits the same orthographic meaning to be part of two different words as the orthography only represents part of the word's meaning. An example is [r-uh-n] having meanings of "noun run" and "intransitive-verb run" among others.

Multiple meaning representations are associated with each phonetic word as appropriate. All meanings of a word are accessed whenever it is "heard." The fact that all meanings are available in different contexts required that they all be initially accessible. As there is no obvious way to initially stop any access path and still maintain the interactive control strategy, all meanings are simultaneously activated. The appropriate meaning for the context must be determined. Controversial evidence that this occurs has been reported in work by Marslen-Wilson and Tyler, (1980); Seidenberg and Tannenhaus, (1980a); Seidenberg, Tannenhaus, and Leiman, (1980b); and Swinney (to appear).

For each category type, the interpretation procedures map a specific word meaning into a network representation of the meaning within the pragmatic space. Here pragmatic space is taken to include the immediate meaning of a word in relation to the other interpreted words. The current implementation includes neither associations of the meaning nor does it include the facility to activate inference processes. Clearly, this suggests subgoals for future research.

In summary, a categorial grammar represents the well formed syntactic-semantic connections that can arise in a spoken utterance in isolation. The grammar depends on defined relationships among lexical and composite categories which are based on the explicit lexicon used for the model. The lexicon contains a phonetic representation with associated multiple meanings, where each meaning contains a grammatical category type and an orthographic representation substituting for an artificial representation of the meaning. Meanings are further associated morphologically. Each category type has a distinctly defined interpretation procedure. Considerations of lexical access, "closeness" criteria among associations, frequency effects, and word composition processes are not considered within the model. Subsequent studies could address these issues.

6. The Model

In this section, HOPE will be described in terms of its knowledge representations, underlying assumptions on which they are based, and an example of "normal" processing. A perspicuous example of a "short" normally processed sentence with a simulated lesion run on the same sentence and discussion of its possible interpretation with respect to aphasic performance is presented in the next section.

Several aspects of the design of HOPE should be briefly mentioned before the more detailed discussion which follows. For a complete discussion of the range of models which can be defined and their behavioral interpretation see "Using HOPE: Neurolinguistic Simulation Investigation" (Gigley, to appear).

Computations within HOPE are time-synchronous. Updating calculations across all information are effectively done in parallel. A Compute-Time-Interval (CTI) is defined as one complete update of all active information in all knowledge spaces of the model.

Activity values are associated with information contained in the knowledge representations during processing. Propagation of activity values among different knowledge representations achieves the selection of contextually appropriate syntactically determined meanings during a simulation.

Time-interval counters are used to coordinate new word introduction and decay interval lengths. The number of time intervals per decay or word interval is specified during model definition and is modifiable for experimental purposes. Interpretation of different relative lengths of these values provides the link between interpretation of the model and clinically described aspects of processing. Values within the model for propagation, threshold, and initial activation are also modifiable, having different related clinical interpretations.

A counter, WORD-CONTROL, is maintained to determine when a sufficient number of compute-time-intervals have elapsed relative to the number of compute-time-intervals that occur between the introduction of each word (defined in Word-Control-Interval). The time between words is constant across the presentation of a sentence in the current version of HOPE.

HOPE incorporates a self-decaying memory management scheme to eliminate an explicitly defined memory capacity restriction. Any active information that is not specifically reinforced or inibited automatically decays over time. The amount and length of a decay interval is modifiable during model specification but remains fixed for any experimental run. There are presently two types of memory representations used, one for the short-term state of active information and the second as a post-refractory state of all "recognized" information. The latter state was felt to be necessary for future work on recall processing and for expansion of the model to include garden-path considerations.

The grammar that is used represents both structural and semantic composition simultaneously. Although the parsing process per se and semantic composition processes are vastly different, all processing within them is coordinated by means of the grammar specification.

Processing within HOPE occurs both serially and in parallel. Any of the serial processes can potentially occur simultaneously, i.e. in parallel. Parallelism is effected due to the time-cycle processing coordination.

Basic computations within the model are decay, refractory-state-activation, post-refractory-state-activation, meaning-propagation, interpretation, firing-information-propagation, and new-word-recognition. Briefly described:

1. DECAY is the automatic memory degradation that occurs after a specified decay time interval resulting in a percentage reduction of the original activity value associated with any active information. It only occurs if no explicit inhibitory or excitatory propagation has affected the information.
2. REFRACTORY-STATE-ACTIVATION occurs whenever information reaches or surpasses threshold and fires. It occurs in the time-interval after firing and is used to block accidental misfiring of information.
3. POST-REFRACTORY-STATE-ACTIVATION occurs at the end of a REFRACTORY state. It is conjectured that this state will be necessary for garden path analysis in future development. By including it, a trace of the right to left firing interpretation pattern is observable during a simulation.
4. MEANING-PROPAGATION results in fixed activation of aspects of a "heard" word's meaning. It activates the predictive aspect of each category type associated with each activated meaning for a newly recognized word. Firing is not a prerequisite for this propagation effect.
5. INTERPRETATION builds the semantic representation for a meaning that has been disambiguated and fired. It confirms any morphological restrictions to the semantic composition. It applies case-control information during the composition of verbs.
6. FIRING-INFORMATION-PROPAGATION occurs when the activity value reaches or surpasses a threshold value. It can be inhibitory or excitatory or both, and depends on what type of information is firing. INHIBITORY-FIRING reduces the activity values of

competing instances of the firing information. For instance, when one specific meaning of a word fires, the activity values of all other possible meanings related to the same phonetic word are reduced. In addition, the activity values of all other active meanings having the same category type are reduced. EXCITATORY-FIRING propagates a portion of the firing activity value to active meanings that can co-occur with the information which is firing.

7. NEW-WORD-RECOGNITION occurs whenever a model defined between-word time interval has elapsed. The phonetic representation is activated and all possible meanings associated with it are activated in fixed, predetermined ways.

The control flow over a compute time update uses information from the end of the previous compute time (the previous state) and is effectively simultaneous. The order of computation is:

1. Calculate DECAY for all information across all spaces that is in the appropriate state.

2. Calculate all FIRING-INFORMATION-PROPAGATION (EXCITATORY-FIRING and INHIBITORY-FIRING) across all spaces using grammar information to control the flow,

3. NEW WORD INTRODUCTION, if appropriate.

Each computation is performed across all spaces before the next computation begins, i.e. all DECAY in a simulation time interval is computed before any firing effects are computed. As DECAY is assumed ineffective if information is excited or inhibited, firing computations always use the values of the previous time interval and override any computed DECAY activity value results in the current time. In future work this strategy will be replaced by a summation of the decay and propagation values.

We will now turn to a discussion of a "normal" model as defined within HOPE. After describing the representations assumed, the serial and parallel computations within the system will be discussed in detail in the framework of an example of a "normal" simulation.

6.1 A Normal Model

HOPE in its "normal" state contains knowledge representations that are based on theoretical linguistic components of language which are supported by evidence from aphasic performance. Additional constraints on the definition and design of HOPE are placed by requiring the capacity for simulated "lesions".

6.1.1 Knowledge Representations Within HOPE -

Knowledge is distributed over different spaces and is encoded as a graph structure (network). The appendix contains a description of the graph notation used throughout the description of the "normal" and "lesioned" model discussions.

Knowledge representations are hierarchical. Spaces within HOPE can be thought of as different substructures of an entire knowledge representation. Spaces contain named nodes and arcs. Any node or arc can simultaneously represent a space having the same name which contains additional knowledge. (Cf. Quillian, 1980, for a discussion of a similar semantic graphical representation of memory using planar representations.)

HOPE contains the set of spaces indicated in Table 1. A brief description of the type of information contained in each space appears with its name. Unless indicated, the defined contents (arcs and nodes) of a space are statically defined throughout a given experiment.

In addition, for each lexical category type defined during the word definition section of model definition, a space having that category name is created. These spaces contain the morphological information between elements within each category.

SPACE NAME	CONTENTS
CATEGORY	Names of all lexical Categories, i.e. defined by word membership
GRAMMAR	The categorial grammar specification
PHONETIC	The phonetic encoding of all known words
PHON-CAT-MEAN	A network representation of all category-meanings associated with each phonetic word
PRAGMATIC	Contains context of interpretation (initially empty in the current version); contains network representation of meaning on termination
VERB-MEANING	Case-control-information for base form of all defined verbs
INTERPRETATION	Contains interpretation functions for all category types

Table 1: Spaces and A Description of Their Contents.

6.1.2 Word Definition -

Each space of each word can be thought of as a different perspective within a multidimensional word representation. For any word, all of its perspectives considered as a group are what the word represents.

Descriptions and constraints on word definition that must be satisfied during experimental specification of the model are:

1. All words must have a phonetic representation.
2. Each phonetic representation must have at least one category meaning pair associated with it.
3. Grammatical (lexical) categories are defined via word membership specification, i.e. defining a word as a "(CN meaning)" will force inclusion of common noun (CN) as a category type in the GRAMMAR space and as a space itself to hold all common noun meanings.
4. Structural morphological relations are contained within appropriate syntactic category spaces. Thus common noun relations such as singular-plural are within the CN space. The VERB space subsumes all verb types in the model. It contains morphological relations between verbs such as past, third-singular, etc.
5. Meaning control information for verbs is present in the VERB-MEANING space. Every word within the VERB category space must have a specification associated with it in VERB-MEANING, either via a morphologically defined relationship specified in the VERB space, or directly by having its control structure specified explicitly within the VERB-MEANING space. The model definition sub-system insures the restrictions on verb specification are followed during initial definition of the knowledge representations.
6. Each lexically defined category type must have an associated category interpretation procedure. The system assures this before it will permit the investigator to terminate the model definition and initialization phase of the system.

The above-mentioned specifications of a word definition are distributed among the following spaces: PHONETIC, PHON-CAT-MEAN, each category space as appropriate, i.e. CN, TERM, etc., and the VERB-MEANING space if the word has an available verb interpretation. It is extremely important when reading the two-dimensional representations which follow to remember that any identical name associated with either a node, an arc, or a space represents one and the same "item," but in different perspectives. The order of spatial description is not relevant.

Figure 3 contains the spatial representation for the phonetically encoded word [b-r-k-s] (barks). [b-r-k-s] is syntactically ambiguous. (It has two syntactic category types.) The figure includes structures which are found in representations of words defined only as CN or only as VIP. This is an example of the representation of an open class or content word.

The arc names, representing lexical category type in space PHON-CAT-MEAN simultaneously represent spaces containing additional knowledge. (All verb types, such as VIP for intransitive verb, are considered members of the VERB space.) Each orthographic meaning is contained in each appropriate lexical category space, such as CN or VERB in the figure. Each space contains the indicated type of information about each word that the system "knows."

Note the morphological relationships, as previously described, within the CN (common noun) space and the VERB space. In addition, the verb-case-control information is associated with the stem form of the verb bark. HOPE permits transitive specification of verb-case-control information. All VERB interpretation functions (VIP, VTP,...) have access to the VERB morphological specifications during interpretation.

Figure 4 contains the HOPE representation for the conceptually depicted representation of [b-r-k-s] in Figure 3.

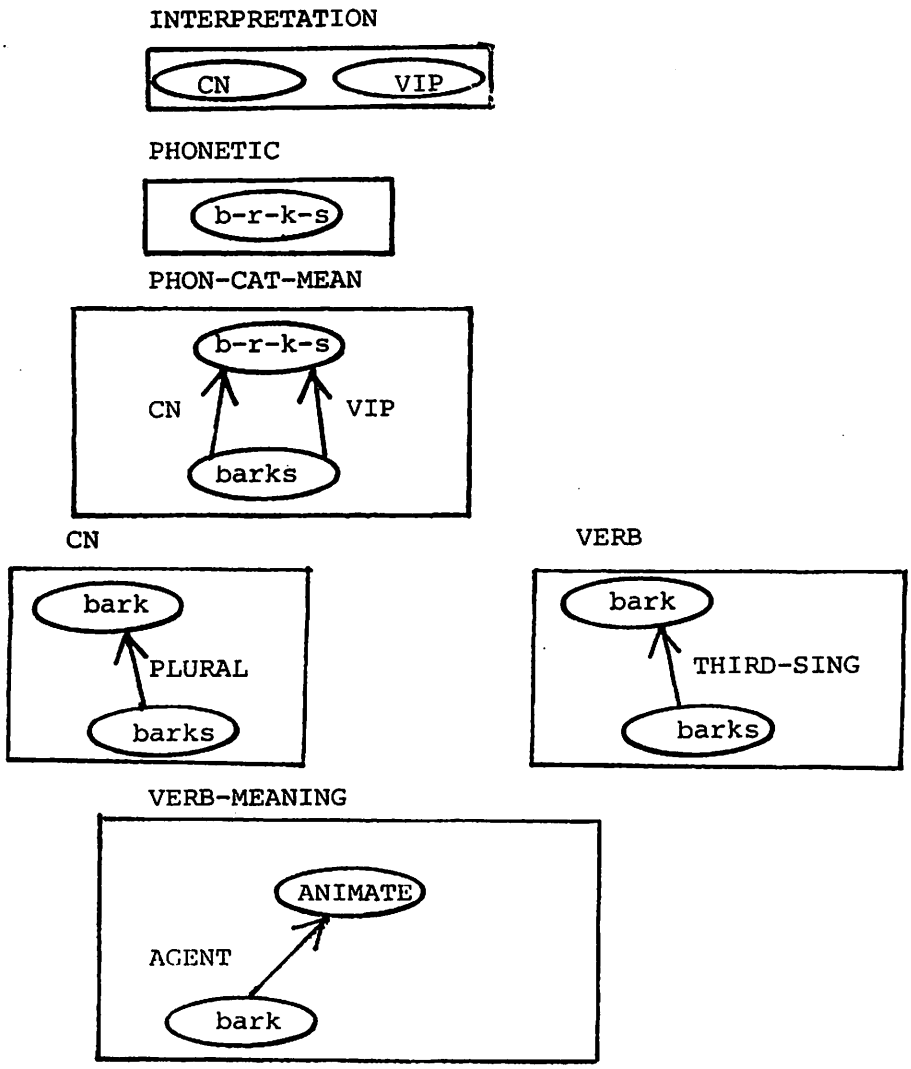


Figure 3: Spatial Representation for the Word [b-r-k-s].

```
==============
interpretation
==============

  cn          vip

========
phonetic
========

  b-r-k-s

=============
phon-cat-mean
=============

  b-r-k-s
       <- cn-- barks
       <- vip-- barks

====                        =====
cn                          verb
====                        =====

barks                         barks
    --plural-> bark               --third-singular-> bark

============
verb-meaning
============
  bark
      --agent-> animate
```

Figure 4: HOPE Representation for the Word [b-r-k-s].

Space names of Figure 3 are enclosed in double hashed lines. Arcs appear as directed arrows with their associated names. Names at the head or tail of arrows represent nodes. Use of the same node name or arc name indicates different aspects of the same data. All directed relationships for a node are indented under the node.

An example of a closed class or function word representation is given in Figure 5 for the DETerminer, THE. Figure 6 contains the HOPE representation for the closed class representation in Figure 5. One should note the "simpler" form of the closed class word representations from the open class word representations (Figures 3 through 6).

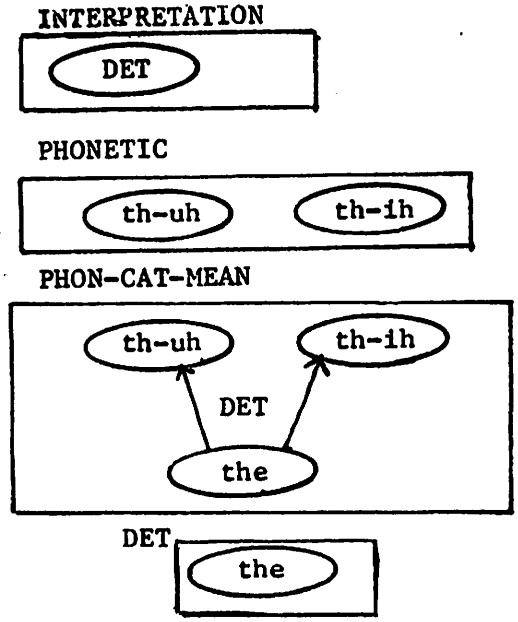


Figure 5: Spatial Representation for the Word [th-uh] or [th-ih].

In the figure, THE has two associated phonetic representations whose meanings are identical as indicated in PHON-CAT-MEAN. There is no morphological relationship.

```
==============
interpretation
==============

  det

========
phonetic
========

  th-uh         th-ih

=============
phon-cat-mean
=============

  th-uh            th-ih
    <- det-- the     <- det-- the

====
det
====

  the
```

Figure 6: HOPE Representation of the Closed Class Word, THE.

The node and arc relationships are as defined in Figure 4 above.

Each syntactic category type has an associated interpretation function represented by the nodes in the INTERPRETATION space. Each such function uses the specific word meaning actively associated with the category type during its application. An example can be given in the interpretation of a CN. The orthographic meaning-representation attached by a CN arc to a phonetic representation in PHON-CAT-MEAN is used to name a node created in the PRAGMATIC space or to "activate" a properly named node that already exists in the PRAGMATIC space, if one allows external context to pre-set the PRAGMATIC space (a feature not in the present version).

There are two different function specifications for the interpretation of each category type, derived or lexical. If the interpretation is of a derived category, the interpreted representation in the PRAGMATIC space is associated with the appropriately designated composite category as specified in the GRAMMAR. If the interpretation is lexical (not of a derived category), such as for CN in the examples, the interpretation builds the representation but does not associate it with a type.

6.1.3 The Grammar -

The specific grammar used throughout the examples of sentence comprehension will now be described. The formulation of the rules of the grammar is dependent on the lexical categories defined. The strict ordering of types (arguments to functor categories) which the grammar uses necessitates that the grammar be definable in terms of the lexical categories selected. This flexibility is encoded in the model specification stage of HOPE. The experimenter is free to define his lexicon as he chooses, specifying the category types and interactions among the types to fit his determination of their relationship. Each category type must also have an appropriately defined interpretation function.

A noted difficulty inherent in model definition is determination of the lexical categories to which a word belongs. Often the definition is based on personal semantic judgments which cannot necessarily be expressed. Fluctuations in the meaning of words adds to the problem. A second difficulty pertains to the categorial specification of the grammar. (Cf. Ades and Steedman, 1979; and Bar-Hillel, 1964 for discussions of the use of a categorial grammar. For a discussion of some concerns in the categorial specification for English, cf. Bach, 1980a; Bach, 1980b; and Bach, 1981).

The lexical categories in the currently defined experimental model which are used throughout the examples are:

Determiner	DET
Common Noun	CN
Term	TERM
Intransitive Verb	VIP
Transitive Verb	VTP

Endcontour represents the intonation contour associated with the end of a phrase or the end of a sentence and has one input representation for each. It is processed from the input as if it were a lexical category type. Its interpretation is strictly defined as a process. Its affect in the comprehension process in the current model forces "finding the verb."

Endcontour	ENDCONT

Composite categories are:

Sentence	SENTENCE
Term	TERM
Intransitive Verb	VIP

In the categorial grammar definition, "A semantic category is defined as a basic category when it is not a functor or derived category" (Adjukiewicz, 1935; pg. 209). In the grammar of the examples, the categories TERM, CN, SENTENCE, and ENDCONT are basic categories. ENDCONTour is included in the set of basic categories because it satisfies the above definition. However, it is not of the same "quality" as the other basic categories. Categories DET, VIP (intransitive-verb), and VTP (transitive-verb) are functor or derived categories. Their derived specifications are:

DET := TERM/CN

VIP := SENTENCE/ENDCONT

VTP := VIP/TERM

Categories may be both lexical and composite, such as TERM in the example. TERM as a lexical category contains what might be considered as interpretable entities such as proper names. TERM as a composite category can be thought of as the composed interpretation of constituent categories, when it is produced. An example of a composite TERM is "the boy," where the completed interpretation of "boy," followed by the completed interpretation of "the," results in a representation which is in function categorially equivalent to a proper name.

Regardless of which instantiation of TERM has occurred, the resulting TERM entities are equivalent in their function. The relation between lexical category interpretation and composite interpretation as described for TERM holds for all category types specified as both.

The composition rules for the composite categories are represented in the GRAMMAR space of the model as connected networks, as shown in Figures 7 and 8. Figures throughout the remainder of this section will include both the HOPE representation of information (on the left of the figure) and an equivalent graphical representation (on the right of the figure) to aid in understanding the basic structures and processes of the model.

```
DET := TERM/CN

     term

        <-to-form-- det

     cn

        <-predict-- det
```

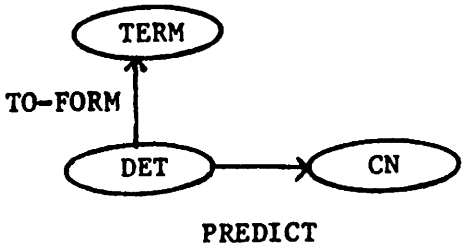


Figure 7: Grammar Representation for DET.

The composite category definition is mapped into the network representation as shown. Described as a derived category, DET := TERM/CN, the CN category is placed at the head of the PREDICT arc from the derived category, DET. The TERM category is placed at the head of the TO-FORM arc, representing the category type of the resultant composite interpretation. Note that in functional notation the derived category specification for DET is (TERM/CN) CN = TERM. This is interpreted as a DET category type concatenated with a CN category type forms a TERM category type.

```
VIP := SENTENCE/ENDCONT

     endcont

        <-predict-- vip

     sentence

        <-to-form-- vip
```

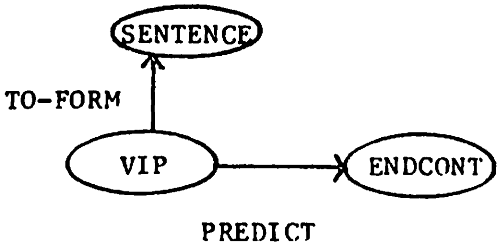


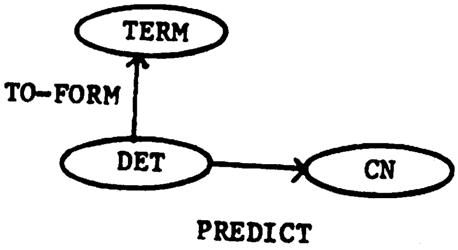
Figure 8: Grammar Representation for SENTENCE.

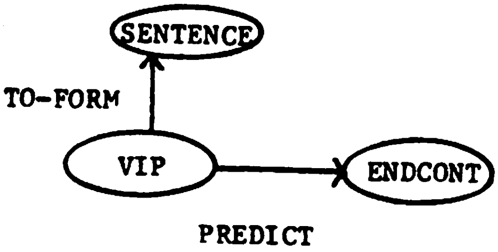
Composite rules associated with SENTENCE and its representation in the GRAMMAR space. The mapping is as described for Figure 7.

A VIP composed with an ENDCONTour of a phrase or utterance produces a SENTENCE type interpretation.

Figure 9 presents the full grammar specification used in the currently defined model. The structural specification of the grammar is entirely left to right for the English fragmont as defined in the example. The interpretation of an entity as the subject of a VERB type is part of the interpretation procedure for VIP semantic interpretation. All verbs at some point in their interpretation are functionally equivalent to VIP types.

```
<< grammar >>

  cn

      <-predict-- det

  det

  endcont

      <-predict-- vip

  sentence

      <-to-form-- vip

  term

      <-predict-- vtp

      <-to-form-- det

  vip

      <-to-form-- vtp

  vtp
```





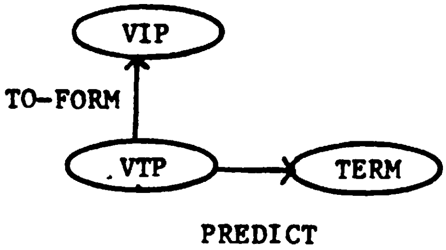


Figure 9: Current Grammar for the Experimental Model.

6.1.4 The Activity Vector -

Processing within HOPE is achieved through interactive communication among knowledge representations. Communication is effected by changes in activity values (confidence values) of all information being actively processed. The activity value of information is maintained in an activity vector (AV) which is associated with all active information. Inactive information has no activity vector; it is available during the process, but not involved in the immediate computation.

Formally defined, an activity vector is a quadruple, (AVAL, TIC, D, DTI), where

AVAL = the activity value (henceforth AVAL)

TIC = the compute Time-Interval-Count with respect to the decay interval length. (This counter keeps track of the number of global updates before decay occurs.)

D = the percentage of activity remaining after decay, and

DTI = the number of compute-time-intervals per decay-time interval.

The TIC, D, and DTI values are part of the state information of any active knowledge within the model. They are associated with the active knowledge to eliminate pointers and additional bookkeeping computations. In other words, active knowledge maintains its own "current" state.

6.1.5 Modifiable Constants -

Constants within the model which determine the state of active information are:

T = The threshold value for firing (propagation),

D =

Ds, The percentage of activity after decay in the Short-Term-State, or

Dpr, The percentage of activity after decay in the Post-Refractory-State,

DTI =

DTIs, The Short-Term-State decay-time-interval, i.e. the number of compute-time-intervals per decay interval for the active information that has propagated, or

DTIpr, The Post-Refractory-State decay-time-interval, i.e. the number of compute-time-intervals per decay-time-interval for active information which has reached the Post-Refractory-State.

R = The REFRACTORY state activity value, i.e. information with this activity value cannot receive or affect information flow. In the present version, this state is entered immediately after information fires. It lasts for one decay-time-interval determined from the firing information.

COMPETITION CONSTANT = The percentage of remaining activity in each of the competing interpretations, excluding the one firing (an inhibitory constant). There are two types:

C-phonetic for interpretations competing with the firing interpretation which have the same phonetic representation, and

C-category for all other active interpretations which are of the same category type as the firing information.

PROPAGATION CONSTANT = The percentage of the AVAL (activity value) of the firing information that is propagated via feedback and feedforward connections,

WCI = Word-Control-Interval, contains the number of compute-time-intervals between the introduction of each new word. (This controls the rate of word introduction to the system relative to other processing).

I1 = The initial activity value for one category-meaning per one phonetic representation, or the initial activity value for one category but multiple associated meanings per one phonetic representation.

I2 = The initial activity value for more than one category type with one or more meanings per one phonetic representation.

Ipr = The INITIAL-POST-REFRACTORY-CONSTANT, i.e. the initial value for the Post-Refractory-State AVAL.

6.1.6 The Implemented Control Strategy -

6.1.6.1 Firing Propagation Effect - The Role of the Grammar -

In HOPE, the grammar controls the flow of information. Its importance in HOPE's design is that it permits determination of propagation effect without explicitly linking together any of the knowledge representations in a static way.

The information within the GRAMMAR space is used in a bi-directional sense. Bottom-up information, such as "hearing" a new word, triggers the grammar PREDICTion information, which in turn, in a top-down manner, influences the selection of the appropriate category-meaning of subsequent incoming words. Interactive confirmation of a specific category-meaning causes interpretation of the meaning to proceed bottom-up, and if the category of the firing information is a PREDICT node in the GRAMMAR, simultaneously influences meaning selection among all currently active meaning competitors, top-down. This top-down propagation can also occur under control of PRAGMATIC information, if a composite category type produced during interpretation appears at the head of a PREDICT arc in GRAMMAR. The top-down propagation effect for a lexical category or composite category of the same type is equivalent.

For example: Given the grammar representation of Figure 7, whenever the CN meaning of a word is selected as appropriate and interpreted, the activity value of its selection is propagated to all DET category-type meanings represented in PHON-CAT-MEAN which are competing at that time.

6.1.6.2 Change of State -

Activity is always initiated in the Short-Term-State and enters the Post-Refractory-State only after it has fired (reached or surpassed threshold) and then entered the REFRACTORY state for one decay interval determined from the interval length of the firing state. During this time it can not affect or be affected by any information propagation. The order of active state transformation is the same for all active information in all knowledge representations (spaces) in HOPE at this time. The incidence of the cyclic change of state of all active information is asynchronous and depends on the contextual state of the information.

The contextual state of information in HOPE is determined from its space-perspective (space location), its AVAL, and its TIC with respect to its DTI. The change in contextual state of all active information is asynchronous during processing. Therefore, the same information can have different effects in different contexts.

6.1.6.3 Memory Management Control -

An automatic decay scheme is used to effectively constrain the size of active memory. Decay occurs for all active information that does not receive reinforcement or inhibition during a decay cycle.

HOPE uses one computational procedure for decay while encompassing two different decay schemes. One is a Short-Term memory control scheme. It is used for information that is active but has not reached threshold. Information remains in this state, the Short-Term-State, unless sufficient decay occurs or it surpasses threshold. The other, the Post-Refractory-State, is used to maintain a trace of the information which has reached threshold. It provides a trace of processing during the comprehension of an utterance which can be interpreted within psychological studies of recall ability, i.e. the ability to recall the utterance verbatim when it is not "too" long, and the ability to only produce paraphrase when the complexity or length of the utterance is "too" great (Clark and Clark, 1977; Miller, 1981).

The two states are distinguishable in the experimentally defined test model used throughout the examples. Whether or not distinct states are necessary could be assessed in future work. It is presently felt that such determination could only be attained in the context of an experimentally defined model which included garden-path constructs in its definition because of "reprocessing" considerations.

In the defined test model, decay rates for both states are exponential. The Short-Term decay rate (Ds) is applied to all active information that is in the Short-Term-State. The Post-Refractory decay rate (Dpr) is applied to all information in the Post-Refractory-State. The decay rates for the two schemes are graphed in Figure 10 as they are defined for the "normal" simulation.

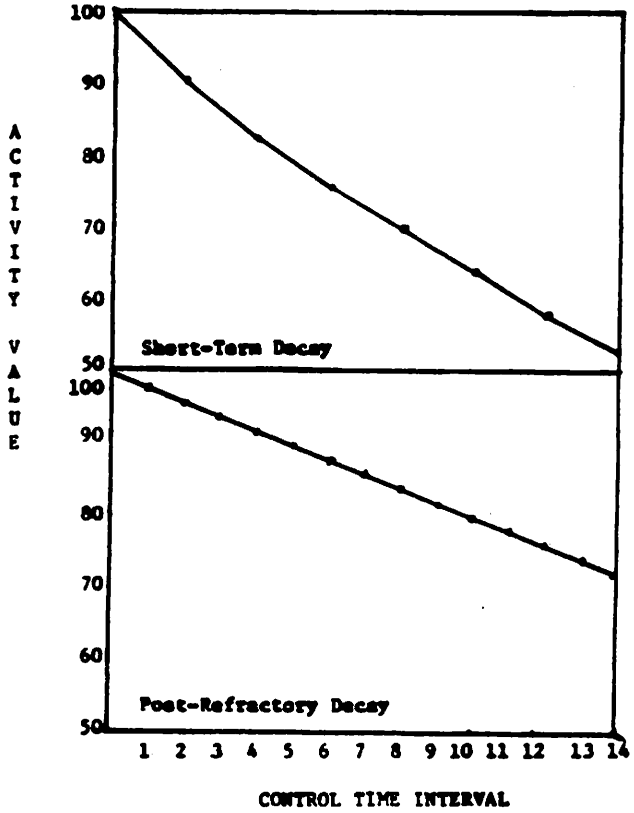


Figure 10: Automatic Decay Rates.

The top graph represents the Short-Term decay rate. The percentage decay after each decay interval (2 CTIs) is approximately 9%. The lower graph represents the Post-Refractory decay rate. The percentage decay after each decay interval (1 CTI) is approximately 2%. These values are arbitrary and used to tune the normal process.

When the activity value (AVAL) of any information decays below a predetermined value, the information can be considered inactive although an explicit change to the inactive state (REST state, i.e. without an AV) is not presently specified. The determination of a reasonable bottom cut off within single sentence processing has not been critical, but will be a concern when more complex syntactic and semantic processing is included in HOPE in the future.

6.1.7 Representation of an "Understood" Utterance. -

Understanding in HOPE is represented as a network showing the relationship among the entities referenced in the utterance. HOPE uses verb-case-control information to build a network representation which depicts the agent and object relationships conveyed by the utterance spoken in isolation.

Figure 11 is an example of the HOPE representation of the resultant network representation for the meaning of the sentence "Paul ran the track." The activity vectors in the HOPE representation can be ignored for this discussion. PAUL is a lexical category type TERM. Successful interpretation produced the node PAUL and the BELONGS-TO arc to TERM.

THE is not explicitly represented in the interpretation. The interpretation of determiners produces the BELONGS-TO arc relating an entity to its TERM interpretation. Functionally the determiner, THE, checks to see if one and only one "free" entity exists in the interpretation to be bound as a TERM.

The interpreted constituent, THE TRACK, is represented by the node TRACK and the BELONGS-TO arc connection to TERM. It represents the interpreted entity formed from a procedural interpretation of CN-TRACK followed by a procedural interpretation for DET-THE.

The verb-case-control information, after interpretation, is depicted by the appropriately labelled AGENT and DIR-OBJect arcs. The intermediate intransitive-verb (VIP) state of ran is recorded by the BELONGS-TO arc connection to VIP. Indication that RAN BELONGS-TO SENTENCE indicates that all morphological and structural constraints have been satisfied for normal termination of the process.

```
=========

pragmatic

=========

   Paul
        <- agent-- ran

   sentence
        <- belongs-to-- ran = (0 0 98 1)

   term
        <- belongs-to-- Paul = (78 0 98 1)
        <- belongs-to-- track = (94 0 98 1)

   track = (90 0 98 1)

        <- dir-obj-- ran

   vip
        <- belongs-to-- ran = (98 0 98 1)
```

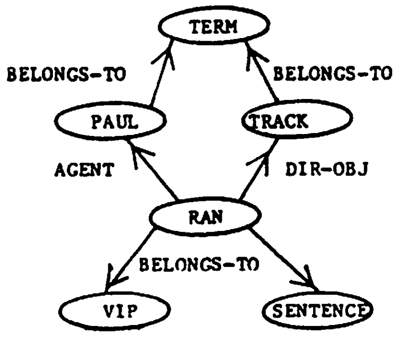


Figure 11: PRAGMATIC Space Representation of the Meaning of an Utterance as a Network.

On the left is the HOPE representation of the meaning of "Paul ran the track." The equivalent network representation is on the right.

6.1.8 An Overview of Propagation in HOPE -

Processing within HOPE is complex. Because of the inclusion of timing variability the complexity is not easily described. An attempt to illustrate what happens over time under the most simplistic conditions will be made. After describing the serial processes, a brief discussion of what processes may occur in parallel will be given. Observation and study of the effect of timing variation on these processes is a primary goal of designing such a model.

It is because of the timing interaction that the model makes its most significant contribution to studying the comprehension process. The intricacies of processing interaction over time are not readily computable using pencil and paper analysis. The computerized model can be thought of as providing a "third-hand" to keep track of functions across variably defined time specifications. This is extremely difficult, if at all possible in the generalized case, without the computer.

Figure 12 shows the propagation paths between spaces. One must keep in mind that the model is not hierarchical in its function. HOPE incorporates both serial and parallel computations. All paths can be traversed in the same CTI. One does not have to completely specify all relationships in a lower space before anything interacts above. All spaces are simultaneously updated.

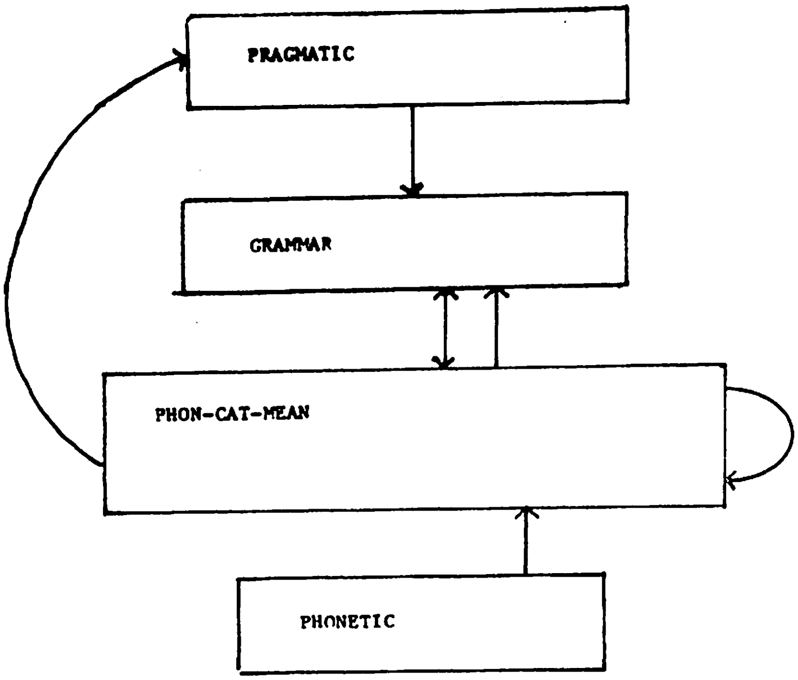


Figure 12: Propagation Paths in the Model.

The following figures are intended to describe the processing included in the basic computations of HOPE. Figures 13 through 15 present graphic depictions of propagation within time-interval computations. Figure 13 includes examples of DECAY, NEW-WORD-INTRODUCTION, and MEANING-PROPAGATION. Figure 14 introduces examples of state changes, and FIRING-INFORMATION-PROPAGATION in addition to the basic description of Figure 13. Figure 15 provides a more detailed description of INHIBITORY-FIRING and simultaneous REFRACTORY-STATE-ACTIVATION for the firing information. In the figures, time intervals are labelled, t1, t2,...; DECAY is labelled "DK"; INTERPRETATION is labelled "INT"; MEANING-PROPAGATION is labelled "MEPROP"; EXCITATORY-FIRING propagation is labelled "EXPROP"; INHIBITORY-FIRING propagation is labelled "INPROP".

Potential interaction between knowledge representations is labelled "?"; and Firing-state, an activation at or above threshold, is indicated by "□". Representation for changes of state are: for REFRACTORY-STATE-ACTIVATION "⬚", and for POST-REFRACTORY-STATE-ACTIVATION "⬭". Solid arrows represent information flow paths, and dashed arrows indicate the result of firing.

Each time-interval is one Compute-Time-Interval (CTI). Updated information is based on the state of information in the immediately preceding time interval, except for the start time interval. In the examples, Word-Control-Interval (WCI) and Decay-Time-Interval (DTIs) are each 2 CTIs (arbitrarily assigned values).

We will begin the propagation flow description at t1 in Figure 13. NEWWORD labels the recognition of the next word in the sentence. This immediately activates the PHONETIC and PHON-CAT-MEAN representations of the word in a fixed manner, an example of MEANING-PROPAPGATION (MEPROP). All possible meanings for the phonetic word are simultaneously active in PHON-CAT-MEAN (see Figure 15). The activation of the PHONETIC representation is at firing threshold (□). Phonetic firing synchronizes GRAMMAR activation by MEANING-PROPAGATION (MEPROP) with NEW-WORD-INTRODUCTION (NEWWORD). The effect is seen in time t2. The amount of activation propagated depends on the number of meanings and category types of the active meanings in PHON-CAT-MEAN. Each derived category type in the GRAMMAR which is also one of the newly activated meanings in PHON-CAT-MEAN is affected by propagation.

Included in t2 is GRAMMAR information that potentially affects activation of meaning for the NEWWORD in t3 (indicated by "?"). Simultaneously, all information at the end of a DTI will DECAY. Information at the end of a DTI has received no inhibitory or excitatory propagation for the length of one DTI. For active meanings in PHON-CAT-MEAN, 2 CTIs have passed (one DTI), and DECAY will occur (DK). This is reflected in an updated state for this information in PHON-CAT-MEAN in t3.

In t3, the active GRAMMAR information DECAYs resulting in a new value of the GRAMMAR information in t4 (DK). The effect of PHONETIC firing in t3 is as described for t1. In t3 the potential interaction of a prior activation of the GRAMMAR with NEWWORD introduction MEANING-PROPAGATION (MEPROP) is shown.

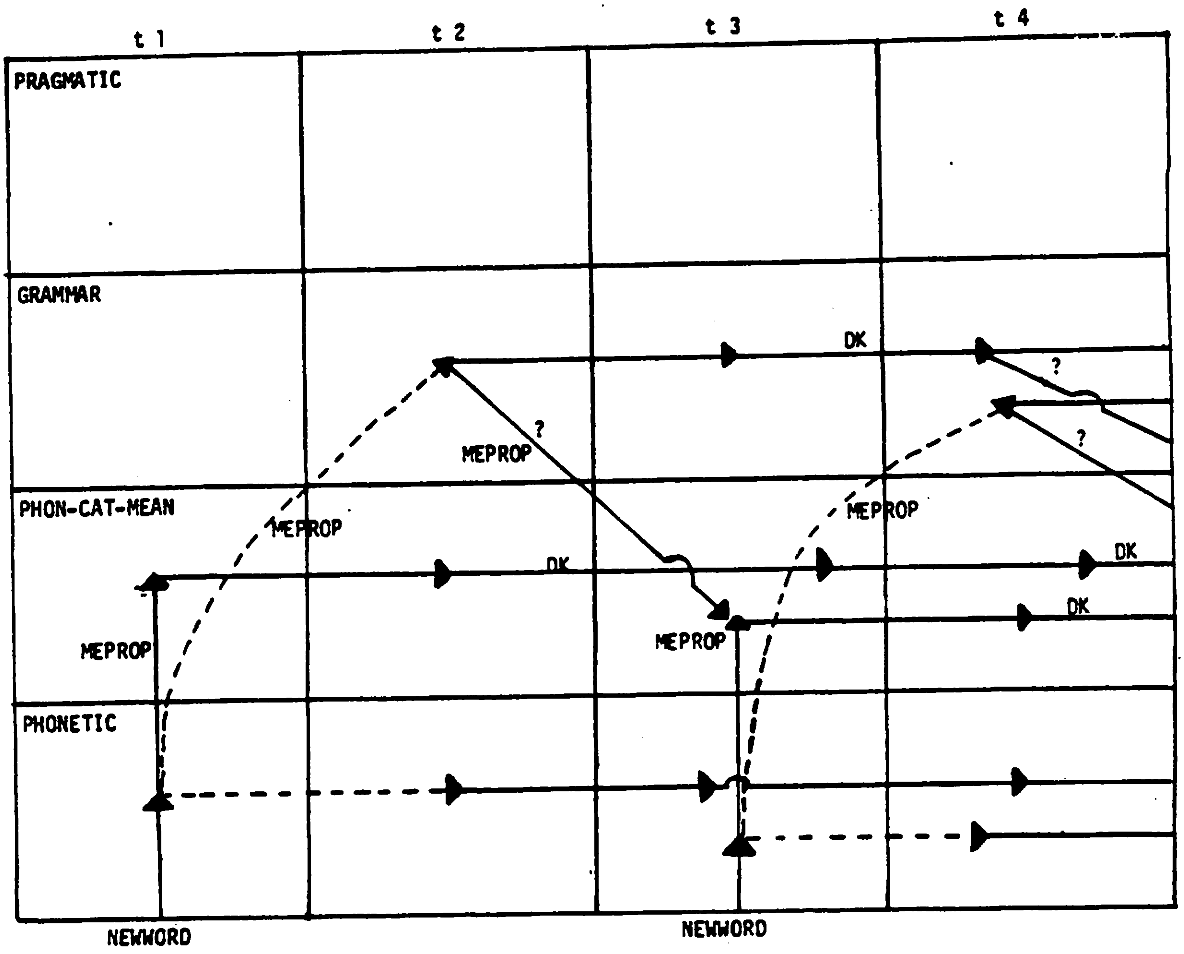


Figure 13: Serial Propagation without State Changes.

In Figure 14, all serial computations as discussed for Figure 13 are assumed. In the following discussion, we will concentrate on changes of state which occurred during different stages of the previously discussed serial computations.

Included in t2 is the change of state of the "fired" PHONETIC information of t1 to the REFRACTORY state (◌). Information remains in this state the length of one DTI of the firing information in the present version of HOPE. The remainder of the computations in t2 are as in Figure 13.

Only additional computations in t3 (with respect to Figure 13) will be described. A representation of the end of the REFRACTORY state for the first fired PHONETIC information is shown in t3. This results in the change of state for this information shown as Post-Refractory-State (⬭) in t4. This state can only occur for fired information after it has been in a REFRACTORY State for the appropriate amount of time. t3 also includes an example of firing in PHON-CAT-MEAN. This represents the interpretation of the correctly disambiguated meaning for a word.

Firing in PHON-CAT-MEAN produces an INTERPRETATION (INT) of the correct meaning in t4. Simultaneously, the interpretation potentially causes EXCITATORY and INHIBITORY effects to all competing active meanings in PHON-CAT-MEAN, seen in t4 (INPROP/EXPROP). (The details of the state changes represented by △ are presented in Figure 15.) Also included in t4 are three REFRACTORY-STATE-ACTIVATIONS due to the parallel firing in PHONETIC and PHON-CAT-MEAN. The GRAMMAR representation is dampened (AV = (0 0 0 0), indicating the information is active but with an AVAL of 0, is unable to influence new word disambiguation), due to the effect of the category type which fired.

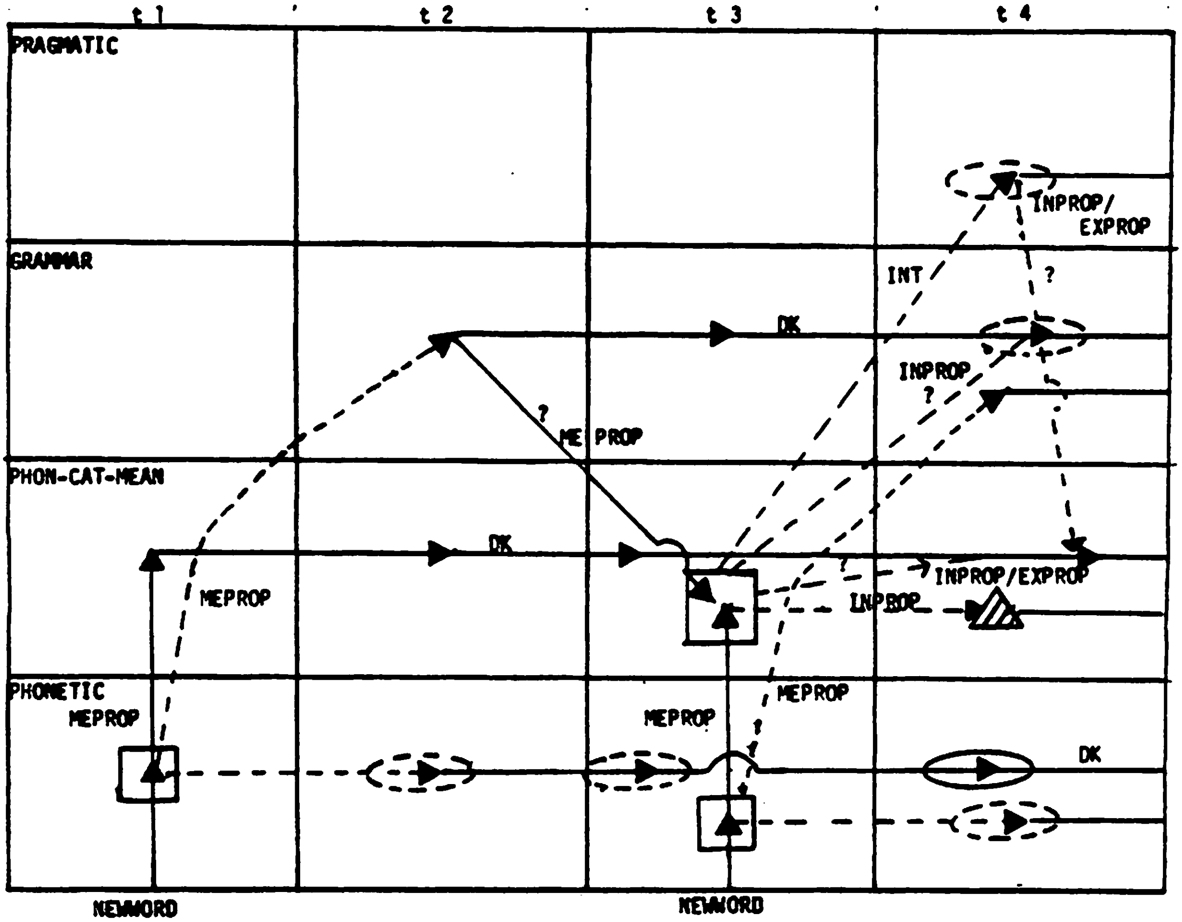


Figure 14: Additional Serial Computations:
Firing, Interpretation, and State Changes.

Figure 15 describes the firing effect shown in Figure 14 (inset in Figure 15). Only active representations are pictured in PHON-CAT-MEAN. One of several "possible" meanings fires at t3. Each m represents a meaning associated with an active word (phonetic representation). Meanings are designated as m(j,k), j=1,number of meanings for a word; k=1,n where n represents an index for each active word for description purposes.

In Figure 15, m(2,1) (the second meaning of the first word) and m(1,2) (the first meaning of the second word) are assumed to be of the same category type. Also meaning m(1,2) is assumed to be firing.

Included in t4 is an example of the change of state of the firing information, m(1,2), to the REFRACTORY state (◌). Simultaneously, meaning m(2,1) is inhibited (INPROP) because it has the same category type as m(1,2), and all competing meanings for the same PHONETIC representation (the active words with the same index as the firing meaning), m(j,2), j=2, number of meanings, are inhibited (INPROP).

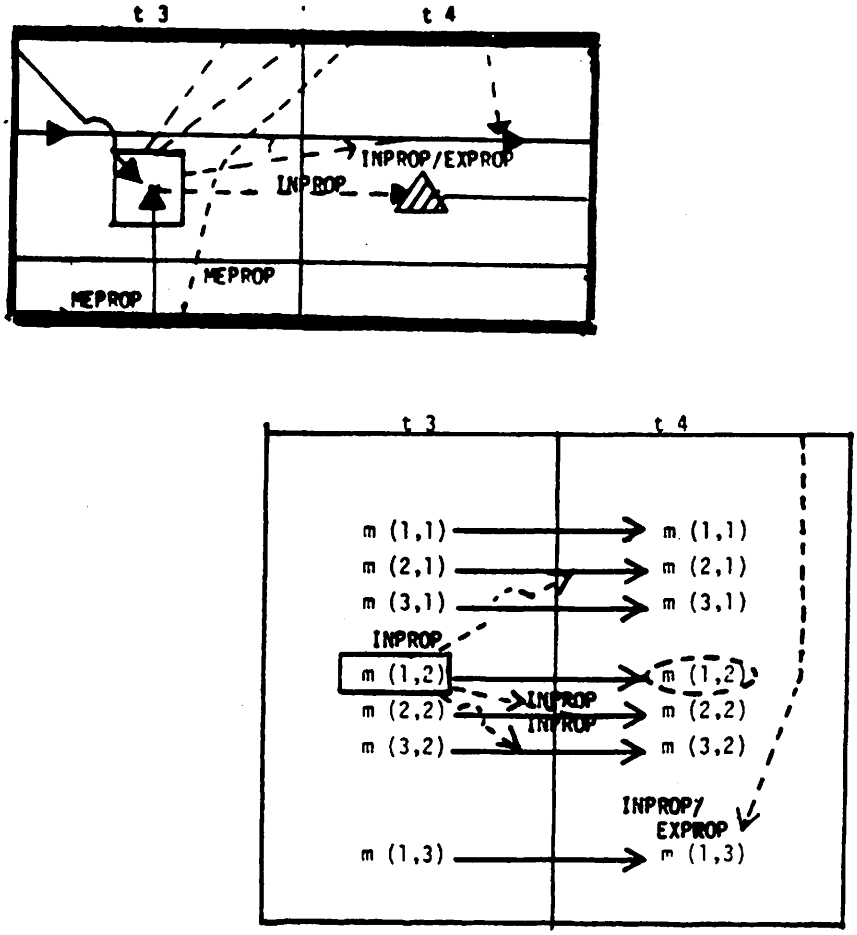


Figure 15: Inhibitory Propagation among Competitors.

Having provided a high level overview of the propagation flow in HOPE, we will now describe the processes more explicitly using examples from a normal simulation.

6.1.9 Serial Computations of the Model: An Algorithmic Description -

Serial computations in HOPE are asynchronous. The applicability of any serial computation to any information requires that it be in a certain state of activity. The serial processes discussed will be described, first by the type of computation, and second, for each context (state) to which the process applies.

Updating of the representation spaces occurs for each time interval and affects all active information, i.e. information having an AV. In addition, when a WCT has passed, new phonetic information becomes active. The effect of "hearing" the next word is computed in addition to the update, when appropriate. The figures associated with each serial computation include HOPE representation on the left. On the right, insets from the serial flow figures (Figures 12-14 above) are provided to show the between-time interactions. The HOPE representation is the end state of the serial flow computation shown on the right. Firing-State in the HOPE representation is indicated by a "*". Each computation will be summarized before presenting its mathematical definition.

Table 2 contains a list of the modifiable parameters and their values that are used throughout the examples in this section and for the "normal" and "lesion" simulations in Section 7. These values are arbitrary.

C-category	85
C-phonetic	72
Counter to terminate process	6
I1 Single meaning - one category type initialization, or Single category type - multiple meaning initialization	95
I2 Multiple category type meanings	75
Iendcont Initial AVAL for endcontour	59
Ipr Initial AVAL for Post-Refractory-State	98
DTIprag PRAGMATIC-Refractory Decay Time Interval	1
PROPAGATION-CONSTANT	33
DTIpr Post-Refractory Decay Time Interval	1
Dpr Post-Refractory-Decay-Rate	98
R Refractory-State Initial AVAL	0
Dr Refractory-State-Decay-Rate	98
DTIs Short-Term Decay Time Interval	2
Ds Short-Term-Decay-Rate	91
T Threshold value	100
Dw Word-Decay-Rate	91
WCI Word-Control-Interval	2

Table 2: Modifiable Parameters in HOPE.

The sentences used throughout the following examples of serial computations are "The dog barks." and "The boy saw the building." In the present version of HOPE, calculations are truncated and divided by 100.

6.1.9.1 New Word Introduction -

NEW-WORD-INTRODUCTION occurs at t1 and thereafter, whenever a WCI has passed. The effect of word introduction during any time t is additive to the state of all active information at that time.

The PHONETIC representation of the NEWWORD is activated with an AVAL at threshold in the Short-Term-State. Simultaneously all category-meanings associated with the newly active phonetic representation (in PHON-CAT-MEAN) are activated in the Short-Term-State. The AVALs for the category-meaning arc-node (CMAN) pairs are determined by the number of category types associated with the phonetic word representation.

In PHON-CAT-MEAN one of 3 possible initial activity levels (AVALs) are assigned to the category-meaning arc-node (CMAN) pairs associated with the "heard" word. If there is only one CMAN pair, or only one category type but two different meanings within that type, the initial assigned AVAL is 95. If multiple CMAN pairs exist, each is assigned an AVAL of 75. Although the values are arbitrary, evidence for different within-syntactic-category-meaning affects than for across-category affect has been suggested in recent work by Swinney (to appear). No allowance is presently made in HOPE for word frequency effects in this AVAL assignment.

Since the phonetic representation is a "stub" for the interactive phonetic perception process, simultaneous activation of a word in the PHONETIC space and all its meanings in PHON-CAT-MEAN can be considered to denote word recognition. The compute Time-Interval-Counter (TIC) for all AVs associated with the newly active nodes and CMAN pairs are reset to the first interval of a DTI for the Short-Term-State. If any active PREDICTed category types in the GRAMMAR space at the previous time have the same category type as the newly activated CMAN pairs, the associated AVAL is the sum of the AVAL associated with the category type (in GRAMMAR) and the initial value AVAL associated with the newly "heard" word, either I1 or I2 in the present version.

In the PHONETIC space, the phonetic node is activated with

AVAL (t) = T,
TIC (t) = DTIs - 1,
D (t) = Ds,
DTI (t) = DTIs.

Simultaneously in PHON-CAT-MEAN, each CMAN pair associated with the phonetic word is activated such that each CMAN pair has an AV where

AVAL (t) =

I1 if the number of categories associated with the phonetic representation is one or if there are multiple category-meanings associated with the phonetic representation having the same category type;

or

I2 if there is more than one category type associated with the phonetic representation regardless of how many meanings are associated within each category type

\+ AVAL (t-1) of the active PREDICT category type (node) in GRAMMAR that matches the category type of the CMAN newly activated for the word.

TIC (t) = DTIs - 1,
D (t) =Ds,
DTI (t) = DTIs.

If there is no match of the category part of CMAN with any active PREDICT nodes (nodes at the head of a PREDICT arc) in the GRAMMAR at time t-1 then the AVAL is either I1 or I2. An example of NEW-WORD-INTRODUCTION with summed activation is seen in Figure 16, where the AVAL at time t-1 of the category type CN in the GRAMMAR, 95, is summed with I1, 95, to produce the AV at time t for CN-DOG having AVAL = 190 which exceeds threshold, 100. This information will "fire" in the next time interval, t+1.

```
           t-1
========

grammar

========

   cn = (95 1 91 2)


==============

phon-cat-mean

==============

   th-uh
        <- det-- the = (95 0 91 2)

=========

phonetic

=========

   th-uh = (0 1 91 2)
```

```
                 t
=======

grammar

=======

   cn = (95 0 91 2)


=============

phon-cat-mean

=============

   d-ao-g
        <- cn-- dog =*(190 1 91 2)

   th-uh
        <- det-- the = (86 1 91 2)


========

phonetic

========

   d-ao-g =*(100 1 91 2)

   th-uh = (0 0 91 2)
```

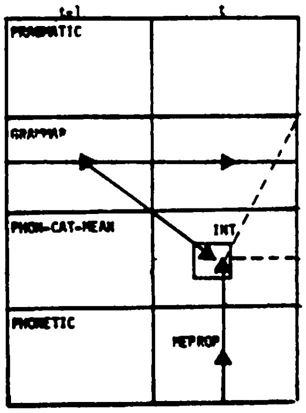


Figure 16: Example of GRAMMAR Prediction on New Word Meanings.

6.1.9.2 Computing Decay -

DECAY occurs in all space representations for all information having an AV which indicates that it is ready to decay (its TIC is 0, indicating a countdown of one DTI). In all spaces, the result of DECAY is calculated using AVAL and D from the AV at the previous time interval. The resultant AV has an AVAL which is the product of AVAL(t-1) and D, TIC is reset to the beginning of a DTI, D and DTI remain unchanged. This can be mathematically described as follows:

All activity vectors (AVAL,TIC,D,DTI), at time t-1 such that AVAL<T (below threshold) and AVAL not equal to 0 (not in the REFRACTORY State) and TIC = 0 (at the end of a DTI) are updated so they reflect the effect of DECAY at time t. Figure 17 shows the change in an AV that occurs during <u>DECAY</u>.

This change is computed:

$\text{AVAL}(t) = \text{AVAL}(t-1) * D(t-1),$
$\text{TIC}(t) = \text{DTI}(t-1) - 1,$
$D(t) = D(t-1),$
$\text{DTI}(t) = \text{DTI}(t-1).$

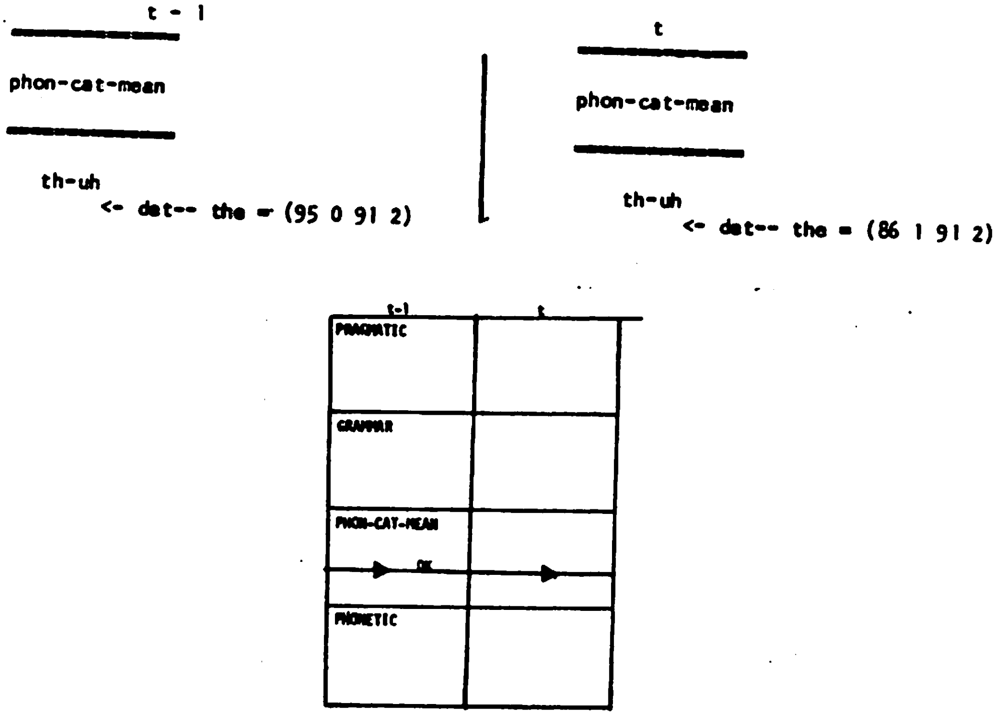


Figure 17: An Example of DECAY(DK).

At the time t-1, AV is ready to DECAY. At time t, DECAY has occurred. The value of the decay rate, approximately 9% for this information, is multiplied by the AVAL at time t-1 resulting in the AVAL of 86 in the figure, at time t. The TIC value is set to the beginning of a DTI (1).

6.1.9.3 Firing-Propagation -

After all active information is decayed as appropriate for a time interval t, all information in a Firing-State (AVAL≥T at time t-1) propagates. A Firing-State is determined from the AVAL. It does not depend on either the space-perspective of the information or on whether the information is in the Short-Term-State or the Post-Refractory-State.

The effects of firing at a schematic level are always the same. Propagation effects depend on the knowledge representation firing (the space-perspective of the firing information) and the structural relationship defined within the GRAMMAR information. The propagation effect of firing at time t-1 will be described for each knowledge representation by space. Propagation effects are asynchronous. There is no order implied in the sequence of descriptions.

PHONETIC Space:

Firing of knowledge in the PHONETIC space coordinates MEANING-PROPAGATION of all meanings associated with the firing phonetic representation in PHON-CAT-MEAN to affect the GRAMMAR space. The AVs associated with the phonetic representation firing that are represented in PHON-CAT-MEAN are propagated to the PREDICT nodes of the GRAMMAR space whose tail node (derived category type) matches the category of the category-meaning arc-node (CMAN) pair in PHON-CAT-MEAN. Figure 18 shows the change of state associated with firing. The firing node enters the REFRACTORY state (REFRACTORY-STATE-ACTIVATION) denoted with an AV having AVAL =0 for [th-uh] at time t. The figure also includes an example of the effect on the GRAMMAR space.

REFRACTORY-STATE-ACTIVATION is computed as follows:

AVAL (t) = R,
TIC (t) = DTI (t-1) - 1,
D (t) = D (t-1),
DTI (t) = DTI (t-1).

The AV of the PREDICT node in GRAMMAR of each category type associated with the newly "heard" word is computed as:

AVAL (t) of the PREDICT node = AVAL (t-1) of the derived category associated meaning in PHON-CAT-MEAN,
TIC (t) = DTI (t-1) - 1 of the derived category associated meaning in PHON-CAT-MEAN,
D (t) = D (t-1) of the derived category associated meaning in PHON-CAT-MEAN,
DTI (t) = DTI (t-1) of the derived category associated meaning in PHON-CAT-MEAN.

```
                t - 1                                 t
========                               |=========
phonetic                               |phonetic
========                               |=========
   th-uh = *(100 1 91 2)               |   th-uh = (0 1 91 2)


=============                          |==============
phon-cat-mean                          |phon-cat-mean
=============                          |==============
   th-uh                               |   th-uh
        <- det-- the = (95 1 91 2)     |        <- det-- the = (95 0 91 2)


=======                                |========
grammar                                |grammar
=======                                |========
                                       |   cn = (95 1 91 2)
```

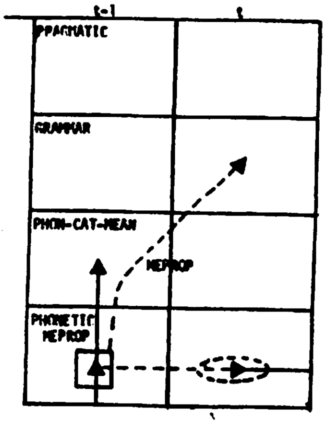


Figure 18: Fixed Propagation Effect on the GRAMMAR (MEPROP).

The effect of a PHONETIC word firing on the PREDICTion role of the GRAMMAR is shown. This is an example of fixed MEANING-PROPAGATION (MEPROP). [th-uh] activates the PREDICT node, CN, with an AVAL of 95, the AVAL associated with the CMAN pair DET-THE in PHON-CAT-MEAN at time t-1. The PHONETIC representation, [th-uh], enters the REFRACTORY State at time t, with AVAL=R, 0, TIC initialized to DTI (t-1) -1, D and DTI remain in the same state.

PHON-CAT-MEAN Space:

Firing propagation from and within the PHON-CAT-MEAN space is the most complicated of the firing schemas because of its multiple effect. It can be both excitatory and inhibitory. It can affect the GRAMMAR space and activates suitable interpretation functions. Figure 15, above, presented an overview of some of the effects of firing in this space. The firing information enters the REFRACTORY State.

Firing in PHON-CAT-MEAN occurs for a CMAN pair having an AV with AVAL$\geq$T at time t-1. FIRING-INFORMATION-PROPAGATION occurs by

1. Applying the correct category INTERPRETATION function (INT) to the PRAGMATIC space. The AVAL associated with the representation created depends on the interpretation function. If there is no categorial composition (defined by the GRAMMAR) during interpretation, the AV associated with the resulting representation is that of the PRAGMATIC REFRACTORY State AV, i.e. immediate propagation occurs. Figure 19 illustrates two consecutive time intervals during which the CMAN pair CN-DOG in PHON-CAT-MEAN fires, an example of non-compositional interpretation. The immediate top-down effect using the state of the GRAMMAR influences disambiguation of previously active meanings in PHON-CAT-MEAN.

   During non-compositional interpretation, the AV in the PRAGMATIC space is computed as:

   AVAL (t) = R
   TIC (t) = DTIprag - 1,
   D (t) = Dpr,
   DTI (t) = DTIprag

   If there is composition during interpretation, the AVAL of the firing CMAN pair of PHON-CAT-MEAN becomes the AVAL of the AV associated with the resulting representation in the PRAGMATIC space. See Figure 34 in the next section, for an example based on VTP interpretation.

2. Feedback propagation of the firing information can disambiguate the meaning of a previously "heard" word. All active CMAN pairs in PHON-CAT-MEAN which have a category type matching the derived category type at the tail of the PREDICT arc to the firing category type (in GRAMMAR) receive excitatory input. This example of EXCITATORY-FIRING (EXPROP) is shown in Figure 19, above.

DET is the derived category at the tail of the PREDICT arc to CN (the firing category type). The AVAL of DET-THE in PHON-CAT-MEAN is excited by the propagation and has a resulting AVAL of 148 at time t.

If the category part of the CMAN pair with AVAL>T is at the head of a PREDICT arc in GRAMMAR, all CMAN pairs in PHON-CAT-MEAN having a category matching the node at the tail of that PREDICT arc in GRAMMAR are updated such that for each

AVAL (t) = AVAL (t) + (PROPAGATION-CONSTANT) *
AVAL(t-1) of the firing information in PHON-CAT-MEAN,
TIC (t) = DTI (t-1) -1
D (t) = D (t-1),
DTI (t) = DTI (t-1).

3. When one of several competing category meanings for the same phonetic word fires, the others are inhibited by an amount determined by the parameter value C-phonetic. The activity value at time t-1 for each of these competing CMAN pairs in PHON-CAT-MEAN is reduced at time t by the percentage C-phonetic.

The AVAL of each competing CMAN pair associated with the same phonetic word as that of the firing CMAN pair is reduced to a percentage of its AVAL at t-1 as follows:

AVAL (t) = (C-phonetic) * AVAL (t-1),
TIC = DTI (t-1) - 1,
D = D (t-1)
DTI = DTI (t-1).

This produces an inhibitory effect, INHIBITORY-FIRING propagation (INPROP). An example is shown in Figure 20.

4. All active CMAN pairs in PHON-CAT-MEAN that have the same category type as the firing CMAN pair are also inhibited, but by a different amount than those competing as phonetically linked alternatives (described in 3, above). The AVAL at time t-1 of each active "category" competitor is reduced at t by the percentage specified in C-category.

```
           t-1
=========
pragmatic
=========

=======
grammar
=======
   cn = (95 0 91 2)

=============
phon-cat-mean
=============
   d-ao-g
         <- cn-- dog =*(190 1 91 2)
   th-uh
         <- det-- the = (86 1 91 2)
```

```
              t
==========
pragmatic
==========
   dog = (0 0 98 1)

========
grammar
========
   cn = (0 0 0 0)

==============
phon-cat-mean
==============
   d-ao-g
         <- cn-- dog = (0 1 91 2)
   th-uh
         <- det-- the =*(148 1 91 2)
```

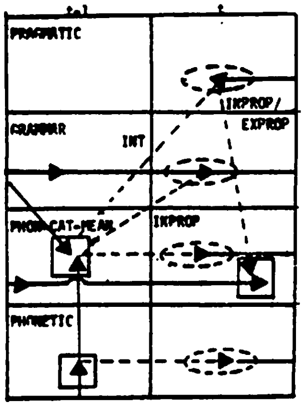


Figure 19: Threshold Firing-Propagation.

Figure 19: Threshold Firing-Propagation

The AV associated with CN-DOG at time t-1 in PHON-CAT-MEAN has an AVAL exceeding threshold, 100. In addition to CN-DOG entering the REFRACTORY State, its firing effect results in changes in information in spaces, GRAMMAR and PRAGMATIC in the example as there are no competing CN CMAN pairs in PHON-CAT-MEAN to be affected.

The AVAL of the firing information, CN-DOG in PHON-CAT-MEAN, is set to R, 0, (REFRACTORY-STATE-ACTIVATION). The AV associated with CN in GRAMMAR is set to a dampened state (active, but not effectively able to influence meaning selection) until new information reinitializes it.

INTERPRETATION occurs in the PRAGMATIC space. An unattached node in PRAGMATIC is a CN. The AV indicates the PRAGMATIC REFRACTORY State because CN is a lexical (non-compositional) category and its propagation from PRAGMATIC occurs immediately. The effect of PRAGMATIC propagation is seen in the changed AV for DET-THE in PHON-CAT-MEAN. This effect is determined by the state of the GRAMMAR with respect to the firing information type.

Each active CMAN pair having a category type matching that of the firing CMAN pair is updated:

AVAL (t) = (C-category) * AVAL (t-1),
TIC (t) = DTI (t-1) - 1,
D (t) = D (t-1)
DTI (t) = DTI (t-1).

This also produces an inhibitory effect, INHIBITORY-FIRING propagation (INPROP). The effect of competing category updating is shown in Figure 20.

5. After firing, information enters the REFRACTORY State. This is shown in Figure 20 for VIP-BUILDING at time t. It is seen in the inset in the change of state (REFRACTORY-STATE-ACTIVATION) and is designated " ".

The activity value of the firing information enters the REFRACTORY State (REFRACTORY-STATE-ACTIVATION) having

AVAL (t) = R,
TIC (t) = DTI (t-1) - 1,
D (t) = D (t-1),
DTI (t) = DTI (t-1).

PRAGMATIC Space:

In the PRAGMATIC space BELONG-TO arc-node pairs have AVs associated with them during interpretation. These pairs reflect successful interpretation and resultant composition of a category type. The type formed by any interpretative procedure is defined within the GRAMMAR.

Propagation from the PRAGMATIC space occurs during time t for all arc-node pairs having an AV with AVAL≥T at time t-1 in the following ways:

1. If the category of the firing arc-node pair (in PRAGMATIC) is at the head of a PREDICT arc in the GRAMMAR and "active" (in GRAMMAR), the propagation affects PHON-CAT-MEAN as described in 2 of the propagation effect for the PHON-CAT-MEAN space. In this way, PRAGMATIC information affects disambiguation of partially interpreted information.

2. The same category type competition computations as shown in Figure 20 for firing information within PHON-CAT-MEAN occur for PRAGMATIC firing information. The only difference is that the source of the firing information is the PRAGMATIC space.

3. The AV of the arc-node pair in PRAGMATIC at time t is set to the PRAGMATIC REFRACTORY State defined as:

   AVAL (t) = R,
   TIC (t) = DTIprag - 1,
   D (t) = Dpr,
   DTI (t) = DTIprag.

```
==============     t - 1
phon-cat-mean*
==============

  b-ih-l-d-ih-ng
       <- cn-- building = (68 0 91 2)
       <- vip-- building =*(112 1 91 2)
       <- vtp-- building = (68 0 91 2)

  b-oy
       <- cn-- boy = (63 0 91 2)

  end
       <- endcont-- stop** = (0 1 91 2)

  s-ao
       <- cn-- saw = (55 0 91 2)
       <- vip-- saw = (99 1 91 2)
       <- vtp-- saw = (55 0 91 2)

  th-uh
       <- det-- the = (78 0 91 2)
```

```
=============     t
phon-cat-mean
=============

  b-ih-l-d-ih-ng
       <- cn-- building = (48 0 91 2)
       <- vip-- building = (0 1 91 2)
       <- vtp-- building = (48 0 91 2)

  b-oy
       <- cn-- boy = (57 1 91 2)

  end
       <- endcont-- stop** = (0 0 91 2)

  s-ao
       <- cn-- saw = (50 1 91 2)
       <- vip-- saw = (84 1 91 2)
       <- vtp-- saw = (50 1 91 2)

  th-uh
       <- det-- the = (70 1 91 2)
```

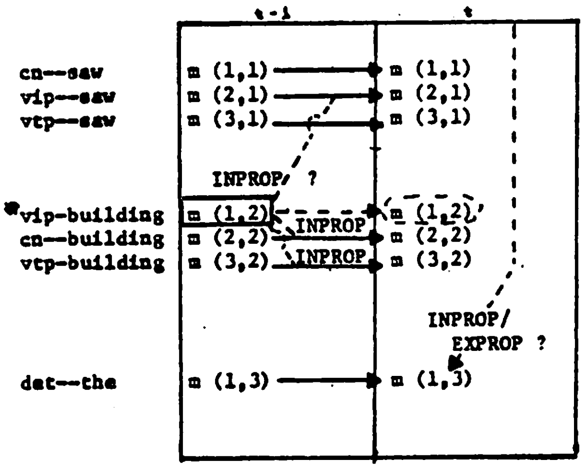


Figure 20: Effect on Competitors in PHON-CAT-MEAN.

Figure 20: Effect on Competitors in PHON-CAT-MEAN.

VIP-BUILDING, in PHON-CAT-MEAN at time t-1 with an AVAL=112, is represented as m(1,2) in the inset. It is ready to fire.

All competing meanings of VIP-BUILDING (CN-BUILDING and VTP-BUILDING) are inhibited. These correspond to m(2,2) and m(3,2) in the inset. The AVAL of each (55 at time t-1) is reduced to 72% (C-phonetic) of its value (48 at time t).

In addition, all competing VIP type meanings are inhibited. In the figure, the AV of VIP-SAW (m(2,1) in the inset) is affected. Its AVAL (99 at time t-1) is reduced to 85% (C-category) of its value (84 at time t).

6.1.9.4 Change of State Computations -

After active information fires, it enters a REFRACTORY State (AVAL=0) for the length of one decay interval based on the DTI of the firing state. At the end of the REFRACTORY State (TIC=0), information enters the Post-Refractory-State. The change of state computation proceeds as follows:

For knowledge in the REFRACTORY State, AVAL (t-1) = 0 and TIC(t-1)=0, the AV of the information reflects a change of state

AVAL(t) = Ipr,
CTI(t) = DTIpr - 1,
D(t) = Dpr,
DTI(t) = DTIpr.

The REFRACTORY State in the PRAGMATIC space in the current design is only one CTI and is shorter than the REFRACTORY State for the lower level representations. Figure 21 shows the change of state for the information in the PHONETIC space associated with d-ao-g (dog).

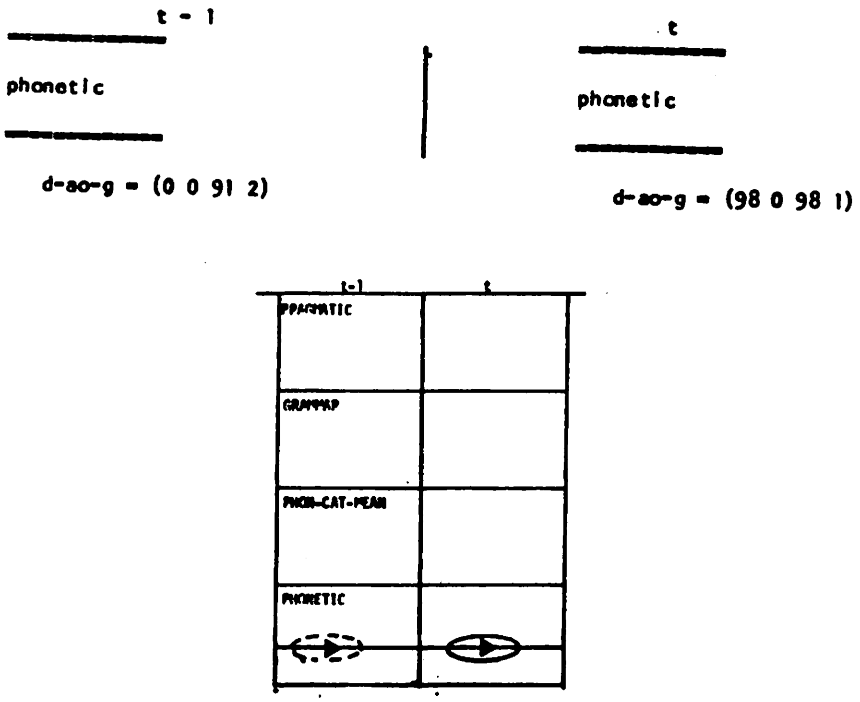


Figure 21: An Example of POST-REFRACTORY-STATE-ACTIVATION.

With AVAL= R, 0, and TIC=0, [d-ao-g] is ready to change state to the Post-Refractory-State at time t-1. At time t, [d-ao-g] is in the initial interval of the Post-Refractory-State. The AVAL is initialized to the Ipr, 98, the the value of TIC is reinitialized for the Post-Refractory-State, 0, and D and DTI are initialized to Dpr, 98, and DTIpr, 1, respectively.

6.1.9.5 Parallel Processing within the Model -

Simultaneous parallel processes having different behavioral interpretations can be seen in the sample runs of the model. When the model is analyzed in parallel, the following processes occur simultaneously for each CTI:

1. Memory decays, in one of the two different state representations, if there is no reinforcement or inhibition;
2. Reinforcement or inhibition effects of firing information propagate among the knowledge representations;
3. Interpretation procedures execute; and
4. New word introduction occurs, when appropriate.

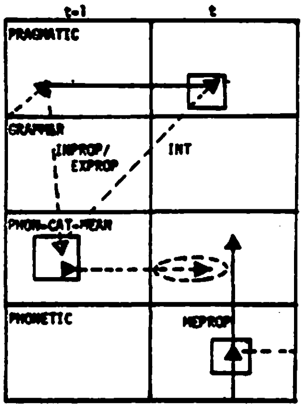
An example of parallel computations is seen in Figure 22.

Figure 22: An Example of Parallel Processing in HOPE.

The state of the model at time t-1, prior to NEW-WORD-INTRODUCTION, with DET-THE ready to "fire" (AVAL=148).

The interpretation of DET-THE, the result of firing in PHON-CAT-MEAN, occurs simultaneously with the introduction of the word [b-r-k-s] (barks) and its immediate effects. The state of the model after the update is shown in the figure at time t. DET-THE is in the REFRACTORY State, PRAGMATIC interpretation has created the TERM representation, and the new word, [b-r-k-s], has been "heard" and has activated its associated meanings.

```
                   t-1
==========

pragmatic

==========

   dog = (0 0 98 1)


========

grammar

========

   on = (0 0 0 0)


==============

phon-cat-mean

==============

   d-ao-g
        <- on-- dog = (0 1 91 2)

   th-uh
        <- det-- the =*(148 1 91 2)

=========

phonetic

=========

   d-ao-g = (0 1 91 2)

   th-uh = (98 0 98 1)
```



```
                    t
=========

pragmatic

=========

   dog = (98 0 98 1)

   term
        <- belongs-to-- dog =*(148 1 91 2)

=======

grammar

=======

   on = (0 0 0 0)


=============

phon-cat-mean

=============

   b-r-k-s
        <- on-- barks = (75 1 91 2)
        <- vip-- barks = (75 1 91 2)

   d-ao-g
        <- on-- dog = (0 0 91 2)

   th-uh
        <- det-- the = (0 1 91 2)

========

phonetic

========

   b-r-k-s =*(100 1 91 2)

   d-ao-g = (0 0 91 2)

   th-uh = (96 0 98 1)
```

Figure 22: An Example of Parallel Processing in HOPE.

In summary, HOPE contains knowledge representations that are distributed in multiple spaces. Its design includes a self-contained memory management scheme, a modifiable grammar that specifies structural and semantic compositional form simultaneously, modifiable parameters to provide an experimental tool to analyze the effect of timing, amount of propagation, decay rate, and degradation of knowledge while addressing issues of possible representations suitable for a given task, in this case linguistic processing. Its usefulness is not only in studying language processing and its pathology, but also in providing a new perspective on problem decomposition by raising issues relevant to analysis of representation and interaction of the selected representation during a time interval.

The following section will illustrate the usefulness of the model by providing an example of "normal" and "lesioned" simulation processing for two simple sentences. A brief discussion of the possible implications of the results of the lesion simulation concludes the paper.

7. A PROCESS EXAMPLE

Normal processing within HOPE depends on the synchronization of the interaction of information to simulate the comprehension process.

7.1 A "Normal" Simulation

The "normal" simulation presents an integrated account of the interactions of the serial computations described in the previous section. A short S-V sentence, "The dog barks." is used to illustrate the synchronized activation of those processes. Consecutive intervals of an actual simulation of the comprehension of the sentence are presented in Figures 25 through 30 and will illustrate the interactions of the knowledge structures of the model which result in convergence to a network representation of the meaning of the interpreted sentence.

Implicit in the figures is the multiple representation of named arcs, nodes, and spaces, where use of the same name in a different space or as a space name indicates a different "perspective" of the same "entity."

For the illustrative simulations, the arbitrary parameter values remain as shown in Table 2. All calculations are truncated. References to the serial flow discussion of the previous section are provided with the figures to facilitate reference. Results of decay and activation propagation in the flow diagrams is captured in the relative sizes of the active nodes in each space. One should note that each space contains all appropriately defined information. However, only active information within each space is displayed during processing. For reference, the grammar defined for the "normal" simulations is given in Figure 23.

```
<< grammar >>

cn

   <-predict-- det

det

endcont

   <-predict-- vip

sentence

   <-to-form-- vip

term

   <-predict-- vtp
   <-to-form-- det

vip

   <-to-form-- vtp

vtp
```

Figure 23: Grammar Representation for "Normal" Simulations.

The grammar represents S-V and S-V-O sentence structures. It includes structural representations for composite and lexical meaning instantiations which are considered equivalent types during interpretation. The graphical representation of the grammar is provided to clearly delineate the connections.

An example set of sentences which covers the syntactic structures specified in the grammar is listed in Table 3. Any interpretation for "normal" and simulated lesion conditions must necessarily analyze simulations of the entire set. Only two sentences will be used to illustrate simulations, sentence A for a "normal" simulation and sentence C to illustrate a "lesion" simulation. One must keep in mind that the conjectured interpretations of the processing during a "lesioned" simulation on one sentence do not necessarily reflect those derived from a complete simulation experiment on the entire set. The single "lesion" simulation is presented to suggest how one approaches assessment of simulation models with respect to clinical validation.

A. The dog barks.
B. Paul ran.
C. The boy saw the building.
D. Paul ran the track.
E. The boy saw Paul.
F. Paul saw Jason.

Table 3: Sentence Structures that Cover the Defined Model.

The sentences include all combinations of lexical and composite category types which are specified as well-formed by the grammar.

Processing begins with the first word introduced at t1. "Hearing" a word results in activation of information in the PHONETIC and PHON-CAT-MEAN spaces. During a second CTI, the "heard" word affects the GRAMMAR representations (MEANING-PROPAGATION) based on the active meanings of the word in PHON-CAT-MEAN. Figure 25 shows the state of information following introduction of the word [th-uh] (THE) at time t1.

Serial flow graphs for between-time computations are included on the right of each figure to show the effective changes from the previous time interval. As in Figures 13-15 in Section 6, serial flow is indicated by solid arrows, while firing propagation effects are indicated by dashed arrows. State changes are characterized as Firing-State "   ", REFRACTORY State "   ", and Post-Refractory-State as "   ". In the HOPE representation the Firing-State is designated with a "*".

Bracketed numbers are labels used to reference the location of the described state and serial computation in the figures. They represent corresponding aspects of information in the two representations of each figure.

To attain the state represented at the end of t1 as seen in Figure 24, the following explicit computations in the named spaces occurred:

PHONETIC:

The new word [th-uh] was initialized with an AVAL of 100 (the threshold value).

PHON-CAT-MEAN:

In the PHON-CAT-MEAN space the CMAN pair for [th-uh] has an activity vector with AVAL 95. The TIC is initialized, D = Ds (91) and DTI = DTIs (2 CTI's).

```
***** process interval 1 *****

  =========
  pragmatic
  =========

  =======
  grammar
  =======

  =============
  phon-cat-mean
  =============

  [2] th-uh                  [3]
           <- det-- the = (95 1 91 2)

  ========
  phonetic
  ========

  [1] th-uh =*(100 1 91 2)
```

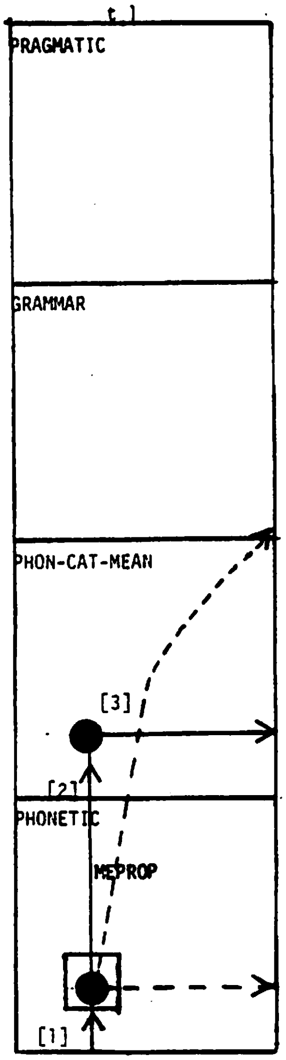


Figure 24: First Interval of "Normal" Simulation Process (t1).

The "heard" word in PHONETIC space is initialized at the threshold value [1] (Figure 16). The associated category-meaning arc-node (CMAN) pair in PHON-CAT-MEAN is activated in the Short-Term-State [2] at the beginning of a Short-Term Decay Interval [3].

Computations underlying the resultant state of Figure 25 summarized by space are:

PHONETIC:

The firing node entered the REFRACTORY State. In HOPE this is noted by having an AVAL = 0. The remainder of the AV of the REFRACTORY State was assumed from the Firing-State AV with a reinitialization of the TIC to the beginning of a DTI.

PHON-CAT-MEAN:

All TICs are updated (decreased by 1) to indicate a time computation. No decay occurred because no counter (TIC) was equal to 0 (the end of a DTI).

GRAMMAR:

PREDICT nodes connected to category types associated with the PHONETIC firing information are activated with AVALs identical to the CMAN associated AVALS in PHON-CAT-MEAN.

In Figure 25, the AVAL of 95 for the CMAN pair DET-THE in PHON-CAT-MEAN is associated with the node CN (the PREDICT node for DET, see Figure 23) in the GRAMMAR space. The AV for CN is initialized in the Short-Term-State with the propagated AVAL.

```
***** process interval 2 *****

  ==========

  pragmatic

  ==========


  ========

  grammar

  ========

  [3] cn = (95 1 91 2)


  ==============

  phon-cat-mean

  ==============

     th-uh
  [2]      <- det-- the = (95 0 91 2)

  =========

  phonetic

  =========

  [1] th-uh = (0 1 91 2)
```

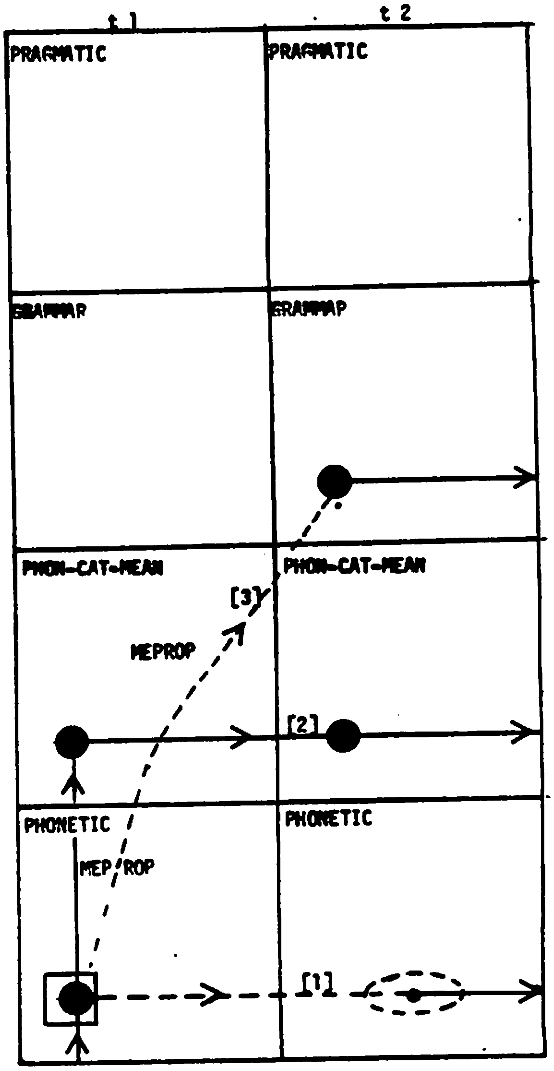


Figure 25: The Second CTI of a DTI (t2).

In the PHONETIC space, the fired node entered the REFRACTORY state [1] (Figure 18).

The Figure provides an example of the changes in the TIC value (decreased by 1) of the activity vector during a DTI [2].

The PREDICT node(s) in the GRAMMAR space, of the derived category type(s) matching the categories of the "heard" word were assigned the same activity vector as the CMAN pair of the PHON-CAT-MEAN space. If more than one CMAN pair exists, multiple predictions are made when present in the GRAMMAR. The GRAMMAR space shows one node which is "activated" by the input [3].

Figure 26 illustrates the prediction effect of the GRAMMAR on subsequent processing. The second word of the sentence, [d-ao-g] (dog), was heard. Fixed MEANING-PROPAGATION for [d-ao-g] proceeded in the same way as for [th-uh] in the previous figures. As there was no PREDICT arc from CN in GRAMMAR (see Figure 23), there will be no change in the GRAMMAR space during the next CTI. However, the predict information associated with the CN node in the GRAMMAR space at time t2 (Figure 24) was added to the new information in PHON-CAT-MEAN, i.e. there was a bottom-up contribution of 95 and a top-down contribution of 95, resulting in an AVAL of 190 for the CN meaning of [d-ao-g] in PHON-CAT-MEAN.

The phonetic CMAN representation, [th-uh]-DET-THE in PHON-CAT-MEAN was at the end of a DTI in t2. The AV associated with it in Figure 25 represents the result of DECAY (Figure 17). The TIC values of the PHONETIC representations for [th-uh] and of the GRAMMAR representation for CN decreased by 1 due to the processing of one CTI (Figure 25).

```
***** process interval 3 *****

  =========

  pragmatic

  =========

  =======

  grammar

  =======

     cn = (95 0 91 2)


  =============

  phon-cat-mean

  =============

  [2] d-ao-g
[3]          <- cn-- dog =*(190 1 91 2)
      th-uh
             <- det-- the = (86 1 91 2)


  ========

  phonetic

  ========

  [1] d-ao-g = *(100 1 91 2)

      th-uh = (0 0 91 2)
```

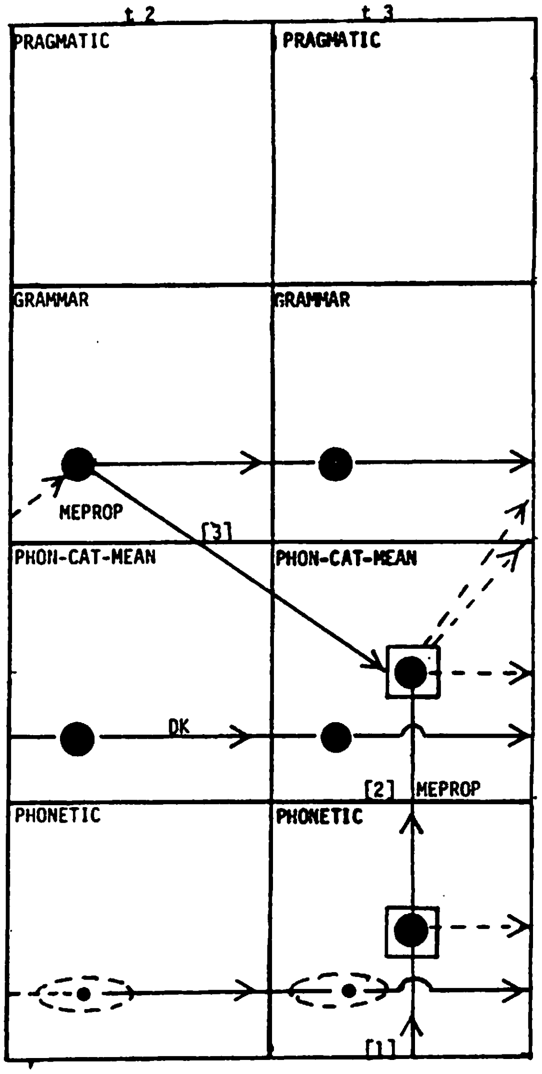


Figure 26: Prediction Effect Illustrated (t3).

A second word was introduced in the PHONETIC space [1]. It activated the associated CMAN pairs in PHON-CAT-MEAN [2] (Figure 16). The top-down predictive affect of GRAMMAR activation combined with the initial activation for the CN meaning to produce an AVAL for the newly "heard" word's associated meaning, which exceeded threshold in this case [3].

Figure 27 illustrates the effect of firing-propagation on the on-line process. Changes affected during the transition to the state represented in the figure are:

PHONETIC:

[th-uh] was at the end of the REFRACTORY State at t3. It entered the Post-Refractory-State, identified by an AVAL of 98 and the DTIpr value of 1.

[d-ao-g] fired at t3 and entered the first CTI of the REFRACTORY State.

PHON-CAT-MEAN:

CN-DOG fired at t3 and entered the REFRACTORY State. The effect of CN-DOG firing used the GRAMMAR representation (see Figure 23) to determine that DET was the derived category that influenced the meaning selection of CN-DOG. (In this example, there was only one; there may be more in other cases.) The effect is to propagate the "interpreted CN" meaning. Only the PROPAGATION-CONSTANT portion (33 %) of the AVAL was combined with the current AVAL of DET-THE at time t3 to produce the AVAL of 148 at time t4. The information remained in the Short-Term-State. There are no competing CN meanings active. Therefore, the effect of competition is not seen.

GRAMMAR:

The effect of CN-DOG firing dampened the CN PREDICT node. It can only be reactivated by subsequent new bottom-up information flow.

PRAGMATIC:

The firing effect of CN-DOG triggered the interpretation of a CN type. This resulted in the creation of the DOG node. (An unattached node in the PRAGMATIC space represents a CN in the example model.) Because the interpretation was non-compositional (by definition in the model specification) the propagation effect of the interpretation was immediate (affecting DET-THE as previously described) and the node immediately entered the PRAGMATIC REFRACTORY State, characterized by having an AVAL of 0 and DTIprag = 1.

```
***** process interval 4 *****
  ==========
  pragmatic
  ==========
  [1] dog = (0 0 98 1)

  ========
  grammar
  ========
  [2] cn = (0 0 0 0)

  ==============
  phon-cat-mean
  ==============
     d-ao-g
          <- cn-- dog = (0 1 91 2)
  [3] th-uh
          <- det-- the =*(148 1 91 2)

  =========
  phonetic
  =========
     d-ao-g = (0 1 91 2)

     th-uh = (98 0 98 1)
```

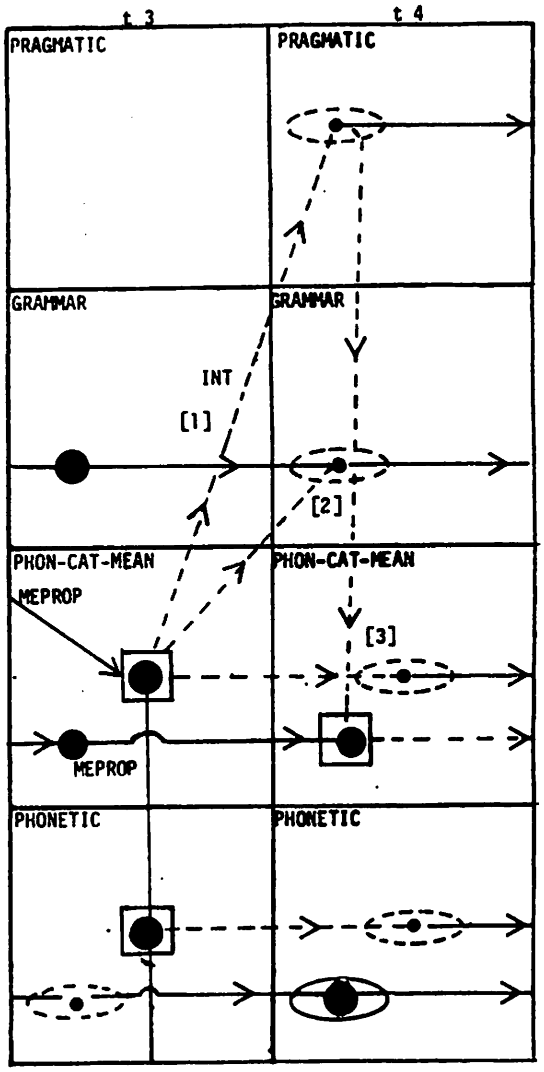


Figure 27: Feedback Confirmation (t4).

An example of bottom-up firing is presented in the figure. The CMAN pair in PHON-CAT-MEAN fired. Its firing produced the node in PRAGMATIC space representing its meaning (dog) [1] (Figure 19).

The PREDICT node in the GRAMMAR was dampened [2].

After successful interpretation in PRAGMATIC, immediate propagation, determined by the state of the GRAMMAR, occurred to affect active meanings in PHON-CAT-MEAN [3].

Figure 28 demonstrates multiple activation of meaning during the on-line process. For each space, the computations reflected in the final state of the figure are:

PHONETIC:

[th-uh] and [d-ao-g] were both in the Post-Refractory-State and underwent decay between t5 and t6.

[b-r-k-s] fired at t5 and entered the REFRACTORY state at t6.

PHON-CAT-MEAN:

The multiple meanings defined for [b-r-k-s] were activated in the Short-Term-State. Since they represent two different categories, they were assigned an initial AVAL of 75.

DET-THE was in the second CTI of the REFRACTORY State, having fired at t4.

CN-DOG, at the end of the REFRACTORY State in t5, has entered the Post-Refractory-State in t6.

GRAMMAR:

The VIP meaning for [b-r-k-s] has an associated PREDICT node in the GRAMMAR. CN does not. (See Figure 23.) The AVAL of VIP-BARKS in PHON-CAT-MEAN propagated to the PREDICT node for VIP (ENDCONT) in t6.

PRAGMATIC:

The CN interpretation of DOG was in the Post-Refractory-State. The TERM representation of "a specific" DOG (the dog) passed the DTI for the REFRACTORY State. It produced no observable firing effect because there was no active PREDICT node, TERM, in the GRAMMAR.

```
***** process interval 6 *****

  ==========

  pragmatic

  ==========

     dog = (96 0 98 1)

     term
  [3]     <- belongs-to-- dog = (0 0 98 1)

  ========

  grammar

  ========

     cn = (0 0 0 0)

  [2] endcont = (75 1 91 2)

  ==============

  phon-cat-mean

  ==============

     b-r-k-s
          <- cn-- barks = (75 0 91 2)
  [1]     <- vip-- barks = (75 0 91 2)
     d-ao-g
          <- cn-- dog = (98 0 98 1)
     th-uh
          <- det-- the = (0 0 91 2)

  =========

  phonetic

  =========

     b-r-k-s = (0 1 91 2)

     d-ao-g = (98 0 98 1)

     th-uh = (94 0 98 1)
```

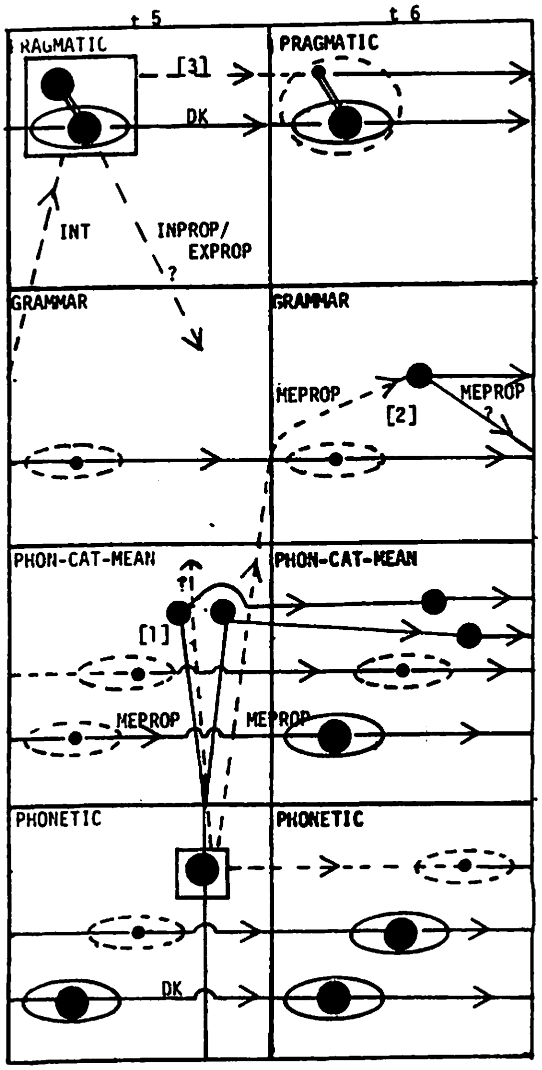


Figure 28: Multiple Predictions and An Interpretation (t6).

Multiple meaning activation occurred for the third word "heard" in the sentence at time t5 [1] (Figure 16). During t6 meaning activation propagated to the PREDICT nodes in the GRAMMAR associated with categories of the newly activated word [2] (Figure 18).

Simultaneously, firing in PHON-CAT-MEAN resulted in the completed interpretation in PRAGMATIC represented by the BELONGS-TO arc connection of DOG to TERM [3].

Figure 29 represents the final state of the simulation. The general processing flow of information from t7 through t10 can be summarized:

When ENDCONT in PHON-CAT-MEAN fired at t7, information propagated in reverse using the GRAMMAR to confirm the selection of the VIP reading for BARKS. When VIP-BARKS fired at t8, the competing CMAN, CN-BARKS, was inhibited to approximately 72 % (C-phonetic) of its preceding value, resulting in an AVAL for CN-BARKS of 43 in the figure.

The PRAGMATIC space shows the result of the firing of the VERB-MEANING space for BARKS. The verb composition, using case control information, proceeded using the intransitive verb interpretation function. The intransitive verb interpretation procedure sought an agent within its procedure and when it found an unattached TERM (DOG in this instance) queried the experimenter for feature compatibility with any features specified for the agent before making the appropriate connection (see Figure 30). This interaction is discussed below.

Top-down information that the ENDCONT composition with VIP completed formed the category type SENTENCE (see Figure 23) which signaled the termination of the process.

Figure 29: Final Converged State of the Representation (t10).

Following ENDCONT interpretation, BARKS was disambiguated as a VIP. The effect of this disambiguation and subsequent firing was that VIP-BARKS entered the REFRACTORY State and CN-BARKS was inhibited [1] (Figure 20).

Interpretation of VIP-BARKS interactively queried for constraint satisfaction [2] and on receipt of an affirmative response, completed the AGENT relationship in the PRAGMATIC space [3] and created a composite type, SENTENCE, determined by the GRAMMAR [4].

Firing from PRAGMATIC and the resultant interpretation of SENTENCE terminated the simulation process.

```
***** process interval 10 *****
  ==========
  pragmatic
  ==========
     dog = (88 0 98 1)
       [3] <- agent-- barks [2]
     sentence
       [4] <- belongs-to-- barks = (0 0 98 1)
     term
          <- belongs-to-- dog = (92 0 98 1)

  ========
  grammar
  ========
     cn = (0 0 0 0)

     endcont = (0 0 0 0)

  ==============
  phon-cat-mean
  ==============
     b-r-k-s
          <- cn-- barks = (48 0 91 2)
       [1] <- vip-- barks = (0 0 91 2)
     d-ao-g
          <- cn-- dog = (90 0 98 1)
     end
          <- endcont-- stop** = (98 0 98 1)
     th-uh
          <- det-- the = (92 0 98 1)

  =========
  phonetic
  =========
     b-r-k-s = (94 0 98 1)               end = (98 0 98 1)

     d-ao-g = (90 0 98 1)                th-uh = (86 0 98 1)
```

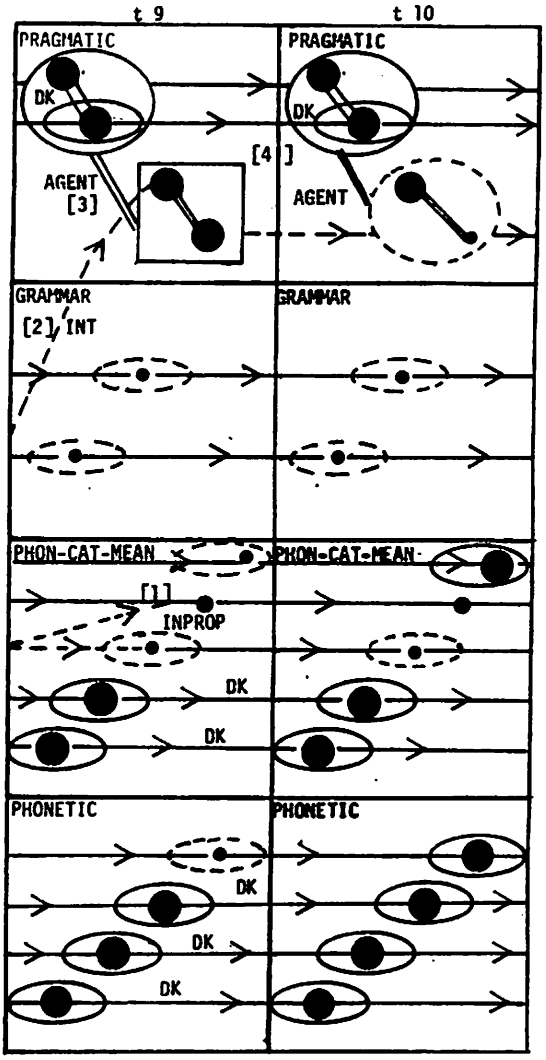


Figure 29: Final Converged State of the Representation (t10).

Of interest in the final representation is evidence of the linguistic claims of left to right vs. right to left processing. They can be seen in the representations of activity values in the PHONETIC space, which contains a left to right trace of the "heard" words, and in the PHON-CAT-MEAN space, which contains a right to left trace of the fired interpretations of meaning. This latter trace reflects the semantic composition of constituents during processing. Also note that the fully interpreted structure is not isomorphic to the input. The interpreted utterance in the PRAGMATIC space does not contain every "heard" word explicitly. This phenomenon is reported during recall studies (Miller, 1981). (Cf. Clark and Clark, 1977; pp. 133-173, for a complete overview of studies of recall and recognition of sentences.)

An example of interactive constraint query is presented in Figure 30. Figure 31 demonstrates the result of a negative response to the query. The processing of constraint satisfaction is a "stub" at this point in the development of HOPE. Future expansion, including semantics, should make this interactive query unnecessary.

```
The constraints to satisfy the relationship agent
for the meaning barks are
Feature-constraints:
animate
Morphological-constraints:
third-singular

Does dog satisfy them?
yes
```

Figure 30: Interactive Constraint Query with Positive Response.

The figure provides an example of an affirmative response to the constraint query produced during the interpretation of VIP-BARKS. The resulting network representation is given in Figure 29 above.

```
=========

pragmatic

=========

   CONSTRAINT-ERROR*
        <- agent-- barks

   dog = (82 0 98 1)


   term
        <- belongs-to-- dog = (86 0 98 1)
```

Figure 31: Result of Negative Response to Constraint Query.

The figure indicates which verbal relationship is in error and that the cause was constraint satisfaction. This is useful in documenting aspects of processing which one might determine experimentally to be of critical import in "lesion" simulations. A question which might be posed in conjunction with this feature of HOPE is: If there is evidence that the "semantic feature" specification for a patient is impoverished in a way that would remove constraint specified features from the meaning of an object or an action, how could it affect comprehension?

Figure 32 demonstrates another error that can occur during interpretation. For example, during "lesion" simulations, words can be interpreted as being "partially" recognized, or "partially" interpreted (not specifically "referentially" instantiated in comprehension, but "vaguely" instantiated).

As the spaces of a word represent perspectives of a word's meanings that are being activated over time, partial recognition or interpretation means that the entire perspective set for the word in context has not been activated. When all aspects of a word's contextually relevant meaning are active, i.e. including the PRAGMATIC space representation, the word is considered to be "referentially instantiated" with a specific meaning. The term "vaguely instantiated" is used to indicate a vagueness in the meaning of a word, i.e. some of the aspects of its meanings are active, but a complete referential instantiation has not been attained.

When only "partial" interpretation is available during processing, HOPE flags the fact that semantic information contextually appropriate to the state of the process, such as a TERM to serve as an AGENT, is unavailable, and "does the best that it can." This can be interpreted behaviorally as "knowing" the "kind" of information needed and realizing that it is "lacking." Perhaps this is the kind of state preceding "figuring out what was misheard" when it occurs during normal comprehension. When incompletely interpreted information exists, the category type necessary to produce the firing interpretation is flagged to be in error.

```
**********

pragmatic

**********

   CONSTRAINT-ERROR*
        <- agent--  building

   agent
        <- FOR-- MISSING-TERM*

   sentence
        <- belongs-to-- building *(0 0 98 1)
```

Figure 32: Effect of Incompletely Interpreted Information.

The figure illustrates states in processing which occur during lesion simulations. When a specific category type necessary to interpretation is not available as a referentially instantiated meaning, the category type of the missing meaning is flagged as "MISSING" and constraint errors are produced by default in the present version of HOPE. It is hypothesized that such constraint errors could be used to provide information that could be used in future versions to determine the missing relationship.

7.2 The "Lesioned" Model

The importance of HOPE to the clinician will be made apparent in this section. In a clinical setting, it is difficult to conjecture how the interaction of processing abilities observed to be intact in isolation can produce an observed behavioral pattern during normal communication performance. The current approaches to neurolinguistics have stressed the importance of characterizing these behavioral patterns by statistically defining correlated performance attributes, while minimizing the importance of the processes which may subserve them. HOPE provides a first attempt not only to study the observed behavioral patterns but to hypothesize, in a computational way, the processes underlying the observed phenomena. With continued expansion of our knowledge about neuroanatomy and the neurophysiological aspects of processing, it is hoped that at some future time the two approaches might be merged to aid in our understanding of the brain and its function.

In the present context, the "lesion" simulations can only be done within a very general level of processing assumption (the cooperative-competitive strategy). However, interpretation of the observed performance in the different "lesion" states has demonstrated inadequacies in dealing with process in current testing paradigms (see Section 2).

The remainder of this section attempts to illustrate the effect of one well accepted cause of agrammatic performance, the dissolution of "closed class" determiner grammatical representation, in the context of one sentence. Questions are raised by the simulation results which have not been considered in prior studies of comprehension performance because neither theoretical assumptions, nor performance assumptions of the test paradigms have recognized or generated their existence. It is only in the context of language performance as a process that the behavioral results receive support.

The usefulness of the simulations therefore is to provide an alternative approach to analysis of language behavior, both "normal" and "lesioned", stressing language as a process of a brain-like structure, rather than merely as a characterizable pattern of performance.

Lesioning experiments that have been performed on the defined model include:

1. elimination of the DET knowledge in the GRAMMAR space (suggested in studies of agrammatism),
2. modification of timing of word introduction with respect to normal decay rate and fixed propagation (interpreted as a "slow down" in propagation effect),
3. elimination of the DET interpretation function while leaving the grammar representation decay and fixed propagation as in the "normal" condition (interpreted as functional dissolution of determiners), and
4. shortening the Short-Term Decay Interval (Ds) leaving fixed propagation and word introduction as in the "normal" simulation (interpreted as a short-term memory defect).

The strength of these simulations lies in the ability to study sets of sentences in several lesion simulations and to determine distinctive patterns of dissolution that discriminate among the "lesion" conditions, or perhaps to define multiple possible underlying "lesion" states which produce the same observable behavior. However, to illustrate the comparative procedure, we will present only one lesion simulation on one sentence.

The elimination from overt speech of the closed class, determiner, information is an observable production deficit in Broca's aphasics (Section 2). Studies previously mentioned have addressed the use of this information in comprehension. The model permits explicit elimination of the information in a manner hypothesized to underlie the processing deficit. (Two distinct hypothesized "lesions" for determiner are mentioned above. One should note, they can also occur together in a simulation.) One can record the effect on the network representations for a set of test sentences whose meaning depends on correct use of the determiner information. The resulting state spaces (see Figures 32 and 33), whether the meaning networks are complete or not, are reported. By comparing the results of simulation runs with clinical performance, better understanding of the comprehension process of natural language should be gained. Better understanding of the process may contribute to the development of more effective methods for testing and communicating with aphasic patients.

7.2.1 A Simulated Lesion Experiment -

One of the goals in designing HOPE is to provide a way of testing the effects of hypothesized processing causes of observed aphasic behavior. Therefore, it is critical that the sentences used in simulation experiments be suitable for clinical evaluation. The sentence used in the "normal" and simulated lesion experiment is "The boy saw the building." This sentence has a distinct noun object reading of building, which is not entirely polysemous with the verb meanings. It was selected because the different meanings of building are clearly determinable and the predictions of the model could be empirically tested.

Figures 33 through 36 show relevant time slice calculations for a "normal" run of the model which are illustrative of the effects of a simulated lesion as seen in Figures 38 through 40. It is assumed that the reader understands the serial flow underlying the final state HOPE representation at this point. Only the final state will be represented in the figures. Bracketed numbers will be used to label aspects of the result as above. The grammar is the same as in Figure 23.

7.2.1.1 The "Normal" Simulation -

The initial processing of the model through introduction of the word [s-ao] (saw) is the same as in Figures 24 through 28 with appropriate substitution of words. In addition, one should note that there are three meanings for [s-ao] instead of two for [b-r-k-s] as is shown in the earlier figures.

An interesting conjecture included in the current design of HOPE is that the activation of the phonetic representation and associated CMAN pairs is reinitialized with every occurrence of a word, as if the word had not been previously "heard" in the sentence. It is hypothesized that the timing of interpretation and order of the introduction of duplicate word occurrences within a sentence will not require the maintenance of a low level trace of previous usage. The limitation of this claim will be one of several interesting conjectures the model can be used to determine computationally. Figure 33 includes an instance of this "resetting" for the second occurrence of the word [th-uh].

```
***** process interval 7 *****
 =========
 pragmatic
 =========
    boy = (94 0 98 1)

    term
         <- belongs-to-- boy = (98 0 98 1)

 =======
 grammar
 =======
    cn = (0 0 0 0)

    endcont = (75 0 91 2)

    term = (75 0 91 2)


 =============
 phon-cat-mean
 =============
    b-oy
         <- cn-- boy = (96 0 98 1)

    s-ao
         <- cn-- saw = (68 1 91 2)
         <- vip-- saw = (68 1 91 2)
         <- vtp-- saw = (68 1 91 2)

    th-uh
     [1] <- det-- the = (95 1 91 2)

 ========
 phonetic
 ========
    b-oy = (96 0 98 1)

    s-ao = (0 0 91 2)

    th-uh = (100 1 91 2)
```

Figure 33: "Normal" Simulation (t7).

During introduction of the second [th-uh] in the sentence, the AVAL in PHONETIC and PHON-CAT-MEAN are both reset [1].

Figure 34: "Normal" Simulation (t12).

The interaction of the creation of a BELONGS-TO TERM relationship by "THE" firing (AVAL = 142 at t11) and the simultaneous introduction and firing of [END] (AVAL = 134) is seen in the AVALs within the PHON-CAT-MEAN space.

The top-down effect of "THE" being fully interpreted forms a TERM. TERM propagates in reverse as described in Figure 27. In the figure this results in AVALs in PHON-CAT-MEAN of 101 for VTP-SAW [1] (Figure 19), which exceeds threshold, and 95 for VTP-BUILDING [2] (Figure 19).

Concurrently, ENDC-STOP** fires propagating in reverse using the GRAMMAR space as described in Figure 29. Its effect results in AVALs in PHON-CAT-MEAN of 99 for VIP-SAW [3] (Figure 19) and 93 for VIP-BUILDING [4] (Figure 19).

```
***** process interval 12 *****

 ==========

 pragmatic

 ==========

    boy = (84 0 98 1)


    building = (96 0 98 1)


    term
         <- belongs-to-- boy = (88 0 98 1)
         <- belongs-to-- building = (0 0 98 1)


 ========

 grammar

 ========

    cn = (0 0 0 0)


    endcont = (0 0 0 0)


    term = (68 1 91 2)



 ==============

 phon-cat-mean

 ==============

    b-ih-l-d-ih-ng                                  s-ao
         <- cn-- building = (98 0 98 1)                  <- cn-- saw = (46 1 91 2)
      [4]<- vip-- building = (93 1 91 2)              [3]<- vip-- saw = (99 1 91 2)
      [2]<- vtp-- building = (95 1 91 2)              [1]<- vtp-- saw =*(101 1 91 2)

    b-oy                                            th-uh
         <- cn-- boy = (74 0 98 1)                       <- det-- the = (0 0 91 2)

    end
         <- endcont-- stop** = (0 1 91 2)
 =========

 phonetic
                                                    end = (0 1 91 2)
 =========

    b-ih-l-d-ih-ng = (98 0 98 1)
                                                    s-ao = (90 0 98 1)

    b-oy = (86 0 98 1)
                                                    th-uh = (94 0 98 1)
```

Figure 34: "Normal" Simulation (t12).

Figure 35: "Normal" Simulation (t13).

The figure shows the result of VTP-SAW firing. Firing of VTP produces inhibitory effects to all other competing meanings for the same phonetic representation and to all other active competing meanings having the same category type [1] (Figure 29).

Inhibition results in the AVALs in PHON-CAT-MEAN of 71 for VIP-SAW, 33 for CN-SAW, and 80 for VTP-BUILDING.

The interpretation of VTP-SAW queries the experimenter for constrain satisfaction and after an affirmative response produces the DIR-OBJect relation [2]. It simultaneously produces the VIP composite type in PRAGMATIC which exceeds threshold (AVAL = 101) [3].

```
**** process interval 13 *****

 =========

 pragmatic

 =========

    boy = (82 0 98 1)


    building = (94 0 98 1)

  [2]    <- dir-obj-- saw

    term
          <- belongs-to-- boy = (86 0 98 1)
          <- belongs-to-- building = (98 0 98 1)

    vip
  [3]    <- belongs-to-- saw =*(101 1 91 2)


 =======

 grammar

 =======

    cn = (0 0 0 0)                term = (68 0 91 2)


    endcont = (0 0 0 0)



 =============

 phon-cat-mean

 =============

    b-ih-l-d-ih-ng                                  s-ao
          <- cn-- building = (96 0 98 1)          [1] <- cn-- saw = (33 1 91 2)
          <- vip-- building = (93 0 91 2)         [1] <- vip-- saw = (71 1 91 2)
       [1]<- vtp-- building = (80 1 91 2)         [1] <- vtp-- saw = (0 1 91 2)

    b-oy                                            th-uh
          <- cn-- boy = (72 0 98 1)                       <- det-- the = (98 0 98 1)

    end
          <- endcont-- stop** = (0 0 91 2)
 ========

 phonetic

 ========

    b-ih-l-d-ih-ng = (96 0 98 1)          s-ao = (88 0 98 1)


    b-oy = (84 0 98 1)                    th-uh = (92 0 98 1)


    end = (0 0 91 2)
```

Figure 35: "Normal" Simulation (t13).

Figure 36: "Normal" Simulation (t15).

The result of SAW-BELONGS-TO-VIP firing at t14 forms the AGENT relation after checking for constraint satisfaction [1] (Figure 30). Successful completion of VIP interpretation creates the composite type SENTENCE which exceeds threshold [2]. Termination proceeds as described for Figure 29. The final state of the simulation is shown in the figure.

```
***** process interval 15 *****
 =========
 pragmatic
 =========
    boy = (78 0 98 1)
     [1]  <- agent-- saw
    building = (90 0 98 1)
          <- dir-obj-- saw

    sentence
          <- belongs-to-- saw = (0 0 98 1)
     [2]
    term
          <- belongs-to-- boy = (82 0 98 1)
          <- belongs-to-- building = (94 0 98 1)

    vip
          <- belongs-to-- saw = (98 0 98 1)

 =======
 grammar
 =======
    cn = (0 0 0 0)              term = (61 0 91 2)

    endcont = (0 0 0 0)
=============
phon-cat-mean
=============
   b-ih-l-d-ih-ng                              s-ao
        <- cn-- building = (92 0 98 1)              <- cn-- saw = (30 1 91 2)
        <- vip-- building = (79 0 91 2)             <- vip-- saw = (60 0 91 2)
        <- vtp-- building = (72 1 91 2)             <- vtp-- saw = (98 0 98 1)

   b-oy                                        th-uh
        <- cn-- boy = (68 0 98 1)                   <- det-- the = (94 0 98 1)

   end
        <- endcont-- stop** = (96 0 98 1)
========
phonetic
========
   b-ih-l-d-ih-ng = (92 0 98 1)        s-ao = (84 0 98 1)

   b-oy = (80 0 98 1)                  th-uh = (88 0 98 1)

   end = (96 0 98 1)
```

Figure 36: "Normal Simulation (t15).

In the simulated lesion experiment, all constants and propagation processes are as previously described for the "normal" model (see Figure 15, Section 6). Each figure represents a corresponding time interval to the previously described "normal" simulation process for the same sentence. The lesion eliminates the grammatical properties of determiners by removing the predictive and compositional information for them from the GRAMMAR space, shown in Figure 37.

Determiners are interpreted in this simulation to be available at a phonetic level as in repetition tasks, or even occasional production, but without a complete functional understanding. They can be thought to function at a semantic level in that a patient could "know" the exact referent based on other than verbal input, or based on his intent to communicate, but be unable to "grammatically" integrate the "semantic" representation into produced behavior. The obvious effect of elimination of the grammatical information is that no prediction based on the appropriate syntactic structure can occur during comprehension.

```
<< grammar >>

  endcont

       <-predict-- vip

  sentence

       <-to-form-- vip

  term

       <-predict-- vtp

  vip

       <-to-form-- vtp

  vtp
```

Figure 37: Grammar for Simulated Lesion.

The absence of the DET network representation of Figure 23 should be noted. The "lesion" state represents the hypothesized dissolution of grammatical structural information without disturbing any other aspects of determiners, phonetic, lexical meaning, or semantic function.

7.2.1.2 The "Lesion" Simulation -

The simulation model includes three clinical performance characteristics that can be used to define the aphasic population to which it applies. They are an assumed inability to grammatically use determiners in on-line sentence processing, a normal ability to access all meanings of each word when it is heard during on-line sentence comprehension, and a normal ability to repeat a sentence in its entirety.

The grammatical deficit is reflected in the GRAMMAR space representation described above; the multiple meaning availability for the "lesion" simulation remains as in the "normal" process model and is encoded as the initial activation (initial AVAL assignment) of newly "heard" words; and the activity within the PHONETIC space in the "lesion" simulation condition is identical to the normal process suggesting normal repetition ability, if one agrees that normal repetition is possible at a strictly phonetic representational level of processing.

Results of the analysis of the "lesion" simulation and conjectured clinical interpretations include a suitable patient being able to understand only the end of the sentence and, if the final word of the sentence is noun/verb ambiguous, selecting the verb meaning.

Comparison across time intervals during processing and for the final representations is necessary to analyze the simulations. Only process time intervals which contain deviations from the "normal" simulation that are conjectured to underlie the final state of the "lesion" simulation are included in this discussion. Their selection is not suggested as the sole interpretation possible, but rather is to be thought of as illustrative of the analysis to be performed across the entire simulation for an entire cover set of sentences such as in Table 3.

Figure 38 is the state of the simulation in the "lesion" condition at the same time interval in the process as shown for the "normal" simulation in Figure 33. Differences noted in the same time intervals between the two states suggest causes for the final produced state representation of what was understood and how it was interrelated. Furthermore, if the performance can be correlated with empirical behavioral evidence for this sentence, and others of the cover set, a method for deciding which of several underlying "lesion" states could be associated with a performance deficit might ensue. Additionally, processing within several lesion states for the same sentence might be shown to result in the same performance, but for different reasons.

One suggested clinical validation procedure that would assure comparability of the final state representations of clinical performance and simulation performance is a picture selection, spoken sentence comprehension task. In this kind of a task, the final state representations of the simulated lesion for each of the set of test sentences could be included in the response selection set for the corresponding spoken sentence presented to the patient. In this way, correlations between the results could be made.

Differences to be noted between Figures 33 and 38 include:

1. None of the "heard" words have reached or surpassed threshold. Firing interpretation based on syntactic prediction has not occurred for any of the words "heard", because of the degraded GRAMMAR representation.
2. PRAGMATIC space has no interpreted representations in contrast to its state in Figure 33 because nothing has fired. One interpretation of this might be that what has been "heard" is only being rotely remembered.
3. The PREDICT AVALs for the word [s-ao] have been activated as in the "normal" condition. This shows that the use of grammatical information is intact and that it is only specific grammatical information, in this case about determiners, that is absent.

Differences to be noted between the "normal" simulation of Figure 34 and the "lesion" one in Figure 39 are:

1. PRAGMATIC representations of what has been understood and in what relationship are notably deviant in Figure 39. In Figure 39, there are no interpreted TERM entities, i.e. the words are "partially" understood, but not "referentially" understood as they are in Figure 34.
2. The quantity of active information in the Short-Term-State in PHON-CAT-MEAN demonstrates a possible strain on the memory capacity of a pre-constituent level of representation of what has been "heard" (at a word meaning level).
3. The active information in the PHONETIC level is identical to that of the "normal" lesion, suggesting that verbatim recall for such a sentence might be intact. The effect of length of a sentence on this level would need to be determined to encode a bottom cut off for memory capacity. Because of resetting of [th-uh], difficulty with the determiner in recall is predicted for the "lesion" simulation as no PRAGMATIC reference is available to infer the originally "heard" relationship. The effect of a different global context on the processing state is evident when one compares this figure with Figure 34, above.

```
***** process interval 7 *****

 =========

 pragmatic

 =========

    [1]
 =======

 grammar

 =======

 [3]endcont = (75 0 91 2)

 [3]term = (75 0 91 2)


=============

phon-cat-mean

=============

   b-oy
        <- cn-- boy = (78 1 91 2)

   s-ao
        <- cn-- saw = (68 1 91 2)
        <- vip-- saw = (68 1 91 2)
        <- vtp-- saw = (68 1 91 2)

   th-uh
        <- det-- the = (95 1 91 2)

========

phonetic

========

   b-oy = (96 0 98 1)

   s-ao = (0 0 91 2)

[2] th-uh = (100 1 91 2)
```

Figure 38: Simulated DET Grammar Lesion (t7).

This figure shows the state of the simulation as it appears having "heard" the first three words of the sentence. The PRAGMATIC space is empty [1]. All information at the PHONETIC level is in a state as in the "normal" simulation [2]. "Normal" propagation activation occurs in the GRAMMAR space [3].

Figure 39: Simulated DET Grammar Lesion (t12).

There are no TERM constituents in PRAGMATIC because of the GRAMMAR "lesion" [1]. The information in PHON-CAT-MEAN is largely decayed with the appropriate meanings reflecting a Post-Refractory-State in Figure 34. In contrast, PHON-CAT-MEAN in Figure 39 contains an "overload" of Short-Term-State information [2].

The only Post-Refractory-State information is at the PHONETIC level, the level of initial triggering of meaning in the processing [3].

ENDCONT, "heard" at t11, has its "normal" effect based on its grammatical specification [4]. This effect is seen in the AVALs of VIP-BUILDING (AVAL=112), which exceeds threshold, and VIP-SAW (AVAL=99) [5].

```
***** process interval 12 *****

 ==========

 pragmatic

 ==========

    [1]
 ========

 grammar

 ========

[4] endcont = (0 0 0 0)


    term = (68 1 91 2)


 ==============

 phon-cat-mean

 ==============

    b-ih-l-d-ih-ng
         <- cn-- building = (68 0 91 2)
     [5] <- vip-- building = (112 1 91 2)
         <- vtp-- building = (68 0 91 2)

    b-oy
     [2] <- cn-- boy = (63 0 91 2)

    end
         <- endcont-- stop** = (0 1 91 2)

    s-ao
         <- cn-- saw = (55 0 91 2)
     [5] <- vip-- saw = (99 1 91 2)
         <- vtp-- saw = (55 0 91 2)

    th-uh
         <- det-- the = (78 0 91 2)


 =========

 phonetic

 =========

    b-ih-l-d-ih-ng = (98 0 98 1)
  [3]                                          s-ao = (90 0 98 1)
    b-oy = (86 0 98 1)
                                               th-uh = (94 0 98 1)

    end = (0 1 91 2)
```

Figure 39: Simulated DET Grammar Lesion (t12).

Figure 40 shows the result of the interpretation for VIP-BUILDING. There are no interpreted TERMs available to serve as AGENT. HOPE presently flags such missing interpretations with the type that is missing and the relation it would satisfy. By default, constraints can not be matched and are also flagged with the missing relation in the incomplete interpretation.

The state represented in Figure 40 can be interpreted as follows:

A sentence has been recognized, but its complete content is not fully interpreted. Only a verb has been interpreted, but there is no AGENT available.

A possible correlated clinical response might be to interpret the sentence as a command, or to randomly select an AGENT, if one were testing in an "acting-out" paradigm. Within a picture selection task, the command interpretation would not be available.

For a patient who does either in this context, the other noted time interval differences suggest that he might additionally be characterized as being able to repeat the words of a sentence in the right order, including determiners. However, the "correct" determiners may not be repeated in all instances (especially their early occurrences in the sentence if they appear a second time.) This is a result of resetting the word activation with each reoccurrence in the sentence. He might also tend to interpret only the ends of sentences, and in light of the evidence from this one sentence, if final words are noun/verb ambiguous, the verb meaning would tend to be selected.

The evidence for sentence final processing and for the verb preference for the last word is seen in the final state of the lesion condition, Figure 41. One can note in the figure that only the final word of the sentence has been referentially instantiated, and that of the two possible meanings for it, the verb meaning was selected because of the manner in which the intonation contour for end-of-sentence was interpreted. All other meanings are only "partially" understood (represented by having AVs but no PRAGMATIC referential instantiation).

To ascertain whether these conjectures really describe the "lesion" results in an empirically verifiable way, one must consider whether they are borne out by the other five test sentences (see Table 3), which cover the defined model's syntactic definition.

Noted differences in final states for the two simulations suggest differences in performance to be validated in clinical studies. Figure 41 shows the final state of processing in the "lesion" simulation. Comparing it with Figure 36, one sees a definite activity overload in the knowledge structures at the lower end of the process. These differences are in addition to those already discussed for Figure 40 above.

Note also that the simulation is one time interval shorter because of the inability to complete the interpretation. If semantic inference were included, it is hypothesized that the time would be longer for the "lesion" condition.

```
***** process interval 13 *****

  =========

  pragmatic

  =========

     CONSTRAINT-ERROR*
          <- agent-- building
  [2]
     agent
          <- FOR-- MISSING-TERM*

     sentence
          <- belongs-to-- building =*(112 1 91 2)
  [1]

  =======

  grammar

  =======

     endcont = (0 0 0 0)


     term = (68 0 91 2)
  =============

  phon-cat-mean

  =============

     b-ih-l-d-ih-ng
          <- cn-- building = (48 1 91 2)
          <- vip-- building = (0 1 91 2)
          <- vtp-- building = (48 1 91 2)

     b-oy
          <- cn-- boy = (57 1 91 2)

     end
          <- endcont-- stop** = (0 0 91 2)

     s-ao
          <- cn-- saw = (50 1 91 2)
          <- vip-- saw = (84 1 91 2)
          <- vtp-- saw = (50 1 91 2)

     th-uh
          <- det-- the = (70 1 91 2)


  ========

  phonetic
                                          end = (0 0 91 2)
  ========

     b-ih-l-d-ih-ng = (96 0 98 1)         s-ao = (88 0 98 1)


     b-oy = (84 0 98 1)                   th-uh = (92 0 98 1)
```

Figure 40: Simulated DET Grammar Lesion (t13).

Figure 40: Simulated DET Grammar Lesion (t13).

VIP-BUILDING is interpreted [1]. Because no TERM is available to serve as AGENT, no query is made for constraint satisfaction. Appropriate "problems" in comprehension are noted in the PRAGMATIC representation [2]. At this point, one would conjecture that inference reasoning to satisfy constraints of the missing agent and awareness of having "heard" a word whose constraints satisfy those needed might together be sufficient to solve the "missing link" relationship (such as random selection of an agent). Reasoning using world knowledge could also be used to produce a coherent final result (such as interpretation of the sentence as a command).

Figure 41: Simulated DET Grammar Lesion--Final State (t14).

Final state of processing with simulated lesion of DET grammatical information. Active information is primarily in its early processing stages [1]. This places an extra burden on memory structures and processes at the lower levels of the comprehension process, possibly straining the Short-Term-State "capacity" of the model.

```
***** process interval 14 *****

 ==========

 pragmatic*

 ==========

    CONSTRAINT-ERROR*
         <- agent-- building

    agent
         <- FOR-- MISSING-TERM*

    sentence
         <- belongs-to-- building = (0 0 98 1)


 ========

 grammar*

 ========

    endcont = (0 0 0 0)


    term = (61 1 91 2)
 ==============

 phon-cat-mean*

 ==============

    b-ih-l-d-ih-ng
         <- cn-- building = (48 0 91 2)
   [1]   <- vip-- building = (0 0 91 2)
         <- vtp-- building = (48 0 91 2)

    b-oy
         <- cn-- boy = (57 0 91 2)

    end
         <- endcont-- stop** = (98 0 98 1)

    s-ao
         <- cn-- saw = (50 0 91 2)
         <- vip-- saw = (84 0 91 2)
         <- vtp-- saw = (50 0 91 2)

    th-uh
         <- det-- the = (70 0 91 2)


 =========

 phonetic*
                                        end = (98 0 98 1)
 =========

    b-ih-l-d-ih-ng = (94 0 98 1)        s-ao = (86 0 98 1)
 [1]
    b-oy = (82 0 98 1)                  th-uh = (90 0 98 1)
```

Figure 41: Simulated DET Grammar Lesion--Final State (t14).

From the above example, it should be apparent that to gain understanding of the effect of the simulated lesion, one must compare activity propagation across compute time intervals as well as analyze the final state of understanding as represented in the lesioned simulation with those for the "normal" simulation. One must also assess these comparisons for a complete set of sentences which covers the syntactic constructs available in the defined "normal" model.

Clinical interpretations for the time interval comparisons have been conjectured throughout the preceding discussion. These conjectures suggest hypotheses for the other sentences tested within a simulation experiment. In this particular case, they involve using proper names instead of compositional TERMS in various combinations to determine the difference in the noun/verb disambiguation process when both are available for a given word. The ability to process only the end of a sentence is noted as slow-rise-time by Brookshire (1974; pg. 3) although not discussed in this paper. For patients exhibiting the ability to process only the ends of sentences, the noted syntactic word disambiguation as demonstrated in the simulation, i.e. verb preference, needs to be validated.

It should be further noted that to validate this additional claim within the context of the characteristics of the "lesion" simulation would require finding and testing a patient who demonstrated normal word meaning access ability during comprehension, who tended to produce agrammatic utterances (one who randomly produces determiners in free speech), who indicated comprehension problems for determiners, and who was able to repeat sentences with determiners, only having difficulty if they reoccurred in the sentence. For such a patient one would first want to determine if the general characteristic of the end of sentence (slow-rise-time) phenomenon occurred and then to determine further whether the effect on word final disambiguation could be observed.

These patient performance characteristics can be interpreted from the "lesion" simulation performance in the following manner. The state of the model, i.e. its assumed lesion characteristic with respect to determiner grammatical information, dictates the general characteristics for patient selection, agrammatic with determiner comprehension problems. The across time interval conjectures and final state of simulation additionally suggest the repetition and the end of sentence criteria. The final verb selection within the end of sentence phenomena is suggested because of the simulation performance exhibited in the final state, an unexpected result of determiner grammatical lesion.

Aspects of this simulation do "match up" in a general way with the clinically documented performance claims of slow-rise-time (Brookshire, 1974) However, within such general performance claims, the simulation has suggested more refined determinations with respect to subject selection and performance evaluation that should be analyzed in combination. These are not all-inclusive characteristics for patient selection, but are the minimal chatacteristics necessary to "match" a patient with the performance on this one sentence, in this one lesion condition. Again, the reader is reminded that in looking at an entire set of sentences for a given lesion state, characterizations, such as presented, may be modified or even eliminated.

The point in providing a refined, explicit characterization of a patient's performance for comparison with the simulation results is not that validation can only be done on such a patient. Rather, it defines a testing methodology necessary to obtain data that contributes to the evolution of the model.

Testing or validation procedures of the model require the use of heterogeneous aphasic populations, where patient data relevant to the specifically noted characteristic performances hypothesized by the simulation are explicitly documented in addition to all other standard clinical classification and medical information.

The final results of testing are used to evolve the model to a better simulation representation of the actual performance in a bi-directional manner. Tests are designed to determine patient abilities on all explicitly hypothesized performance characteristics of the simulation, such as a picture selection task for spoken sentence comprehension, as mentioned above.

For any patient whose clinically determined comprehension performance correlates with the final state of the simulation results, the co-occurring simulation generated hypotheses of performance ability, such as their ability to repeat and ability to comprehend well except for closed class words (using our DET example), will be compared with their clinically determined performance abilities. Mismatches of the simulation determined abilities with the abilities of patients having comprehension performance which matches the simulation results suggest possible alterations for processing in the model. By analyzing the mismatches to determine which patient performance characteristics co-occur with comprehension performance similar to the simulation, one hopes to be able to determine how to modify the simulation processes to better correspond with the across-time and final noted performances (repetition, comprehension, etc.).

In contrast, <u>if</u> one finds patients whose clinically determined performance abilities match the simulation demonstrated "patient abilities" (being able to repeat, etc., as above), and the clinically determined comprehension performance on the cover set of sentences for these patients does not correlate with the final results of the simulation performance, then the patient performance must be used to specify modifications in the model's performance behavior. The patient results can, perhaps, be used to better tune the model--of course, it must be tuned for both the "normal" and the "lesion" condition. In addition, analysis of the final patient comprehension results to determine performance patterns which do occur can lead to modification of hypothesized interactions in the processing of the model.

By using the clinical validation in the above described bi-directional manner, the processing hypothesized in HOPE should evolve to a better representation of the processing involved in the actual performance, one of the stated goals of the research.

Refined empirical determinations, such as described above, can be used to ascertain whether it is possible that the cause of an empirically observed deficit may correlate with the interpreted computational cause of the "lesion" simulation performance. Being able to study within a clinical setting and correlate the general patient performance deficits in combination with the more detailed, specific performance deficits (as suggested from the simulation) with those demonstrated in the "known" lesion state simulation, demonstrates the plausibility of using the model as a research tool to refine experimental paradigms and to simultaneously begin to hypothesize the underlying processing deficits which produce the behaviors.

Methods must still be developed to assess these interpretations and the "state" of comprehension. Only through careful examination of human performance--both normal and lesion--on sentences similar to those used in the simulations can the facility to interpret the results be developed. Several interpretations are possible for any specific output produced. Subsequent analysis will be used to ferret out the hypothesized details of processing at different intermediate stages and will lead to the design and application of clinical tests addressing the hypotheses. In this way the model will continue to evolve toward a better simulation, while clinical assessment hopefully will be enhanced through the associated test design and use.

8. Conclusion

We have developed a simulation model of normal comprehension processing that can be lesioned in neurologically interesting ways. The cooperative-computation paradigm is used to resolve syntactic ambiguities in converging to the meaning representation of a phonetically presented utterance. Lesion experiments on the model will include degradation of knowledge representations, modification of timing synchrony, and memory decay. These will be validated by neurolinguistic testing of aphasic patients.

The value of the model is in its usefulness in providing a tool that permits experimentation with timing controlled interaction schemas. Even though the constant values and prediction values are arbitrary in the present instantiation of the model, it permits evaluation of some of the assumptions made in present neurological theory.

How much linguistic theory can be accounted for within the model is an interesting aspect for future study. Presently there is no effect of word frequency in the model. A typical question to be raised is: At what level of interactive complexity is this effect necessary to be able to "tune" the parameters of the model for the normal process? With simple declarative sentences such as the example model currently handles, word frequency is not necessary.

Other questions to be considered include:

What happens as semantically based interactions are introduced?

How do word associations affect the interactive process?

When do they occur?

The model provides a tool to assess whether association should occur at the initial "hearing" of a word or after its interpretation, or as a result of an inference process. Each selection will introduce new information having a different representation and will introduce it at a different time in the process. To test at this level, the representations and possible time interactions need to be determined or hypothesized. Part of the goal in designing the model as a tool is to help define strategies for collecting and analyzing data that better address the problems of interactive processes.

The model is designed to permit simulation of lesion effects hypothesized to underlie processing behaviors of aphasic patients. As better understanding of the processing occurs, better plans of rehabilitation for patients can be formulated.

With regard to its contribution to understanding of the neural substrates of language processing, the model is premature. With advances in technology, this will be a challenge for the future. Any neuro-anatomical correlations of the model can not be assessed. The state of technology is in its infancy. Knowledge of the neuroanatomy of the human brain at this time does not permit the level of correlation one needs to be able to make any claims with respect to the performance of a model. Descriptions of state of the art technology and recent correlations with standardly evaluated performance can be found in Kertesz (1979), Naeser, M. A.; and Hayward, R. W. (1978), Naeser, M. A.; Hayward, R. W.; Laughlin, S. A.; Becker, J. M.; Jerigan, T. L.; and Zatz, L. M. (1981), Naeser, M. A.; Hayward, R. W.; Laughlin, S.; and Zatz, L. (1981), Risberg, J. (1980), Stump and Williams (1980), Wood, F. (1980), and Galaburda (1982). At best, a claim for generalized interactions among neural networks as a basis of the decision processes possibly involved in language comprehension is demonstrated.

Finally, the behavioral aspects of language processing, as with any human process, are individually and contextually variable. The model attempts to define a possible common processing strategy that will permit such vast variability, and yet provide for the overall commonality observed behaviorally in the communication process. As such it is a prototype for a class of linguistic performance models that will, we hope, provide a useful tool for studying possible causes of performance deficits found in aphasia.

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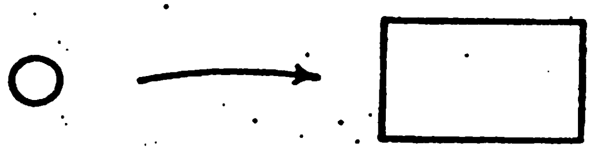
Appendix

GRAPH PROCESSING NOTATION

The model to be described makes extensive use of graph processing. A brief description of the notation used in the examples will now be presented. The system uses the GRASPER system (Lowrance, 1979) for representing knowledge that interacts during processing:

1. A GRASPER-GRAPH consists of a collection of nodes, directed edges (arcs), and spaces.

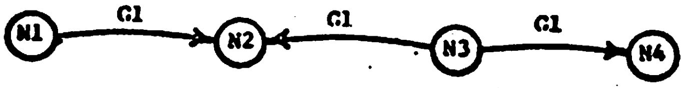


2. Each node has a unique name.

3. Arcs also have names but they are not necessarily unique.

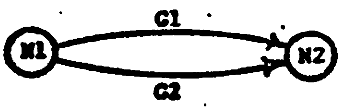
4. Each arc connects a pair of nodes.

5. When two or more arcs with the same name and direction leave a node, then each arc must point to a different node.

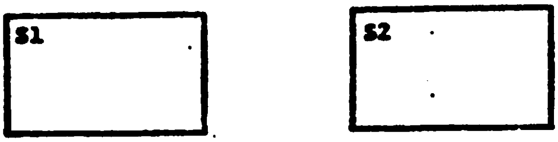


Graph Processing Notation

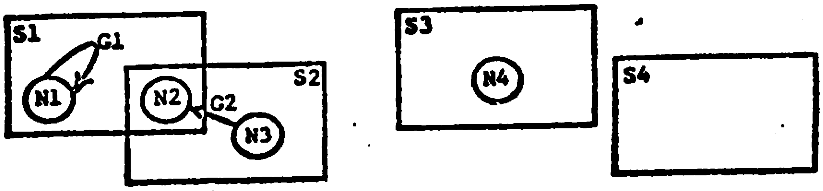
6. When two or more arcs leave a node and both point to the same node, then each must have a different name.



7. Spaces have unique names.



8. Each space contains a subset of all the nodes and arcs. A node can be in any space. An arc can be in a space only if the pair of nodes it connects are also in that space.



The figures and definitions are from the informal definition of the GRASPER language manual (Lowrance, 1978; pp 4-5.)

9. An arc-node pair as referenced in the model description is an arc name and one connected node name that is considered as a unit. Given the following figure, the arc-node pair for DET is PREDICT CN. The direction of the arc is not important in this terminology.