SPEECH UNDERSTANDING SYSTEMS

Summary of Results of the Five-Year Research Effort at Carnegie-Mellon University

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PREFACE

This report is an augmented version of a report originally issued in September of 1976, during the demonstration at the end of the five-year speech effort. The first section reports on the various speech understanding systems developed at CMU during the five year period and highlights their individual contributions. Section II contains a brief description of several techniques and knowledge sources that contributed to the success of the final systems. Section III gives detailed performance results of the Harpy and Hearsay-II systems. Results include the performance of the systems not only for the 1000 word task but for several simpler tasks. Section IV contains reprints of papers presented at various conferences since September 1976. Section V contains a list of publications of the CMU speech group.

The CMU Speech Group gratefully acknowledges the following contributions which have been instrumental to the successful conclusion of the five-year speech understanding systems research effort at Carnegie-Mellon University:

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I. MULTI-SYSTEM APPROACH TO SPEECH UNDERSTANDING*

Raj Reddy

INTRODUCTION

In 1971, a group of scientists recommended the initiation of a five-year research program towards the demonstration of a large-vocabulary connected speech understanding system (Newell et al., 1971). Instead of setting vague objectives, the group proposed a set of specific performance goals (see Fig. 1.1 of Newell et al., 1971). The system was required to accept connected speech from many speakers based on a 1000 word vocabulary task-oriented grammar, within a constrained task. The system was expected to perform with less than 10% semantic errors, using about 300 million instructions per second of speech (MIPSS)** and to be operational within a five year period. The proposed research was a highly ambitious undertaking, given the almost total lack of experience with connected speech systems at that time.

The Harpy and Hearsay-II systems developed at Carnegie-Mellon University had the best overall performance at the end of the five year period. Figure 1 illustrates the performance of the Harpy system relative to the original specifications. It not only satisfies the original goals, but exceeds some of the stated objectives. It recognizes speech from male and female speakers using a 1011-word-vocabulary document retrieval task. Semantic error is 5% and response is an order of magnitude faster than expected. The Hearsay-II system achieves similar accuracy and runs about 2 to 20 times slower than Harpy.

Of the many factors that led to the final successful demonstration of these systems, perhaps the most important was the systems development methodology that evolved. Faced with prospects of developing systems with a large number of unknowns, we opted to develop several intermediate "throw-away" systems rather than work towards a single carefully designed ultimate system. Many dimensions of these intermediate systems were deliberately finessed or ignored so as to gain deeper understanding of some aspect of the overall system. The purpose of this paper is to

GOAL (Nov. 1971)	HARPY (Nov. 1976)
Accept connected speech	Yes
from many	5 (3 male, 2 female)
cooperative speakers	yes
in a quiet room	computer terminal room
using a good microphone	close-talking microphone
with slight tuning/speaker	20-30 sentences/talker
accepting 1000 words	1011 word vocabulary
using an artificial syntax	avg. branching factor = 33
in a constraining task	document retrieval
yielding < 10% semantic error	5%
requiring approx. 300 MIPSS**	requiring 28 MIPSS
	using 256k of 36 bit words
	costing $5 per sentence processed

Figure 1. Harpy performance compared to desired goals.

* Paper to appear in Carnegie-Mellon Computer Science Research Review, 1977.

** The actual specifications stated "a few times real-time" on a 100 MIPS (Million instructions per second) machine.

- Task characteristics
  - speakers; number, male/female, dialect
  - vocabulary and syntax
  - response desired
- Signal gathering environment
  - room noise level
  - transducer characteristics
- Signal transformations
  - digitization speed and accuracy
  - special-purpose hardware required
  - parametric representation
- Signal-to-symbol transformation
  - segmentation?
  - level transformation occurs
  - label selection technique
  - amount of training required
- Matching and searching
  - relaxation: breadth-first
  - blackboard: best-first, island driven
  - productions: best-first
  - Locus: beam search
- Knowledge source representation
  - networks
  - procedures
  - frames
  - productions
- System organization
  - levels of representation
  - single processor / multi-processor

Figure 2. Design choices for speech understanding systems.

illustrate the incremental understanding of the solution space provided by the various intermediate systems developed at CMU.

Figure 2 illustrates the large number of design decisions which confront a speech understanding system designer*. For each of these 10 to 15 design decisions, we have 3 to 10 feasible alternative choices. Thus the solution space for speech systems seems to contain 10^6 to 10^8 possible system designs. Given the interactions between design choices, it is not possible to evaluate each design choice in isolation outside the framework of the total system.

* Further discussion of many of these design choices can be found in Reddy (1976).

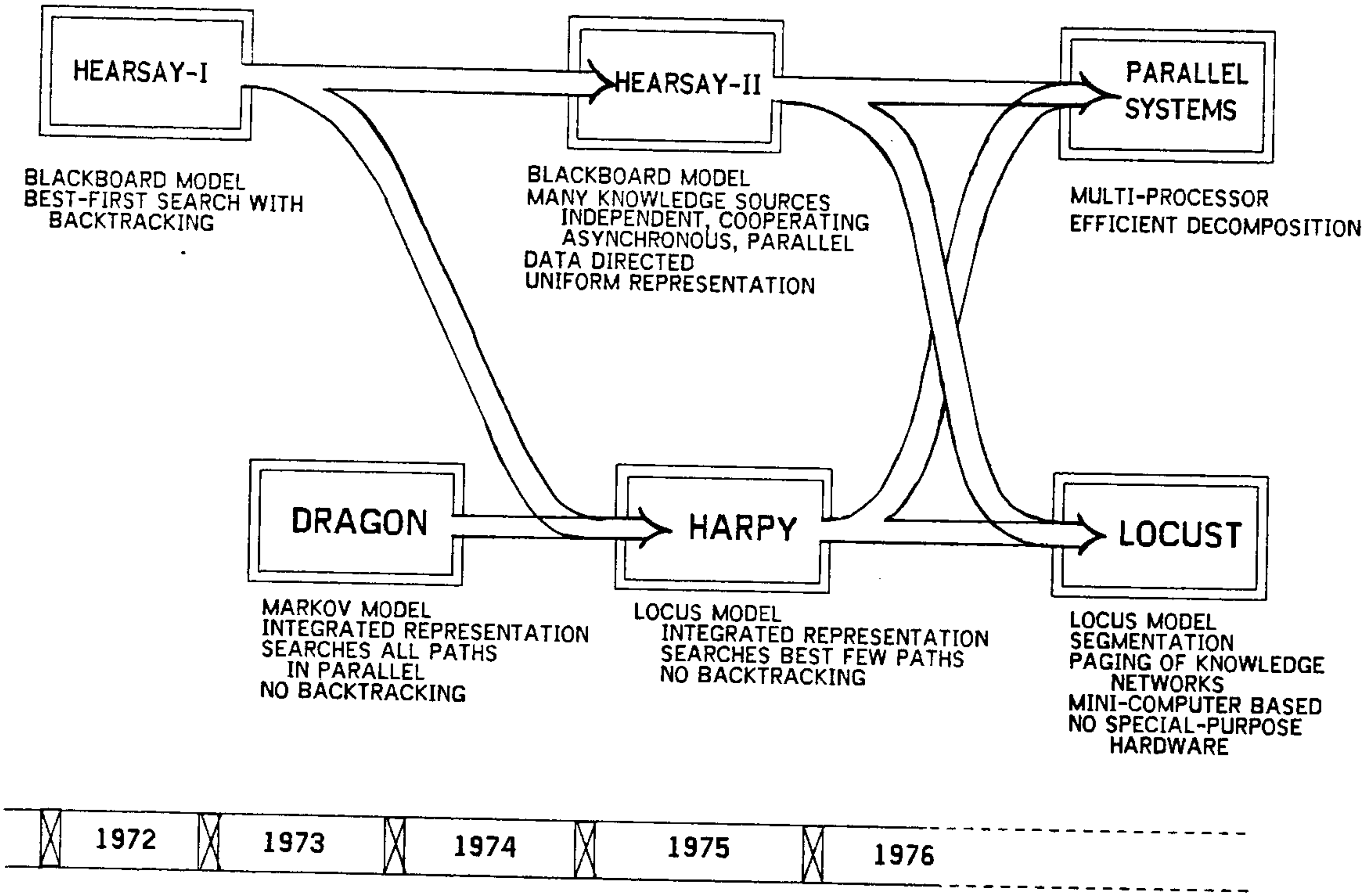

Figure 3. CMU Speech Understanding Systems Genealogy

SYSTEMS

Figure 3 shows the genealogy of the speech understanding systems developed at CMU. In this section we will briefly outline the interesting aspects of each of these systems and discuss their contributions towards the development of speech understanding systems technology. More complete descriptions of these systems can be found in the references listed at the end.

The Hearsay-I System (Erman, Fennell, Lowerre, Neely, and Reddy)*

Hearsay-I (Reddy, Erman and Neely 1973; Reddy, Erman, Fennell and Neely 1973), the first speech understanding system developed at Carnegie-Mellon University, was demonstrated in June of 1972. This system was one of the first connected speech understanding systems to use task dependent knowledge to achieve reduction of the search space. Recognition uses a best-first search strategy.

Model

Hearsay-I was the first system to utilize independent, cooperating knowledge sources and the concept of a global data base, or "blackboard", through which all knowledge sources communicate. Knowledge sources consist of the acoustic-phonetic, syntactic, and semantic modules. Each module operates in the "hypothesize-and-test" mode. Synchronous activation of the modules leads to a best-first search strategy. Several other systems have used this strategy (Forgie 1974). This system was one of the first to use syntactically derived word diagrams and trigrams, as anti-productions (Neely 1973), to predict forward and backward from "islands of reliability". Task dependent knowledge, such as a board position in the chess task, is used by the semantic module (Neely 1973) to reject meaningless partial parses early in the recognition process. The acoustic-phonetic module uses amplitude and zero-crossing parameters to obtain a multilevel segmentation into syllable-size and phoneme-size units (Erman, 1974).

Performance

Over a wide range of tasks, the average sentence error rate was 69% with a a word error rate of 45%. Speed varied between 3 and 15 MIPSS over 162 utterances containing 578 words. Hearsay-I yields much higher accuracies on tasks with which it is carefully trained. For the chess task, for instance, average sentence and word error rates were 21 and 7 percent, respectively, with an average speed of 2 MIPSS.

Discussion

Hearsay-I, as a successful connected-speech understanding system, served to clarify the nature and necessary interaction of several sources of knowledge. Its flexibility provided a means for testing and evaluating competing theories, allowing the better theories to be chosen as a basis for later systems. In retrospect, we believe this system organization would have been adequate for the ARPA specifications given present acoustic-phonetic knowledge.

* The principle contributors towards the development of each of these systems are listed within parentheses.

The Dragon System (Baker)

Baker formulated the recognition process as a dynamic programming problem. The Dragon recognition system (Baker, 1975), based on this model was first demonstrated in April of 1974. The system was motivated by a desire to use a general abstract model to represent knowledge sources. The model, that of a probabilistic function of a Markov process, is flexible and leads to features which allow it to function despite high error rates. Recognition accuracy was greater with Dragon than with Hearsay-I, but the system ran significantly slower.

Model

Dragon was the first system to demonstrate the use of a Markov model and dynamic programming in a connected speech understanding system. It included several interesting features, such as delayed decisions and integrated representation, and is based on a general theoretical framework. The general framework allows acoustic-phonetic, syntactic, and semantic knowledge to be embodied in a finite-state network. Each path through this precomplied network represents an allowed pronunciation of a syntactically acceptable sentence. Recognition proceeds left-to-right through the network, searching all possible paths in parallel to determine the globally optimal path (i.e., the path which best matches the spoken utterance). Acoustic inputs are peak-to-peak amplitudes and zero-crossings from overlapping, one-third octave filters, sampled every centi-second.

Performance

Recognition accuracy was greater with Dragon than that obtained with Hearsay-I, but at a cost of speed, Dragon being approximately 5 to 10 times slower. Over a wide variety of tasks, the average sentence error rate was 51%. Speed ranged from 14 to 50 MIPSS. The computation is essentially linear with the number of states in the Markov network. Performance was later improved by Lowerre (Lowerre, 1976).

Discussion

Dragon, with more accurate performance than Hearsay-I, served to stimulate further research into factors that led to its improved performance. Many of the ideas motivating its design were important in the development of subsequent connected-speech understanding systems. Although later systems do not use the Markov Model and do not guarantee finding the globally optimal path, the concepts of integrated representation of knowledge sources and delayed decisions proved to be very valuable.

The Harpy System (Lowerre and Reddy)

The Harpy system (Lowerre 1976) was the first connected speech system to satisfy the original specifications given in the Newell report and was first demonstrated in September of 1976. System design was motivated by an investigation of the important design choices contributing to the success of the Dragon and Hearsay-I systems. The result was a combination of the "best" features of these two systems with additional heuristics to give high speed and accuracy.

Model

The Harpy system uses the locus model of search. The locus model of search, a very successful search technique in speech understanding research, is a graph-searching technique in which all except a beam of near-miss alternatives around the best path are pruned from the search tree at each segmental decision point, thus containing the exponential growth without requiring backtracking. This technique was instrumental in making Harpy the most successful connected speech understanding system to date. Harpy represents syntactic, lexical, and juncture knowledge in a unified network as in Dragon, but without the a-priori transition probabilities. Phonetic classification is accomplished by a set of speaker-dependent acoustic-phonetic templates based on LPC parameters which represent the acoustic realizations of the phones in the lexical portion of the network.

Performance

The system was tested on several different tasks with different vocabularies and branching factors. On the 1011-word task using the AIX05 grammar (see Appendix III-C), the system word error rate was 3% and the semantic error rate was 5% (see fig. 1). The system was also tested with connected digits recognition attaining a 2% word error rate. Using speaker-independent templates, error rate increases to 7% over 20 speaker including 10 new speakers. Using telephone input increases the error rate to 7% to 11% depending on the noise characteristics of the telephone system.

Discussion

Backtracking and redundant computation have always been problematic in AI systems. The Harpy system eliminates these in an elegant way, using the beam search technique. By compiling knowledge ahead of time, Harpy achieves a level of efficiency that is unattainable by systems that dynamically interpret their knowledge. This permits Harpy to consider many more alternatives and deal with error and uncertainty in a graceful manner.

The Hearsay-II System (Erman, Hayes-Roth, Lesser, and Reddy)

Hearsay-II has been the major research effort of the CMU speech group over the last three years. During this period, solutions were devised to many difficult conceptual problems that arose during the implementation of Hearsay-I and other earlier efforts. The result represents not only an interesting system design for speech understanding but also an experiment in the area of knowledge-based systems architecture. Attempts are being made by other AI groups to use this type of architecture in image processing and other knowledge-intensive systems.

Hearsay-II is similar to Hearsay-I in that it is based on the hypothesize-and-test paradigm, using cooperating independent knowledge sources communicating through a global data structure (blackboard). It differs in the sense that many of the limitations and shortcomings of Hearsay-I are resolved in Hearsay-II.

Hearsay-II differs from the Harpy system in that it views knowledge sources as different and independent and thus cannot always be integrated into a single representation. Further, it has as a design goal the ability to recognize, understand, and respond even in situations where sentences cannot be guaranteed to agree with some predefined, restricted language model as is the case with the Harpy system.

Model

The main features of the Hearsay-II system structure are: 1) the representation of knowledge as self-activating, asynchronous, parallel processes, 2) the representation of the partial analysis in a generalized three-dimensional network; the dimensions being level of representation (e.g., parametric, segmental, syllabic, lexical, syntactic), time, and alternatives, with contextual and structural support connections explicitly specified, 3) a modular structure for incorporating new knowledge into the system at any level, and 4) a system structure suitable for execution on a parallel processing system.

Performance

The present system has been tested using about 100 utterances of the training data for the 1011-word vocabulary task. For a grammar with simple syntax (AIX05, the same one used by Harpy), the sentence error rate is about 16% (semantic error 16%). For a grammar with more complex syntax (AIX15, see appendic III-C), the sentence error rate is about 42% (semantic error 26%). The system runs about 2 to 20 times slower than Harpy.

Discussion

Hearsay-II represents an important and continuing development in the pursuit of large-vocabulary speech understanding systems. The system is designed to respond in a semantically correct way even when the information is fuzzy and only partial recognition is achieved. Independent knowledge sources are easily written and added to Hearsay-II; knowledge sources may also be removed in order to test their effectiveness. The Hearsay-II system architecture offers great potential for exploiting parallelism to decrease recognition times and is capable of application to other knowledge-intensive AI problems dealing with errorful domains. Many more years of intensive research would be necessary in order to evaluate the full potential of this system.

The Locust System (Bisiani, Greer, Lowerre, and Reddy)

Present knowledge representation and search used in Harpy tend to require much memory and are not easily extendable to very large languages (vocabularies of over 10,000 words and more complex syntax). But we do not view this as an insurmountable limitation. Modified knowledge representation designed for use with secondary memories and specialized paging should overcome this difficulty. In addition, it appears larger-vocabulary speech understanding systems can be implemented on mini-computers without significant degradation in performance. Locust is designed to demonstrate the feasibility of these ideas.

Model

The model is essentially the same as the Harpy system except, given the limitations of storage capacity of main memory, the knowledge representation has to be reorganized significantly . The network is assumed to be larger than main memory, stored on secondary memory, and retrieved using a specialized paging mechanism. The choice of the file structure representation and clustering of the states into pages of uniform size are the main technical problems associated with the development of this system.

Discussion

A paging system for the 1011 word vocabulary is currently operational on a PDP-11/40E and has speed and accuracy performance comparable to Harpy on a PDP-10 (KA10). Simulation of various paging models is currently in progress. As memories with decreased access times become available, this class of systems is expected to perform as accurately and nearly as fast as systems requiring no secondary memory.

Parallel Systems (Feiler, Fennell, Lesser, McCracken, and Oleinick)

Response time for the present systems is usually greater than real-time, with indications that larger vocabularies and more complex syntax will require more time for search. One method of achieving greater speed is to use parallel processing. Several systems designed and developed at CMU exploit multi-processor hardware such as C.mmp and Cm*.

Models

Several systems are currently under development as part of multi-processor research projects which attempt to explore potential parallelism of Hearsay and Harpy-like systems. Fennell and Lesser (1977) studied the expected performance of parallel Hearsay systems and issues of algorithm decomposition. McCracken (1977) is studying a production system implementation of the Hearsay model. Oleinick (1977) and Feiler (1977) are studying parallel decompositions of the Harpy algorithm. Several of these studies are not yet complete, but preliminary performance results are very encouraging. Oleinick has demonstrated a version of Harpy that runs faster than real-time on C.mmp for several tasks.

Discussion

The main contribution of these system studies (when completed) will be to show the degree of parallelism which can reasonably be expected in complex speech understanding tasks. Attempts to produce reliable and cost-effective speech understanding systems would require extensive studies in this direction.

DISCUSSION

In the previous section we have briefly outlined the structure and contributions of various speech systems developed at CMU. In retrospect, it is clear that the slow rate of progress in this field is directly attributable to the large combinatorial space of design decisions involved. Thus, one might reasonably ask whether the human research strategy in solving this and other similar problems can benefit from search reduction heuristics that are commonly used in AI programs. Indeed, as we look around, it is not uncommon to find research paradigms analogous to depth-first exploration, breadth-first with shallow cut-off, backtracking, "jumping-to-conclusions", thrashing, and so on.

Our own research has been dominated by two such paradigms. First is a variant of best-first search: find the weakest link (and thus the potential for most improvement) in the system and attempt to improve it. Second is a variant of the beam search: when several alternative approaches look promising, we use limited parallel search with feed-forward. The systems shown in Figure 3 are examples of this type of system iteration and multi-systems approach.

Many system design decisions require an operational total systems framework to conduct experiments. However, it is not necessary to have a single system that permits all possible variations of system designs. Given enough working components, with well-designed interfaces, one can construct new system variants without excessive effort.

The success of the speech understanding research effort is all the more interesting because it is one of the few examples in AI research of a five year prediction that was in fact realized on time and within budget. It is also one of the few examples in AI where adding additional knowledge can be shown to lead to system speed-up as well as improved accuracy.

We note in conclusion that speech understanding research, in spite of the many superficial differences, raises many of the same issues that are central to other areas of AI. Faced with the problem of reasoning in the presence of error and uncertainty, we generate and search alternatives which have associated with them a likelihood value representing the degree of uncertainty. Faced with the problem of finding the most plausible symbolic description of the utterance in a large combinatorial space, we use techniques similar to those used in least-cost graph searching methods in problem solving. Given the problems of acquisition and representation of knowledge, and control of search, techniques used in speech are similar to most other knowledge intensive systems. The main difference is that given human performance the criteria for success, in terms of accuracy and response time, far exceed the performance requirements of other AI tasks except perhaps vision.

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II. KNOWLEDGE SOURCES AND TECHNIQUES

The Zapdash Parameters, Feature Extraction, Segmentation, and Labeling for Speech Understanding Systems (Goldberg, Reddy, and Gill)

Introduction

In spite of early success with very simple parametric representations of speech (see Reddy 1966 and Erman 1974), recent emphasis has been on highly accurate but computationally expensive parameter extraction techniques such as LPC spectral analysis, formant tracking, etc. We feel that simpler, more efficient methods must first be applied to reduce the amount of input data before more expensive analysis is performed. The uniform application of LPC analysis to all the input produces accurate but very redundant results, and at high cost. (see Goldberg 1975)

Our approach involves two levels of parameter extraction and analysis. The first level produces an accurate segmentation with strong clues as to manner of articulation and phonetic identity of the segments. For this purpose, we have developed the ZAPDASH parameters, described below. They provide a highly efficient basis for an accurate, robust segmenter and broad classifier. After the phonetic elements are isolated, a uniform LPC labeling stage is applied only where it is needed to further refine the segment identification. Preliminary evaluations show significant computational savings is possible with no sacrifice of segmentation or labeling accuracy.

The ZAPDASH Parametric Representation

As digital processing of speech becomes commonplace, it becomes desirable to have a parametric representation of speech which is simple, fast, accurate, and directly obtainable from the PCM representation of speech. The ZAPDASH representation of speech (Zerocrossings And Peaks of Differenced And SmootH waveforms) is of this nature. An important means of reducing computational cost in much of the low level processing of speech is to reduce the quantity of data in the input representation to the minimum necessary for accurate analysis of the phonetic content of the speech signal. Our past experience shows that very simple measures of activity in the low and the high frequency bands (approximately: <1kHz. and >1kHz.) would suffice for all but the fine labeling stage. Peak-to-peak amplitudes and zero-crossing counts provide simple measures of the amount of activity within each particular band. In ZAPDASH, the PCM data is used to generate a differenced waveform and a down-sampled, smoothed waveform (for 10KHz sampling rate, the smoothing FIR filter coefficients were -1 0 1 2 4 4 4 2 1 0 -1, used every 4th point). Peak-to-peak distances and number of zero-crossings are calculated each 10 ms, resulting in 400 8-bit parameters per second of speech. ZAPDASH can be calculated in 15 to 20 computer instructions per sample and, therefore, can be extracted in less than a 1/3 real time on minicomputers with 2 micro-sec. instruction time. A simple parametric representation like ZAPDASH appears to provide sufficient information for accurate phone segmentation, thus sharply reducing the amount of more detailed spectral analysis required by many other methods. The resulting four parametric measurements (Smoothed Peak-to-peak, Smoothed Zero-crossing, Differenced Peak-to-peak, and Differenced Zero-crossing) are sufficient to detect, with reasonable accuracy, a set of 10 features, described below, which are quite useful for both segmentation and initial broad labeling. The ZAPDASH parameters are used by the first stage segmenter to make decisions on manner of articulation. The resulting segmentation and broad classification is accurate yet inexpensive. Further refinement of the segment labels using spectral analysis is then much more economical.

Segmentation and Broad Classification

The first stage of the program contains an hierarchical, feature-extraction based segmenter and classifier. A number of features relating to manner of articulation are extracted. Silence, voicing, frication, front-back placement, high-low placement, consonant-like, flap-like, aspiration-like, nasal, and sibilant decisions are made using the ZAPDASH parameters. In the processing of an utterance, a set of segments is chosen, with broad classification, for the entire utterance. These identify regions of the signal such as SIL-silence, SON-sonorant, UFR-unvoiced fricative, VBK-back vowel, etc. Further sub-segmentation and/or reclassification is conditional upon segment class type, context, and feature values. There are 59 classes currently used internally, although many overlap one another in the acoustic space.

Modified LPC Labeling

At the second stage, where no further refinement is possible using the ZAPDASH information, a fine labeler is applied at the mid-points of all segments. The original PCM signal is compared against stored templates by a modified LPC distance metric. Itakura's minimum prediction residual metric (Itakura 1975) is used to compare the segment mid-point to a set of speaker-specific trained templates. The segment class is used to provide a sub-set of the approximately 100 templates, or a set of *a priori* weights to be added to the metric values for all templates. In this way, the manner-of-articulation and the contextual information provided by the earlier feature extraction improve the labeling.

Results

The highly efficient segmentation procedures in the first level segmenter and the limitation upon the need for LPC analysis provide a factor of 5 speedup over the uniform procedures used by HARPY and Hearsay-II. Preliminary tests with this program indicate that results for HARPY using this parameterization will be just as accurate and will be computed faster than the results obtained with the more redundant parameterization it now uses. Present performance of ZAPDASH can be summarized as follows: Segmentation -- less than 20% extra segments, less than 2% missed segments, and boundary placement within an average of 10 ms. of the manually defined location. Labeling (broad classes) -- 90% correct, (finer labeling) -- correct template in first place 50% of the time, in the first five places 75% of the time. A more detailed evaluation will be available shortly.

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A Syllable Based Word Hypothesizer for Hearsay-II (Smith)

Problem and Motivation

A central problem for speech understanding systems is efficiently and accurately determining what words are implied at the lexical level by the data at lower levels. One solution to the problem is to map each word hypothesized by syntactic and semantic information to the lower level representation, then match and rate the word.

But as speech systems permit larger vocabularies and languages with less restricted syntax and semantics, they must depend more on bottom-up methods to limit the search space of possible word sequences. The effectiveness of a hypothesizer can be measured by the percent of the correct words and the number of competing words it hypothesizes. One method of bottom up word hypothesization is to go directly from the phone sequences found for the utterance to word hypotheses as in the BBN HWIM speech system (Klovstad, 1976). The solution used in Hearsay-II uses an intermediate level of syllables between the words and phone segments.

Solution

The word hypothesizer uses equivalence classes of syllables (called Syltypes) to support word hypotheses (Smith, 1976). These Syltypes were defined so that syllables which were likely to be given similar segments and labels by the speech system would have the same Syltype. No attempt is made by the word hypothesizer to distinguish between words which have the same sequence of Syltypes. The word verifier later makes this distinction as it rates the words.

The Syltypes we now use are defined by a sequence of states corresponding to phoneme equivalence classes. A Markov probability model relates the state sequence of a Syltype to the segment labels hypothesised by the segmenter and labeler. A word may be hypothesised by the following sequence of events: For each syllable nucleus in the utterance (defined by a heuristic using segment labels and an amplitude function), the most likely Syltype state sequences are found by searching the segments from the nucleus out to adjacent nuclei, or perhaps the utterance boundaries. For each Syltype hypothesized with a "good" rating the set of words containing syllables mapping to the Syltype, are retrieved using an inverted lexicon. A multi-syllabic word in the set is rejected if it matches poorly with adjacent Syltype hypotheses. The word verifier is then called to rate each word. Those with a poor rating are rejected.

Results

Since the word hypothesizer's ratings for words are used only to determine whether to reject the word or to verifier the word, it is used as a filter for the word verifier. The performance relevant to this task is the percentage of the spoken words correctly hypothesized and the fraction of the vocabulary hypothesized per spoken word. The results from twenty test sentences indicate that, for a 1011 word vocabulary, 67% of the correct words are hypothesized when 80 words are hypothesized per spoken word (8% of the vocabulary). Of course these numbers can be varied by changing thresholds. If the speech system can function with only 57% of the correct words hypothesized bottom-up, then only 51 words need to be hypothesized per spoken word (5% of the vocabulary). Similarly, higher accuracy can be obtained with a greater number of competing word hypotheses.

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Wizard: A Word Verifier for Hearsay-II (McKeown)

Problem and Motivation

A key problem for speech understanding systems is the verification of word hypotheses generated by various knowledge sources in the system. The verifier must assign a likelihood score which is commensurate with the match between the underlying acoustic data and the phonetic description of the word. The goodness of a score may be only temporally significant; the scores should rank order competitive words in any time area such that the correct word is high in the ordering. In addition to this acceptance criteria, it is also necessary for the verifier to reject absolutely a large percentage of the hypothesized words, without rejecting a significant number of correct words, in order to constrain the combinatorics at higher levels.

Solution

In HEARSAY II, words may be generated bottom-up by the word hypothesizer (POMOW) or predicted top-down by the syntax and semantics module (SASS). Each uses a very different strategy for verification since bottom-up hypothesis have a known approximate begin/end time while top-down hypotheses use a verified word to predict words to the left or right, and thus only one time is known.

The word verifier, WIZARD, uses a general Markov model for speech recognition (BAKER,1975 ; LOWERRE,1976). The acoustic information is a segmentation of the utterance where each segment is represented as a vector of phoneme probabilities. Each word in the lexicon is represented by a statically defined network which embodies alternate pronunciations of the word. This model finds the optimal path through the word network and assigns as the word score a normalized sum of all the log-probabilities for states (phonemes) on that path. Networks do not take into account word junctures but do handle internal phoneme junctures. Thus WIZARD attempts to verify words as if they exist in isolation.

Wizard handles bottom-up words in the following manner: The predicted begin/end times are mapped into their respective begin/end segments: bseg/eseg. All paths which begin at bseg-1/bseg/beg+1 and end at eseg-1/eseg/eseg+1 are explored in parallel. Each of the nine possible optimal mappings is examined and the best of these is chosen as the mapping of the word network over the segmented acoustic data. This possible time shifting allows the verifier to recover from incorrect times due to differences in representation of the acoustic data between knowledge sources. As a result, the verifier may change times on word hypotheses as well as rate them.

Words which are hypothesized top-down pose a different problem in terms of verification, since only the begin or end time is known. In this mode it is necessary for WIZARD to predict the missing time as well as to return a rating. A major problem is bounding the number of segments considered in a prediction. Currently several heuristics are employed. Since all states on the optimal path must be mapped to at least one segment, the lower bound on the number of segments is the minimal number of network transitions (mintran). An upper bound was experimentally determined to be 4*mintran, thus on the average no more than 4 segments are mapped into any one state. This number is a function of the segmentation, which tends to over-segment, and the network descriptions, which allow reduced spellings. The POMOW word hypothesizer generates an upper bound based on the expected number of vowel nuclei in the word and their position relative to the beginning of the prediction. The smaller of these upper bounds is used. WIZARD iteratively maps each of the segments from the given begin segment to the upper bound. It considers those mappings which fall between the lower and upper bounds and picks the best after appropriate normalization. The time of the best end segment is returned along with the rating.

Results and Conclusions

The results summarized in Table I are for five data sets, containing 100 utterances, in which 332 correct words were hypothesized bottom-up by POMOW. In addition, 13053 incorrect words were generated. The vocabulary size for POMOW and WIZARD was approximately 550 words. WIZARD rated each of the words using begin/end times generated bottom-up. Each verification took, on the average, 100ms of CPU time on a DEC PDP-10 (KA). For each rating threshold (15,10) the number of correct and incorrect words that were accepted or rejected is tabulated. From this data the number of words hypothesized per word position and the percent of the vocabulary hypothesized per word position can be calculated. These numbers give a vocabulary independent measure of performance, allowing comparisons between various system configurations. An average rank order of the correct word is provided which measures, at each threshold, the number of words in each word position that must be examined in order to include the correct word. The range of rank orders between the data sets (20 utterances/set) is also indicated.

TABLE I

THR 15	# HYPED BY POMOW	ACCEPTED	REJECTED	5.6 RANK ORDER
CORRECT	332	326 (98%)	6 (2%)	(3.6 - 7.1)
INCORRECT	13053	10426 (80%)	2627 (20%)	
TOTAL	13385	10752 (80%)	2633 (20%)	
#/WORD POS	40 (8%)	32 (6%)	8 (2%)	
THR 10	# HYPED BY POMOW	ACCEPTED	REJECTED	4.5 RANK ORDER
CORRECT	332	312 (94%)	20 (6%)	(3.4 - 5.6)
INCORRECT	13053	6462 (49%)	6591 (51%)	
TOTAL	13385	6774 (51%)	6611 (49%)	
#/WORD POS	40 (8%)	20 (4%)	20 (4%)	

Sample results of verification in the prediction mode are presented in Table II. In this mode it is important that the best rating for the predicted word comes from a mapping that closely approximates the actual time in which the word appears. If this is not the case there is the danger that a correct word, which is highly rated, will be hypothesized with times which will disrupt the recognition of word sequences by top end knowledge sources. Small errors in the determination of the missing time can propagate time errors which may cause whole words to be missed. Table II summarizes the results of an experiment to predict begin/end times of 529 words where both times were actually known. The distance, in segments, is calculated from the known word bound and its predicted word bound. The table also shows the distribution of distances for the best mapping. Given that the average segment duration is 3.2cs, a distance of 2 would correspond to a range of predicted bounds 6.5cs about the actual bound. Each prediction takes, on the average, 180ms of CPU time.

TABLE II

BEST RANKED PREDICTED WORD BOUNDARY

DIST	FREQ	%	CUM %
0	125	24%	24%
1	209	40%	64%
2	103	19%	83%
3	41	8%	91%
4	20	4%	95%
5	17	3%	98%
6	7	1%	99%
7	4	1%	100%
8	2	0%	
9	1	0%	
10	0		

Areas of further research involve dynamic generation of multiple word networks using static networks and word juncture rules, alternate score normalization schemes, and improvement in the effectiveness of bounding predictions using vowel nuclei.

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Word Pair Adjacency Acceptance Procedure in Hearsay-II (Robert Cronk)

Introduction

In the Hearsay-II speech understanding system, several knowledge sources attempt to construct sequences of words from the word candidates hypothesized on the blackboard. Pairs of words which are approximately time-contiguous and syntactically adjacent (may be paired in the grammar) are considered for extending word sequences. To avoid the combinatorial explosion which occurs in a grammar with a large branching factor, a procedure is required which will constrain the number of word pairs to those which have a high probability of being the correct ones.

Such a procedure must be computationally inexpensive, since it must make decisions on hundreds of pairs of hypothesized words. It must rely upon knowledge of word junctures and upon the information contained in the segmental transcription of the spoken utterance. And it must reject as many incorrect pairs (word pairs not actually spoken) as possible, without rejecting any of the correct pairs.

This paper describes the word pair adjacency acceptance procedure (JUNCT) developed for Hearsay-II, the knowledge it uses, and the current results.

Description

Input to the JUNCT procedure is a pair of word hypotheses. If it determines that the words are adjacent, based upon the times associated with the hypotheses, the juncture rules contained in the procedure, and the blackboard segmental description of the spoken utterance the pair is accepted as a valid sequence; otherwise it is rejected.

Word junctures which JUNCT must use to make its decisions fall within three distinct cases:

(1) Time-contiguous hypotheses: Words which are time contiguous in the blackboard are immediately accepted by JUNCT as a possible sequence. No further tests for adjacency are performed.

(2) Overlapping hypotheses: When two words overlap in time, juncture rules are applied in the context of the blackboard segmental transcription of the utterance to determine if such a juncture is allowable for the word pair.

(3) Separated hypotheses: When the words are separated by some interval of time, rules are applied, as in the overlap case, to determine whether the pair can be accepted as a valid sequence in the utterance.

The juncture rules used by JUNCT are of two types: (1) allowable overlaps of word end-phoneme and begin-phoneme, and (2) tests for disallowed segments within the word juncture. A bit matrix of allowable overlaps is precompiled into the procedure, and is indexed by the end-phoneme and begin-phoneme of the word pair. Any overlap juncture involving phonemes which are not allowed to share segments is rejected by JUNCT. In the separation case, as in allowed overlaps, the blackboard segmental description of the spoken utterance is examined in the context of the end-phoneme and begin-phoneme of the word pair to determine if any disallowed segments are present in the juncture gap. If such segments are found, the word pair is rejected. Only when a word pair passes all rule tests which apply in the segmental context of its juncture is it accepted as a valid sequence.

Current Results

Stand-alone performance evaluation runs were made over 60 utterances using words generated from files produced by the Hearsay-II word hypothesizer. Syntactically adjacent pairs of words whose ratings were 40 and above (on a scale from 0 to 100) and whose times (left-word end time and right-word begin time) were within a 200 millisecond interval were considered. All of the words used for testing the procedure were hypothesized "bottom-up" in Hearsay-II; no predictions were used in the evaluation runs. The following table summarizes the performance of the JUNCT procedure.

	CORRECT WORD PAIRS	INCORRECT WORD PAIRS	TOTAL
ACCEPTED	188 (95%)	2891 (41%)	3079 (42%)
REJECTED	5 (5%)	4224 (59%)	4233 (58%)
TOTAL	197	7115	7312

It is expected that, as lower-level sources of knowledge provide more accurate times for word hypotheses, the rules for acceptance of valid word pairs may be tightened, further increasing the speed and performance of Hearsay-II.

Syntactic Processing in Hearsay-II (Hayes-Roth, Erman, Fox, and Mostow)

The basic tasks facing the three syntactic knowledge sources in Hearsay-II are: to parse syntactically acceptable sequences of words; to predict words that can be (syntactically) adjacent to the ends of a word sequence; and to construct larger sequences when predicted words are verified. The chief obstacle is finding all possible syntactic structures that can produce a given sequence of words. Of the traditional parsing mechanisms, only bottom-up Kay-type parsers have addressed the problem of building phrase-structure trees which are not necessarily anchored at the start (or end) of a sentence. But these methods are still inadequate for parsing in the current environment because of their requirement that all constituents of a phrase be present in order for a phrase to be recognized. In Hearsay-II, a general method for such partial parsing of incomplete phrase structures has been developed and is used to parse grammatical word sequences, to predict extensions, and to join up to three sequences of words together in a new syntactic structure.

The details of the method are now briefly described. To minimize redundant computing, the syntactic (context-free) grammar is converted to an equivalent template normal form grammar in which all sequential productions have binary derivations (e.g., A → B C D is replaced by A → B X and X → C D). Thus, frequently occurring grammatical subsequences are replaced by a common higher-order non-terminal thereby minimizing recomputation of common subexpressions (Hayes-Roth and Mostow, 1975).

The word-sequence hypothesizer, WOSEQ, generates the initial word sequences that are partial-parsed. Given a word sequence w1 ... wn, the RECOGNIZE parser knowledge source works in a conventional bottom-up manner, with the exception that any words or phrases (non-terminals) that are required by a grammar rule to precede (follow) a constituent at the first (last) position of the sequence are pseudo-recognized; that is, if the word sequence w1 ... wn can be derived from the productions S → A T, T → w1 V, V → U X, U → ... wn, A → w0, and X → w(n+1), then the non-terminals A and X will be pseudo-recognized and the sequence w1 ... wn will be parsed as an instance of S, with closest left-missing constituent A and closest right-missing constituent X. Bottom-up parsing continues until all of the words in the input sequence are subsumed by each highest-order phrase or until no further rewrites are possible. The highest-order phrases constructed that derive the entire word sequence are referred to as spanning phrases. Because parsing is discontinued on spanning phrases, the partial-parse technique essentially identifies minimal (lowest-order) parses of each sequence. Each distinct parse of a sequence specifies a spanning phrase and the pseudo-recognized closest missing constituents. There may, of course, be several distinct parses of any word sequence. If no parse of a sequence is found, it is rejected. Whenever a sequence hypothesized by the word-sequence hypothesizer is rejected, that knowledge source wakes up, decomposes the rejected sequence into maximal subsequences, and then hypothesizes any sufficiently rated new word sequences.

Given a spanning parse of a sequence w1 ... wn with closest left and right-missing constituents A and X, the words that can be adjacent to <w1 or wn> are all rightmost derivatives of A or leftmost derivatives of X. If a spanning phrase has no closest left-missing (right-missing) constituent, the possible adjacent words are found by "going up-and-over": the rightmost (leftmost) derivatives are computed for each constituent that can be directly adjacent to this left-complete (right-complete) phrase in some higher-level spanning phrase. Predictions of words are made by the PREDICT knowledge source whenever the extension of a previously parsed word sequence is scheduled and executed. Predictions may be made to both sides or to only one side depending on the relative and absolute numbers of grammatically possible words on the two sides. In any case, if none of the predicted words on one side is verified, the word-sequence hypothesis, although syntactically valid, is deactivated. No further processing of that sequence can occur unless it is retrieved by another sequence extension colliding with it on the side that failed the extension effort. Such a salutary collision results in the reactivation of the sequence.

When predicted words are verified, the CONCAT knowledge source may extend the parse by concatenating the verified words to the predicting word reference. Given the sequence <w1 ... wn> and verified preceding predicted words a1, a2, ..., ak and verified succeeding predicted words b1, b2, ..., bm, an attempt is made to partial-parse all sequences <ai w1 ... wn bj> as well as all sequences <x1 x2 ... xp ai w1 ... wn bj y1 y2 ... yq> where <x1 x2 ... xp ai> (<bj y1 y1 ... yq>) is a previously parsed sequence of words on the blackboard that is time-adjacent to and precedes (succeeds) <w1 ... wn>. All successfully parsed sequences generate phrasal hypotheses. Thus, in addition to simply extending sequences a-word-at-a-time in each direction, finding a predicted word as the terminus of an existing adjacent sequence can trigger the concatenation of three sequences at once.

Conclusion

Because the words that are hypothesized from other knowledge sources form arbitrary sequences that usually do not completely satisfy constituent structures of phrase rewriting rules, a general mechanism for partial-parsing is needed. The current implementation generates minimal spanning phrases and retains at most one closest missing constituent on each side of each phrase. Partial-parsing times average about 50 msec on the KL10 for a 1000 word vocabulary with a 15 branching-factor grammar. Extensions of sequences are quickly computed by running down the right or left sons of the binary sequence nodes of the closest missing constituents. Three adjacent sequences are syntactically concatenated by partial-parsing the concatenated word sequences. The current implementation provides an efficient solution to essential problems of syntactic processing. In addition, the three related knowledge sources decompose this processing into natural components with a grain-size that is attractive for focusing and control.

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Focus and Control in Hearsay-II (Hayes-Roth and Lesser)

The Hearsay-II speech understanding system currently comprises 13 knowledge sources (KSs), 11 of which are data-directed. Each data-directed KS is invoked whenever new or modified blackboard data configurations matching patterns of interest are found. Monitoring for potentially relevant data changes is performed in two steps: changes in hypotheses or links at particular levels are collected in change sets specific to each KS; procedures called preconditions then closely examine each accumulated change and its blackboard context to determine if the exact pattern of interest is present. Once such a pattern is detected, the relevant KS is invoked (scheduled) to operate upon it. The basic control problem is to execute first those preconditions and KSs that are most likely to lead to successful recognition of the utterance. The two chief subgoals are: (1) to find the best interpretation as quickly as possible and (2) to reduce the number of incorrect hypotheses that are generated and tested. In fact, if too many incorrect hypotheses are examined, working storage capacity of the system may be exceeded, thus precluding eventual correct recognition of the utterance.

The current approach to the control problem follows closely the design of the focus of attention mechanism described in detail in Hayes-Roth and Lesser (1976). The basic concepts of that paper are quickly reviewed here: (1) The Competition Principle: the best of several alternatives should be performed first; (2) The Validity Principle: more processing should be given to KSs operating on more valid data; (3) The Significance Principle: more processing should be given to KSs whose expected results are more significant; (4) The Efficiency Principle: more processing should be given to KSs that perform most reliably and inexpensively; (5) The Goal Satisfaction Principle: more processing should be given to KSs whose responses are most likely to satisfy processing goals.

The degree to which a precondition or KS satisfies these principles is reflected by its desirability, an increasing function of its validity, duration, level of analysis, importance, concordance with control thresholds (goals), (relative and absolute) expected superiority over the best competing alternative in the same time area, and the time elapsed since an improved degree of recognition was achieved (stagnation) in that time area. While the desirability of a KS instantiation awaiting execution is determined directly from only one data pattern and the declarative control knowledge about the direction (on the blackboard) and relative effectiveness of its actions, the desirability of a precondition is taken to be the maximum of such values over all hypotheses in its change set.

Using this general scheme, we have implemented one particular control strategy by setting particular processing goals on the blackboard. Initially the segmenter/labeller is executed and is forced to run to completion. This insures that bottom-up syllable hypothesization will have the benefit of complete segmental contexts. The syllable hypothesizer is executed in turn, and for a similar reason is also forced to run to completion. At this point the syllable-to-word KS responds to new syllables and generates all potentially plausible words. The strategy module then establishes thresholds governing which of these words is hypothesized. It attempts to have several highly rated words hypothesized in each area of the utterance. After this processing is completed, the word-sequence hypothesizer examines all words in parallel and identifies promising connected sequences of time-adjacent syntactically possible pairs of words (seeds). The best of these in each time are then hypothesized. From this point on, a complex sequence of data-directed preconditions and KSs is invoked, scheduled, and executed to control syntactic parsing, hypothesization of plausible words to extend syntactic sequences, concatenation of verified words or phrases with adjacent phrases, and the generation of further seeds when the system is stagnating. Whenever any new complete parse is found, a special KS is invoked to determine which remaining hypotheses and KS instantiations are insufficiently attractive to preserve. These are either rejected or deleted. Processing then continues until a quiescence occurs reflecting that the remaining alternatives are insufficiently credible to continue. If a sufficiently plausible sentence has been recognized, the stopping condition KS decides to terminate the analysis; or if no complete sentence has been formed, an attempt is made to interpret the best partial sequences by the syntax and semantics knowledge source.

Conclusion

Each precondition and KS is regarded as a [condition→action] schema, with known inputs (blackboard hypotheses and links), a known direction of action (bottom-up, top-down, or same-level and forwards, backwards, or same-time), known reliability and efficiency, and therefore, a known expected result. By comparing the expected results of all scheduled activities to the current state of recognition and desired areas of activity, the best pending instantiation can be execued first. As a result of tuning the various weighting factors, we seem to have achieved a desirable balance of breadth- and depth-first search (in a global sense) with effective suppression of sub-optimal (in a local sense) activities. Further, by separating expensive searches into two or more successive steps (e.g., change sets and preconditions do gross filtering and only subsequent KSs do fine, expensive processing; or, before expensive syntactic searches are performed, inexpensive searches are made for plausible sequences of syntactic word pairs), it appears that we have achieved some efficiency in the overall organization and control of the search process.

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Policies for Rating Hypotheses, Halting, and Selecting a Solution in Hearsay-II (Hayes-Roth, Lesser, Mostow, and Erman)

Purpose of hypothesis validity ratings

The rating policy module (RPOL) in Hearsay-II provides a uniform basis for comparing the plausibility of different hypotheses. The hypotheses may be competing alternative interpretations of the same portion of the utterance at some level of the blackboard, in which case the hypothesis whose validity rating is higher is considered more likely to be the correct interpretation. However, the hypotheses may describe different portions of the utterance, or provide representations at different levels of the blackboard. Having a uniform rating policy means that such hypotheses may nonetheless be meaningfully compared on the basis of their validity ratings. This information is used in three ways by Hearsay-II:

(1) to focus attention in promising directions by considering higher-rated (more likely correct) hypotheses before lower-rated hypotheses. This is implemented by making the priority of a scheduled action an increasing function of the validity ratings of the hypotheses which are being acted upon (Hayes-Roth and Lesser, 1976). Also, certain types of actions are not even scheduled on hypotheses which fail minimum plausibility tests specified by knowledge source modules. These tests use validity ratings as a measure of plausibility.

(2) to select the most likely correct interpretation of the utterance if there is more than one phrasal hypothesis spanning the utterance. The highest-rated such hypothesis is then the chosen interpretation.

(3) to prune the search once a solution (*i.e.*, an utterance-spanning phrasal hypothesis) has been found. This is done by restricting further processing to those actions which are capable of leading to a better (higher-rated) solution.

Computation of hypothesis validity ratings

Hypotheses in Hearsay-II represent interpretations of the speech signal at various levels of representation: segmental (lowest level), syllabic, lexical, word-sequential, and phrasal (highest level). An hypothesis may be either *conjunctive*, representing a logical product, or temporal sequence, of lower level hypotheses or *disjunctive*, representing a logical summation of lower level alternative hypotheses. The degree to which each lower level hypothesis supports the upper hypothesis is indicated by an *implication* between -100 (maximally disconfirming) and +100 (maximally confirming). This number is attached to a link in the blackboard from the lower to the upper hypothesis.

The *validity rating* VLD(H) of an hypothesis H is a measure of the extent to which that hypothesis is supported, ultimately, from the acoustic data. The lowest level hypotheses are rated by the bottom-end processor. The rating of a higher level hypothesis H is computed from the validities of the hypotheses which support H directly from below, and is stored on the blackboard as part of H. The validity rating of H need only be recomputed when the validity or implication of its support changes, or when H receives new support. In such cases, RPOL immediately propagates resultant validity changes up through the blackboard. Storing the ratings on the blackboard avoids the expense of recomputing them recursively whenever they are used.

The validity rating VLD(H) of a *disjunctive* hypothesis H supported by n lower level hypotheses H1, ..., Hn via respective links L1, ..., Ln is given by

$$\text{Max VLD(Hi)}*\text{IMPLICATION(Li)}/100,\ (1 \le i \le n).$$

Similarly, the validity rating of a *conjunctive* hypothesis at the word level or below is given by

$$(1 + (n-1)/10) * (\text{Sum VLD(Hi)}*\text{IMPLICATION(Li)}/100),\ (1 \le i \le n).$$

The weighting factor (1 + (n-1)/10) reflects the increased plausibility of an hypothesis which has many conjunctive supports.

Above the word level, a somewhat different function is used to rate conjunctive hypotheses. The validity VLD(H) of a phrasal or word sequence hypothesis H is given by the duration-weighted average validity of its n underlying words Wi, where duration is measured in number of syllables. *I.e.*, VLD(H) = (Sum VLD(Wi)*length(Wi)) / Sum length(Wi), ($1 \le i \le n$),

where length(Wi) = length (in syllables) of the word hypothesis Wi. This formula is based on the empirical observation that the longer a word Wi, the greater the correlation between its correctness and the correctness of H.

Halting conditions and heuristic pruning

A phrasal hypothesis can be thought of as a subpath through a flow graph whose arcs are word hypotheses, and whose source and sink are respectively the beginning and end of the utterance. A solution (utterance-spanning phrase) then corresponds to a complete path through the graph. The validity rating of a subpath (hypothesis) is given by the average arc (word hypothesis) validity along the subpath, weighted by arc (word) length measured in syllables.

There is a qualitative difference between the task of searching for a solution (complete path) and the task of deciding when to stop searching and accept the current best solution. The former task can efficiently be done best-first, *i.e.*, by extending the most promising path at each step in the search. In contrast, the latter task inherently involves searching all possible paths in order to guarantee that no path is better than the best one found so far. Once a path has been found, the goal of processing should be to enable such a guarantee to be made as quickly as possible. In order to accelerate the attainment of this goal, two heuristics for pruning the search are used.

The first heuristic consists of rejecting every word, word sequence, and phrase hypothesis which, due to its low rating, cannot be extended into a better solution than the best already found. This heuristic can be thought of as a form of alpha-beta pruning, simplified for the case of a one-player game. Rejecting a subpath (hypothesis) amounts to abandoning certain nodes in the search tree which correspond to extensions of that subpath. In operation, an hypothesis is rejected if, when it is extended into an utterance-spanning path using the highest-rated word hypotheses currently on the blackboard, the resulting (not necessarily syntactically legal) path is rated lower than the best existing solution. Further processing on rejected hypotheses is cancelled. This operationalization is imperfect in that it ignores the possibility of "missing arcs," *i.e.*, words which may subsequently be predicted by the syntax module (added as arcs in the graph) and be rated high enough to invalidate previous decisions to reject earlier hypotheses.

The second heuristic is based on the observation that, if a better solution than the current best solution exists, it must be possible to construct it by extending some existing subpath (hypothesis) which is rated higher than the subpath of the existing solution spanning the same time interval. (Once again, the missing arc problem is ignored.) All hypotheses (subpaths) which do not have this property are deactivated, *i.e.*, incapacitated as active stimuli. Any scheduled inferential action based on a stimulus set of hypotheses is cancelled if all the hypotheses in the set are deactivated. This heuristic can be thought of as another form of alpha-beta pruning, modified to allow sharing of common subtrees in the search tree. Deactivating a subpath (hypothesis) amounts to deferring expansion of certain search tree nodes which correspond to extensions of that subpath.

The observed effect of these two heuristics is to cancel a large amount of scheduled processing once a solution is found, and to focus attention on those activities which are capable of leading to a better solution. When no such activities are left to pursue, RPOL halts processing, selects the highest-rated solution, and passes it to the semantics module to be interpreted.

Solutions and partial solutions

RPOL also halts processing when Hearsay-II exceeds predefined limits on size or execution time. In this case, RPOL chooses the highest-rated utterance-spanning phrasal hypothesis as its solution. If no such hypothesis has been generated, RPOL tries to extract a maximum of information from the blackboard by selecting the best partial parses (phrasal hypotheses) and passing them to the semantics module for further interpretation (Hayes-Roth, Fox, Gill, and Mostow, 1976). Here, the "best" phrase hypothesis H at time t is considered to be the hypothesis whose time interval includes t and which has the highest information content, defined by VLD(H) * length(H). RPOL finds the best hypothesis at each time t (measured in syllables from the beginning of the utterance), and passes the (typically small) set of such hypotheses to the semantics module. Thus even when Hearsay-II fails to find a complete solution, the best partial solution (set of partial interpretations) is found, and this information is used in determining the system's response to the utterance (Hayes-Roth, Gill, and Mostow, 1976).

Conclusions

The task of rating hypotheses in Hearsay-II is handled by the system policy module RPOL. The role of knowledge source modules in this task is limited to linking together hypotheses and specifying the implications with which lower hypotheses support upper hypotheses. Thus the effects of hypothesis rating changes due to new information are automatically propagated throughout the blackboard without requiring the help of the knowledge source modules. The centralized implementation of rating computation and propagation has made it easy to experiment with different rating formulas. It has also simplified the task of developing new knowledge source modules.

The uniform rating scheme employed permits the meaningful comparison of the plausibility of any two hypotheses. Validity ratings are used by Hearsay-II to focus processing, to prune the search, and to select the best solution or partial solution. In addition, hypothesis validity ratings are used by the knowledge source modules for plausibility tests which must be satisfied in order for various inferencing rules to be applied. Thus validity ratings help to guide processing in a best-first direction until a solution is found, and to validate it quickly thereafter as the best possible solution.

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Semantics and Pragmatics in Hearsay-II (Hayes-Roth, Fox, Gill, and Mostow)

A speech understanding system differs from a recognition system in two principal ways. First, an understanding system verifies that the sentences it hears are meaningful and plausible. This requires use of semantic knowledge. Second, the understanding system expects particular types of communication to occur in specific discourse contexts and interprets the sentences it recognizes accordingly. Such expectation and contextual interpretation requires pragmatic knowledge. The purpose of semantics and pragmatics knowledge sources is to convert this knowledge about meanings, intentions, and communication conventions into effective action. The most significant type of action is one that constrains the recognition process, a search for a plausible parse of the spoken utterance. The second most important type of action is to hypothesize what was intended, when what was said cannot fully be recognized. The last type of effective action needed is to interpret (deduce the intention) of a successfully parsed utterance.

The complexity of artificial spoken languages may be constrained by restricting either the way ideas are expressed (syntax) or the number of ideas that can be expressed (semantics). Our approach, in the news retrieval and computer science abstract retrieval tasks, has been to develop one comprehensive semantic grammar (average branching factor 50) used for interpretation of recognized word sequences and to vary systematically the syntactic con,traint of the languages used for speech recognition *per se* (branching factors 5, 15, 25). Regardless of the particular syntax used for recognition, the same general semantic grammar is used for semantic analysis. This grammar is a template grammar like those developed for Parry by Colby, with distinct templates for each unique type of semantic form (Colby, 1974; Hayes-Roth and Mostow, 1975). Semantic interpretation is accomplished by extracting from the (parse) tree of instantiated templates the particular words or expressions filling the various functional "slots."

Partially recognized sentences are also easily interpreted in this framework. When the attempt to recognize a complete sentence has failed, the best (longest and most highly rated) syntactic word sequences in each time area of the utterance are passed to semantic analysis. All templates fully or partially satisfied by word sequences are instantiated. The most fully matched semantic pattern is then chosen as the interpretation of the utterance. Thus, the recognized sequence "Newell or Simon" would be interpreted effectively as if "List all abstracts by Newell or Simon from any journal from any date" had been recognized.

The capacity to provide semantic constraint during recognition is determined primarily by the reliability of predictions regarding what the speaker is likely to say. We have implemented a discourse knowledge source including a conversation model that prompts the speaker with questions, provides information about using the system and the organization of the data base, and predicts the (semantic and syntactic) type of utterance next expected. Earlier versions of the syntax and semantics knowledge source biased recognition actions in favor of predicted communication forms. However, both because any valid sentence is permitted at any time and because the system is usually employed for isolated sentence understanding, no direct semantic bias is currently used. The basic scheme for such bias is, however, conceptually simple: given an expected type of utterance (a highest-level semantic template), recursively compute the expected lower-order subtemplates and, ultimately, the words and phrases that would instantiate the expected meaning templates. During recognition, priority is given to actions based on expected forms, at the expense of delayed processing of unexpected word sequences.

Conclusions

We have identified three types of actions to be performed by semantics and pragmatics knowledge sources: (1) bias recognition in favor of expected forms; (2) interpret semantically plausible, partial sequences; and (3) correctly interpret the intention of the speaker when a sentence is fully recognized. These actions are effected in Hearsay-II by combining semantic template grammars with a conversational model that anticipates the speaker's general intention and can enumerate its manner of expression. The realization of such actions, at least in restricted domains of discourse, can now be considered a well-understood technology.

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Discourse Analysis and Task Performance in Hearsay-II (Hayes-Roth, Gill, and Mostow)

The discourse analysis module (DISCO) in Hearsay-II uses knowledge about the state of the conversation to interpret the speaker's intention and to direct the appropriate actions within the task program. Usually, the intention of the speaker is to establish a general area of interest, to retrieve articles by keyword expression, to further qualify a keyword expression, to print selected articles, or to request certain information about the retrieved articles, such as title, date, author, author's affiliation, or publisher. The speaker can also ask for help or complain about the system's response.

The state of discourse is represented by the contents of several semantic registers, one of which points to a node in a finite state automaton discourse model. (See Figure 1.) Each node in the model corresponds to a general sentence pattern or template (Hayes-Roth, Fox, Gill, and Mostow, 1976). (See Figure 2.) Other registers hold the current menu (general area of interest), the most recent keyword expression, the article most recently referred to, the most recently retrieved articles, and the subset of retrieved articles which satisfy further qualifications specified by the speaker. The finite state model is used to interpret yes-or-no responses and partially-recognized utterances, and to make predictions about what the speaker is likely to say next. All possible transitions between nodes in the model are permitted; the arcs in the model indicate the transitions which are considered likely.

Figure 3 shows a sample interaction between DISCO and a speaker. Utterances enclosed in square brackets denote recognized spoken utterances. In the example shown, the first utterance

[WE'RE INTERESTED IN LEARNING]

is recognized by the semantics module as an instance of the $SELECTION template, and the semantic feature $LEARNING (indicated area of interest, or menu) is extracted. This semantic interpretation of the utterance is passed to DISCO, which records the indicated area of interest, LEARNING, in the MENU register, and sets the NODE register to point at the $SELECTION node in the finite state model. DISCO then predicts that the next utterance will be an instance of the $REQUEST template and will concern the area of LEARNING. These predictions can be used to bias subsequent processing to favor recognition of keywords in the LEARNING menu and function words characteristic of a $REQUEST (Hayes-Roth, Fox, Gill, and Mostow, 1976). Such predictions can also be used to respond gracefully in the case of a partially-recognized utterance (Hayes-Roth, Lesser, Mostow, and Erman, 1976). In the example, if the speaker's second utterance

[WERE ANY ARTICLES ON LEARNING WRITTEN IN MAY 1974]

were not fully recognized, DISCO would assume that the speaker had REQUESTed some articles about LEARNING and could ask him to repeat the request. If the utterance fragment "LEARNING WRITTEN IN MAY 1974" were recognized and interpreted by the semantics module, DISCO could retrieve articles on learning dated May, 1974.

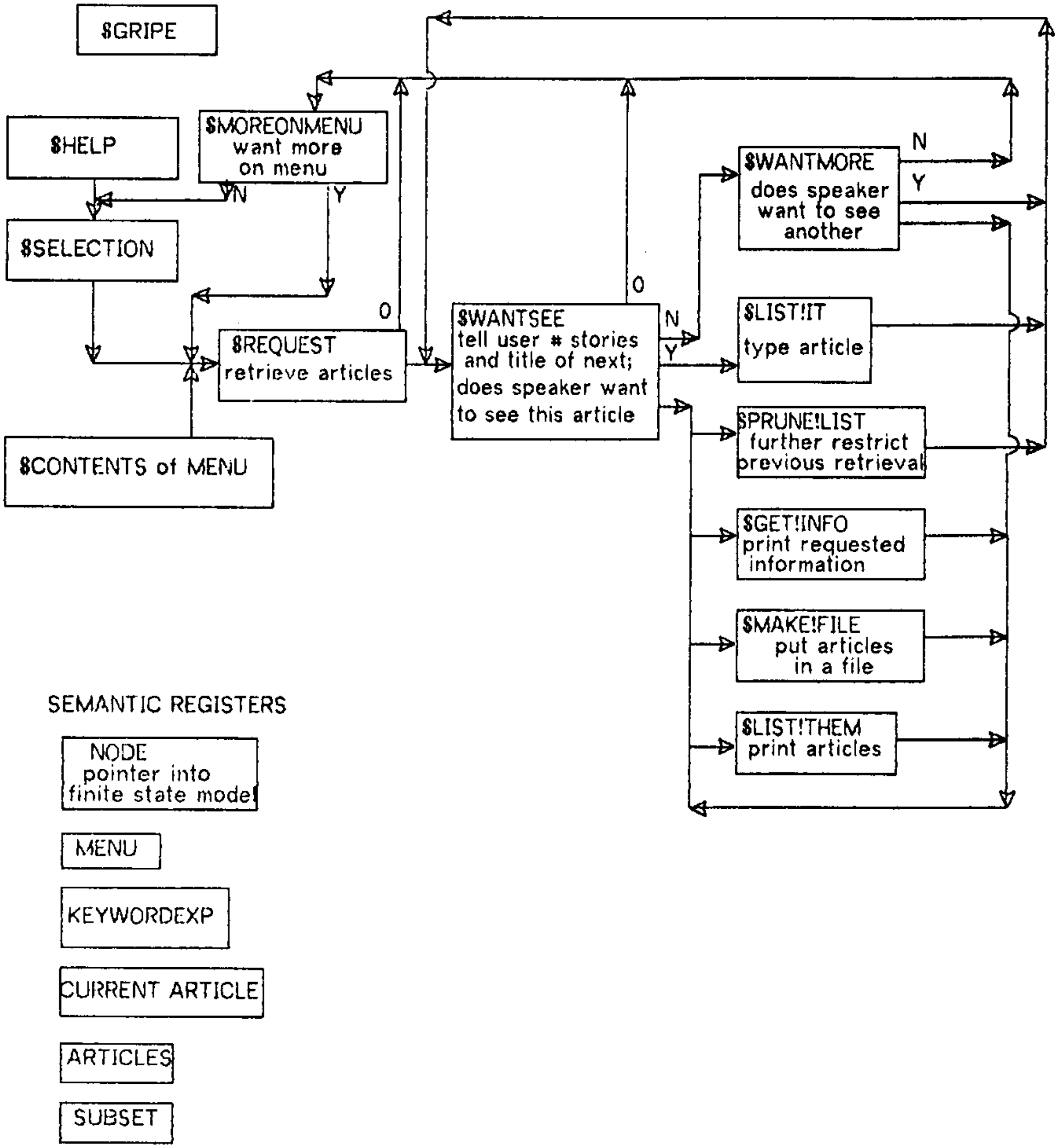

$GRIPE
$HELP
$MOREONMENU want more on menu
N
Y
$SELECTION
0
$REQUEST retrieve articles
$CONTENTS of MENU
$WANTSEE tell user # stories and title of next; does speaker want to see this article
0
N
Y
$WANTMORE does speaker want to see another
N
Y
$LIST!IT type article
$PRUNE!LIST further restrict previous retrieval
$GET!INFO print requested information
$MAKE!FILE put articles in a file
$LIST!THEM print articles
SEMANTIC REGISTERS
NODE pointer into finite state model
MENU
KEYWORDEXP
CURRENT ARTICLE
ARTICLES
SUBSET

Figure 1: Semantic registers and finite state discourse model.
labels Y and N indicate YES and NO responses;
0 indicates empty retrieval set.

$SELECTION [WE'RE INTERESTED IN LEARNING]
Specifies a menu. DISCO responds by printing keywords and phrases from the menu.

$REQUEST [WERE ANY ARTICLES ON LEARNING WRITTEN IN MAY 1974]
Specifies a set of articles. DISCO retrieves the articles and asks for further directions.

$PRUNE!LIST [WHICH OF THESE MENTION ROBOTS]
Further specifies a set of articles. DISCO removes articles from the currently retrieved set which don't satisfy the new restrictions.

$GET!INFO [WHO WROTE THESE]
Requests information about the retrieved articles. DISCO prints the requested information.

$LIST!THEM [PLEASE LIST THEM]
Requests output of a set of articles. DISCO prints all the articles in the currently retrieved set.

$LIST!IT [PRINT IT]
Requests output of a single article. DISCO prints the article most recently referred to.

$STOP!LISTING [STOP LISTING PLEASE]
Requests cessation of output. DISCO aborts the current output operation.

$MAKE!FILE [MAKE A FILE OF THESE PIECES]
Requests file output. DISCO creates a file containing the retrieved articles.

$CONTENTS!MENU [WHAT ARE THE KEYWORDS FOR LEARNING]
Requests the contents of a menu. DISCO lists the keywords and phrases of the menu.

$HELP [WHAT CAN I ASK]
Requests assistance or information about the system. DISCO attempts to fulfill the request.

$GRIPE [WHY ARE YOU SO SLOW]
Complaint. DISCO responds with a pacifying message.

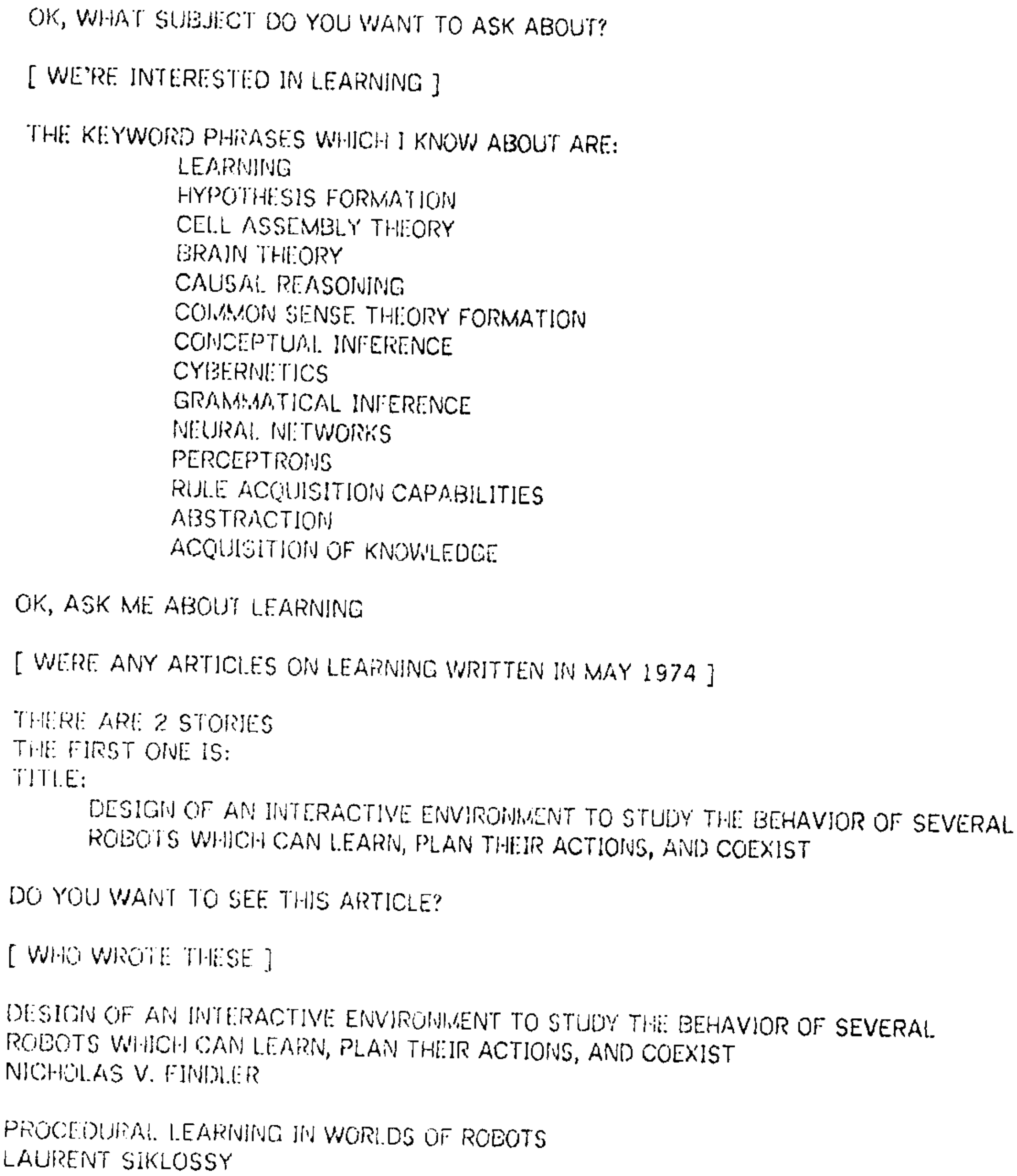
The following three nodes represent responses to yes-or-no questions asked by DISCO.

$WANTSEE
DISCO has printed the title of an article and asked, "Do you want to see this article?"

$WANTMORE
DISCO has printed some of the articles in the currently retrieved set and asked, "Do you want to see another of these articles?"

$MOREONMENU
DISCO has exhausted the currently retrieved set and asked, "Do you want to ask more about <current menu>?" where <current menu> is the most recent area of interest.

Figure 2. Templates corresponding to nodes in the finite state model.
Instances of templates are shown in square brackets.
Text describes the intention of each utterance template and DISCO's response to it.



```
OK, WHAT SUBJECT DO YOU WANT TO ASK ABOUT?

[ WE'RE INTERESTED IN LEARNING ]

THE KEYWORD PHRASES WHICH I KNOW ABOUT ARE:
            LEARNING
            HYPOTHESIS FORMATION
            CELL ASSEMBLY THEORY
            BRAIN THEORY
            CAUSAL REASONING
            COMMON SENSE THEORY FORMATION
            CONCEPTUAL INFERENCE
            CYBERNETICS
            GRAMMATICAL INFERENCE
            NEURAL NETWORKS
            PERCEPTRONS
            RULE ACQUISITION CAPABILITIES
            ABSTRACTION
            ACQUISITION OF KNOWLEDGE

OK, ASK ME ABOUT LEARNING

[ WERE ANY ARTICLES ON LEARNING WRITTEN IN MAY 1974 ]

THERE ARE 2 STORIES
THE FIRST ONE IS:
TITLE:
      DESIGN OF AN INTERACTIVE ENVIRONMENT TO STUDY THE BEHAVIOR OF SEVERAL
      ROBOTS WHICH CAN LEARN, PLAN THEIR ACTIONS, AND COEXIST

DO YOU WANT TO SEE THIS ARTICLE?

[ WHO WROTE THESE ]

DESIGN OF AN INTERACTIVE ENVIRONMENT TO STUDY THE BEHAVIOR OF SEVERAL
ROBOTS WHICH CAN LEARN, PLAN THEIR ACTIONS, AND COEXIST
NICHOLAS V. FINDLER

PROCEDURAL LEARNING IN WORLDS OF ROBOTS
LAURENT SIKLOSSY
```

Figure 3. Sample interaction between DISCO and speaker.
Spoken utterances are enclosed in square brackets.

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PARALLEL PROCESSING IN SPEECH UNDERSTANDING SYSTEMS

Parallelism in Artificial Intelligence Problem-solving (Lesser and Fennell)

Background

Many artificial intelligence problem-solving tasks require large amounts of processing power because of the size of the search space that needs to be examined during the course of problem solution. This is especially true for tasks that involve the interpretation of real-world perceptual data which is generally very noisy (i.e., speech and image understanding systems). For example, a speech-understanding system capable of reliably understanding connected speech involving a large vocabulary is likely to require from 10 to 100 million instructions per second of computing power, if the recognition is to be performed in real time. Recent trends in technology suggest that raw computing power of this magnitude can be economically obtained through a closely-coupled network of asynchronous "simple" processors. The major problem with using a network multiprocessor is in specifying the various problem-solving algorithms in such a way as to exhibit a structure appropriate for exploiting the available parallelism.

This restructuring of an artifiicial intelligence task for parallel processing may not be as difficult as might be expected. The basic problem-solving paradigm that is used to resolve ambiguities resulting from the error in input data and the imprecise and errorful nature of knowledge sources implicitly involve parallel activity. This parallel activity arises because many weakly supported alternative hypotheses must be "simultaneously" evaluated in order to locate a consistent hypothesis which is a solution to the problem. These problem-solving techniques are implemented through sophisticated control structures that (1) permit the selective searching (usually heuristic) of a large part of the state-space of possibilities and (2) allow the combining of multiple, diverse sources of knowledge (e.g., in the speech domain, acoustics, syntax, semantics, prosodics) so as to cooperate in resolving ambiguity [Reddy 76, Woods 74, and Lesser 75A]. The state-space searching in existing systems is implemented through backtracking control structures; these are basically sequential implementations of non-deterministic control structures. Thus, a large potential for parallelism arises from implementing these non-deterministic control structures in a parallel manner, i.e., searching different parts of the state space in parallel. In addition, if these diverse knowledge sources (KS's) can be made independent, there exists the potential for a proportional speed-up in the recognition process by executing them in parallel. Finally, there is the possibility of decomposing each knowledge source into separate parallel processes.

Summary of Current Research

In order to test the ease and effectiveness with which an artificial intelligence task could be structured for and executed on a multiprocessor, an organization for a knowledge-based artificial intelligence problem-solving system was developed which takes maximum advantage of any separability of the processing or date components available within that organization. Knowledge sources are intended to be largely independent and capable of adynchronous execution in the form of knowledge source processes. Overall system control is distributed and primarily data-directed, being based on events occurring in a globally shared data base. Such a problem-solving organization is believed to be particularly amenable to implementation in the hardware environment of a network of closely-coupled asynchronous processors which share a common memory. The Hearsay II speech-understanding system (HSII) [Lesser 75, Fennell 77, Erman 75], which has been developed using the techniques for system organization described above, has provided a context for evaluating the multiprocessing aspects of this system architecture.

Based on multiprocess simulations and implementation of these systems on the C.mmp multiprocessor, the following results were obtained [Fennell 75]:

1. There does exist extensive parallelism in the speech understanding task (e.g., given a small configuration of knowledge sources, between 4-14 processors could be effectively utilized).
2. The overheads involved in supporting the multiprocessing and synchronization primitives are quite high (e.g., over 100%).
3. The locking structures had to ve very carefully tailored to the particular set of knowledge sources; otherwise, the effective parallelism would be significantly degraded.

In trying to understand the implications of the last two results, some tentative observations were made. The first and somewhat surprising observation was that the basic self-correcting nature of the information flow in the HSII system, which comes from knowledge source cooperation through a hypothesize-and-test paradigm, may obviate the need for most uses of explicit synchronization techniques to maintain data integrity. To elaborate on this point, one knowledge source can correct the mistake of another knowledge source whether the error arises from a mistake in the theory behind the knowledge source or from incorrect synchronization (i.e., working on partially invalid data). Another example of this self-correcting type of computation structure is the relaxation method (iterative refinement) used to solve partial differential equations. This type of computational structure, when put on asynchronous multiprocessors, can be decomposed so as to avoid a lot of explicit synchronization at the expense of more cycles for convergence. This type of decomposition is accomplished by not requiring each point to be calculated based on the most up-to-date values of its neighboring points. The iterative refinement nature of computation will correct (within a certain range) for this lack of synchronization. It is felt the feed-forward/feed-backward data-directed problem-solving paradigm of HSII has similar properties. The other observation was that a drastic decrease in the cost of certain types of synchronization primitives could be accomplished if their implementation is tailored to their (statistical) usage.

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The HSII/C.mmp System (Lesser, Buchalter, McCracken, Robertson, and Suslick)

The HSII/C.mmp system has been developed to test whether an asynchronous multiprocess architecture such as C.mmp (16 PDP-11 processors sharing a common memory) can be effectively applied to speed up the higher level processing of a speech understanding system. Extensive simulation studies were done on a PDP-10 using a multiprocess version of Hearsay-II to test the feasibility of the idea before embarking on the actual implementation (Fennell and Lesser 1977).

A prototype version of this system written in L*, a system building language developed by Newell *et al.* 1970-71, was constructed and running in February of 1976. In addition, an algebraic-language interpreter, SL*, was constructed for executing knowledge sources written in an Algol dialect. However, the knowledge source modules were very primitive, and no substantial results were obtained except the measurement of the overhead of certain Hearsay-II primitives. As a result of these measurements, a reimplementation was begun in order to significantly speed up the system (especially those system primitives which deal with synchronization operations), and to make it possible to run large knowledge source modules in the small address space environment that the PDP-11 provides. This reimplementation is now almost complete, with preliminary results indicating a speed-up of approximately 10 over the original version. In addition, a translator has been developed which takes most PDP-10 statements written in SAIL and translates them into equivalent SL* statements. Thus, it should be possible in the next few months to run, without major code conversion, the knowledge source modules of the PDP-10 Hearsay-II system on the HSII/C.mmp system.

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A Parallel Production System for Speech Understanding (McCracken)

The question addressed by this thesis (McCracken 1977) is whether or not a production system architecture[1] can remedy some of the chronic problems of knowledge representation and system organization in large knowledge-based artificial intelligence systems, particularly speech understanding systems. Of particular interest is the problem of exploiting parallel machine architectures to obtain near real-time response. To explore this question, a production system version of the Hearsay-II speech understanding system, called HSP, for HearSay Production system, is being implemented on C.mmp, the CMU multi-mini-processor. A large fraction of the Hearsay-II speech knowledge has been translated into productions for HSP, specifically: POMOW (word recognizer), POSSE-WOMOS (word verifier) and SASS (syntax and semantics)[2].

Expected results come under two main categories: comparisons between the way knowledge is encoded in HSP versus Hearsay-II, and comparisons in the use of parallelism. The major differences between the HSP and Hearsay-II architectures are: (1) the basic knowledge unit in HSP, a production, is considerably smaller than a Hearsay-II Knowledge Source ; (2) HSP encodes knowledge in a more formal and simple, but less expressive, language than Hearsay-II; (3) HSP totally segregates condition from action (i.e., read from write), while Hearsay-II allows a mixture; and (4) there is virtually no use of local working memory in HSP (only a single shared working memory), whereas Hearsay-II knowledge sources make use of rather large local data contexts in addition to the shared Blackboard. It is expected that these architectural differences will yield an improvement for HSP in effective parallelism, in clarity of knowledge, in ease of augmentation, and in other problem areas, such as handling of error, directionality control, and performance analysis.

[1] A production system encodes all long-term knowledge as simple condition-action rules which operate from a shared working memory. For entry into the subject see: R. Davis and J. King, An Overview of Production Systems, Computer Science Department, Stanford University, Oct. 1975.

[2] POSSE, WOMOS, and the version of SASS used are from an earlier version of Hearsay-II used in the Spring of 1972.

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III. PERFORMANCE MEASUREMENT

In this section we present the detailed performance results obtained for the Harpy and Hearsay-II systems in September of 1976. Since then both systems have been improved; future papers will provide results of improved performance. The purpose of this section is to provide a record of system performance as measured on September 8, 1976.

In addition to the performance of the systems on the 1011-word tasks, this section also contains results of experiments on connected digit recognition, effect of telephone on accuracy, effect of multiple speakers (using speaker independent templates) on accuracy, and effects of branching factor and vocabulary size on the performance of the Harpy system.

Performance of the Harpy and Hearsay-II Systems

Figure 1 gives the performance of the Harpy system on the 1011-word AI abstract retrieval task. The vocabulary used in this task and the phone dictionary associated with the vocabulary is given in Appendix III-B.

Given the vocabulary and protocols taken of humans interacting with a mock system, Hayes-Roth generated a set of typical sentences that are likely to be useful in the abstract retrieval task. No attempt was made to restrict these to any specific grammar. However, care was taken to see that each word in the vocabulary occured at least once in these sentences. These sentences (a total of 496) served two purposes: 1) as a set of training sentences (spoken by Lee Erman), and 2) for the design of a family of languages with varying branching factors that accept at least the training sentences and possibly many more.

Goodman designed many such languages. Two extreme examples are a language where any word (of the 1011) could follow any other word, permitting many nonsense sentences, and another in which only the 496 training sentences were legal. Of the several languages chosen for the experimentation, three specific ones--AIX05, AIX15, and AIXF--are given in Appendix III-C (an earlier version of AIXF was developed by Hayes-Roth).

The grammar that allowed Harpy to reach the performance goals of the ARPA program was AIX05, with a static branching factor of 9.53 and an average dynamic fanout of 33.4. The others were too large to fit within the memory of the PDP-10 system. However, it was possible to study the performance of AIX15 and AIXF using variants which used smaller vocabularies, created by eliminating some of the proper nouns.

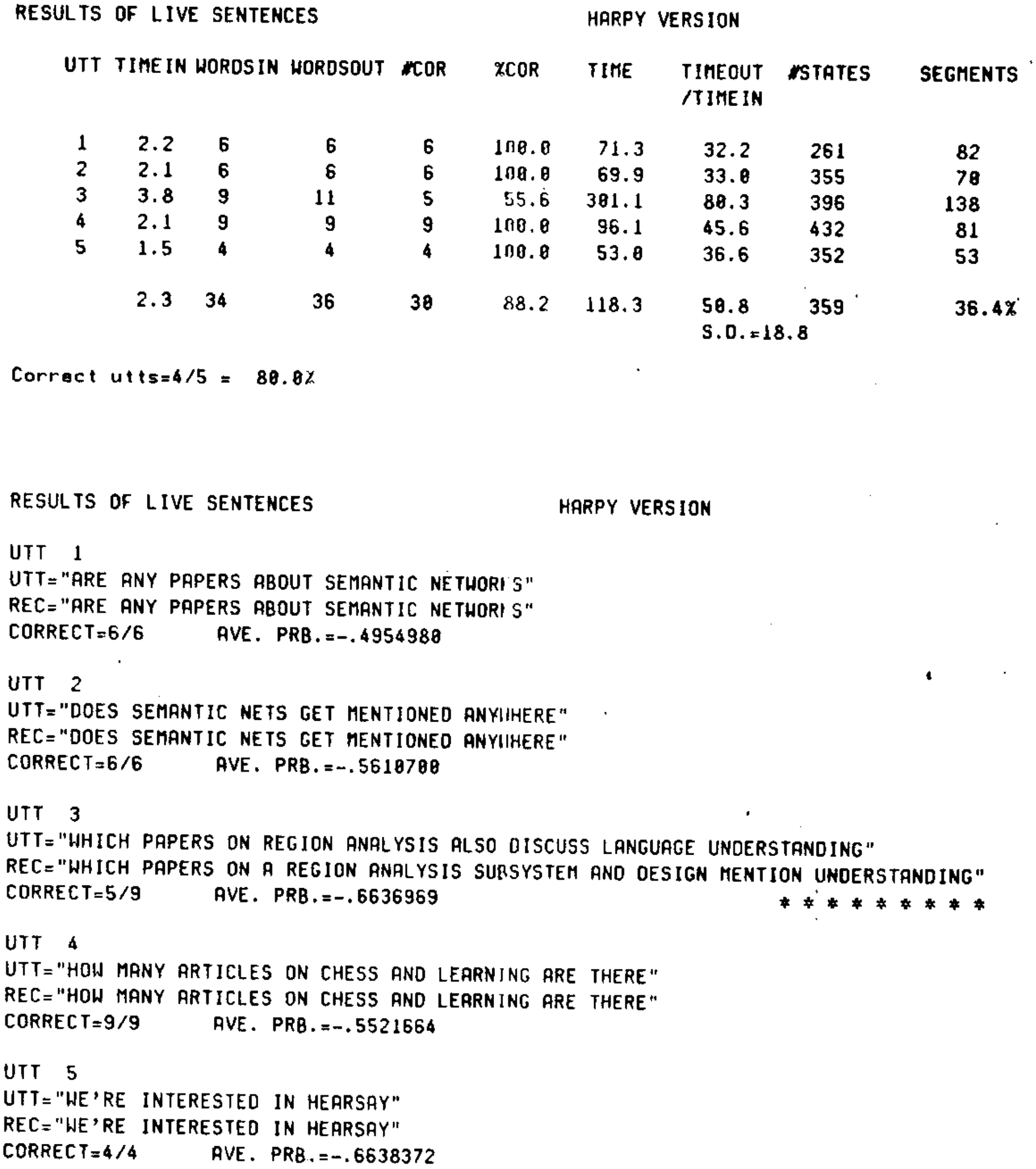
The training sets for the other four speakers (two male and two female) consisted of a small subset of the original training sentences. These were used to generate speaker-dependent phone templates for each of the speakers (see the paper by Lowerre in Section IV on speaker adaptation).

A completely new set of 100 test sentences was created by Hayes-Roth which were not part of the training set. These are given in Appendix III-A. Erman recorded all the 100 test sentences and the other four speakers recorded a subset of twenty one sentences each. These sentences were used only for testing the performance of the system; the system was not tuned in any way in response to errors in this set.

The Harpy system achieved an aggregate 91% sentence accuracy and 95% semantic accuracy over all the 5 speakers and required 27.9 million instructions per second of speech processed (Fig. 1). Hearsay-II (Fig. 3) was tested on only twenty two sentences for lack of time and achieved 91% semantic accuracy and required about 85 mipss. Figures 2 and 4 give the performance of the two systems on test sentences recorded live in the classroom on September 8. The Harpy system recognized four of the five sentences recorded by two male and one female speaker correctly. The Hearsay-II system recognized three of the five. These sentences were generated by the observers who were given copies of the grammar; the sentences were in no way preselected. The classroom environment was somewhat more noisy than the terminal room environment normally used to collect training data.

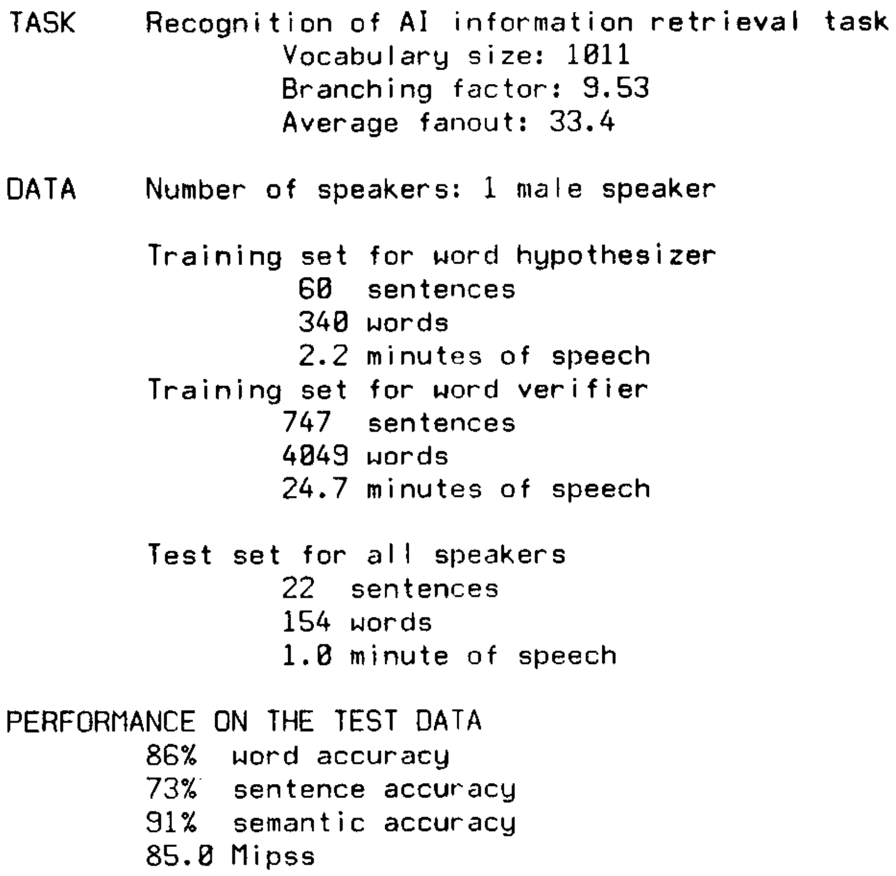
```
TASK
        Recognition of AI information retrieval task
                Vocabulary size: 1011
                Branching factor: 9.53
                Average fanout: 33.4

DATA
        Number of speakers: 5
                3 male
                2 female
        Training set for speaker LE
                496  sentences
                4049 words
                24.7 minutes of speech
        Training set for speakers DS KP BH CW
                256  sentences
                1444 words
                10.1 minutes of speech

        Test set for all speakers
                184  sentences
                1138 words
                6.5  minutes of speech

PERFORMANCE ON THE TEST DATA
        97%  word accuracy
        91%  sentence accuracy
        95%  semantic accuracy
        27.9 Mipss
```

Figure 1. Harpy results for the AI retrieval task test data.



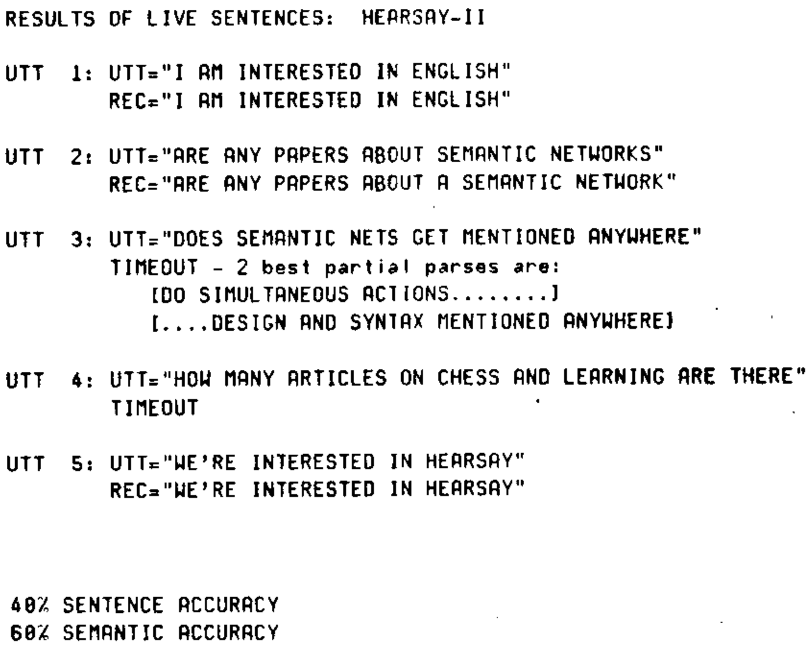
```
RESULTS OF LIVE SENTENCES                              HARPY VERSION

   UTT TIMEIN WORDSIN WORDSOUT #COR    %COR    TIME    TIMEOUT  #STATES    SEGMENTS
                                                       /TIMEIN

    1    2.2    6        6       6     100.0    71.3     32.2     261         82
    2    2.1    6        6       6     100.0    69.9     33.0     355         70
    3    3.8    9       11       5      55.6   301.1     80.3     396        138
    4    2.1    9        9       9     100.0    96.1     45.6     432         81
    5    1.5    4        4       4     100.0    53.0     36.6     352         53

         2.3   34       36      30      88.2   118.3     50.8     359        36.4%
                                                         S.D.=18.8

Correct utts=4/5 =  80.0%


RESULTS OF LIVE SENTENCES                           HARPY VERSION

UTT  1
UTT="ARE ANY PAPERS ABOUT SEMANTIC NETWORKS"
REC="ARE ANY PAPERS ABOUT SEMANTIC NETWORKS"
CORRECT=6/6       AVE. PRB.=-.4954980

UTT  2
UTT="DOES SEMANTIC NETS GET MENTIONED ANYWHERE"
REC="DOES SEMANTIC NETS GET MENTIONED ANYWHERE"
CORRECT=6/6       AVE. PRB.=-.5610700

UTT  3
UTT="WHICH PAPERS ON REGION ANALYSIS ALSO DISCUSS LANGUAGE UNDERSTANDING"
REC="WHICH PAPERS ON A REGION ANALYSIS SUBSYSTEM AND DESIGN MENTION UNDERSTANDING"
CORRECT=5/9       AVE. PRB.=-.6636969                                   * * * * * * * * * *

UTT  4
UTT="HOW MANY ARTICLES ON CHESS AND LEARNING ARE THERE"
REC="HOW MANY ARTICLES ON CHESS AND LEARNING ARE THERE"
CORRECT=9/9       AVE. PRB.=-.5521664

UTT  5
UTT="WE'RE INTERESTED IN HEARSAY"
REC="WE'RE INTERESTED IN HEARSAY"
CORRECT=4/4       AVE. PRB.=-.6638372
```

Figure 2. Harpy results for the live demonstration, 8 September 1976.



```
TASK     Recognition of AI information retrieval task
                 Vocabulary size: 1011
                 Branching factor: 9.53
                 Average fanout: 33.4

DATA     Number of speakers: 1 male speaker

         Training set for word hypothesizer
                  60  sentences
                  340 words
                  2.2 minutes of speech
         Training set for word verifier
                 747  sentences
                 4049 words
                 24.7 minutes of speech

         Test set for all speakers
                 22  sentences
                 154 words
                 1.0 minute of speech

PERFORMANCE ON THE TEST DATA
         86%  word accuracy
         73%  sentence accuracy
         91%  semantic accuracy
         85.0 Mipss
```

Figure 3. Hearsay-II results for the AI retrieval task test data.



```
RESULTS OF LIVE SENTENCES:  HEARSAY-II

UTT  1: UTT="I AM INTERESTED IN ENGLISH"
        REC="I AM INTERESTED IN ENGLISH"

UTT  2: UTT="ARE ANY PAPERS ABOUT SEMANTIC NETWORKS"
        REC="ARE ANY PAPERS ABOUT A SEMANTIC NETWORK"

UTT  3: UTT="DOES SEMANTIC NETS GET MENTIONED ANYWHERE"
        TIMEOUT - 2 best partial parses are:
           [DO SIMULTANEOUS ACTIONS........]
           [....DESIGN AND SYNTAX MENTIONED ANYWHERE]

UTT  4: UTT="HOW MANY ARTICLES ON CHESS AND LEARNING ARE THERE"
        TIMEOUT

UTT  5: UTT="WE'RE INTERESTED IN HEARSAY"
        REC="WE'RE INTERESTED IN HEARSAY"


40% SENTENCE ACCURACY
60% SEMANTIC ACCURACY
```

Figure 4. Hearsay-II results for the live demonstration, 8 September 1976.

Connected Digit Recognition using Symbolic Representation of Pronunciation Variability (Goodman, Lowerre, Reddy, and Scelza)

Most connected speech recognition systems, such as Harpy and Hearsay-II, use some form of symbolic representation to represent alternative pronunciations of the vocabulary, whereas most isolated word recognition systems use word templates. In an attempt to compare relative performance of systems that use symbolic representations of words, the Harpy system was run on four tasks requiring the recognition of random sequences of digits. Recording was in a computer terminal room environment (approximately 60 dBA) with speakers recording one session per day in order to include as much intra-speaker variability as possible. Both male and female speakers were used.

3-Digits Task

This task was selected as a typical numerical data input task. Sentences are connected sequences of three digits, such as "zero three eight". Each of ten speakers spoke thirty training sentences and 100 test sentences over a period of three weeks. Using speaker-specific phoneme templates, the word error rate over all ten speakers was about 2%.

7-Digits Task

This task, sometimes refered to as the "telephone number task", consists of connected seven digit sequences such as "seven three nine six one seven three". This task was selected as a benchmark. Error rate for the single speaker was 1%.

Telephone Input Task

Sentences are three digit connected sequences, as in the 3-digits task. Recordings were taken over telephone lines in order to determine the effects of restricted frequency response, distortion, envelope delay, etc. The error rate under these conditions was 7%.

Speaker Independent Task

This task is similar to the 3-digits task. However, recognition is performed using speaker-independent phoneme templates computed from the training data for all speakers. The word error rate was about 7% on test data of 1200 random three-digit sequences from twenty speakers, including ten new speakers.

A summary of the results for these tasks is shown in the accompanying tables. The total test data are 2700 sentences, representing more than an hour of recorded speech. While this is already a large amount of data, a more extensive and thorough study is to be initiated.

TASK	3-Digit	7-Digit	Telephone	Speaker-Independent
Vocabulary Size	10	10	10	10
Branching Factor	10	10	10	10
No. of Speakers	10	1	4	20
Male	7	1	3	14
Female	3		1	6
Training Set				
No. of Sentences	300	30	120	300
No. of Words	900	210	360	900
Mins. of Speech	7.5	1.4	3.1	7.6
Words/minute	120	150	116	118
Test Set				
No. of Sentences	1000	100	400	1200
No. of Words	3000	700	1200	3600
Mins. of Speech	25.1	4.8	10.3	33.0
Words/minute	120	146	117	109
Performance on Test Data				
%Word Accuracy	98	99	93	93
%Sent.Accuracy	96	96	82	83
Mipss	3.5	3.5	3.5	3.5

Effects of Branching Factor and Vocabulary Size on Performance (Goodman, Lowerre, and Reddy)

Analysis

Analysis of the languages of a given set of recognition tasks permits the comparison of the relative difficulties of the tasks. We have developed notions of equivalent vocabulary size, branching factor, effective branching factor, search space size, and search space reduction (Goodman 1976). All of these are useful as relative comparison measure.

Design

A family of languages having varying characteristics is required in order to be able to compare language measures with actual performance data. Such a family has been generated for the AI abstract retrieval task by interactive grammatical inference. There are four subfamilies for each of the (approx.) vocabulary sizes 250, 500, 750, and 1000 words. Several grammars representing differing branching factors exist within each subfamily. With the 250 word grammar, for instance, the available branching factors are 1.23, 3.87, 4.6, 8.2, 8.8, 11.9, 33.3, and 39.5.

Results

The relationships between accuracy and speed versus branching factor and vocabulary size are summarized in the accompanying tables. As expected, there is positive correlation in all cases. In the case of speed versus branching factor, the relationship is almost linear. A more comprehensive study of measures for grammatical complexity and their predictive abilities is necessary before any significance can be attached to these preliminary results.

Table I. Effects of branching factor on error rates of the Harpy system within the 250 word family of grammars.

		STATIC	
		BRANCHING	ERROR
GRAMMAR	MIPSS	FACTOR	RATE
AIS06	6.63	4.6	0%
AIS10	9.36	8.2	4%
AIS15	13.65	11.9	6%
AIS30	44.72	33.3	16%
AIS40	59.15	39.5	16%

Table II. Speed versus vocabulary size for Harpy when branching factor is held constant (approx. 10).

		BRANCHING	
GRAMMAR	MIPSS	FACTOR	VOCABULARY SIZE (APPROX)
AIS10	9.36	8.2	250
AIM12	16.77	10.5	500
AIX05	26.00	9.5	1000

References

R. G. Goodman (1976). "Analysis of languages for mån-machine voice communication," Ph.D. dissertation., Comp. Sci. Dept., Stanford Univ., Tech. Rept. Comp. Sci. Dept., C-MU, Pittsburgh, Pa.

APPENDICES for Section III

Appendix III-A lists the 100 test sentences used by the Harpy and Hearsay-II systems, along with characteristics measuring their complexity relative to several grammars.

Appendix III-B is the phonetic dictionary for the 1011 words used in the AI retrieval language.

Appendix III-C contains the complete definition of three of the grammars (AIXF, AIX15, and AIX05) used in testing the systems. These grammars have become standards for future development and testing. AIXF was not used to test Harpy because the network was too large to be generated.

Appendix III-A. Characteristics of the AI Retrieval Task sentences

Below is a description of the test sentences used for the Harpy and Hearsay-II systems. The September Hearsay-II results used 22 of the sentences randomly selected from the 100. The entire set of 100 was used for the 100 single-speaker test sentences for Harpy, and 21 of them were used for the other four speakers tested on Harpy.

CMU Test Sentences

The branching factors previously given for the languages used by the CMU speech understanding systems (HARPY and Hearsay-II) are "static" branching factors (SBF) (as derived by Gary Goodman and described in his recent thesis). Intuitively, they can be thought of as being derived by doing a Monte Carlo probing of a network describing all acceptable word sequences and taking the average of the number of words possible following any legal initial sequence. Other groups have generated somewhat similar numbers.

What we present here is a characterization of the lexical fanout allowed by our grammars for the particular test sentences. The notion is to calculate the average fanout for each sentence-initial sequence of words (i.e., going left-to-right).

The method used here is the following: For any sequence of words, denote by Word Branches (WB) the number of words that may legally follow that sequence in the given language. Consider a sentence of length N-1 words to have N WB's -- each is calculated from the initial sequence of i words, i=0,1...N. (I.e., the first WB for any sentence is always the same -- the number of legal first words.) Then, for any sentence or collection of sentences, the Average Fanout (AF) is the arithmetic mean of the WB's of the sentence(s).

The languages used (all defined using the same 1011-word vocabulary) are called AIX05, AIX15, and AIXF. The first two have static branching factors of 10 and 28, respectively. This summary is over 100 test sentences containing a total of 683 words.

	AF			
AIX05	AIX15	AIXF	sents	words/sent
33.4	46.5	68.0	100	6.83 (average over all)
17.3	26.0	33.4	2	3
31.3	45.4	84.0	10	4
36.1	50.7	73.0	11	5
29.7	41.5	60.3	21	6
33.6	47.0	70.2	24	7
37.2	51.1	70.3	15	8
30.1	40.5	63.0	9	9
42.3	61.5	70.8	3	10
42.8	57.9	76.3	3	11
21.2	29.9	53.4	2	12

The 100 sentences, presented with fanouts according to the AIX05 language.

```
[ 66 DO 6 ANY 6 OF 3 THESE 3 MENTION 192 PSYCHOLOGY 3  words=6
        AF=39.857
[ 66 WHICH 21 COGNITIVE 1 PSYCHOLOGY 2 CONTAINED 192 WINOGRAD'S 1
        ARTICLE 1  words=6 AF=40.571
[ 66 WHAT 26 TOPICS 1 ARE 1 RELATED 1 TO 192 SEMANTIC 2 NETWORKS 3 .
         words=7 AF=36.500
[ 66 DOES 196 PATTERN 3 DIRECTED 1 FUNCTION 1 INVOCATION 3 GET 2
        DISCUSSED 1 ANYWHERE 1  words=8 AF=30.444
[ 66 WHICH 21 TITLES 1 CONTAIN 1 THE 1 PHRASE 192 TIME 2 COMPLEXITY 3
         words=7 AF=35.875
[ 66 DOES 196 THAT 1 ARTICLE 1 MENTION 192 TIME 2 OR 1 SPACE 1 BOUNDS
        3  words=8 AF=51.444
[ 66 WHICH 21 OF 2 THEM 1 DISCUSSES 192 EVALUATION 1 FUNCTIONS 3
         words=6 AF=40.857
[ 66 ARE 292 THERE 2 ANY 5 ABSTRACTS 1 WHICH 1 REFER 1 TO 192 PAPERS
        1 BY 96 NEWELL 3  words=10 AF=60.000
[ 66 WHERE 5 IS 192 PREDICATE 1 CALCULUS 3 MENTIONED 1  words=5
        AF=44.667
[ 66 WHAT 26 ARE 3 SOME 1 OF 1 THE 1 AREAS 1 OF 192 ARTIFICIAL 1
        INTELLIGENCE 3  words=9 AF=29.500
[ 66 WHAT 26 WAS 1 ITS 1 TITLE 1  words=4 AF=19.000
[ 66 WHO 5 WAS 2 THE 1 AUTHOR 1  words=4 AF=15.000
[ 66 WHERE 5 DOES 1 HE 1 WORK 1  words=4 AF=14.800
[ 66 WHAT 26 IS 4 HER 1 AFFILIATION 1  words=4 AF=19.600
[ 66 WHAT 26 ADDRESS 1 IS 1 GIVEN 1 FOR 1 THE 1 AUTHORS 1  words=7
        AF=12.250
[ 66 HOW 4 MANY 8 REFERENCES 1 ARE 1 GIVEN 1  words=5 AF=13.500
[ 66 PLEASE 4 LIST 1 THE 1 AUTHORS 1  words=4 AF=14.600
[ 66 PLEASE 4 MAKE 1 ME 1 A 1 FILE 1 OF 1 THOSE 1  words=7 AF=9.500
[ 66 CAN 2 I 1 HAVE 1 THESE 1 ABSTRACTS 1 LISTED 1  words=6 AF=10.429
[ 66 ARE 292 ANY 6 ARTICLES 2 ABOUT 192 STRUCTURED 1 PATTERN 1
        RECOGNITION 3  words=7 AF=70.375
[ 66 DO 6 ANY 6 OF 3 THE 1 ABSTRACTS 1 MENTION 192 LEARNING 3
         words=7 AF=34.750
[ 66 HOW 4 MANY 8 OF 1 THESE 1 ALSO 1 DISCUSS 192 ABSTRACTION 3
         words=7 AF=34.500
[ 66 WHICH 21 PAPERS 7 ON 192 LANGUAGE 6 UNDERSTANDING 4 ARE 1 ABOUT
        192 ENGLISH 3  words=8 AF=54.667
[ 66 DO 6 ANY 6 PAPERS 5 ON 192 AUTOMATIC 7 PROGRAMMING 3 EXIST 1
         words=7 AF=35.750
[ 66 WHAT 26 ABOUT 288 PROGRAM 1 VERIFICATION 3  words=4 AF=76.800
[ 66 I 2 AM 2 INTERESTED 1 IN 192 ARTIFICIAL 1 INTELLIGENCE 3
         words=6 AF=38.143
[ 66 THE 3 AREA 2 I 1 AM 1 INTERESTED 1 IN 1 IS 192 UNDERSTANDING 3
         words=8 AF=30.000
[ 66 DON'T 1 GET 1 ME 1 ANY 1 ARTICLES 1 WHICH 1 MENTION 192 GAME 2
        PLAYING 3  words=9 AF=26.900
[ 66 I 2 AM 2 ONLY 1 INTERESTED 1 IN 1 PAPERS 1 ON 192 CHESS 4
```

```
          words=8 AF=30.000
[ 66 LET'S 1 RESTRICT 1 OUR 1 ATTENTION 1 TO 1 PAPERS 1 SINCE 1
         NINETEEN 1 SEVENTY 1 FOUR 1  words=10 AF=6.909
[ 66 DO 6 ANY 6 PAPERS 5 THIS 1 YEAR 1 CITE 96 ROSENFELD 3  words=7
         AF=23.000
[ 66 ARE 292 COMPUTER 7 NETWORKS 4 MENTIONED 2 ANYWHERE 1  words=5
         AF=62.000
[ 66 ARE 292 ANY 6 ARTICLES 2 ABOUT 192 GRAIN 1 OF 1 COMPUTATION 3
          words=7 AF=70.375
[ 66 ARE 292 ANY 6 ARTICLES 2 BY 96 ROSENFELD 3  words=5 AF=77.500
[ 66 ARE 292 ANY 6 BY 96 FEIGENBAUM 3 AND 96 FELDMAN 1  words=6
         AF=80.000
[ 66 ARE 292 THERE 2 ANY 5 ABSTRACTS 1 WHICH 1 REFER 1 TO 192 PAPERS
         1 BY 96 HOLLAND 3  words=10 AF=60.000
[ 66 ARE 292 THERE 2 ANY 5 NEW 2 PAPERS 1 ON 192 PROGRAM 1
         VERIFICATION 3  words=8 AF=62.667
[ 66 DO 6 ANY 6 OF 3 THESE 3 ALSO 2 MENTION 192 PLANNER-LIKE 1
         LANGUAGES 3  words=8 AF=31.333
[ 66 DOES 196 PROBLEM 1 SOLVING 3 GET 2 MENTIONED 1 ANYWHERE 1
          words=6 AF=38.571
[ 66 WHICH 21 PAPERS 7 CITE 96 NEWELL 3 AND 96 SIMON 1  words=6
         AF=41.429
[ 66 ANY 1 ABSTRACTS 1 REFERRING 1 TO 192 AI 4 OR 191 ARTIFICIAL 1
         INTELLIGENCE 1  words=8 AF=50.889
[ 66 ARE 292 ASSOCIATIVE 2 MEMORIES 4 DISCUSSED 1 IN 1 RECENT 1
         JOURNALS 1  words=7 AF=46.000
[ 66 ARE 292 LEARNING 4 AND 191 NEURAL 1 NETWORKS 2 MENTIONED 2
         ANYWHERE 1  words=7 AF=69.875
[ 66 DID 99 REDDY 5 PRESENT 2 A 1 PAPER 1 AT 2 IJCAI 1  words=7
         AF=22.125
[ 66 DIDN'T 1 THAT 1 PAPER 1 QUOTE 96 DREYFUS 3  words=5 AF=28.000
[ 66 DOES 196 PICTURE 1 RECOGNITION 3 GET 2 MENTIONED 1 ANYWHERE 1
          words=6 AF=38.571
[ 66 GET 1 ME 2 EVERYTHING 1 ON 192 DYNAMIC 3 CLUSTERING 3  words=6
         AF=38.286
[ 66 GENERATE 1 A 1 COPY 1 OF 1 THOSE 1  words=5 AF=11.833
[ 66 GIVE 2 ME 4 THE 1 DATE 1 OF 1 THAT 1 ABSTRACT 1  words=7
         AF=9.625
[ 66 HOW 4 CAN 1 I 1 USE 1 THE 1 SYSTEM 1 EFFICIENTLY 1  words=7
         AF=9.500
[ 66 I 2 AM 2 INTERESTED 1 IN 192 LEARNING 3  words=5 AF=44.333
[ 66 I'D 1 LIKE 1 TO 2 SEE 1 THE 1 MENUS 1  words=6 AF=10.429
[ 66 SELECT 1 FROM 1 ARTICLES 1 ON 192 GAME 2 PLAYING 3  words=6
         AF=38.000
[ 66 WHAT 26 ADDRESSES 1 ARE 1 GIVEN 1 FOR 1 THE 1 AUTHORS 1  words=7
         AF=12.250
[ 66 WHAT 26 PAPERS 1 ON 192 PREFERENTIAL 1 SEMANTICS 3 ARE 1 THERE 1
          words=7 AF=36.375
[ 66 WHEN 3 WAS 194 A 20 SEMANTIC 1 NETWORK 3 LAST 2 REFERRED 1 TO 1
          words=8 AF=32.333
```

```
[ 66 WHICH 21 PAPERS 7 CITE 96 FELDMAN 3  words=4 AF=38.600
[ 66 WHO 5 HAS 1 WRITTEN 1 ABOUT 192 AUTOMATIC 7 PROGRAMMING 3
           words=6 AF=39.286
[ 66 WHO 5 WAS 2 QUOTED 1 IN 1 THAT 1 ARTICLE 1  words=6 AF=11.000
[ 66 WHICH 21 IS 1 THE 1 OLDEST 1  words=4 AF=18.000
[ 66 ARE 292 ANY 6 NEW 1 BOOKS 1 BY 96 TERRY 1 WINOGRAD 3  words=7
          AF=58.250
[ 66 CAN 2 I 1 HAVE 1 THESE 1 ABSTRACTS 1 LISTED 1  words=6 AF=10.429
[ 66 DID 99 CARL 1 HEWITT 5 PRESENT 2 A 1 PAPER 1 AT 2 THE 1 IFIP 1
          MEETINGS 1 IN 1 SEPTEMBER 1  words=12 AF=14.000
[ 66 DID 99 ANY 4 ACL 1 PAPERS 1 CITE 96 RICK 1 HAYES-ROTH 3  words=7
          AF=33.875
[ 66 DO 6 ANY 6 OF 3 THOSE 1 PAPERS 1 MENTION 192 AXIOMATIC 1
          SEMANTICS 3  words=8 AF=31.000
[ 66 DURING 1 WHAT 1 MONTHS 1 WERE 1 THEY 1 PUBLISHED 1  words=6
          AF=10.286
[ 66 HOW 4 MANY 8 RECENT 1 ISSUES 1 CONCERN 192 INVARIANCE 1 FOR 1
          PROBLEM 1 SOLVING 3  words=9 AF=27.800
[ 66 HOW 4 MANY 8 SUMMARIES 1 DISCUSS 192 KNOWLEDGE 2 BASED 1 SYSTEMS
          3  words=7 AF=34.625
[ 66 HAVE 97 ANY 2 NEW 1 PAPERS 1 BY 96 LEE 1 ERMAN 3 APPEARED 1
           words=8 AF=29.778
[ 66 I'D 1 LIKE 1 TO 2 KNOW 1 THE 1 PUBLISHERS 1 OF 1 THAT 1 STORY 1
           words=9 AF=7.600
[ 66 IS 290 HUMAN 3 BEHAVIOR 5 OR 191 HUMAN 3 MEMORY 3 DISCUSSED 2 IN
          1 A 1 RECENT 1 SUMMARY 1  words=11 AF=47.250
[ 66 LIST 2 THE 2 ABSTRACTS 1 BY 96 HERB 1 SIMON 3  words=6 AF=24.429
[ 66 WAS 290 ALLEN 2 NEWELL 3 CITED 2 IN 1 THAT 1 SUMMARY 1  words=7
          AF=45.750
[ 66 WHAT 26 ABOUT 288 ALLEN 2 COLLINS 3  words=4 AF=77.000
[ 66 WHERE 5 DID 1 THAT 1 ARTICLE 1 APPEAR 1  words=5 AF=12.500
[ 66 WHO 5 HAS 1 WRITTEN 1 ABOUT 192 LANGUAGE 6 COMPREHENSION 3 AND
          191 LANGUAGE 6 DESIGN 1  words=9 AF=47.200
[ 66 QUIT 1 LISTING 1 PLEASE 1  words=3 AF=17.250
[ 66 WEREN'T 1 SOME 1 ARTICLES 1 PUBLISHED 1 ON 192 GOAL 1 SEEKING 1
          COMPONENTS 3  words=8 AF=29.667
[ 66 WHAT 26 SORTS 1 OF 192 LANGUAGE 6 PRIMITIVES 3 ARE 1 WRITTEN 1
          UP 1  words=8 AF=33.000
[ 66 HASN'T 192 A 21 CURRENT 1 REPORT 1 ON 192 PRODUCTION 1 SYSTEMS 3
          BEEN 1 RELEASED 1  words=9 AF=47.900
[ 66 ARE 292 THERE 2 ANY 5 ISSUES 1 ABOUT 192 COOPERATING 1 SOURCES 1
          OF 1 KNOWLEDGE 3  words=9 AF=56.400
[ 66 DID 99 VIC 1 LESSER 5 PRESENT 2 PAPERS 1 AT 2 IFIP 1  words=7
          AF=22.125
[ 66 DID 99 ANYONE 1 PUBLISH 1 ABOUT 192 LARGE 1 DATA 1 BASES 3 IN 1
          COMMUNICATIONS 1 OF 1 THE 1 ACM 1  words=12 AF=28.385
[ 66 DO 6 ANY 6 AUTHORS 1 DESCRIBE 192 DRAGON 3  words=5 AF=45.667
[ 66 DOES 196 HE 1 WORK 1 AT 1 CMU 1  words=5 AF=44.333
[ 66 DO 6 ANY 6 RECENT 4 ACM 1 CONFERENCES 1 CONSIDER 192 SEMANTIC 2
          NETS 3 OR 191 SEMANTIC 2 NETWORKS 1  words=11 AF=39.583
```

```
[ 66 DO 6 RESPONSES 1 EVER 1 COME 1 FASTER 1  words=5 AF=12.667
[ 66 HAS 96 LEE 1 ERMAN 4 BEEN 1 REFERENCED 1 IN 1 ANY 1 OF 1 THOSE 1
          words=9 AF=17.300
[ 66 HAS 96 ALLEN 2 NEWELL 4 PUBLISHED 2 ANYTHING 1 RECENTLY 1
          words=6 AF=24.571
[ 66 HAVE 97 ANY 2 NEW 1 PAPERS 1 BY 96 TERRY 1 WINOGRAD 3 APPEARED 1
          words=8 AF=29.778
[ 66 HOW 4 BIG 1 IS 1 THE 1 DATA 1 BASE 1  words=6 AF=10.714
[ 66 HOW 4 MANY 8 OF 1 THESE 1 ALSO 1 DISCUSS 192 DYNAMIC 3 BINDING 3
          words=8 AF=31.000
[ 66 HOW 4 MANY 8 RECENT 1 ISSUES 1 CONCERN 192 DISPLAY 1 TERMINALS 3
          words=7 AF=34.500
[ 66 KILL 1 THE 1 LISTING 1  words=3 AF=17.250
[ 66 PLEASE 4 MAKE 1 ME 1 A 1 FILE 1 OF 1 THOSE 1  words=7 AF=9.500
[ 66 WHAT 26 IS 4 HIS 1 AFFILIATION 1  words=4 AF=19.600
[ 66 WHICH 21 OF 2 THESE 5 CITES 96 PERRY 1 THORNDYKE 3  words=6
         AF=27.714
[ 66 WHICH 21 PAPERS 7 ON 192 DESIGN 6 IN 1 THE 1 ARTS 4 ALSO 2
         DISCUSS 192 DESIGN 5 AUTOMATION 3  words=11 AF=41.667
[ 66 WHO 5 WAS 2 QUOTED 1 IN 1 THAT 1 ARTICLE 1  words=6 AF=11.000
[ 66 WHICH 21 PAPERS 7 WERE 1 WRITTEN 2 AT 1 NRL 1 OR 1 AT 1 SMC 1
          words=9 AF=10.200
```

Appendix III-B. AI Retrieval Language Dictionary

A	(-,0) (AX!,UH4!,EH4!,EYL EYC! EYR)
ABOUT	(-,0) (AH2,AX,EH3,0) (← (-,0),-{4}) (B,0) (AWL,0) AWC! (AWR,0) ((← (-,0),-{4}) (T,0),DX)
ABSTRACT	(-,0) AE3 (← (-,0),-) S (-,0) (DR (R,0),T R) AE2! ((← (-,0),-{4}) (T,0),DX)
ABSTRACTION	(-,0) AE3 (← (-,0),-) S (-,0) (DR (R,0),T R) AE2! (← (-,0),-) SH IH5 N
ABSTRACTS	(-,0) AE3 (← (-,0),-) S (-,0) (DR (R,0),T R) AE2! (← (-,0),-) S (HH,0)
ACL	(-,0) (EYL,0) EYC (EYR,0) S IY (EH EL,EL2)
ACM	(-,0) (EYL,0) EYC! (EYR,0) S IY AH2 M
ACQUISITION	(-,0) AE5 (← (-,0),-) WH IH! (Z{4},(Z,0) S) IH2 SH IH5 N
ACTIONS	(-,0) AE5 (← (-,0),-) SH! IH5 N (Z{4},(Z,0) S)
ACTIVE	(-,0) AE (← (-,0),-) T! IH V (F,0)
ACYCLIC	(-,0) (EYL,0) EYC (EYR,0) S IH3! (← (-,0),-{4}) (K,0) L UH2 (← (-,0),-{4}) (K,0)
ADAPTATION	(-,0) AE4 (← (-,0),-,D) (D,0) AE5 (← (-,0),-) T (EYL,0) EYC! (EYR,0) SH IH5 N
ADAPTIVE	(-,0) (IX,UH) (← (-,0),-) (D,0) AE (← (-,0),-) T IX V (F,0)
ADDITION	(-,0) IH3 ((← (-,0),-) (D,0),DX) IH3! SH IH5 N
ADDRESS	(-,0) ((AE,IX),UH) (← (-,0),-) DR R EH2! S (HH,0)
ADDRESSES	(-,0) ((AE,IX),UH) (← (-,0),-) DR R EH2! S IH4 (Z{4},(Z,0) S)
ADVISING	(-,0) (IX,UH) (← (-,0),-) (D,0) V (AYL,0) AYC! (AYR,0) (Z{4},(Z,0) S) (IH3,IY) NX
AESTHETICS	(-,0) AX S TH EH (← (-,0),-) T IH (← (-,0),-) S (HH,0)
AFFILIATION	(-,0) (EH3,AH) F (IH,0) EL IY (EYL,0) EYC! (EYR,0) SH IH5 N
AFFILIATIONS	(-,0) AX (-,0) F EH2 L IY2 (EYL,0) EYC! (EYR,0) SH IH5 N (Z{4},(Z,0) S)
AFTER	(-,0) AE! F ((← (-,0),-) T,DX) ER
AI	(-,0) (EYL,0) EYC! (EYR,0) (AYL,0) AYC (AYR,0)
ALGEBRAIC	(-,0) AE3 EL (← (-,0),-) SH{,8} IH (← (-,0),-{4}) (B,0) R (EYL,0) EYC (EYR,0) IH2 (← (-,0),-{4}) (K,0)
ALGOL	(-,0) AE4 EL (← (-,0),-) (G,0) OW3 EL3
ALGORITHM	(-,0) AE EL (← (-,0),-) (G,0) (AA,OW) R! IH (TH,DH) (IH,IX,0) M
ALGORITHMIC	(-,0) AE EL (← (-,0),-) (G,0) (AA,OW) R! IH (TH,DH) M IH (← (-,0),-{4}) (K,0)
ALL	(-,0) OW4! EL
ALL-OR-NONE	(-,0) OW4! EL (-,0) (AA4,0) ER2!{7,14} (-,0) N UH (N,DX)
ALLEN	(-,0) AE! EL3 (IH6 N,EN)
ALSO	(-,0) (AO,OW4) EL S (IH6 (OW2,0),OW)
ALWAYS	(-,0) AO EL W (EYL,0) EYC! (EYR,0) (Z{4},(Z,0) S)
AM	(-,0) ((EH2!,AE3!) M,EM!)
AMONG	(-,0) (IX!,AX!) M UH2 NX
AN	(-,0) AE5! (EN,N)
ANALOGY	(-,0) AE5 (N,EN) AE4! (EL,L) OW4 (← (-,0),-) SH{,8} IY
ANALYSIS	(-,0) UH4 N AE EL3! (UH2{2,6},IH6,0) S IH6 S (HH,0)
ANALYZER	(-,0) AE5 N EL2 (AYL,0) AYC! (AYR,0) (Z{4},(Z,0) S) ER2
AND	(-,0) AE5!{5,10} N (← (-,0),-,0) (D,0)
ANN	(-,0) AE4! (N,DX)
ANOTHER	(-,0) AH N AA2! (DH,TH) (ER,AA2)
ANSWER	(-,0) AE5! N S ER
ANSWERING	(-,0) AE4 N S! (R,ER) IH5 NX
ANTHONY	(-,0) AE4 (N,←) (← (-,0),-,0) TH IH4! N IY
ANY	(-,0) (EH3,EH) (N{2},DX) IY! (IY3,0)
ANYONE	(-,0) (EH3,EH) (N{2},DX) IY! (IY3,0) (-,0) W AH (N,DX)
ANYTHING	(-,0) (EH3,EH) (N{2},DX) IY! TH (IH3,IY) NX
ANYWHERE	(-,0) (EH3,EH) (N{2},DX) IY! (-,0) W (EH3,0) ER
APPEAR	(-,0) (AH3,UH2) (← (-,0),-) (P,PH) IY2! ER{,18}
APPEARED	(-,0) (AH3,UH2) (← (-,0),-) (P,PH) IY2! ER{,18} (← (-,0),-) (D,DH,0)
APPLICATION	(-,0) AE3 (← (-,0),-) (P L,PL (L,0)) IH6 (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH IH5 N
APPRENTICE	(-,0) EH3 (← (-,0),-) (P R,PR (R,0)) EH2! N (← (-,0),-,0) T IH4 S (HH,0)
APPROACH	(-,0) UH{2} (← (-,0),-) (P R,PR (R,0)) OW2! (← (-,0),-) SH{,8}
APRIL	(-,0) (EYL,0) EYC! (EYR,0) (← (-,0),-) (P R,PR (R,0)) (IH EL,EL2)
ARBIB	(-,0) AA R (← (-,0),-{4}) (B,0) IY (← (-,0),-) (B,0)
ARE	(-,0) (AA3!{1} (ER2,ER),ER2!)
AREA	(-,0) IH2! ER IY2 UH

AREAS	(-,0) IH2! ER IY2 UH (Z{4},(Z,0) S)
AREN'T	(-,0) (AA3! (ER2,ER),ER2!) (N (← (-,0),-{4}) (T,0),DX)
ARPA	(-,0) AA! (ER,ER2) (← (-,0),-) P{1} IH
ART	(-,0) AA! (ER,0) ((← (-,0),-{4}) (T,0),DX)
ARTICLE	(-,0) (AA3 (ER,0), ER2) ((← (-,0),-) T,DX) IH8! (← (-,0),-) K{1} EL2
ARTICLES	(-,0) (AA3 (ER,0), ER2) ((← (-,0),-) T,DX) IH8! (← (-,0),-) K{1} EL (Z{4},(Z,0) S)
ARTIFICIAL	(-,0) (AA3 (ER,0), ER2) ((← (-,0),-) T,DX) IH7! (-,0) F IH3 SH EL
ARTS	(-,0) AA3! (ER,0) (← (-,0),-) S (HH,0)
ASIMOV	(-,0) AE (Z{4},(Z,0) S) IH6 M OW4! F (HH,0)
ASK	(-,0) AE3! S - (K,0)
ASSEMBLY	(-,0) UH4 S EH4 M! (← (-,0),-{4}) (B,0) L IY
ASSERTIONS	(-,0) AH S ER! SH IH5 N (Z{4},(Z,0) S)
ASSIMILATION	(-,0) IH6 S IH M EL3 (EYL,0) EYC! (EYR,0) SH IH5 N
ASSOCIATION	(-,0) UH4 S OW3 (S,SH) IY AE! SH (AX,IX,IH5) (N,DX)
ASSOCIATIVE	(-,0) UH4! S OW3 (S,SH) IY IH7 ((← (-,0),-) T,DX) IH3 V (F,0)
AT	(-,0) (AE4!,AE2!) ((← (-,0),-{4}) (T,0),DX)
ATTENTION	(-,0) (IH2,UH) (← (-,0),-) T EH2! N SH IH5 N
AUGMENTED	(-,0) AA (← (-,0),-) M EH N ((← (-,0),-,0) T,DX) IH3 (← (-,0),-) (D,0)
AUGUST	(-,0) AO (← (-,0),-) (G,0) IH3! S -{4} (T,0)
AUTHOR	(-,0) AO! (-,0) TH ER
AUTHORS	(-,0) AO! (-,0) TH ER (ER3,0) (Z{4},(Z,0) S)
AUTOMATED	(-,0) AO ((← (-,0),-) T,DX) EH3 M (EYL,0) EYC (EYR,0) ((← (-,0),-) T,DX) IH3 (← (-,0),-) (D,0)
AUTOMATIC	(-,0) AO ((← (-,0),-) T,DX) EH3 M AE! ((← (-,0),-) T,DX) IH3 (← (-,0),-{4}) (K,0)
AUTOMATION	(-,0) AA ((← (-,0),-) T,DX) OW2! M (EYL,0) EYC (EYR,0) SH IH5 N
AVAILABLE	(-,0) AH V (EH, (EYL,0) EYC EYR) EL! (IX,IH) (← (-,0),-{4}) (B,0) EL
AWARD	(-,0) UW2 W! UW4 ER ((← (-,0),-) (D,0),DX)
AXIOMATIC	(-,0) AE (← (-,0),-) S IY UH M AE ((← (-,0),-) T,DX) IH3 (← (-,0),-) (K,0)
AXIOMS	(-,0) AE (← (-,0),-) S IY! UH M (Z{4},(Z,0) S)
AZRIEL	(-,0) AE5! (Z{4},(Z,0) S) IH (ER,R) EL2
BACKGAMMON	(← (-,0),-{4}) (B,0) AE4 (← (-,0),-) (G,0) AE4! M IH6 (N,DX)
BANERJI	(← (-,0),-{4}) (B,0) IH7 N ER! (← (-,0),-) SH{,8} IY
BANK	(← (-,0),-{4}) (B,0) AE! NX (← (-,0),-{4}) (K,0)
BARROW	(← (-,0),-{4}) (B,0) EH3! (ER,R) OW
BASE	(← (-,0),-{4}) (B,0) (EYL,0) EYC! (EYR,0) S (HH,0)
BASEBALL	(← (-,0),-{4}) (B,0) (EYL,0) EYC! (EYR,0) S - (B,0) AO EL2
BASED	(← (-,0),-{4}) (B,0) (EYL,0) EYC! (EYR,0) S -{4} (T,0)
BASES	(← (-,0),-{4}) (B,0) (EYL,0) EYC (EYR,0) S IH4 (Z{4},(Z,0) S)
BATES	(← (-,0),-{4}) (B,0) (EYL,0) EYC (EYR,0) (← (-,0),-) S (HH,0)
BAY	(← (-,0),-{4}) (B,0) (EYL,0) EYC! (EYR,0)
BEEN	(← (-,0),-{4}) (B,0) IH2! (N,DX)
BEFORE	(← (-,0),-{4}) (B,0) (IY,IH) F! AO ER
BEHAVIOR	(← (-,0),-{4}) (B,0) IY (HH,HH2,0) (EYL,0) EYC! (EYR,0) V Y ER3
BELIEF	(← (-,0),-{4}) (B,0) (IH,IY) L IY! F (HH,0)
BERKELEY	(← (-,0),-{4}) (B,0) ER2 (← (-,0),-{4}) (K,0) L! IY2
BERLINER	(← (-,0),-{4}) (B,0) ER2 L! UH4 N (EH,0) ER
BERNARD	(← (-,0),-{4}) (B,0) (AA4,0) ER2 N AA3! ER (← (-,0),-) (D,0)
BERT	(← (-,0),-{4}) (B,0) ER2! ((← (-,0),-{4}) (T,0),DX)
BETWEEN	(← (-,0),-{4}) (B,0) (IH,IY) (← (-,0),-) T! OW IH2 (N,DX)
BIG	(← (-,0),-{4}) (B,0) (IH!,IX!) (← (-,0),-) (G,0)
BILL	(← (-,0),-{4}) (B,0) IH! EL
BINDING	(← (-,0),-{4}) (B,0) (AYL,0) AYC (AYR,0) N (← (-,0),-,D) (D,0) (IH3,IY) NX
BINDINGS	(← (-,0),-{4}) (B,0) (AYL,0) AYC! (AYR,0) N (← (-,0),-,D) (D,0) (IH3,IY) NX (Z{4},(Z,0) S)
BIOMEDICINE	(← (-,0),-{4}) (B,0) (AYL,0) AYC (AYR,0) OW M EH2! ((← (-,0),-) (D,0),DX) IH4 S IH6 (N,DX)
BLEDSOE	(← (-,0),-{4}) (B,0) L AH2! (← (-,0),-) S OW
BLOCK	(← (-,0),-{4}) (B,0) L AO! (← (-,0),-{4}) (K,0)
BOBROW	(← (-,0),-{4}) (B,0) (AWL,0) AWC! (AWR,0) (← (-,0),-{4}) (B,0) R OW
BONNIE	(← (-,0),-{4}) (B,0) AA! N IY
BOOK	(← (-,0),-{4}) (B,0) UW!{4} (← (-,0),-{4}) (K,0)

BOOKS	(← (-,0),-{4}) (B,0) UW!{4} (← (-,0),-) S (HH,0)
BOUNDS	(← (-,0),-{4}) (B,0) (AWL,0) AWC! (AWR,0) N (← (-,0),-) S (HH,0)
BRAIN	(← (-,0),-{4}) (B,0) R (EYL,0) EYC (EYR,0) (N,DX)
BRUCE	(← (-,0),-{4}) (B,0) R UW3! S (HH,0)
BUCHANAN	(← (-,0),-{4}) (B,0) Y IY2! (← (-,0),-) (K,0) AE5 N UH4 (N,DX)
BUSINESS	(← (-,0),-{4}) (B,0) IH (Z{4},(Z,0) S) (N IX,EN) S (HH,0)
BUT	(← (-,0),-{4}) (B,0) UH! ((← (-,0),-{4}) (T,0),DX)
BY	(← (-,0),-{4}) (B,0) (AYL,0) AYC! (AYR,0)
CACM	(-,0) S IY (EYL,0) EYC! (EYR,0) S IY AH2 M
CAI	(-,0) S IY (EYL,0) EYC (EYR,0) (AYL,0) AYC! (AYR,0)
CALCULUS	(← (-,0),-) (K,0) AE3! EL4 (← (-,0),-) (K,0) IH3 L IH6 S (HH,0)
CAN	(← (-,0),-) (K,G) (AE4!,IH3!) (N,DX)
CAPABILITIES	(← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) (← (-,0),-) P OW3 (← (-,0),-{4}) (B,0) IH EL IH6 (← (-,0),-) T IY (Z{4},(Z,0) S)
CAR	(← (-,0),-) (K,0) AA! (ER2{,12},0) ER
CARL	(← (-,0),-) (K,0) AA3! ER2 EL3
CARTOGRAPHY	(← (-,0),-) (K,0) AA3! ER (← (-,0),-) T AO (← (-,0),-) (G,0) ER F IY
CASE	(← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) S (HH,0)
CAUSAL	(← (-,0),-) (K,0) AO! (Z{4},(Z,0) S) UH2 EL
CEASE	(-,0) S IY! S (HH,0)
CELL	(-,0) S (EH,AA3) EL2!
CHARNIAK	(← (-,0),-) SH{,8} ER N IY! AE5 (← (-,0),-{4}) (K,0)
CHECKER	(← (-,0),-) SH{,10} EH! (← (-,0),-) (K,0) ER
CHECKING	(← (-,0),-) SH EH (← (-,0),-) (K,0) (IH3,IY) NX
CHESS	(← (-,0),-) SH{,10} EH4! S (HH,0)
CHOOSE	(← (-,0),-) SH (IH2,0) UH! (Z{4},(Z,0) S)
CHRISTOPHER	(← (-,0),-) (K,0) R IH2 S! - T IH (-,0) F ER2
CHUCK	(← (-,0),-) SH{,10} AA3! (← (-,0),-{4}) (K,0)
CIRCLE	(-,0) S (IH,IX,0) ER (← (-,0),-) (K,0) EL
CIRCUIT	(-,0) S (IH,0) ER (← (-,0),-) (K,0) UH! ((← (-,0),-{4}) (T,0),DX)
CIRCUITS	(-,0) S ER (← (-,0),-) (K,0) IX (← (-,0),-) S (HH,0)
CITE	(-,0) S (AYL,0) AYC! (AYR,0) ((← (-,0),-{4}) (T,0),DX)
CITED	(-,0) S (AYL,0) AYC! (AYR,0) ((← (-,0),-) T,DX) IH3 (← (-,0),-) (D,0)
CITES	(-,0) S (AYL,0) AYC! (AYR,0) (← (-,0),-) S (HH,0)
CLIMBING	(← (-,0),-) (K,0) L (AYL,0) AYC! (AYR,0) M IH5 NX
CLUSTERING	(← (-,0),-) (K,0) L UH2! S - T ER (IH3,IY) NX
CMU	(-,0) S IY EH2 M! Y (IH4,0) UW2
CODE	(← (-,0),-) (K,0) OW! (← (-,0),-) (D,0)
CODING	(← (-,0),-) (K,0) OW! (← (-,0),-) (D,DX) (IH3,IY) NX
COGNITION	(← (-,0),-) (K,0) AA3 (← (-,0),-) (G,0) N IH3! SH IH5 N
COGNITIVE	(← (-,0),-) (K,0) AA3! ((← (-,0),-,0) N,DX) IH4 ((← (-,0),-) T,DX) IH4 V (F,0)
COLBY	(← (-,0),-) (K,0) OW3! EL3 (← (-,0),-{4}) (B,0) IY
COLES	(← (-,0),-) (K,0) OW EL (Z{4},(Z,0) S)
COLLINS	(← (-,0),-) (K,0) AO EL3 UH2 N (Z{4},(Z,0) S)
COME	(← (-,0),-) (K,0) AA5! M
COMMENTS	(← (-,0),-) (K,0) AA M EH2! N (← (-,0),-) S (HH,0)
COMMITTEE	(← (-,0),-) (K,0) EM! IH2 ((← (-,0),-) T,DX) IY
COMMON	(← (-,0),-) (K,0) AA M AX (N,DX)
COMMUNICATION	(← (-,0),-) (K,0) AH M UW3 N IH3 (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH IH5 N
COMMUNICATIONS	(← (-,0),-) (K,0) AH M UW N IH (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH IH5 N (Z{4},(Z,0) S)
COMPLEX	(← (-,0),-) (K,0) AA M (← (-,0),-,0) (P L,PL (L,0)) EH (← (-,0),-) S (HH,0)
COMPLEXITY	(← (-,0),-) (K,0) AA{2} M (← (-,0),-,0) (P L,PL (L,0)) EH4! (← (-,0),-) S IH7 ((← (-,0),-) T,DX) IY
COMPONENTS	(← (-,0),-) (K,0) AX M (← (-,0),-,0) P OW N AX N (← (-,0),-) S (HH,0)
COMPREHENSION	(← (-,0),-) (K,0) AA M (← (-,0),-,0) (P R,PR (R,0)) IY HH2! EH2 N SH IH5 N
COMPUTATION	(← (-,0),-) (K,0) AA! M (← (-,0),-,0) P IH3 (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N
COMPUTATIONAL	(← (-,0),-) (K,0) AA M (← (-,0),-,0) P IH3 (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N (AH EL,EL)
COMPUTER	(← (-,0),-) (K,0) (AH2 M,EM) (← (-,0),-,0) (P,PH) IH2! (UW2,0) ((← (-,0),-) T,DX) ER
COMPUTERS	(← (-,0),-) (K,0) (AH2 M,EM) (← (-,0),-,0) (P,PH) IH2! (UW3,0) ((← (-,0),-) T,DX) ER (Z{4},(Z,0) S)

COMPUTING	(← (-,0),-) (K,0) (AH2 M,EM) (← (-,0),-,0) (P,PH) IH2! (UW3,0) ((← (-,0),-) T,DX) IH2 NX
CONCEPTUAL	(← (-,0),-) (K,0) AX N S EH (← (-,0),-) SH{,10} UW EL
CONCERN	(← (-,0),-) (K,0) (IH7,IH3) N S ER! (N,DX)
CONCERNED	(← (-,0),-) (K,0) (IH7,IH3) N S ER! N (← (-,0),-) (D,0)
CONCERNING	(← (-,0),-) (K,0) (IH7,IH3) N S ER! N IH5 NX
CONCURRENT	(← (-,0),-) (K,0) IH5 N (← (-,0),-) K! ER EH2 N ((← (-,0),-{4}) (T,0),DX)
CONFERENCE	(← (-,0),-) (K,0) AA! N (-,0) F ER IH6 N S (HH,0)
CONFERENCES	(← (-,0),-) (K,0) AA! N (-,0) F ER IH6 N S IH4 S (HH,0)
CONFINE	(← (-,0),-) (K,0) (IH7,IH3) N F! (AYL,0) AYC (AYR,0) (N,DX)
CONSIDER	(← (-,0),-) (K,0) IH3 N S IH3! ((← (-,0),-) (D,0),DX) ER
CONSIDERED	(← (-,0),-) (K,0) ((IH7,IH3) N,EN) S IH2! ((← (-,0),-) (D,0),DX) ER (← (-,0),-) (D,0)
CONSTRAINT	(← (-,0),-) (K,0) (IH7,IH3) N S - DR R (EYL,0) EYC (EYR,0) N (0,T)
CONSTRUCTING	(← (-,0),-) (K,0) (IH7,IH3) N S - DR R EH3! (← (-,0),-) T (IH3,IY) NX
CONSTRUCTION	(← (-,0),-) (K,0) (IH7,IH3) N S - DR R EH3! (← (-,0),-) SH IH5 N
CONSULTANT	(← (-,0),-) (K,0) IH7! N S AO EL (← (-,0),-) T IH6 N (← (-,0),-) (0,T)
CONSULTATION	(← (-,0),-) (K,0) AA N S EL3 (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N
CONSULTATIONS	(← (-,0),-) (K,0) AA N S AX (L,0) (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N (Z{4},(Z,0) S)
CONTAIN	(← (-,0),-) (K,0) (IH7,IH3) N ((← (-,0),-) T,DX) (EYL,0) EYC! (EYR,0) (N,DX)
CONTAINED	(← (-,0),-) (K,0) (IH7,IH3) N ((← (-,0),-) T,DX) (EYL,0) EYC! (EYR,0) N (← (-,0),-) (D,DH,0)
CONTAINS	(← (-,0),-) (K,0) (IH7,IH3) N ((← (-,0),-) T,DX) (EYL,0) EYC! (EYR,0) N (Z{4},(Z,0) S)
CONTEXT	(← (-,0),-) (K,0) AA N (← (-,0),-) T EH3! (← (-,0),-) S -{4} (T,0)
CONTINUOUS	(← (-,0),-) (K,0) IH3! N (← (-,0),-) T IH3 N Y UH2 AH S (HH,0)
CONTROL	(← (-,0),-) (K,0) (IH7,IH3) N (← (-,0),-) (SH{,10},T) R OW! EL
CONTROLLED	(← (-,0),-) (K,0) (IH7,IH3) N (← (-,0),-) (T,SH{,10}) R OW (EL,0) (← (-,0),-) (D,0)
CONVENTION	(← (-,0),-) (K,0) (IH7,IH3) N (V,F) UH! N (← (←,0) -) SH IH5 N
CONVENTIONS	(← (-,0),-) (K,0) (IH7,IH3) N (V,F) UH! N (← (←,0) -) SH IH5 N (Z{4},(Z,0) S)
COOPERATING	(← (-,0),-) (K,0) OW AO! (← (-,0),-) (P,0) ER2 (EYL,0) EYC (EYR,0) ((← (-,0),-) T,DX) (IH3,IY) NX
COOPERATION	(← (-,0),-) (K,0) OW AO! (← (-,0),-) (P,0) ER2 (EYL,0) EYC (EYR,0) SH IH5 N
COPY	(← (-,0),-) (K,0) AA! (← (-,0),-) P IY
COPYING	(← (-,0),-) (K,0) AO! (← (-,0),-) P IY (IH3,0) NX
CORRECTNESS	(← (-,0),-) (K,0) ER EH ((← (-,0),-) T,DX) N IX S (HH,0)
COULD	(← (-,0),-) (K,0) UH! (← (-,0),-) (D,0)
CURRENT	(← (-,0),-) (K,0) ER! (IH5 N,EN) ((← (-,0),-{4}) (T,0),DX)
CURVED	(← (-,0),-) (K,0) UH4! ER (F,V) (← (-,0),-) (D,0)
CYBERNETICS	(-,0) S (AYL,0) AYC! (AYR,0) (← (-,0),-{4}) (B,0) ER N EH ((← (-,0),-) T,DX) IH3 (← (-,0),-) S (HH,0)
CYCLIC	(-,0) S IH3! (← (-,0),-{4}) (K,0) L UH2 (← (-,0),-{4}) (K,0)
DANNY	((← (-,0),-) (D,0),DX) AE4! N IY
DATA	((← (-,0),-) (D,0),DX) (EYL,0) EYC! (EYR,0) ((← (-,0),-) (D,0),DX) UH
DATE	((← (-,0),-) (D,0),DX) (EYL,0) EYC! (EYR,0) ((← (-,0),-{4}) (T,0),DX)
DATES	((← (-,0),-) (D,0),DX) (EYL,0) EYC! (EYR,0) (← (-,0),-) S (HH,0)
DAVE	((← (-,0),-) (D,0),DX) (EYL,0) EYC! (EYR,0) V (F,0)
DAVID	((← (-,0),-) (D,0),DX) (EYL,0) EYC! (EYR,0) V IH2 (← (-,0),-) (D,0)
DEBATE	((← (-,0),-) (D,0),DX) IH2 (← (-,0),-{4}) (B,0) (EYL,0) EYC (EYR,0) ((← (-,0),-{4}) (T,0),DX)
DECEMBER	((← (-,0),-) (D,0),DX) IH2 S EH! M (← (-,0),-{4}) (B,0) ER
DECISION	((← (-,0),-) (D,0),DX) IH2 S IH (← (-,0),-) SH IH5 N
DEDUCTION	((← (-,0),-) (D,0),DX) (IY,IH2,IX) (← (-,0),-) (D,0) AA3! (← (-,0),-) SH IH5 N
DEDUCTIVE	((← (-,0),-) (D,0),DX) (IY,IH2,IX) ((← (-,0),-) D,DX) AA3! ((← (-,0),-) T,DX) IH2 V (F,0)
DEMAND	((← (-,0),-) (D,0),DX) IH! M AE4 N (← (-,0),-) (D,0)
DENOTATIONAL	((← (-,0),-) (D,0),DX) IY N OW (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N EL
DEPTH	((← (-,0),-) (D,0),DX) EH4! (← (-,0),-) TH (HH,0)
DERIVATION	((← (-,0),-) (D,0),DX) IH2 ER (IH,0) V (EYL,0) EYC (EYR,0) SH! IH5 N
DESCRIBE	((← (-,0),-) (D,0),DX) IH4! S - (K,WH,0) R (AYL,0) AYC (AYR,0) B
DESCRIPTION	((← (-,0),-) (D,0),DX) IH4 S - (K,0) R IH2 (← (-,0),-) SH IH5 N
DESCRIPTIONS	((← (-,0),-) (D,0),DX) IX S - (K,0) R IH (← (-,0),-) SH IH5 N (Z{4},(Z,0) S)
DESIGN	((← (-,0),-) (D,0),DX) (IH6,IX,0) (Z{4},(Z,0) S) (AYL,0) AYC! (AYR,0) (N,DX)
DESIRE	((← (-,0),-) (D,0),DX) (IH,IY) (Z{4},(Z,0) S) (AYL,0) AYC! (AYR,0) ER
DETECTION	((← (-,0),-) (D,0),DX) (IH,IY) (← (-,0),-) T EH! (← (-,0),-) SH IH5 N
DEVICES	((← (-,0),-) (D,0),DX) (IH,IY) V! (AYL,0) AYC (AYR,0) S IH6 (Z{4},(Z,0) S) (HH,0)

DIAGNOSIS	((← (-,0),-) (D,0),DX) (AYL,0) AYC! (AYR,0) IH3 (← (-,0),-) N OW2 S IH4 S (HH,0)
DIALOGUE	((← (-,0),-) (D,0),DX) (AYL,0) AYC! (AYR,0) AA EL3 AO (← (-,0),-) (G,0)
DICK	((← (-,0),-) (D,0),DX) IH2! (← (-,0),-{4}) (K,0)
DID	((← (-,0),-) (D,0),DX) (IH2!,IH3!) ((← (-,0),-) (D,0),DX,D)
DIDN'T	((← (-,0),-) (D,0),DX) IH3! (← (-,0),-) (D,0) IH5 N ((← (-,0),-{4}) (T,0),DX)
DIMENSIONAL	((← (-,0),-) (D,0),DX) IH2 M EH2! N (← (-,0),-,0) SH{,10} EN EL3
DIRECTED	((← (-,0),-) (D,0),DX) ER R EH3! ((← (-,0),-) T,DX) (IH3,IX) (← (-,0),-) (D,DH,0)
DISCUSS	((← (-,0),-) (D,0),DX) IH4 S - (K,0) AA2! S (HH,0)
DISCUSSED	((← (-,0),-) (D,0),DX) IH4 S - (K,0) AA2! S -{4} (T,0)
DISCUSSES	((← (-,0),-) (D,0),DX) IH4 S - (K,0) AA2! S IH6 (Z{4},(Z,0) S)
DISCUSSING	((← (-,0),-) (D,0),DX) IH4 S - (K,0) AA2! S IH5 NX
DISPLAY	((← (-,0),-) (D,0),DX) (IH4,0) S - (P L,PL (L,0)) (EYL,0) EYC! (EYR,0)
DO	(← (-,0),-) D!{2} (IH2,0) UX{6,12}
DOES	((← (-,0),-) (D,0),DX) AH2! (Z{4},(Z,0) S)
DOESN'T	((← (-,0),-) (D,0),DX) AX! (Z{4},(Z,0) S) AX N ((← (-,0),-{4}) (T,0),DX)
DOMAIN	((← (-,0),-) (D,0),DX) OW M (EYL,0) EYC! (EYR,0) (N,DX)
DON'T	((← (-,0),-) (D,0),DX) OW2 OW! N ((← (-,0),-{4}) (T,0),DX)
DONALD	((← (-,0),-) (D,0),DX) AA! (N,DX) EL2 (← (-,0),-) (D,0)
DONE	((← (-,0),-) (D,0),DX) AA2!{,22} (N,DX)
DOUG	((← (-,0),-) (D,0),DX) AA2! (← (-,0),-) (G,0)
DRAGON	(← (-,0),-) DR R AE! (← (-,0),-) (G,0) IH5 N
DRAGONS	(← (-,0),-) DR R AE! (← (-,0),-) (G,0) IH3 N (Z{4},(Z,0) S)
DRAWINGS	(← (-,0),-) DR R AA! IH5 NX (Z{4},(Z,0) S)
DREW	(← (-,0),-) DR R (IH,0) UW!
DREYFUS	(← (-,0),-) DR R (AYL,0) AYC! (AYR,0) F AH S (HH,0)
DRIVING	(-,0) ((← (-,0),-) SH,R) (AYL,0) AYC! (AYR,0) V (IH3,IY) NX
DURING	((← (-,0),-) (D,0),DX) ER IY2! NX
DYNAMIC	((← (-,0),-) (D,0),DX) (AYL,0) AYC! (AYR,0) N AE5 M IH3 (← (-,0),-{4}) (K,0)
EACH	(-,0) IY! (← (-,0),-) SH (HH,0)
EARL	(-,0) ER2! EL2
EARLIEST	(-,0) ER! L IY (IX,0) S -{4} (T,0)
EARNEST	(-,0) ER (N,DX) IH6 S -{4} (T,0)
ED	(-,0) EH2! (← (-,0),-) (D,0)
EDINBURGH	(-,0) EH2! ((← (-,0),-) (D,0),DX) (IH5 N,EN) (← (-,0),-,B) (B,0) ER2
EFFICIENTLY	(-,0) EH4 (-,0) F IH2! SH IH5 N ((← (-,0),-) (0,T),DX) L IY2
EIGHT	(-,0) (EYL,0) EYC! (EYR,0) ((← (-,0),-{4}) (T,0),DX)
EIGHTEEN	(-,0) (EYL,0) EYC! (EYR,0) ((← (-,0),-) T,DX) IY (N,DX)
EIGHTY	(-,0) (EYL,0) EYC! (EYR,0) ((← (-,0),-) T,DX) IY
ELECTRONIC	(-,0) (IY L,EL3) EH2! (← (-,0),-) (T,SH{,10}) R AA2 N IH3 (← (-,0),-{4}) (K,0)
ELECTRONICS	(-,0) (IY L, EL3) EH2! (← (-,0),-) (T,SH{,10}) R AA2 N IH3 (← (-,0),-) S (HH,0)
ELEVEN	(-,0) EH (L,EL) EH! V (IH5 N,EN)
ELLIOT	(-,0) EH EL3 IY! IH4 ((← (-,0),-{4}) (T,0),DX)
ENGLISH	(-,0) (IH3,IY) NX (← (-,0),-,0) (G,0) L IH6! SH (HH,0)
ENVIRONMENT	(-,0) IH3 N V (AYL,0) AYC! (AYR,0) ER! N M IH5! (← (-,0),-) (T,0)
ERIK	(-,0) (AE2,EH) ER! IH8 (← (-,0),-{4}) (K,0)
ERMAN	(-,0) ER M IH5! (N,DX)
ERNST	(-,0) IH8 ER! N S -{4} (T,0)
EUGENE	(-,0) Y UW3! (← (-,0),-) SH{,10} IY (N,DX)
EVALUATION	(-,0) IH6 V AA EL3 Y UW (EYL,0) EYC! (EYR,0) SH IH5 N
EVALUATOR	(-,0) IH6 V AA EL3 Y UW (EYL,0) EYC! (EYR,0) ((← (-,0),-) T,DX) ER
EVENTS	(-,0) (IY,AX) V EH4! N (← (-,0),-) S (HH,0)
EVER	(-,0) IH4! V ER2
EVERY	(-,0) (EH,EH2) V R! IY2
EVERYTHING	(-,0) (EH,EH2) (V,0) R! IY2 TH (IH3,IY) NX
EXAMPLE	(-,0) EH (← (-,0),-) (Z{4},(Z,0) S) AE M (← (-,0),-,0) P EL
EXAMPLES	(-,0) EH (← (-,0),-) (Z{4},(Z,0) S) AE M (← (-,0),-,0) P EL (Z{4},(Z,0) S)
EXIST	(-,0) IH3 (← (-,0),-) (Z{4},(Z,0) S) IH7! S -{4} (T,0)
EXPERT	(-,0) EH2 (← (-,0),-) S! - P ER ((← (-,0),-{4}) (T,0),DX)

EXPLANATION	(-,0) EH (← (-,0),-) S - (P L,PL (L,0)) IH N (EYL,0) EYC! (EYR,0) SH IH5 N
EXPRESSIONS	(-,0) IH3 (← (-,0),-) S - (P R,PR (R,0)) EH3! SH (IH5 N,EN) (Z{4},(Z,0) S)
FABLES	(-,0) F (EYL,0) EYC (EYR,0) (← (-,0),-{4}) (B,0) AX (L,0) (Z{4},(Z,0) S)
FACES	(-,0) F (EYL,0) EYC! (EYR,0) S IH4 (Z{4},(Z,0) S)
FACTS	(-,0) F AE! (← (-,0),-) S (HH,0)
FAHLMAN	(-,0) F AO EL2 M UH4 (N,DX)
FAIRY	(-,0) F EH! (ER,R) IY
FASTER	(-,0) F AE3! S - T ER
FEATURE-DRIVEN	(-,0) F IY (← (-,0),-) SH{,10} ER! (← (-,0),-) DR R IH V (((IH,IX) N),EN)
FEBRUARY	(-,0) F EH3! (← (-,0),-{4}) (B,0) (R,Y) (UW (W,0),0) AA (ER,R) IY
FEDERAL	(-,0) F EH! ((← (-,0),-) D,DX) ER2 EL3
FEIGENBAUM	(-,0) F (AYL,0) AYC (AYR,0) (← (-,0),-) (G,0) IH5 N (← (-,0),-,0) (B,0) (AWL,0) AWC! (AWR,0) M
FELDMAN	(-,0) F EH2! EL (← (-,0) ,-) M IH6 (N,DX)
FICTION	(-,0) F IH2 (← (-,0),-) SH! IH5 N
FIFTEEN	(-,0) F IH2! F ((← (-,0),-) T,DX) IY (N,DX)
FIFTY	(-,0) F IH2! F ((← (-,0),-) T,DX) IY
FIKES	(-,0) F (AYL,0) AYC! (AYR,0) (← (-,0),-) S (HH,0)
FILE	(-,0) F (AYL,0) AYC! (AYR,0) EL3
FINISH	(-,0) F IH3! N IH5 SH (HH,0)
FINISHED	(-,0) F IH3! N IH5 SH -{4} (T,0)
FIRST	(-,0) F (AA3 ER,ER2) S! -{4} (T,0)
FIVE	(-,0) F (AYL,0) AYC! (AYR,0) (V,F)
FOR	(-,0) F (AA4,0) ER!
FORESTS	(-,0) F AA2 ER! IH S - S (HH,0)
FORMAL	(-,0) F AA4! ER2 (M,0) EL2
FORMATION	(-,0) F AA4 ER M (EYL,0) EYC! (EYR,0) SH IH5 N
FORTY	(-,0) F AA4! (ER,ER2) ((← (-,0),-) T,DX) IY
FOUR	(-,0) F AA4! ER
FOURTEEN	(-,0) F AA4! ER ((← (-,0),-) T,DX) IY (N,DX)
FRAME	(-,0) F R (EYL,0) EYC! (EYR,0) M
FRAMES	(-,0) F R (EYL,0) EYC (EYR,0) M (Z{4},(Z,0) S)
FROM	(-,0) F R AH! M
FU	(-,0) F UW2!
FUNCTION	(-,0) F AA! NX (← (-,0),-,0) SH IH5 N
FUNCTIONS	(-,0) F AA! NX (← (-,0),-,0) SH IH5 N (Z{4},(Z,0) S)
FUZZY	(-,0) F UH2! (Z{4},(Z,0) S) IY
GAME	(← (-,0),-) (G,0) (EYL,0) EYC! (EYR,0) M
GAMES	(← (-,0),-) (G,0) (EYL,0) EYC! (EYR,0) M (Z{4},(Z,0) S)
GARY	(← (-,0),-) (G,0) AE2! ER IY2
GASCHNIG	(← (-,0),-) (G,0) AE5 SH N IH3 (← (-,0),-{4}) (K,0)
GENERAL	(← (-,0),-) SH{,10} EH2 N ER2! EL3
GENERATE	(← (-,0),-) SH{,10} EH2 N ER (EYL,0) EYC! (EYR,0) ((← (-,0),-{4}) (T,0),DX)
GENERATION	(← (-,0),-) SH{,10} IH5 N ER (EYL,0) EYC! (EYR,0) SH IH5 N
GEOMETRIC	(← (-,0),-) SH{,10} IY IH M EH2! (← (-,0),-) DR R IH8 (← (-,0),-{4}) (K,0)
GEORGE	(← (-,0),-) SH{,10} UW4 ER! (← (-,0),-) SH{,10}
GET	(← (-,0),-) (G,0) (EH2!,IH3!) ((← (-,0),-{4}) (T,0),DX)
GIPS	(← (-,0),-) (G,0) IH3! (← (-,0),-) S (HH,0)
GIVE	(← (-,0),-) (G,0) IH2! (F,V (F,0))
GIVEN	(← (-,0),-) (G,0) IH3! V UH4 (N,DX)
GM	(← (-,0),-) SH{,10} IY! EH2 M
GO	(← (-,0),-) (G,0) OW!{,36}
GO-MOKU	(← (-,0),-) (G,0) OW M DW! (← (-,0),-) (K,0) UW
GOAL	(← (-,0),-) (G,0) OW! EL
GOALS	(← (-,0),-) (G,0) OW3! EL (Z{4},(Z,0) S)
GRAIN	(← (-,0),-) (G,0) R (EYL,0) EYC! (EYR,0) (N,DX)
GRAMMARS	(← (-,0),-) (G,0) R AE5 M ER! (Z{4},(Z,0) S)
GRAMMATICAL	(← (-,0),-) (G,0) ER M AE! ((← (-,0),-) T,DX) IH8 (← (-,0),-{4}) (K,0) EL
GRAPH	(← (-,0),-) (G,0) R AE3! F (HH,0)

GRAPHICS	(← (-,0),-) (G,0) R AE2! F IH2 (← (-,0),-) S (HH,0)
HAMBURG	(-,0) (HH,0) AA! M (← (-,0),-,B) (B,0) ER2 (← (-,0),-) (G,0)
HANS	(-,0) (HH,0) AA! N (-,0) S (HH,0)
HAPPEN	(-,0) (HH,0) AE! (← (-,0),-) P EH2 (N,DX)
HARRY	(-,0) (HH2,HH) AE2! (ER,R) IY2
HAS	(-,0) (HH,HH2,0) AE4! (Z{4},(Z,0) S)
HASN'T	(-,0) (HH,HH2,0) AE! (Z{4},(Z,0) S) IH6 N ((← (-,0),-{4}) (T,0),DX)
HAVE	(-,0) (HH,HH2,0) (AE!,AE5!) V (F,0)
HAVEN'T	(-,0) (HH,HH2,0) AE! (V,←) (EH2 N,EN) ((← (-,0),-{4}) (T,0),DX)
HAYES-ROTH	(-,0) (HH,HH2,0) (EYL,0) EYC (EYR,0) (Z{4},(Z,0) S) R AA TH (HH,0)
HE	(-,0) (HH,HH2,0) IY!
HEARSAY	(-,0) (HH,HH2,0) IY2 ER (-,0) S (EYL,0) EYC! (EYR,0)
HELP	(-,0) (HH,0) AA3! EL3 (← (-,0),-) (P,0)
HENDRIX	(-,0) (HH,0) EH2 N ((← (-,0),-,0) (DR,D),DX) ER IH2! (← (-,0),-) S (HH,0)
HER	(-,0) (HH!,HH2!) ER!
HERB	(-,0) (HH,0) ER! (← (-,0),-{4}) (B,0)
HERBERT	(-,0) (HH,0) ER2! (← (-,0),-{4}) (B,0) ER ((← (-,0),-{4}) (T,0),DX)
HETEROSTATIC	(-,0) (HH,0) EH (← (-,0),-) DR R OW S - T AE ((← (-,0),-) T,DX) IH3 (← (-,0),-) (K,0)
HEURISTIC	(-,0) (HH,HH2,0) (EH3,IY2,0) ER IH2! S (- T,0) IH2 (← (-,0),-{4}) (K,0)
HEWITT	(-,0) (HH,HH2,0) Y UW IH4 (← (-,0),-) (T,0)
HILARY	(-,0) (HH,HH2,0) EL3 ER! IY2
HILL	(-,0) (HH,HH2,0) AH3! EL4
HIS	(-,0) (HH,0) IH3! (Z{4},(Z,0) S)
HISTORY	(-,0) (HH,0) IH3! S - DR ER IY
HOLLAND	(-,0) (HH,0) AA! EL3 EN (← (-,0),-,0) (D,0)
HOW	(-,0) (HH,HH2,0) (AWL,0) AWC! (AWR,0)
HUGH	(-,0) (HH,HH2,0) IH2 UH!
HUMAN	(-,0) (HH,HH2,0) UW3! M1 UH (N,DX)
HUNDRED	(-,0) (HH,0) (AA5!,AA2!) N (← (-,0),-) (DR,D,0) ER (← (-,0),-) (D,0)
HUNGRY	(-,0) (HH,0) UH2! NX (← (-,0),-) (G,0) R IY3
HUNT	(-,0) (HH,0) UH2! N ((← (-,0),-{4}) (T,0),DX)
HYPOTHESIS	(-,0) (HH,0) (AYL,0) AYC! (AYR,0) (← (-,0),-) P AA TH IH6 S IH6 S (HH,0)
I	(-,0) (AYL,0) AYC! (AYR,0)
I'D	(-,0) (AYL,0) AYC! (AYR,0) (← (-,0),-) (D,0)
I'M	(-,0) (AYL,0) AYC! (AYR,AYX,0) M
IEEE	(-,0) (AYL,0) AYC (AYR,0) ((← (-,0),-) T,DX) R IH! (← (-,0),-) P (EL,AX EL) IY
IFIP	(-,0) (AYL,0) AYC! (AYR,0) F IH2 (← (-,0),-) (P,0)
IJCAI	(-,0) (AYL,0) AYC (AYR,0) (← (-,0),-) SH{,10} (EYL,0) EYC! (EYR,0) S IY (EYL,0) EYC (EYR,0) (AYL,0) AYC (AYR,0)
ILLINOIS	(-,0) IH3 EL3 UH4 N (OYL,0) OYC! (OYR,0)
IMAGE	(-,0) EH2 M! IH3 (← (-,0),-) SH{,8}
IMAGES	(-,0) EH2 M! IH3 (← (-,0),-) SH{,8} IH3 (Z{4},(Z,0) S)
IMPROVING	(-,0) IH3 M (← (-,0),-,0) P! R (IH,0) UW! V (IH3,IY) NX
IN	(-,0) (UH!,IH3!,IX!) (N,DX)
INDUCTIVE	(-,0) IH4 N (← (-,0),-,D) (D,0) AA3 (← (-,0),-) T IH2 V (F,0)
INDUSTRIAL	(-,0) IH4 N (← (-,0),-,D) (D,0) AA2! S - DR (R,0) IH2 EL3
INEXACT	(-,0) IH5 N IH3! (← (-,0),-) (Z{4},(Z,0) S) AE ((← (-,0),-{4}) (T,0),DX)
INFERENCE	(-,0) IH3 N F! R IH6 N S (HH,0)
INFERENCES	(-,0) IH3 N F! R IH6 N S IH4 (Z{4},(Z,0) S)
INFERENTIAL	(-,0) IH3 N F ER2! EH2 N SH EL
INFORMATION	(-,0) IH3 N F ER2 M (EYL,0) EYC (EYR,0) SH! IH5 N
INHERITANCE	(-,0) IH3 N (HH,HH2,0) EH3 ER! IH2 (← (-,0),-) T IH4 N S (HH,0)
INSANE	(-,0) IH3 N S (EYL,0) EYC! (EYR,0) (N,DX)
INSTITUTE	(-,0) IH3 N S - T IH4 (← (-,0),-) T UW3! ((← (-,0),-{4}) (T,0),DX)
INTELLIGENCE	(-,0) IH3 N ((← (-,0),-) T,DX) EH EL IH6! (← (-,0),-) SH IH3 N S (HH,0)
INTELLIGENT	(-,0) IH3 N ((← (-,0),-) T,DX) EH EL IH6! (← (-,0),-) SH IH3 N (← (-,0),-) (0,T)
INTENSITY	(-,0) IH3 N (← (-,0),-) T EH2! N S IH4 ((← (-,0),-) T,D,DX) IY
INTENTIONS	(-,0) IH5 N (← (-,0),-) T EH2 N SH IH5 N (Z{4},(Z,0) S)

INTERACTIVE	(-,0) IH3 N ((← (-,0),-) DR,DX) ER AE3 (← (-,0),-) T IH3 V (F,0)
INTERESTED	(-,0) IH3! N ((← (-,0),-) DR,DX) ER S (- T,0) IH3 (← (-,0),-) (D,DH,0)
INTERPRETABLE	(-,0) IH7 N ((← (-,0),-) DR,DX) ER (← (-,0),-) (P,0) ER2! ((← (-,0),-) T,DX) UW4 (← (-,0),-{4}) (B,0) EL
INTERPRETIVE	(-,0) IH5 N ((← (-,0),-) DR,DX) ER3! (← (-,0),-,0) P ER ((← (-,0),-) T,DX) IH2 V (F,0)
INTERRUPTS	(-,0) IH3 N ((← (-,0),-,0) DR,DX) ER3! AA2 (← (-,0),-) S (HH,0)
INTERVIEW	(-,0) IH5 N ((← (-,0),-) DR,DX) ER! (V,F) Y UW
INTONATION	(-,0) IH5 N (← (-,0),-) T UH N! (EYL,0) EYC (EYR,0) SH IH5 N
INVARIANCE	(-,0) IH3 N V EH3 ER! IY (IH4{3},0) N (-,0) S (HH,0)
INVARIANCES	(-,0) IH3 N V EH3 ER! IY (IH4{3},0) N (-,0) S IH4 (Z{4},(Z,0) S)
INVESTMENT	(-,0) IH5 N V EH4 S! - M IH5 N (← (-,0),-{4}) (T,0)
INVOCATION	(-,0) IH3 N (-,0) V{1} IH8 (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH IH5 N
IRV	(-,0) ER2! V (F,0)
IS	(-,0) IH3! (Z{4},(Z,0) S)
ISN'T	(-,0) IH3! (Z{4},(Z,0) S) (IH6 N,EN) ((← (-,0),-{4}) (T,0),DX)
ISOMERS	(-,0) (AYL,0) AYC (AYR,0) S EH4 M! ER (Z{4},(Z,0) S)
ISSAC	(-,0) (AYL,0) AYC! (AYR,0) (Z{4},(Z,0) S) IH3 (← (-,0),-{4}) (K,0)
ISSUE	(-,0) IH3 SH! UW3{5}
ISSUED	(-,0) IH3 SH! UW3{5} (← (-,0),-) (D,0)
ISSUES	(-,0) IH3 SH! UW3{5} (Z{4},(Z,0) S)
IT	(-,0) IH4! ((← (-,0),-) (T,0), DX)
ITERATION	(-,0) IH3 ((← (-,0),-) T,DX) ER (EYL,0) EYC! (EYR,0) SH IH5 N
ITS	(-,0) IH4! (← (-,0),-) S (HH,0)
JACK	(← (-,0),-) SH{,10} AE3! (← (-,0),-{4}) (K,0)
JAMES	(← (-,0),-) SH{,10} (EYL,0) EYC! (EYR,0) M (-,0) (Z{4},(Z,0) S)
JANUARY	(← (-,0),-) SH{,10} AE4! N V (UH,IH2) (AA4,0) (ER,R) IY
JEAN	(← (-,0),-) SH{,10} IY! (N,DX)
JEFFREY	(← (-,0),-) SH{,10} EH3! F R IY2
JERRY	(← (-,0),-) SH{,10} EH! ER IY
JOHN	(← (-,0),-) SH{,10} AA2! (N,DX)
JOSEPH	(← (-,0),-) SH{,10} OW! S IH F (HH,0)
JOURNAL	(← (-,0),-) SH{,10} ER! N (AA,0) EL3
JOURNALS	(← (-,0),-) SH{,10} ER! N (AA,0) EL3 (Z{4},(Z,0) S)
JUDEA	(← (-,0),-) SH{,10} UW3! (← (-,0),-) (D,0) IY IH2
JUDICIAL	(← (-,0),-) SH{,10} UW3! (← (-,0),-) (D,0) IH3 SH EL3
JULY	(← (-,0),-) SH{,10} AX! L (AYL,0) AYC (AYR,0)
JUNE	(← (-,0),-) SH{,10} (IH2,0) UW! (N,DX)
KARL	(← (-,0),-) (K,0) AA3! ER2 EL3
KEITH	(← (-,0),-) (K,0) IY! TH (HH,0)
KEN	(← (-,0),-) (K,0) EH2! (N,DX)
KEY	(← (-,0),-) (K,0) IY!
KEYS	(← (-,0),-) (K,0) IY! S (HH,0)
KILL	(← (-,0),-) (K,0) IH5! EL
KIND	(← (-,0),-) (K,0) (AYL,0) AYC! (AYR,0) N (← (-,0),-) (D,0)
KINDS	(← (-,0),-) (K,0) (AYL,0) AYC (AYR,0) N! (0,D) (Z{4},(Z,0) S)
KING	(← (-,0),-) K! (IH3,IY) NX
KNOW	(-,0) N OW!
KNOWLEDGE	(-,0) N AA! EL3 IH6 (← (-,0),-) SH{,12}
KNOWN	(-,0) N OW! (N,DX)
KUGEL	(← (-,0),-) (K,0) UW2! (← (-,0),-) (G,0) EL
LABS	(-,0) L AE! (← (-,0),-{4}) (B,0) (Z{4},(Z,0) S)
LAMBDA	(-,0) L AE M (← (-,0),-) (D,0) (AH,UH)
LANGUAGE	(-,0) L (AA,AE4) NX (← (-,0),-,0) WH! IH3 (← (-,0),-) (ZH (SH{,10},0),SH{,10})
LANGUAGES	(-,0) L (AA,AE4) NX (← (-,0),-,0) WH! IH3 (← (-,0),-) (ZH (SH{,10},0),SH{,10}) IH7!{6,16} (Z{4},(Z,0) S)
LARGE	(-,0) L AA R (← (-,0),-) SH (HH,0)
LAST	(-,0) L AE! S -{4} (T,0)
LATELY	(-,0) (L,L2) (EYL,0) EYC! (EYR,0) (← (-,0),-) (T (-,0),0) L IY
LATEST	(-,0) L (EYL,0) EYC! (EYR,0) ((← (-,0),-{4}) (T,0),DX) IH4 S -{4} (T,0)
LAURENT	(-,0) L AA4 ER2! IH4 N (← (-,0),-) (T,0)

LEARNING	(-,0) L2 ER! N IH7 NX
LECTURES	(-,0) L EH (← (-,0),-) SH!{,10} ER (Z{4},(Z,0) S)
LEE	(-,0) L IY!
LENAT	(-,0) L AA2! (N,DX) AH2 ((← (-,0),-{4}) (T,0),DX)
LEONARD	(-,0) L AA2 EN! ER ((← (-,0),-) (D,0),DX)
LES	(-,0) L UH4! S (HH,0)
LESSER	(-,0) L AH! S ER2
LET	(-,0) L AH2! ((← (-,0),-{4}) (T,0),DX)
LET'S	(-,0) L AH2! (← (-,0),-) S (HH,0)
LEXICOMETRY	(-,0) L EH (← (-,0),-) S IH2! (← (-,0),-) (K,0) AA M UH4 (← (-,0),-) DR R IY2
LIGHT	(-,0) L (AYL,0) AYC! (AYR,0) ((← (-,0),-{4}) (T,0),DX)
LIKE	(-,0) L (AYL,0) AYC! (AYR,0) (← (-,0),-{4}) (K,0)
LIMIT	(-,0) L IH M UH4! ((← (-,0),-{4}) (T,0),DX)
LIMITED	(-,0) L IH M UH4! ((← (-,0),-) (T,D,0), DX) IH4 (← (-,0),-) (0,D)
LINDA	(-,0) L IH6 N! (← (-,0),-,D) (D,0) UH4
LINE	(-,0) L (AYL,0) AYC! (AYR,0) (N,DX)
LINEAR	(-,0) L IH3! N IY ER
LINGUISTICS	(-,0) L IH3 NX (← (-,0),-) WH IH S - T IH3 (← (-,0),-) S (HH,0)
LISP	(-,0) L IH6! S - (P,0)
LIST	(-,0) L IH6! (Z{4},(Z,0) S) (- (T,0),0)
LISTED	(-,0) L IH6! S - T (IX,IH4) (← (-,0),-) (0,DH,0)
LISTING	(-,0) L UH4 S - T! (IH3,IY) NX
LOCATION	(-,0) L OW3 (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH IH5 N
LOCATIONS	(-,0) L OW3 (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH IH5 N (Z{4},(Z,0) S)
LOGIC	(-,0) L AO (← (-,0),-) SH!{,8} IH3 (← (-,0),-{4}) (K,0)
LOGICAL	(-,0) L AO (← (-,0),-) SH!{,8} IH3 (← (-,0),-) (K,0) EL
LONG	(-,0) L2 OW4! NX
LOSING	(-,0) L UW3! (Z{4},(Z,0) S) (IH3,IY) NX
LOW	(-,0) L OW
MACHINE	(-,0) M IH5 SH! IY (N,DX)
MACHINES	(-,0) M IH5 SH! IY N (Z{4},(Z,0) S)
MACRO	(-,0) M AE5 (← (-,0),-) (K,0) R OW
MADELINE	(-,0) M AE! ((← (-,0),-) (D,0),DX) AH EL IH6 (N,DX)
MAGAZINES	(-,0) M AE5 (← (-,0),-) (G,0) IH4 (Z{4},(Z,0) S) IY N (Z{4},(Z,0) S)
MAKE	(-,0) M (EYL,0) EYC! (EYR,0) (← (-,0),-{4}) (K,0)
MANAGEMENT	(-,0) M AE5 (DX,N) EH2! SH{,8} M EH2 N ((← (-,0),-{4}) (T,0),DX)
MANIPULATING	(-,0) M IH5 N IH3 (← (-,0),-) P Y UH2 L (EYL,0) EYC! (EYR,0) ((← (-,0),-) T,DX) (IH3,IY) NX
MANIPULATORS	(-,0) M IH5 N IH3 (← (-,0),-) P Y UW2 L (EYL,0) EYC! (EYR,0) ((← (-,0),-) T,DX) ER (Z{4},(Z,0) S)
MANNA	(-,0) M AA! N AA
MANTRA	(-,0) M AO N! (← (-,0),-) DR R IH2
MANY	(-,0) M (EH2,EH3) (N,DX) IY!
MAPPING	(-,0) M AE5 (← (-,0),-) P (IH3,IY) NX
MARCH	(-,0) M AA! R (← (-,0),-) SH (HH,0)
MARKET	(-,0) M AA2 ER2! (← (-,0),-) (K,0) IH3 ((← (-,0),-{4}) (T,0),DX)
MARR	(-,0) M AA! ER2
MARSLAND	(-,0) M AO ER (Z{4},(Z,0) S) L UH4! N (← (-,0),-,0) (D,0)
MARTELLI	(-,0) M ER2! (← (-,0),-) T EL3 IY2
MARVIN	(-,0) M AA R! V IH (N,DX)
MARY	(-,0) M AE2! ER IY2
MASINTER	(-,0) M UH4 S EH2! N ((← (-,0),-) T,DX) ER
MASSACHUSETTS	(-,0) M AE5 S IH5 (← (-,0),-) SH{,8} UW3! S IH4 (← (-,0),-) S (HH,0)
MATCHING	(-,0) M AE5! (← (-,0),-) SH{,10} IH5 NX
MAY	(-,0) M (EYL,0) EYC EYR!
MCCARTHY	(-,0) M AA5 (← (-,0),-) (K,0) AA3! ER2 TH IY
MCCORDUCK	(-,0) M (← (-,0),-) (K,0) AA4! ER ((← (-,0),-) D,DX) IH8 (← (-,0),-{4}) (K,0)
MCDERMOTT	(-,0) M IH3 (← (-,0),-) DR ER M EH4 (← (-,0),-) (T,0)
ME	(-,0) M IY!
MEANING	(-,0) M IY N! (IH3,IY) NX

MEANS	(-,0) M IY N! (Z{4},(Z,0) S)
MEDICAL	(-,0) M EH ((← (-,0),-) (D,0),DX) IH2 (← (-,0),-{4}) (K,0) EL
MEETING	(-,0) M IY! ((← (-,0),-) T,DX) IH7 NX
MEETINGS	(-,0) M IY! ((← (-,0),-) T,DX) IH7 NX (Z,(S,0,S))
MELTZER	(-,0) M AA2 EL3! (← (-,0),-) S ER
MEMORIES	(-,0) M EH2! M (OW4,0) (R,ER2) IY2 (Z(S,0),S)
MEMORY	(-,0) M EH2! M (OW4,0) (R,ER2) IY2
MENTION	(-,0) M (EH2,IH) N! (← (-,0),-,0) SH{,10} IH5 N
MENTIONED	(-,0) M (EH2,IH) N! (← (-,0),-,0) SH{,10} IH5 N ((← (-,0),-{4}) (D,0),DX)
MENTIONING	(-,0) M (EH2,IH) N (← (-,0),-,0) SH IH5! N (IH3,IY) NX
MENTIONS	(-,0) M (EH2,IH) N! (← (-,0),-,0) SH IH3 N (Z{4},(Z,0) S)
MENU	(-,0) M EH2! N Y (AX,IH7)
MENUS	(-,0) M EH2! N Y IH7 (Z{4},(Z,0) S)
META-SYMBOLIC	(-,0) M EH ((← (-,0),-) T,DX) IH3 S IH5! M ((← (-,0),-{4}) (B,0),B) AO! EL IH3 (← (-,0),-{4}) (K,0)
METAMATHEMATICS	(-,0) M EH ((← (-,0),-) T,DX) IH5 M AE TH AH2 M! AE5 ((← (-,0),-) T,DX) IH3 (← (-,0),-) S (HH,0)
METHODS	(-,0) M EH2 TH IH4 (← (-,0),-) S (HH,0)
MICHAEL	(-,0) M (AYL,0) AYC! (AYR,0) (← (-,0),-) (K,0) EL
MICHALSKI	(-,0) M IH (← (-,0),-) (K,0) AO! EL S - (K,0) IY
MICHIE	(-,0) M IH2! (← (-,0),-) SH{,8} IY
MIKE	(-,0) M (AYL,0) AYC! (AYR,0) (← (-,0),-{4}) (K,0)
MINIMAL	(-,0) M IH3 N IH! M EL2
MINKER	(-,0) M IH2! NX (← (-,0),-) (K,0) ER2
MINSKY	(-,0) M IH3 N S - (K,0) IY!
MITCHELL	(-,0) M IH3! (← (-,0),-) SH{,10} EL3
MLISP	(-,0) EH4 M (-,0) L IH6! S - (P,0)
MLISP2	(-,0) EH4 M (-,0) L IH6! S - T IH2 UW (UW2,0)
MODEL	(-,0) M AA! ((← (-,0),-) D,DX) EL2
MODELING	(-,0) M AA! ((← (-,0),-) D,DX) EL (IH3,IY) NX
MODELS	(-,0) M! (AO,AA) ((← (-,0),-) D,DX) EL3! (Z{4},(Z,0) S)
MONITOR	(-,0) M AA N UH! ((← (-,0),-) T,DX) (EH,0) ER
MONKEY	(-,0) (M,M)) UH2 NX (← (-,0),-) (K,0) IY
MONTH	(-,0) M (AA!,UH2!) N (← (-,0),-,0) TH (HH,0)
MONTHS	(-,0) M (AA!,UH2!) N (← (-,0),-,0) (T,0,TH) S (HH,0)
MORE	(-,0) M AA4! ER2
MOST	(-,0) M OW! S -{4} (T,0)
MOSTOW	(-,0) M AA S - T (AWL,0) AWC! (AWR,0)
MOTION	(-,0) M OW SH IH5 N
MOVE	(-,0) M UW2! V (F,0)
MOVEMENTS	(-,0) M UW2 V M EH2 N (← (-,0),-) S (HH,0)
MOVIES	(-,0) M UW2 V! IY (Z{4},(Z,0) S)
MULTILEVEL	(-,0) M EL2 ((← (-,0),-{4}) (T,0),DX) IY L EH V! EL
MULTIPROCESS	(-,0) M OW4 EL2 ((← (-,0),-{4}) (T,0),DX) IY! (← (-,0),-) (P R,PR (R,0)) AO S IH7 S (HH,0)
MUSIC	(-,0) M (Y,0) IY IH4! (Z{4},(Z,0) S) IH4 (← (-,0),-{4}) (K,0)
MUST	(-,0) M UH2! S -{4} (T,0)
MYSELF	(-,0) M (AYL,0) AYC (AYR,0) S AH2! EL F (HH,0)
NAGEL	(-,0) N (EYL,0) EYC! (EYR,0) (← (-,0),-) (G,0) EL
NASH-WEBBER	(-,0) N AE5 SH W EH3! (← (-,0),-{4}) (B,0) ER
NATIONAL	(-,0) N AE5 SH IH4 N EL2
NATURAL	(-,0) N AE5! (← (-,0),-) SH{,10} ER2 EL3
NETS	(-,0) N AH2!{3,6} (← (-,0),-) S (HH,0)
NETWORK	(-,0) N EH2 (← (-,0),-) (T -,0) W (AA4,0) ER2! (← (-,0),-{4}) (K,0)
NETWORKS	(-,0) N EH2 (← (-,0),-) (T -,0) W ER2! (← (-,0),-) S (HH,0)
NEURAL	(-,0) N AA4! (R,ER2) EL2
NEW	(-,0) N (IH2,0) UW! (UW2,0)
NEWBORN	(-,0) N (IH3,0) UW! (← (-,0),-{4}) (B,0) AA4 ER2 (N,DX)
NEWCOMER	(-,0) N (IH3,0) UW! (← (-,0),-) (K,0) AA M ER
NEWELL	(-,0) N (IH5,UH,0) UW2!{10,30} EL
NEWEST	(-,0) N UW IH! S -{4} (T,0)

NEWEY	(-,0) N (UH4,0) UW! IY
NEWSLETTER	(-,0) N IH5! (UW3,0) (Z{4},(Z,0) S) L EH2 ((← (-,0),-) T,DX) ER
NEXT	(-,0) N EH! (← (-,0),-) S - (T,0)
NIH	(-,0) EN (AYL,0) AYC! (AYR,0) (EYL,0) EYC (EYR,0) (← (-,0),-) SH (HH,0)
NILS	(-,0) N IH3! EL (Z{4},(Z,0) S)
NILSSON	(-,0) N IY EL3! (-,0) S UH4 (N,DX)
NINE	(-,0) N (AYL,0) AYC (AYR,0) N!
NINETEEN	(-,0) N (AYL,0) AYC (AYR,0) N ((← (-,0),-) T,DX) IY! (N,DX)
NINETY	(-,0) N (AYL,0) AYC (AYR,0) N ((← (-,0),-) T,DX) IY!
NO	(-,0) N OW4!
NOMINATING	(-,0) N AA M UH N (EYL,0) EYC! (EYR,0) ((← (-,0),-) T,DX) (IH3,IY) NX
NOMINATION	(-,0) N AA M UH N (EYL,0) EYC! (EYR,0) SH IH5 N
NOMINEES	(-,0) N AA M UH! N IY (Z{4},(Z,0) S)
NON-INDEPENDENT	
	(-,0) N AA N IH3 N ((← (-,0),-) D,DX) IH3! (← (-,0),-) P EH2 N ((← (-,0),-,0) D,DX,0) IH2 N ((← (-,0),-{4}) (T,0),DX)
NONDETERMINISTIC	
	(-,0) N AA2 N ((← (-,0),-) D,DX) IY! (← (-,0),-) (DR,T) ER M IH7 N IH3 S - T IH3 (← (-,0),-{4}) (K,0)
NORI	(-,0) N AA4! ER2 IY
NORMAN	(-,0) N OW4! ER2 M UH (N,DX)
NOT	(-,0) N AA! ((← (-,0),-{4}) (T,0),DX)
NOTES	(-,0) N OW! (← (-,0),-) S (HH,0)
NOVEMBER	(-,0) N OW! V EH3 M (← (-,0),-{4}) (B,0) (ER,AH3)
NRL	(-,0) (EH N,EN) AA3 ER2! EH EL
OBJECT	(-,0) AO (← (-,0),-) SH{,8} IH2!{,14} ((← (-,0),-{4}) (T,0),DX)
OBJECTS	(-,0) AO (← (-,0),-) SH{,8} IH2!{,14} (← (-,0),-) S (HH,0)
OCTOBER	(-,0) AA2 ((← (-,0),-) T,DX) OW! (← (-,0),-{4}) (B,0) ER
OF	(-,0) (UH,UH2) V!
OHLANDER	(-,0) OW EL2! AE4 N ((← (-,0),-) D,DX) ER
OK	(-,0) OW (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0)
OLDEST	(-,0) OW! EL ((← (-,0),-) (D,0),DX) IH6 S -{4} (T,0)
ON	(-,0) AA2! (N,DX)
ON-LINE	(-,0) AA N L2 (AYL,0) AYC! (AYR,0) (N,DX)
ONE	(-,0) W AA4! (N,DX)
ONES	(-,0) W AA! N (Z{4},(Z,0) S)
ONLY	(-,0) OW4! N2 L2 IY
ONTOGENY	(-,0) EH2 N (← (-,0),-) T AO! (← (-,0),-,0) SH{,8} IH5 N IY
OPERATIONAL	(-,0) AO (← (-,0),-) (P,0) ER2 (EYL,0) EYC! (EYR,0) SH (IH5 N,EN) EL2
OPTIMAL	(-,0) AA ((← (-,0),-) T,DX) IH6 M! EL2
OPTIMIZED	(-,0) AA (← (-,0),-) T IH5 M (AYL,0) AYC! (AYR,0) (Z{4},(Z,0) S) - (0,D)
OR	(-,0) (OW3,AA4,0) ER2!{5,14}
ORDER	(-,0) UW4 ER! ((← (-,0),-) D,DX) ER
ORDERS	(-,0) UW4 ER! ((← (-,0),-) D,DX) ER (Z{4},(Z,0) S)
ORGANIZATION	(-,0) AA4 ER (← (-,0),-) (G,0) IH3 N IH6 (Z{4},(Z,0) S) (EYL,0) EYC! (EYR,0) SH IH5 N
ORIENTED	(-,0) UW4 ER2! IY EH2 N ((← (-,0),-) T,DX) IH4 (← (-,0),-) (D,0)
OUR	(-,0) (AA3,(AWL,0) AWC (AWR,0)) ER!
OURSELVES	(-,0) AA R S EH2 (EL!,L!) (V,←) (Z{4},(Z,0) S)
OVERLAYS	(-,0) OW V ER L (EYL,0) EYC (EYR,0) (Z{4},(Z,0) S)
PACKET	(← (-,0),-) P AE3! (← (-,0),-) (K,0) IH3 ((← (-,0),-{4}) (T,0),DX)
PAIR	(← (-,0),-) P EH! ER
PAMELA	(← (-,0),-) P AE! (M,←) AA EL3 AA4
PAPER	(← (-,0),-) P (EYL,0) EYC! (EYR,0) (← (-,0),-) (P,0) ER2
PAPERS	(← (-,0),-) P (EYL,0) EYC! (EYR,0) (← (-,0),-) (P,0) ER (Z{4},(Z,0) S)
PAPERT	(← (-,0),-) P AE3! (← (-,0),-) (P,0) ER (← (-,0),-) (T,0)
PARALLELISM	(← (-,0),-) P EH3 ER UH2 EL3! EL IH6 (Z{4},(Z,0) S) (IH6 M,EM)
PARANOIA	(← (-,0),-) (P,0) ER UH N (OVL,0) OVC! (OVR,0) IH2
PARAPHRASE	(← (-,0),-) P AE2 ER (AX,0) F R (EYL,0) EYC! (EYR,0) (Z{4},(Z,0) S)
PARRY	(← (-,0),-) P AE2 ER! IY2
PARTIAL	(← (-,0),-) P AA3 ER SH{,10} IH EL

PASCAL	(← (-,0),-) P AE4! S - (K,0) AE EL3
PAT	(← (-,0),-) P AE! ((← (-,0),-{4}) (T,0),DX)
PATHFINDER	(← (-,0),-) P AE4 TH F (AYL,0) AYC! (AYR,0) N ((← (-,0),-) D,DX) ER
PATTERN	(← (-,0),-) P AE3! (DX,((← (-,0),-) T,DX)) ER (N,DX)
PEARL	(← (-,0),-) (P,0) ER2! EL2
PERCEPTION	(← (-,0),-) (P,0) ER S EH4! (← (-,0),-) SH{,10} IH5 N
PERCEPTRONS	(← (-,0),-) (P,0) ER S EH! (← (-,0),-) DR R AA N (Z{4},(Z,0) S)
PERFORMANCE	(← (-,0),-) (P,0) ER2 F AA4! ER2 M UH N S (HH,0)
PERRY	(← (-,0),-) P EH3 ER! IY
PETER	(← (-,0),-) P IY! ((← (-,0),-) T,DX) (EH3,0) ER
PHOTOGRAMMETRY	(-,0) F OW ((← (-,0),-) T,DX) IH8 (← (-,0),-) (G,0) R AE M IH7! (← (-,0),-) DR R IY2
PHRASE	(-,0) F R (EYL,0) EYC! (EYR,0) (Z{4},(Z,0) S)
PHRASES	(-,0) F R (EYL,0) EYC! (EYR,0) (Z{4},(Z,0) S) IH4 (Z{4},(Z,0) S)
PHYSICIANS	(-,0) F IX (Z{4},(Z,0) S) IH! SH IH5 N (Z{4},(Z,0) S)
PICTURE	(← (-,0),-) P IH3 (← (-,0),-) SH{,10} ER
PIECE	(← (-,0),-) P IY! S (HH,0)
PINGLE	(← (-,0),-) P (IH3,IY) NX (← (-,0),-) (G,0) EL2!
PLANES	(← (-,0),-) (P L,PL (L,0)) (EYL,0) EYC (EYR,0) N (Z{4},(Z,0) S)
PLANNER-LIKE	(← (-,0),-) (P L,PL (L,0)) AE5! (DX,N) ER (EL,L) (AYL,0) AYC! (AYR,0) (← (-,0),-{4}) (K,0)
PLANNING	(← (-,0),-) (P L,PL (L,0)) AE5! (DX,N) (IH3,IY) NX
PLANS	(← (-,0),-) (P L,PL (L,0)) AE5! N (Z{4},(Z,0) S)
PLAYING	(← (-,0),-) (P L,PL (L,0)) (EYL,0) EYC! (EYR,0) (IH3,IY) NX
PLEASE	(← (-,0),-) (P (L,L2),PL (L,0)) IY! (Z{4},(Z,0) S)
POKER	(← (-,0),-) P OW (← (-,0),-) (K,0) ER
POLYHEDRA	(← (-,0),-) P AO EL UH4 IY SH{,10} ER3 IH2
PREDICATE	(← (-,0),-) (P R,PR (R,0)) EH4! ((← (-,0),-) (D,0),DX) IH3 (← (-,0),-) (K,0) IH3 ((← (-,0),-{4}) (T,0),DX)
PREFERENTIAL	(← (-,0),-) (P R,PR (R,0)) EH3! F ER2 EH N (← (-,0),-,0) SH{,8} EL3
PRESENT	(← (-,0),-) (P R,PR (R,0)) IH5! (Z{4},(Z,0) S) EH2 N ((← (-,0),-{4}) (T,0),DX)
PRICE	(← (-,0),-) (P R,PR (R,0)) (AYL,0) AYC! (AYR,0) S (HH,0)
PRICE'S	(← (-,0),-) (P R,PR (R,0)) (AYL,0) AYC! (AYR,0) S IH4 (Z{4},(Z,0) S)
PRIMITIVES	(← (-,0),-) (P R,PR (R,0)) IH M AX (← (-,0),-) T IX V (Z{4},(Z,0) S)
PRINT	(← (-,0),-) (P R,PR (R,0)) (IH2,IH8) N! ((← (-,0),-{4}) (T,0),DX)
PRINTED	(← (-,0),-) (P R,PR (R,0)) (IH2!,AE4!) N ((← (-,0),-) T,DX) IX (← (-,0),-) (D,0)
PRINTING	(← (-,0),-) (P R,PR (R,0)) (IH2!,AE4!) N ((← (-,0),-) T,DX) IH5 NX
PROBLEM	(← (-,0),-) (P R,PR (R,0)) AO (← (-,0),-{4}) (B,0) EL! M
PROBLEMS	(← (-,0),-) (P R,PR (R,0)) AA (← (-,0),-{4}) (B,0) EL M (Z{4},(Z,0) S)
PROCEDURAL	(← (-,0),-) (P,0) ER2 S IY (← (-,0),-) SH{,10} ER2! EL
PROCEDURES	(← (-,0),-) P (R AX! , ER) S IY (← (-,0),-) SH{,10} ER (Z{4},(Z,0) S)
PROCEEDING	(← (-,0),-) P (R AX! , ER) S IY ((← (-,0),-) (D,0),DX) IH5 NX
PROCEEDINGS	(← (-,0),-) P (R AX! , ER) S IY ((← (-,0),-) (D,0),DX) IH5 NX (Z{4},(Z,0) S)
PROCESSES	(← (-,0),-) (P R,PR (R,0)) AO S IH4 S (IY,IX) (Z{4},(Z,0) S)
PROCESSING	(← (-,0),-) (P R,PR (R,0)) AA! S IH6 S (IH3,IY) NX
PRODUCE	(← (-,0),-) P (R AX!, ER) ((← (-,0),-) (D,0),DX) UW S (HH,0)
PRODUCED	(← (-,0),-) P (R AX, ER) ((← (-,0),-) (D,0),DX) UW! S -{4} (T,0)
PRODUCTION	(← (-,0),-) (P,0) ER ((← (-,0),-) (D,0),DX) AA2 (← (-,0),-) SH! IH4 (N,DX)
PRODUCTIVITY	(← (-,0),-) (P R,PR (R,0)) AA5! ((← (-,0),-) D,DX) AH (← (-,0),-) T IH3 V IH4 ((← (-,0),-) T,DX) IY
PROGRAM	(← (-,0),-) (P R,PR (R,0)) UW4 (← (-,0),-) (G,0) R AE5! M
PROGRAMMING	(← (-,0),-) (P R,PR (R,0)) UW4 (← (-,0),-) (G,0) R AE2! (M IH5,M1) NX
PROGRAMS	(← (-,0),-) (P R,PR (R,0)) OW (← (-,0),-) (G,0) R AE5! M (Z{4},(Z,0) S)
PROGRESS	(← (-,0),-) (P R,PR (R,0)) AO! (← (-,0),-) (G,0) R EH4 S (HH,0)
PROOF	(← (-,0),-) (P R,PR (R,0)) UW! F (HH,0)
PROOFS	(← (-,0),-) (P R,PR (R,0)) UW F S (HH,0)
PROPERTIES	(← (-,0),-) (P R,PR (R,0)) AO (← (-,0),-) (P,0) ER! ((← (-,0),-) T,DX) IY (Z{4},(Z,0) S)
PROTOCOL	(← (-,0),-) (P R,PR (R,0)) OW ((← (-,0),-) T,DX) OW! (← (-,0),-) (K,0) AO EL
PROTOCOLS	(← (-,0),-) (P R,PR (R,0)) OW ((← (-,0),-) T,DX) OW! (← (-,0),-) (K,0) AO EL (Z{4},(Z,0) S)
PROVER	(← (-,0),-) (P R,PR (R,0)) UW2! V ER2
PROVING	(← (-,0),-) (P R,PR (R,0)) UW! V IH5 NX
PSYCHOLOGY	(-,0) S (AYL,0) AYC! (AYR,0) (← (-,0),-) (K,0) AO (L,EL3) UH4 (← (-,0),-) SH IY

PUBLISH	(← (-,0),-) (P,0) (UH2,AO) (← (-,0),-{4}) (B,0) L IH4! SH (HH,0)
PUBLISHED	(← (-,0),-) (P,0) (UH2,AO) (← (-,0),-{4}) (B,0) L IH4! SH - (D,0)
PUBLISHER	(← (-,0),-) (P,0) (UH2,AO) (← (-,0),-{4}) (B,0) L IH2! SH ER
PUBLISHERS	(← (-,0),-) (P,0) (UH2,AO) (← (-,0),-{4}) (B,0) L IH2! SH ER (Z{4},(Z,0) S)
PURPOSE	(← (-,0),-) (P,0) ER2! (← (-,0),-) P UH4 S (HH,0)
PUTNAM	(← (-,0),-) P AA! (← (-,0),-) N UH4 M
QUERIES	(← (-,0),-) WH IY3 (ER (R,0),R) IY2! (Z{4},(Z,0) S)
QUESTION	(← (-,0),-) WH EH3! S (-,0) SH IH5 N
QUIT	(← (-,0),-) WH IH! ((← (-,0),-{4}) (T,0),DX)
QUOTE	(← (-,0),-) WH OW! ((← (-,0),-{4}) (T,0),DX)
QUOTED	(← (-,0),-) WH OW! ((← (-,0),-) T,DX) IX (← (-,0),-) (D,0)
RADIO	(-,0) R (EYL,0) EYC! (EYR,0) ((← (-,0),-) D,DX) IY OW
RAJ	(-,0) R AO! ZH
RALSTON	(-,0) R AO EL2! S - T UH (N,DX)
RANAN	(-,0) R AA! N AA2 (N,DX)
RAPHAEL	(-,0) R AE4! F IY2 EL3
RAYMOND	(-,0) R (EYL,0) EYC! (EYR,0) M UH N (← (-,0),-) (D,0)
REAL-WORLD	(-,0) R IY2 EL (-,0) W ER2! EL (← (-,0),-) (D,0)
REASONING	(-,0) R IY! (Z{4},(Z,0) S) (IH6,0) N (IH3,IY) NX
RECENT	(-,0) R IY2! S (IH5 N,EN) ((← (-,0),-{4}) (T,0),DX)
RECENTLY	(-,0) R IY2! S (IH6 N,EN) ((← (-,0),-{4}) (T,0),DX) L IY
RECOGNITION	(-,0) R EH3! (← (-,0),-) (K,0) IX (← (-,0),-) N IH3 SH IH5 N
REDDY	(-,0) R{,15} EH2! ((← (-,0),-) (D,0),DX) IY
REDUCTION	(-,0) R IY2 ((← (-,0),-) D,DX) AA2! (← (-,0),-) SH IH5 N
REED	(-,0) R IY (← (-,0),-) (D,0)
REFER	(-,0) (R,0) IY2! (-,0) F ER
REFERENCE	(-,0) R EH3! (-,0) F ER N S (HH,0)
REFERENCED	(-,0) R EH3! (-,0) F ER N S -{4} (T,0)
REFERENCES	(-,0) R EH3! (-,0) F ER N S IH6 (Z{4},(Z,0) S)
REFERRED	(-,0) R IY2! (-,0) F ER (← (-,0),-) (D,0)
REFERRING	(-,0) R IY2! (-,0) F ER (IH3,IY,0) NX
REGARDING	(-,0) R IY2! (← (-,0),-) (G,0) AA2 ER (DX,0) IH5 NX
REGION	(-,0) R IY! (← (-,0),-) SH{,8} IH5 N
REGULARLY	(-,0) R EH! (← (-,0),-) (G,0) (Y,0) UW (EL,L) ER L IY
REITER	(-,0) R IH2 ((← (-,0),-) T,DX) ER
RELATE	(-,0) R (IH3,IY2) L (EYL,0) EYC EYR! ((← (-,0),-{4}) (T,0),DX)
RELATED	(-,0) R (IH3,IY2) L (EYL,0) EYC EYR! ((← (-,0),-) T,DX) (IH3,IX) (← (-,0),-) (D,DH,0)
RELATES	(-,0) R (IH3,IY2) L (EYL,0) EYC EYR! (← (-,0),-) S (HH,0)
RELATIONAL	(-,0) R IY L (EYL,0) EYC! (EYR,0) SH N EL
RELEASED	(-,0) R (IH3,IY2) L IY! S -{4} (T,0)
REPORT	(-,0) R IH3 (← (-,0),-) P AA4! ER ((← (-,0),-{4}) (T,0),DX)
REPORTER	(-,0) R IH3 (← (-,0),-) P AA4! ER ((← (-,0),-) T,DX) ER
REPORTERS	(-,0) R (IH3,IY2) (← (-,0),-) P OW! ER2 ((← (-,0),-) T,DX) ER (Z{4},(Z,0) S)
REPORTS	(-,0) R (IH3,IY2) (← (-,0),-) P OW! (R,ER2) (← (-,0),-) S (HH,0)
REPRESENTATION	(-,0) R EH3 (← (-,0),-) (P R,PR (R,0)) IH2! (Z{4},(Z,0) S) IH4 N (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N
REPRESENTING	(-,0) R EH3 (← (-,0),-) (P R,PR (R,0)) IH2! (Z{4},(Z,0) S) EH2 N ((← (-,0),-) T,DX) (IH3,IY) NX
REQUEST	(-,0) R (IH3,IY2) (← (-,0),-) (K,0) OW AE S -{4} (T,0)
RESEARCH	(-,0) R IY S ER! (← (-,0),-) SH{,10}
RESOLUTION	(-,0) R IH6! (Z{4},(Z,0) S) UH2 (EL,L) OW2 SH IH5 N
RESOURCE	(-,0) R IY S UW4! ER S (HH,0)
RESPONSES	(-,0) R (IH3,IY2) S - (P,0) AA! N S (-,IX) (Z{4},(Z,0) S)
RESTRICT	(-,0) R (IH3,IY2) S (-,0) (DR (R,0),T R) IH2! ((← (-,0),-{4}) (T,0),DX)
RETRIEVAL	(-,0) (R (IH3,IY2),ER3) (← (-,0),-,0) (SH{,10},DR) (R,0) IY2! V UW EL
RETRIEVE	(-,0) R (IH3,IY2) (← (-,0),-) (SH{,10},T) R IY! V (F,0)
REVIEWS	(-,0) R (IH3,IY2) (←,V) (F,0) IY UW (Z{4},(Z,0) S)
RHOMBERG	(-,0) R AA M (← (-,0),-{4}) (B,0) ER2 (← (-,0),-) (G,0)
RICH	(-,0) R IH3! (← (-,0),-) SH{,10}
RICHARD	(-,0) R IH2! (← (-,0),-) SH{,10} ER (← (-,0),-) (D,0)

RICK	(-,0) R IH! (← (-,0),-{4}) (K,0)
RIEGER	(-,0) R IY2! (← (-,0),-,0) (G,0) ER
RIESBECK	(-,0) R IY S - (B,0) EH4 (← (-,0),-{4}) (K,0)
RISEMAN	(-,0) R (AYL,0) AYC! (AYR,0) (Z{4},(Z,0) S) M EH2 (N,DX)
ROBERT	(-,0) R AO! (← (-,0),-{4}) (B,0) ER ((← (-,0),-{4}) (T,0),DX)
ROBOT	(-,0) R OW (← (-,0),-{4}) (B,0) AO! ((← (-,0),-{4}) (T,0),DX)
ROBOTIC	(-,0) R OW (← (-,0),-{4}) (B,0) AO! ((← (-,0),-) T,DX) IH3 (← (-,0),-{4}) (K,0)
ROBOTICS	(-,0) R OW (← (-,0),-{4}) (B,0) AO! ((← (-,0),-) T,DX) IH3 (← (-,0),-) S (HH,0)
ROBOTS	(-,0) R OW (← (-,0),-{4}) (B,0) AA (← (-,0),-) S (HH,0)
ROCHESTER	(-,0) R AA! (← (-,0),-) SH{,10} EH4 S - DR ER
ROGER	(-,0) R AO! (← (-,0),-) SH{,10} ER
RON	(-,0) R AA! (N,DX)
ROSENFELD	(-,0) R OW! (OW3,0) (Z{4},(Z,0) S) IH6 N (-,0) F EH4 EL (← (-,0),-) (D,DH,0)
RUBIN	(-,0) R UW! (← (-,0),-{4}) (B,0) IH (N,DX)
RULE	(-,0) R UW2! EL
RULES	(-,0) R UW4! EL (Z{4},(Z,0) S)
RUMELHART	(-,0) R AA M EL2 (HH,0) AA3 ER (← (-,0),-) (T,0)
RUTGERS	(-,0) R AA5 (← (-,0),-) (G,0) ER! (Z{4},(Z,0) S)
RYCHENER	(-,0) R IH (← (-,0),-) N ER
S-L-GRAPHS	(-,0) EH2 S AH2 EL! (← (-,0),-) (G,0) R AE F S (HH,0)
SACERDOTI	(-,0) S AE S ER ((← (-,0),-) (D,0),DX) AO ((← (-,0),-) T,DX) IY
SAMMEY	(-,0) S AE5 M EH4 (← (-,0),-) (T,0)
SANDEWALL	(-,0) S AE4! N (← (-,0),-) (D,0) W EL2
SATISFACTION	(-,0) S AE (T,DX) IX S F AE (← (-,0),-) SH IH5 N
SAY	(-,0) S (EYL,0) EYC! (EYR,0)
SCENE	(-,0) S IY! (N,DX)
SCHANK	(-,0) SH AE5! NX (← (-,0),-,0) (K,0)
SCIENCE	(-,0) S (AYL,0) AYC! (AYR,0) IH5 N S (HH,0)
SCOTT	(-,0) S - (K,0) AA3! ((← (-,0),-{4}) (T,0),DX)
SEARCH	(-,0) S ER (← (-,0),-) SH (HH,0)
SEE	(-,0) S IY!
SEEK	(-,0) S (IY!,IX!) (← (-,0),-{4}) (K,0)
SEEKING	(-,0) S (IY,IX!) (← (-,0),-) (K,0) (IH3,IY) NX
SEGMENTATION	(-,0) S EH2 (← (-,0),-) (G,0) M UH4! N (← (-,0),-) T (EYL,0) EYC (EYR,0) SH IH5 N
SELECT	(-,0) S (AX,IX) L EH! ((← (-,0),-{4}) (T,0),DX)
SELTZER	(-,0) S EH EL2! (← (-,0),-) S ER
SEMANTIC	(-,0) S IH6! M AE5 N ((← (-,0),-) T,DX) IH3 (← (-,0),-{4}) (K,0)
SEMANTICS	(-,0) S IH6! M AE5 N ((← (-,0),-) T,DX) IH3 (← (-,0),-) S (HH,0)
SENSE	(-,0) S EH N S (HH,0)
SENTENCE	(-,0) S (EH2 (← (-,0),-) EN,(EH2 N,EN) (← (-,0),-,0) T EH2 N) S! (HH,0)
SENTENCES	(-,0) S (EH2 (← (-,0),-) EN,(EH2 N,EN) (← (-,0),-,0) T EH2 N) S! IH6 (Z{4},(Z,0) S)
SEPTEMBER	(-,0) S EH! (← (-,0),-) T EH M (← (-,0),-{4}) (B,0) ER
SERIAL	(-,0) S IH2 ER IY2! AH EL
SESSION	(-,0) S (AH2,EH) (-,0) SH! IH5 N
SESSIONS	(-,0) S (AH2,EH) (-,0) SH! IH5 N (Z{4},(Z,0) S)
SEVEN	(-,0) S AH2 V! UH4 (N,DX)
SEVENTEEN	(-,0) S (AH2,EH) V! ((IH5,EH2) N,EN) ((← (-,0),-) T,DX) IY (N,DX)
SEVENTY	(-,0) S (AH2,EH) V! ((IH5,EH2) N,EN) ((← (-,0),-) T,DX,0) IY
SEVERAL	(-,0) S EH2 V! R EL
SEYMOUR	(-,0) S IY M! OW ER2
SHAPE	(-,0) SH (EYL,0) EYC! (EYR,0) (← (-,0),-) (P,0)
SHAW	(-,0) SH AO!
SHE	(-,0) SH IY!
SHOOTING	(-,0) SH UW3! ((← (-,0),0) T,DX) (IH3,IY) NX
SHORTLIFFE	(-,0) SH AA4 ER2 (← (-,0),-) (T,0) L IH7 F (HH,0)
SHOULD	(-,0) SH (IH3,0) UH4! ((← (-,0),-) (D,0),DX)
SHOW	(-,0) SH AA5! (OW,0)
SIGART	(-,0) S IH3! (← (-,0),-) (G,0) AA3 (R,ER) ((← (-,0),-{4}) (T,0),DX)

SIKLOSSY	(-,0) S IH2 (← (-,0),-) (K,0) L AA2! S IY
SIMON	(-,0) S (AYL,0) AYC! (AYR,0) M (UH2,IH3) (N,DX)
SIMULATION	(-,0) S IH3 M Y UH! L (EYL,0) EYC! (EYR,0) SH (IH5 N,EN)
SIMULTANEOUS	(-,0) S (AYL,0) AYC! (AYR,0) M EL3 (← (-,0),-) T (EYL,0) EYC (EYR,0) N IY IH3 S (HH,0)
SIMULTANEOUSLY	(-,0) S (AYL,0) AYC! (AYR,0) M EL3 (← (-,0),-) T (EYL,0) EYC (EYR,0) N IY IH3 S L IY
SINCE	(-,0) S (IH3,IH6) N! S (HH,0)
SIX	(-,0) S IH3! (← (-,0),-) S (HH,0)
SIXTEEN	(-,0) S IH! (← (-,0),-) S - T IY (N,DX)
SIXTY	(-,0) S IH! (← (-,0),-) S - T IY
SIZE	(-,0) S! (AYL,0) AYC (AYR,0) (Z{4},(Z,0) S)
SLAGLE	(-,0) S L (EYL,0) EYC (EYR,0) (← (-,0),-) (G,0) EL
SLOW	(-,0) S L OW!
SMC	(-,0) EH4 S EH2! M S IY
SMITH	(-,0) S M IH3! TH (HH,0)
SNARING	(-,0) S N (EYL,0) EYC! (EYR,0) ER (IH3,IY) NX
SO	(-,0) S OW3!
SOBEL	(-,0) S OW3! (← (-,0),-{4}) (B,0) EL
SOFTWARE	(-,0) S AO! F (-,0) (T,0) W ER2
SOLOWAY	(-,0) S AO EL3 UW2 W (EYL,0) EYC! (EYR,0)
SOLUTIONS	(-,0) S OW L! UW SH IH5 N (Z{4},(Z,0) S)
SOLVING	(-,0) S AA! EL2 V IH5 NX
SOME	(-,0) S AA! M
SOMETHING	(-,0) S AA! M TH (IH3,IY) NX
SOMEWHERE	(-,0) S AA! M W EH3 ER
SORT	(-,0) S UW4! ER ((← (-,0),-{4}) (T,0),DX)
SORTS	(-,0) S UW4! ER (← (-,0),-) S (HH,0)
SOURCES	(-,0) S UW4 ER S IH4! (Z{4},(Z,0) S)
SPACE	(-,0) S - (P,0) (EYL,0) EYC! (EYR,0) S (HH,0)
SPANNING	(-,0) S - (P,0) AE5 (N,DX) (IH3,IY) NX
SPEECH	(-,0) S - (P,0) IY! (← (-,0),-) SH (HH,0)
SPEED	(-,0) S - (P,0) IY! (← (-,0),-) (D,0)
SPROULL	(-,0) S - (P R,PR (R,0)) AO EL3
SRI	(-,0) EH4 S AA2 ER2 (AYL,0) AYC! (AYR,0)
STANFORD	(-,0) S - T AE5 N F ER (← (-,0),-) (D,0)
STATE	(-,0) S - T (EYL,0) EYC! (EYR,0) ((← (-,0),-{4}) (T,0),DX)
STEREO	(-,0) S - T IH3! ER IY2 OW
STEVE	(-,0) S - T IY! V (F,0)
STOCHASTIC	(-,0) S - T IH3 (← (-,0),-) (K,0) AE4! S - T IH3 (← (-,0),-{4}) (K,0)
STOCK	(-,0) S - T AO! (← (-,0),-{4}) (K,0)
STOP	(-,0) S - T AA! (← (-,0),-) (P,0)
STORAGE	(-,0) S - T UW4! ER IH2 (← (-,0),-,0) (ZH (SH,0), SH)
STORED	(-,0) S - T (AA4,AO) ER! (← (-,0),-) (D,0)
STORIES	(-,0) S - T (AA4,AO) ER! IY (Z{4},(Z,0) S)
STORY	(-,0) S - T AO! ER IY
STRUCTURE	(-,0) S - DR R EH3 (← (-,0),-) SH{,8} ER
STRUCTURED	(-,0) S - DR R EH3! (← (-,0),-) SH{,8} ER (← (-,0),-) (D,DH,0)
STRUCTURES	(-,0) S - DR R EH3! (← (-,0),-) SH{,8} ER (Z{4},(Z,0) S)
STUDIES	(-,0) S - T UH4! ((← (-,0),-) D,DX) IY (Z{4},(Z,0) S)
SUBJECT	(-,0) S AA! (← (-,0),-) SH IH3 ((← (-,0),-{4}) (T,0),DX)
SUBJECTS	(-,0) S AA! (← (-,0),-) SH IH3 (← (-,0),-) S (HH,0)
SUBPROBLEMS	(-,0) S UH2 (← (-,0),-) (P R,PR (R,0)) AO! (← (-,0),-{4}) (B,0) EL2 M (Z{4},(Z,0) S)
SUBSELECT	(-,0) S AA! (← (-,0),-{4}) (B,0) S AX EL EH ((← (-,0),-{4}) (T,0),DX)
SUBSYSTEM	(-,0) S UH2 (← (-,0),-{4}) (B,0) S IH4! S - T (IH6 M,EM)
SUMEX	(-,0) S UH2! M EH2 (← (-,0),-) S (HH,0)
SUMMARIES	(-,0) S UH4! M R IY2 (Z{4},(Z,0) S)
SUMMARY	(-,0) S UH4! M R IY2
SUNG	(-,0) S UH4! NX
SUNSHINE	(-,0) S UH2 N SH (AYL,0) AYC! (AYR,0) (N,DX)

SURE	(-,0) SH ER!
SURNOTES	(-,0) S (IH,0) ER N OW2! OW (← (-,0),-) S (HH,0)
SURVEY	(-,0) S ER V (EYL,0) EYC! (EYR,0)
SURVEYS	(-,0) S ER V (EYL,0) EYC! (EYR,0) (Z{4},(Z,0) S)
SUSSEX	(-,0) S UH2! S IH3 (← (-,0),-) S
SUZUKI	(-,0) S IH4 (Z{4},(Z,0) S) UW3! (← (-,0),-) (K,0) IY
SYKES	(-,0) S (AYL,0) AYC! (AYR,0) (← (-,0),-) S (HH,0)
SYMBOL	(-,0) S IH5 M! (← (-,0),-,B) (B,0) EL2
SYNCHRONIZATION	(-,0) S IH3 N (← (-,0),-) K! ER N IH4 (Z{4},(Z,0) S) (EYL,0) EYC (EYR,0) SH (IH5 N,EN)
SYNTACTIC	(-,0) S IH3 N (← (-,0),-) T AE! (← (-,0),-) T IH3 K
SYNTAX	(-,0) S IH3 N ((← (-,0),-) T,DX) AE! (← (-,0),-) S (HH,0)
SYNTHESIS	(-,0) S IH5 N TH IH6! S IH4 S (HH,0)
SYNTHESIZER	(-,0) S IH5 N TH IH6 S (AYL,0) AYC! (AYR,0) (Z{4},(Z,0) S) ER
SYSTEM	(-,0) S IH4! S - T (IH6 M,EM)
SYSTEMS	(-,0) S IH4! S - T IH6 M (Z{4},(Z,0) S)
TAKE	((← (-,0),-) T,DX) (EYL,0) EYC EYR! (← (-,0),-{4}) (K,0)
TALES	((← (-,0),-) T,DX) (AE,EYL EYC EYR) L (Z{4},(Z,0) S)
TASK	((← (-,0),-) T,DX) AE S - (K,0)
TECH-II	((← (-,0),-) T,DX) EH! (← (-,0),-) T (IH2,0) UW3
TECHNICAL	((← (-,0),-) T,DX) EH (← (-,0),-) (K,0) N IH (← (-,0),-) (K,0) EL
TECHNIQUES	((← (-,0),-) T,DX) EH (← (-,0),-) (K,0) N IY (← (-,0),-) S (HH,0)
TECHNOLOGY	((← (-,0),-) T,DX) EH3 (← (-,0),-) N AA EL3! UH4 (← (-,0),-) SH{,8} IY
TED	((← (-,0),-) T,DX) EH! (← (-,0),-) (D,0)
TELEOLOGICAL	((← (-,0),-) T,DX) IY2 EL3 IH2 EL3! AO (← (-,0),-) SH{,8} IH3 (← (-,0),-) (G,K) EL2
TELL	((← (-,0),-) T,DX) (AA3,0) EL!
TEMPORAL	((← (-,0),-) T,DX) EH! M (← (-,0),-,0) (P R,PR (R,0)) OW4 EL2
TEN	((← (-,0),-) T,DX) EH! (N,DX)
TERMINAL	(← (-,0),-) DR ER2 M! (IH5,UH2) N EL2
TERMINALS	((← (-,0),-) T,DX) ER2 M! IH5 N EL2 (-,0) (Z{4},(Z,0) S)
TERMINATE	((← (-,0),-) T,DX) ER M IH5 N (EYL,0) EYC! (EYR,0) ((← (-,0),-{4}) (T,0),DX)
TERMINATION	((← (-,0),-) T,DX) ER M IH5 N (EYL,0) EYC! (EYR,0) SH IH5 N
TERRY	((← (-,0),-) T,DX) AE2! (ER,R) IY2
TEXT	((← (-,0),-) T,DX) EH! (← (-,0),-) S -{4} (T,0)
TEXTURE	((← (-,0),-) T,DX) EH! (← (-,0),-) S (-,0) SH{,11} ER
THANK	(-,0) TH (AE,AE5) NX! (← (-,0),-{4}) (K,0)
THANKS	(-,0) TH (AE,AE5) NX! (← (-,0),-) S (HH,0)
THAT	(-,0) (TH,DH) AE! ((← (-,0),-{4}) (T,0),DX)
THAUMATURGIST	(-,0) TH AA M UH4 (← (-,0),-) T ER (← (-,0),-) SH{,8} IH3 S - (0,T)
THE	(-,0) (DH,TH) (IY!,UH!,IH6!{2},AH!{1,4})
THEIR	(-,0) (TH,DH) AH2! ER
THEM	(-,0) (DH,TH) EH4! M
THEOREM	(-,0) TH IH3! ER (IH M,EM)
THEORY	(-,0) (DH,TH) IH2! (ER,R) IY2
THERE	(-,0) (TH,DH{,13}) (EH3,AH2,0) ER!{2}
THESE	(-,0) (DH,TH) IY! (Z{4},(Z,0) S)
THEY	(-,0) DH (EYL,0) EYC! (EYR,0)
THIRTEEN	(-,0) TH IH! R ((← (-,0),-) T,DX) IY (N,DX)
THIRTY	(-,0) TH IH! R ((← (-,0),-) T,DX) IY
THIS	(-,0) (DH,TH) IH4! S (HH,0)
THOMAS	((← (-,0),-) T,DX) AA M IH6 S (HH,0)
THORNDYKE	(-,0) TH AO ER2! N ((← (-,0),-) D,DX) (AYL,0) AYC! (AYR,0) (← (-,0),-{4}) (K,0)
THOSE	(-,0) (DH,TH) (AA2,0) OW! (Z{4},(Z,0) S)
THOUGHT	(-,0) TH AO! ((← (-,0),-{4}) (T,0),DX)
THREE	(-,0) TH R IY!
THROUGH	(-,0) TH R UW!
TILL	((← (-,0),-) T,DX) IH7! EL3
TIME	((← (-,0),-) T,DX) (AYL,0) AYC! (AYR,0) M
TIMES	((← (-,0),-) T,DX) (AYL,0) AYC (AYR,0) M! (Z{4},(Z,0) S)

TITLE	((← (-,0),-) T,DX) (AYL,0) AYC! (AYR,0) ((← (-,0),-) T,DX) (AH3,0) EL
TITLES	((← (-,0),-) T,DX) (AYL,0) AYC! (AYR,0) ((← (-,0),-) T,DX) (AH3,0) EL (Z{4},(Z,0) S)
TO	((← (-,0),-) T,DX) (IH4!,(IH2,0) UW!,IX!)
TOPIC	((← (-,0),-) T,DX) AA! (← (-,0),-) (P,0) IH3 (← (-,0),-{4}) (K,0)
TOPICS	((← (-,0),-) T,DX) AO (← (-,0),-) (P,0) IH3! (← (-,0),-) S (HH,0)
TOPOLOGY	((← (-,0),-) T,DX) AO (← (-,0),-) P AO EL3! UH4 (← (-,0),-) SH{,10} IY
TRANSACTION	(← (-,0),-) (SH{,8},DR) (R,0) AE4! N S AE (← (-,0),-) SH{,8} IH5 N
TRANSACTIONS	(← (-,0),-) (SH{,8},DR) (R,0) AE4! N S AE (← (-,0),-) SH{,8} IH5 N (Z{4},(Z,0) S)
TRANSFER	(← (-,0),-) (SH{,8},DR) (R,0) AE4! N S F ER2
TRANSITION	(← (-,0),-) (SH{,8},DR) (R,0) AE4! N S IH SH{,8} IH5 N
TRANSMIT	(← (-,0),-) (SH{,8},DR) (R,0) AE4! N S M (IH3,IH) ((← (-,0),-{4}) (T,0),DX)
TRANSMITTING	(← (-,0),-) (SH{,8},DR) (R,0) AE4! N S M (IH3,IH) ((← (-,0),-) T,DX) IH5 NX
TREES	(← (-,0),-) (SH{,8},DR) (R,0) IY! (Z{4},(Z,0) S)
TROUBLE	(← (-,0),-) (SH{,8},DR) (R,0) AA! ((← (-,0),-{4}) (B,0),B) EL
TRY	(← (-,0),-) (SH{,8},DR) (R,0) (AYL,0) AYC! (AYR,0)
TUTOR	((← (-,0),-) T,DX) UW! ((← (-,0),-) T,DX) ER
TUTORIAL	((← (-,0),-) T,DX) UW3! ((← (-,0),-) T,DX) AA4 ER IY2 EL3
TUTORING	((← (-,0),-) T,DX) UW! ((← (-,0),-) T,DX) ER (IH3,IY) NX
TV	((← (-,0),-) T,DX) IY! V IY2
TWELVE	((← (-,0),-) T,DX) OW AA5 EL V (F,0)
TWENTY	((← (-,0),-) T,DX) OW EH4 N ((← (-,0),-) T,DX,0) IY
TWO	((← (-,0),-) T,DX) (IH2,0) UW! (UW2,0)
TYPES	((← (-,0),-) T,DX) (AYL,0) AYC! (AYR,0) (← (-,0),-) S (HH,0)
U.S.	(-,0) Y UW EH4! S (HH,0)
UHR	(-,0) Y UW4! ER
ULLMAN	(-,0) AO EL M IH4 (N,DX)
UNDERSTANDING	(-,0) UH4! N ((← (-,0),-) (D,0),DX,0) ER3 S (- T,-,T,0) AE4 N ((← (-,0),-) (D,0),DX,0) (IH3,IX) NX
UNIFORM	(-,0) Y UH! N IH F AA4 ER2 (M,←)
UNIVERSALS	(-,0) Y IH4 N! EH3 V ER2 S EL (Z{4},(Z,0) S)
UP	(-,0) AA2! (← (-,0),-) (P,0)
US	(-,0) IH6! S (HH,0)
USE	(-,0) Y UW! (Z{4},(Z,0) S)
USING	(-,0) Y UW3! (Z{4},(Z,0) S) (IH3,IY) NX
USSR	(-,0) Y UW EH4! S EH S AA2 ER2
USUALLY	(-,0) Y UW3! (ZH (SH,0),SH) EL2 IY
VARIETY	(-,0) V ER2! (AYL,0) AYC! (AYR,0) IH3 ((← (-,0),-) T,DX) IY
VERIFICATION	(-,0) V EH3 ER IH F (IX,IH3) (← (-,0),-) (K,0) (EYL,0) EYC! (EYR,0) SH (IH5,IX) (N,DX)
VIC	(-,0) (V,F) IH2! (← (-,0),-{4}) (K,0)
VIEWS	(-,0) (F,V) IY! UW (Z{4},(Z,0) S)
VISION	(-,0) (F,V) IH2! (← (-,0),-) SH IH5 N
VISUAL	(-,0) V IH2! (← (-,0),-) (ZH (SH,0),SH) UW2 EL
VOLUMES	(-,0) V AH! EL Y IH5 M (Z{4},(Z,0) S)
WALDINGER	(-,0) W AO EL ((← (-,0),-) D,DX) IH2! NX ER
WALLY	(-,0) W AO! EL3 IY2
WANT	(-,0) W AA N! (← (-,0),-,0) (T,0)
WAS	(-,0) W! (AA,UH,AA4) (Z{4},(Z,0) S)
WASN'T	(-,0) W AA! (Z{4},(Z,0) S) IH6 N ((← (-,0),-{4}) (T,0),DX)
WATSON	(-,0) W AA4 (← (-,0),-) S IH5 N
WAVEFORMS	(-,0) W (EYL,0) EYC (EYR,0) V F AO R M (Z{4},(Z,0) S)
WE	(-,0) W (IY2!,IY!)
WE'D	(-,0) W IY! (← (-,0),-) (D,0)
WE'RE	(-,0) W EH3! ER{10,20}
WE'VE	(-,0) W IY! (V,←)
WEAK	(-,0) W IY! (← (-,0),-{4}) (K,0)

Appendix III-C-1. AI Retrieval Language Grammar: AIXF

```
<$UTTERANCE>::= [ <$SENTENCE1> ]
<$A>::= THE
        A
        AN
<$ACQUIRE>::= HAVE
        SEE
        KNOW
        GET
<$AFFILIATION>::= <ADDRESS/S>
        <AFFILIATION/S>
<ADDRESS/S>::= ADDRESSES
        ADDRESS
<AFFILIATION/S>::= AFFILIATIONS
        AFFILIATION
<$AI>::= AI
        ARTIFICIAL INTELLIGENCE
<$ALSO>::= ALSO
        IN ADDITION
<$ALSO!MENTION!TOPICS>::= <$MENTION> <$TOPICS>
        <$MENTION> <$TOPICS> <$ALSO>
        <$ALSO> <$MENTION> <$TOPICS>
<$MENTION>::= CITE
        REFER TO
        <$BE> <$RE1>
        <DISCUSS/S>
        CONCERN
        CONTAIN THE PHRASE
        DESCRIBE
        RELATE TO
        <$HAVE> <$MENTIONED@HAVE>
        CONSIDER
        <MENTION/S>
<$TOPICS>::= <$TOPIC>
        <$TOPIC> <$CONJUNCTION> <$TOPIC>
<$ALWAYS>::= ALWAYS
        USUALLY
        REGULARLY
<$ANY!NODATE!PIECES>::= <$PIECES1>
        <$SOMETHING>
        <$SOME!> <$PIECES1>
<$PIECES1>::= <STORY/S>
        <ARTICLE/S>
        <BOOK/S>
        <PAPER/S>
        <ABSTRACT/S>
        <PROCEEDING/S>
        <REPORT/S>
        <ISSUE/S>
        <JOURNAL/S>
        NOTES
        <REVIEW/S>
        <VOLUME/S>
        PIECE
        <SURVEY/S>
        <SUMMARY/S>
        TECHNICAL PAPERS
```

```
<$PIECES1 2>::= <STORY/S 2>
        <ARTICLE/S 2>
        <BOOK/S 2>
        <PAPER/S 2>
        <ABSTRACT/S 2>
        <PROCEEDING/S 2>
        <REPORT/S 2>
        <ISSUE/S 2>
        <JOURNAL/S 2>
        NOTES
        <REVIEW/S 2>
        <VOLUME/S 2>
        PIECE
        <SURVEY/S 2>
        <SUMMARY/S 2>
        TECHNICAL PAPERS
<$SOMETHING>::= ANYTHING
        SOMETHING
        EVERYTHING
<$SOME!>::= <$A>
        <$SOME>
<$ANY!PIECES>::= <$PIECES>
        <$SOME!PIECES>
        <$SOME1> OF THE <$PIECES>
        <$SOMETHING> <$RECENT>
<$PIECES>::= <$PIECES1>
        <$DATE> <$PIECES1>
        <$PIECES1> <$WHEN!DATE>
        <$PIECES1> <$WRITTEN1> <$WHEN!DATE>
        <$RECENT> <$PIECES1>
<$SOME!PIECES>::= <$SOMETHING>
        <$A> <$PIECES>
        <$SOME1> <$THAT!PIECE4>
        <$SOME1> <$PIECES>
<$SOME1>::= ALL
        MANY
        ANY
        ANY MORE
        MORE
        SOME
        ANOTHER
        SOME MORE
<$RECENT>::= LATEST
        RECENT
        NEW
        CURRENT
<$ANY!SOURCE!PIECES>::= <$SOURCE!PIECES>
        <$SOME!> <$SOURCE!PIECES>
        <$SOME!> <$RECENT> <$SOURCE!PIECES@RECENT>
        <$SOME> <$PIECES> <$FROM> <$SOURCE>
        <$RECENT> <$SOURCE!PIECES@RECENT>
        <$PIECES> <$FROM> <$SOURCE>
<$SOURCE!PIECES>::= <$CONFERENCE>
        <$SOURCE> <$PIECES1 2>
        <PROCEEDING/S> <$FROM> <$A> <$CONFERENCE>
        <$CONFERENCE> <$PIECES1 2>
        <$PIECES> <$FROM> <$SOURCE>
<$SOURCE!PIECES@RECENT>::= <$CONFERENCE>
```

```
          <$SOURCE> <$PIECES1 2>
          <PROCEEDING/S> <$FROM> <$A> <$CONFERENCE>
          <$CONFERENCE> <$PIECES1 2>
<$ARTICLE0TITLE>::= HUMAN PROBLEM SOLVING
          THOUGHT AND LANGUAGE
<$ASK>::= ASK
          REQUEST
          DEMAND
          SAY
<$AUTHORS>::= <$AUTHORS1>
          <$AUTHORS1> <$CONJUNCTION> <$AUTHORS1>
<$AUTHORS1> = REDDY
          DREYFUS
          ANN RUBIN
          ANTHONY MARTELLI
          BERNARD MELTZER
          BERT RAPHAEL
          BONNIE NASH-WEBBER
          CHRISTOPHER RIESBECK
          CHUCK RIEGER
          DAVE RUMELHART
          DAVID MARR
          DAVID MICHIE
          DICK SELTZER
          DONALD NORMAN
          DOUG LENAT
          DREW MCDERMOTT
          EARL HUNT
          EARL SACERDOTI
          ED RISEMAN
          ELLIOT SOLOWAY
          ERIK SANDEWALL
          EUGENE CHARNIAK
          GARY HENDRIX
          GEORGE ERNST
          HERBERT BLOCK
          HILARY PUTNAM
          HUGH NAGEL
          IRV SOBEL
          JACK MINKER
          JACK MOSTOW
          JAMES SLAGLE
          JEAN SAMMET
          JEFFREY ULLMAN
          JOHN GASCHNIG
          JOHN MCCARTHY
          JOHN NEWCOMER
          JOSEPH WEIZENBAUM
          JUDEA PEARL
          KARL PINGLE
          KEITH PRICE
          KEN RALSTON
          KING SUNG FU
          LAURENT SIKLOSSY
          LINDA MASINTER
          LES EARNEST
          MADELINE BATES
          MARY NEWBORN
```

MARY SHAW
MIKE RYCHENER
MITCHELL NEWEY
NORI SUZUKI
PAMELA MCCORDUCK
PAT WINSTON
PERRY THORNDYKE
PETER KUGEL
RANAN BANERJI
RAYMOND SPROULL
RICH FIKES
RICH SMITH
RICHARD MICHALSKI
RICHARD WALDINGER
ROBERT REITER
ROGER SCHANK
RON OHLANDER
SCOTT FAHLMAN
SEYMOUR PAPERT
STEVE REED
STEVE COLES
STEVE ZUCKER
TED SHORTLIFFE
THOMAS MARSLAND
THOMAS SYKES
VIC LESSER
WALLY RHOMBERG
WOODY BLEDSOE
YORICK WILKS
ZOHAR MANNA
SIMON
NEWELL
WOODS
HOLLAND
ROSENFELD
FEIGENBAUM
FELDMAN
NILSSON
UHR
WINOGRAD
MINSKY
ALLEN COLLINS
ALLEN NEWELL
AZRIEL ROSENFELD
BILL WOODS
BRUCE BUCHANAN
CARL HEWITT
DANNY BOBROW
ED FEIGENBAUM
GIPS
HANS BERLINER
HARRY BARROW
HERB SIMON
ISSAC ASIMOV
JERRY FELDMAN
JOHN HOLLAND
KEN COLBY
LEE ERMAN

```
        LEONARD UHR
        MARVIN MINSKY
        MICHAEL ARBIB
        NILS NILSSON
        RAJ REDDY
        RICK HAYES-ROTH
        TERRY WINOGRAD
<$CONJUNCTION>::= AND
        NOT
        OR
        BUT NOT
        AND NOT
        OR NOT
<$AUTHORS!DATE>::= <AUTHOR/S> AND <DATE/S>
        <DATE/S> AND <AUTHOR/S>
<AUTHOR/S>::= AUTHORS
        AUTHOR
<DATE/S>::= DATES
        DATE
<$BE>::= <$BE1>
        <$HAVE> BEEN
<$BE1>::= <$BE[PRES]>
        <$BE[PAST]>
<$HAVE>::= HAVE
        HAS
<HAPPEN/S>::= HAPPEN
<$BE!>::= <$BE>
        <$BE1> NOT
        ISN'T
        AREN'T
        WASN'T
        WEREN'T
<$BE!TOPICS!MENTIONED>::= <$HAVE!> <$TOPICS> BEEN <$MENTIONED[PP]> <$SOMEWHERE>
        <$BE!> <$TOPICS> <$MENTIONED[PP]>
        <$HAVE!> <$TOPICS> BEEN <$MENTIONED[PP]>
        <$DO!> <$TOPICS> GET <$MENTIONED[PP]> <$SOMEWHERE>
        <$DO!> <$TOPICS> GET <$MENTIONED[PP]>
<$HAVE!>::= <$HAVE>
        HAVEN'T
        <$HAVE> NOT
        HASN'T
<$MENTIONED[PP]>::= <$CITED>
        DISCUSSED
        MENTIONED
        CONSIDERED
        <$WRITTEN> ABOUT
<$SOMEWHERE>::= IN <$ANY!PIECES>
        SOMEWHERE
        ANYWHERE
        AT ALL
<$SOMEWHERE 2>::= IN <$ANY!PIECES>
        SOMEWHERE
        ANYWHERE
        AT ALL
<$DO!>::= <$DO>
        <$DON'T>
<$BE[PRES]>::= IS
        ARE
```

```
<$BE[PAST]>::= WAS
        WERE
<$BE[THERE]>::= <$BE!>
        <$DO!> <$HEARSAY> HAVE
        <$BE!THERE>
<$HEARSAY>::= YOU
        THE DATA BANK
        THE DATA BASE
        HEARSAY
        THE SYSTEM
<$BE!THERE>::= <$BE!> THERE
        <$HAVE!> THERE BEEN
<$BE[THERE]!ANY!PIECES>::= <$BE[THERE]> <$ANY!PIECES>
        DO YOU HAPPEN TO HAVE <$ANY!PIECES>
        <$HOW!MANY!PIECES2> ARE THERE
<$HOW!MANY!PIECES2>::= <$HOW!MANY>
        <$HOW!MANY> <$PIECES>
<$CHESS>::= CHESS
        GAME PLAYING
<$CHOOSE>::= GET
        CHOOSE
        SELECT
        SUBSELECT
        RETRIEVE
<$CITE>::= <CITE/S>
        REFERENCE
        QUOTE
        REFER TO
        <$HAVE> <$CITED>
<CITE/S>::= CITES
        CITE
<$CITED>::= CITED
        QUOTED
        REFERENCED
        REFERRED TO
<$COMMAND>::= TRY TO GET <$WHAT>
<$WHAT>::= <$WHAT2>
        <$WHAT2> <$CONJUNCTION> <$WHAT1>
<$CONFERENCE3>::= <$A> <$CONFERENCE>
        <$CONFERENCE>
<$CONFERENCE>::= <$CONFERENCE1>
        <$CONFERENCE1> <$CONFERENCE2>
<$CONFERENCE1>::= IJCAI
        ACM
        IEEE
        IFIP
<$CONFERENCE2>::= <MEETING/S>
        <CONFERENCE/S>
        <SESSION/S>
        <CONVENTION/S>
<MEETING/S>::= MEETINGS
        MEETING
<CONFERENCE/S>::= CONFERENCES
        CONFERENCE
<SESSION/S>::= SESSIONS
        SESSION
<CONVENTION/S>::= CONVENTIONS
        CONVENTION
```

```
<$CONTAIN>::= <CONTAIN/S>
        CONTAINED
<CONTAIN/S>::= CONTAINS
        CONTAIN
<$CONTENTS!MENU>::= <$GIMME> THE <$KEYWORDS>
        <$WHAT!WHICH> <$KEYWORDS> <$RELATE!TO> <$SUPER!MENU>
        <$WHAT!WHICH> <$MENU!MENU> <$RELATE!TO> <$SUPER!MENU>
        <$WHAT!WHICH> <$KEYWORDS> <$MAY> <$I> USE FOR RETRIEVAL
        <$WHAT!BE> THE <$KEYWORDS>
<$GIMME>::= <$IWANNA>
        <$LEMME> <$ACQUIRE>
        <$WOULD> <$HEARSAY> RETRIEVE
        <$WOULD> <$HEARSAY> <$LIST>
        <$LIST>
        <$WOULD> <$HEARSAY> <$GIVE> <$ME>
        <$GIVE> <$ME>
        <$GIVE1>
        <$LIST> FOR <$ME>
        <$IWANNA> TO <$ACQUIRE>
        TRY TO GET
<$KEYWORDS>::= KEY <WORD/S>
        KEY <PHRASE/S>
        RETRIEVAL <KEY/S>
<$WHAT!WHICH>::= WHAT
        WHICH
<$RELATE!TO>::= <RELATE/S> TO
        <$BE> RELATED TO
<$SUPER!MENU>::= <$AI>
        GAME PLAYING
        LEARNING
        INFERENCE
        SEMANTIC NETWORKS
        COMPUTATIONAL LINGUISTICS
        UNDERSTANDING
        ADAPTATION
        INTERACTIVE DESIGN
        DESIGN
        AUTOMATIC PROGRAMMING
        HYPOTHESIS FORMATION
        DEDUCTIVE RETRIEVAL
        GEOMETRIC MODELING
        INTERACTIVE KNOWLEDGE SYSTEMS
        COGNITIVE SCIENCE
        COGNITION
        AUTOMATION
        DATA STRUCTURES
        FORMAL SEMANTICS
        LANGUAGE UNDERSTANDING
<$MENU!MENU>::= <TOPIC/S>
        TOPIC <MENU/S>
        <MENU/S>
        <SUBJECT/S>
        <AREA/S>
<$MAY>::= CAN
        COULD
        SHOULD
        MUST
        MAY
```

```
<$I>::= I
        WE
<$WHAT!BE>::= <$WHAT!WHICH> <$BE>
        WHAT'S
<$DATE>::= <$DATE1>
        THE LAST <$NUMBER> <$TIMES>
        <$DATE1> <$CONJUNCTION> <$DATE1>
        <$DATE1> <$THROUGH> <$DATE1>
<$DATE1>::= <$YEAR>
        <$MONTH>
        THE <MONTH/S> OF <$MONTH>
        <$MONTH> <$YEAR>
<$NUMBER>::= <$HUNDREDS>
        <$NUMBER1>
        <$HUNDREDS> <$NUMBER1>
<$TIMES>::= MONTHS
        ISSUES
        VOLUMES
        YEARS
        TIMES
<$THROUGH>::= TO
        THROUGH
        TILL
<$YEAR>::= NINETEEN <$NUMBER1>
<$MONTH>::= MAY
        JANUARY
        FEBRUARY
        MARCH
        APRIL
        JUNE
        JULY
        AUGUST
        SEPTEMBER
        OCTOBER
        NOVEMBER
        DECEMBER
<MONTH/S>::= MONTHS
        MONTH
<$DESIRE>::= <$WANT>
        WOULD LIKE
        DESIRE
<$WANT>::= DESIRE
        SEEK
        WANT
        WISH
<$DIGITS>::= ONE
        TWO
        THREE
        FOUR
        FIVE
        SIX
        SEVEN
        EIGHT
        NINE
<$DO>::= DO
        DOES
        DID
<$DON'T>::= DON'T
```

```
        DIDN'T
        DOESN'T
        <$DO> NOT
<$DO!SOME!>::= <$DO!> <$SOME!>
<$FILE>::= FILE
        COPY
<$FINISHED>::= <$FINISHED1>
        ALL <$FINISHED1>
<$FINISHED1>::= THROUGH
        DONE
        FINISHED
<$FROM>::= IN
        OF
        FROM
        AMONG
<$GET!AFFILIATION>::= WHERE <$DO> <$THEY> WORK
        <$DO!> <$THEY> WORK <$WHERE>
        <$WHAT!BE> <$THEIR> <$AFFILIATION>
        WHAT <ADDRESS/S> <$BE> GIVEN FOR <$ITS!AUTHOR>
<$THEY>::= THEY
        HE
        SHE
<$WHERE>::= <$WHERE1>
        <$WHERE1> <$CONJUNCTION> <$WHERE1>
<$THEIR>::= THEIR
        HIS
        HER
<$ITS!AUTHOR>::= <$ITS> <AUTHOR/S>
        THE <AUTHOR/S> <$OF!THAT!PIECE>
<$GET!AUTHOR>::= <$PROVIDE> <$ITS!AUTHOR>
        WHO
        WHO WROTE <$THAT!PIECE>
        WHO <$BE> <$ITS!AUTHOR>
<$PROVIDE>::= <$GIMME>
        <$WHAT!BE>
<$THAT!PIECE>::= <$THESE>
        <$THAT!PIECE2>
<$GET!AUTHOR!DATE>::= <$PROVIDE> <$ITS!AUTHOR!DATE>
<$ITS!AUTHOR!DATE>::= <$ITS> <$AUTHORS!DATE>
        THE <$AUTHORS!DATE> <$OF!THAT!PIECE>
<$GET!DATE>::= <$PROVIDE> <$ITS!DATE>
        <$WHEN> <$WHAT!WHICH> <MONTH/S> <$BE[PAST]> <$THAT!PIECE> <$WRITTEN1>
        WHEN <$BE> <$THAT!PIECE> <$WRITTEN1>
<$ITS!DATE>::= <$ITS> <DATE/S>
        THE <DATE/S> <$OF!THAT!PIECE>
<$WHEN>::= <$FROM>
        SINCE
        AFTER
        BEFORE
        DURING
<$WRITTEN1>::= PUBLISHED
        PRINTED
        WRITTEN
        WRITTEN UP
        ISSUED
        RELEASED
        PRODUCED
<$WRITTEN1 2>::= PUBLISHED
```

```
          PRINTED
          WRITTEN
          WRITTEN UP
          ISSUED
          RELEASED
          PRODUCED
<$GET!INFO>::= <$GET!AFFILIATION>
          <$GET!AUTHOR>
          <$GET!AUTHOR!DATE>
          <$GET!DATE>
          <$GET!NEWEST>
          <$GET!TITLE>
          <$GET!TITLE!NEWEST>
          <$GET!TITLE!OLDEST>
          <$GET!PUBLISHER>
          <$GET!REFERENCES>
          <$GET!OLDEST>
<$GET!NEWEST>::= <$PROVIDE> THE <$NEWEST>
<$GET!TITLE>::= <$PROVIDE> <$ITS!TITLE>
          WHICH <ONE/S>
<$GET!TITLE!NEWEST>::= <$GET!TITLE> OF THE <$NEWEST>
<$GET!TITLE!OLDEST>::= <$GET!TITLE> OF THE <$OLDEST>
<$GET!PUBLISHER>::= <$PROVIDE> <$ITS!PUBLISHER>
          <$BE> <$THAT!PIECE> PUBLISHED <$IN> <$SOURCE2>
          WHERE DID <$THAT!PIECE> APPEAR
<$GET!REFERENCES>::= <$PROVIDE> <$ITS!REFERENCES>
          WHO <$BE[PAST]> <$CITED> <$IN> <$THAT!PIECE>
          <$DO!> <$THAT!PIECE> <$CITE> <$SOURCE2>
          <$HOW!MANY> REFERENCES <$WERE!THERE!IN!THAT!PIECE>
<$GET!OLDEST>::= <$PROVIDE> THE <$OLDEST>
<$NEWEST>::= <$NEWEST1>
          <$NEWEST1> ONES
          <$NEWEST1> <$NUMBER>
          <$NEWEST1> <$NUMBER> <$PIECES1>
          <$NEWEST1> <$FROM> <$THAT!PIECE>
          <$NEWEST1> <$PIECES1 2>
<$OLDEST>::= <$OLDEST1>
          <$OLDEST1> ONES
          <$OLDEST1> <$NUMBER>
          <$OLDEST1> <$FROM> <$THAT!PIECE>
<$ITS!PUBLISHER>::= <$ITS> <PUBLISHER/S>
          THE <PUBLISHER/S> <$OF!THAT!PIECE>
<$IN>::= IN
          BY
<$SOURCE2>::= <$CONFERENCE3>
          <$SOURCE>
          <$A> <$SOURCE>
          <$A> <$RECENT> <$SOURCE>
<$ITS!REFERENCES>::= <$ITS> <REFERENCE/S>
          THE <REFERENCE/S> <$FROM> <$THAT!PIECE>
          <$ANY!PIECES> <$CITED> <$IN> <$THAT!PIECE>
<$HOW!MANY>::= <$WHAT!WHICH>
          HOW MANY
<$WERE!THERE!IN!THAT!PIECE>::= <$BE!THERE>
          <$BE> GIVEN
          <$BE[THERE]> <$FROM> <$THAT!PIECE>
<$ITS!TITLE>::= <$ITS> <TITLE/S>
          THE <TITLE/S> <$OF!THAT!PIECE>
```

```
<ONE/S>::= ONE
        ONES
<$IWANNA>::= <$I'D> LIKE
        <$I> <$DESIRE>
<$LEMME>::= LET <$ME>
        LET'S
        <$MAY> <$I>
<$WOULD>::= WOULD
        CAN
        COULD
<$LIST>::= LIST
        PRINT
        TRANSMIT
        WRITE
<$GIVE>::= <$GIVE1>
        GET FOR
        TELL
<$ME>::= ME
        US
<$GIVE1>::= GET
        GIVE
        SHOW
<$GRIPE>::= <$BE> <$HEARSAY> <$ALWAYS> <$SLOW>
        HAVEN'T YOU FINISHED
        WHY <$BE> <$HEARSAY> SO SLOW
        DO RESPONSES EVER COME FASTER
        HOW <$MAY> <$I> <$IMPROVE!HS>
        DO ALL QUERIES TAKE THIS LONG
        HOW LONG DOES IT TAKE
        WHEN WILL <$HEARSAY> HAVE THE ANSWER
        DOES IT ALWAYS TAKE THIS LONG TO ANSWER <$ME>
        WHAT <$MAY> <$I> DO TO <$IMPROVE!HS>
<$SLOW>::= SO SLOW
        SLOW
        THIS SLOW
<$IMPROVE!HS>::= HELP
        SPEED <$HEARSAY> UP
        HELP <$HEARSAY>
        USE <$HEARSAY> EFFICIENTLY
<$HELP>::= HELP
        HOW BIG IS THE DATA BASE
        <$WHAT!SORTS!OF> <RETRIEVAL/S> CAN <$HEARSAY> DO
        TELL <$ME> WHAT TO DO
        <$WHAT!WHICH> <$MENU!MENU> <$MAY> <$I> <$SEEK>
        <$WHAT!SORTS!OF> RETRIEVAL <KEY/S> <$MAY> <$I> <$SEEK>
        <$WHAT!SORTS!OF> <$PIECES1> <$BE[PRES]> AVAILABLE
        <$WHAT!SORTS!OF> <$MENU!MENU> <$BE> STORED
        WHAT IS KNOWN <$RE> EVERY <$PIECES1>
        WHAT DO <$I> HAVE TO DO
        CAN YOU HELP
        <$WHAT!SORTS!OF> <$MENU!MENU> <$BE!THERE>
        CAN YOU HELP <$ME>
        HELP <$ME>
        <$PROVIDE> <$A> <$MENU!MENU>
        <$WHAT!IS> <$SOME> <$MENU!MENU> <$FROM> <$AI>
        <$WHAT!WHICH> FACTS ARE STORED
        <$WHAT!IS> THE SIZE OF <$HEARSAY>
        WHAT <$MAY> <$I> <$ASK>
        WHAT CAN <$HEARSAY> DO
<$WHAT!SORTS!OF>::= <$WHAT!WHICH> <$SORTS> OF
<RETRIEVAL/S>::= RETRIEVAL
<$SEEK>::= REQUEST
        CHOOSE
        SEEK
<KEY/S>::= KEYS
        KEY
<$RE>::= <$RE1>
        <$WHICH> <$MENTION>
<$WHAT!IS>::= WHAT'S
        WHAT <$BE[PRES]>
<$SOME>::= <$SOME1>
        <$SOME1> OF THE
<$HOW!MANY!AUTHORS>::= <$HOW!MANY> <AUTHOR/S>
        <$DO!SOME!> <AUTHOR/S>
<$HOW!MANY!BE>::= <$HOW!MANY!OF!THEM> <$BE>
        <$BE1> <$SOME!OF!THEM>
<$HOW!MANY!OF!THEM>::= <$HOW!MANY>
        <$HOW!MANY> OF <$THAT!PIECE3>
<$SOME!OF!THEM>::= <$THAT!PIECE>
        <$SOME1> OF <$THAT!PIECE4>
<$THAT!PIECE3>::= <$THAT!PIECE2>
        <$THEM>
<$HOW!MANY!PIECES>::= <$HOW!MANY!PIECES2>
        <$DO!> <$ANY!PIECES>
<$HOW!MANY!SOURCE!PIECES>::= <$DO!> <$ANY!SOURCE!PIECES>
        <$HOW!MANY!PIECES> <$FROM> <$SOURCE2>
        <$WHAT!WHICH> <$SOURCE>
        <$HOW!MANY> <$SOURCE!PIECES>
<$SOURCE>::= <$AI> JOURNAL
        ASSOCIATION FOR COMPUTATIONAL LINGUISTICS
        COGNITIVE PSYCHOLOGY
        ACL
        AI TEXT
        ARPA SURNOTES
        SIGART NEWSLETTER
        COMMUNICATIONS OF THE ACM
        CACM
        COMPUTING <SURVEY/S>
        COMPUTING REVIEWS
        INFORMATION AND CONTROL
        IEEE <TRANSACTION/S>
        IJCAI <PROCEEDING/S>
        IFIP <PROCEEDING/S>
        JOURNAL OF THE ACM
<$HUNDREDS>::= <$NUMBER1> HUNDRED
        A HUNDRED
<$NUMBER1>::= <$DIGITS>
        <$NUMBER2>
        <$TEENS>
<$I!BE>::= <$I'M>
        <$I'VE> BEEN
<$I'M>::= I AM
        I'M
        WE'RE
        WE ARE
<$I'VE>::= I HAVE
```

```
          WE'VE
          WE HAVE
  <$I'D>::= <$I> WOULD
          I'D
          WE'D
  <$ITS>::= THE
          THEIR
          ITS
  <$OF!THAT!PIECE>::= OF <$THAT!PIECE>
          FROM <$THAT!PIECE>
  <PUBLISHER/S>::= PUBLISHERS
          PUBLISHER
  <REFERENCE/S>::= REFERENCE
          REFERENCES
  <TITLE/S>::= TITLES
          TITLE
  <WORD/S>::= WORDS
          WORD
  <PHRASE/S>::= PHRASES
          PHRASE
  <$LAST>::= LAST
          MOST RECENTLY
  <$LEARNING>::= LEARNING
          GRAMMATICAL INFERENCE
          NEURAL NETWORKS
          ABSTRACTION
          DYNAMIC CLUSTERING
          CELL ASSEMBLY THEORY
  <$LIST!THEM>::= THE <$NEWEST>
          <$THE!NEXT>
          <$GIMME> <$THE!NEXT>
          <$MAY> <$I> HAVE <$THAT!PIECE> <$LISTED>
          <$LIST> THE <$NEWEST>
          <$LIST> <$THAT!PIECE>
  <$THE!NEXT>::= THE NEXT
          THE NEXT <$NUMBER>
          THE FIRST
          UP TO <$NUMBER>
          BETWEEN <$NUMBER> AND <$NUMBER> OF THEM
          <$NUMBER> MORE
          THE FIRST <$NUMBER>
  <$LISTED>::= LISTED
          PRINTED
          WRITTEN
  <$LISTING>::= LISTING
          PRINTING
          TRANSMITTING
          WRITING
  <$MAKE>::= COPY
          WRITE
          MAKE
          PRODUCE
          GENERATE
  <$MAKE!A!FILE>::= <$MAKE> <$ME> A <$FILE>
          <$MAKE!A!FILE> OF THE <$NEWEST>
          <$MAKE> A <$FILE>
  <$MAKE!FILE>::= <$MAKE!A!FILE>
          <$MAKE!A!FILE> <$FROM> <$THAT!PIECE>
```

```
<$RE1>::= RELATED TO
        ABOUT
        REGARDING
        ON
        REFERRING TO
        DISCUSSING
        CONCERNING
        MENTIONING
<DISCUSS/S>::= DISCUSSES
        DISCUSS
<$MENTIONED>::= <$BE> <$RE>
        <$MENTIONED@HAVE>
<$MENTIONED@HAVE>::= <$MENTIONED[PP]>
        RELATED TO
        CONCERNED
<MENTION/S>::= MENTIONS
        MENTION
<$WRITTEN>::= <$WRITTEN1>
        <$RECENTLY> <$WRITTEN1>
        <$WRITTEN1> <$RECENTLY>
<$WRITTEN 2>::= <$WRITTEN1 2>
        <$RECENTLY 2> <$WRITTEN1 2>
        <$WRITTEN1 2> <$RECENTLY 2>
<TOPIC/S>::= TOPICS
        TOPIC
<MENU/S>::= MENUS
        MENU
<SUBJECT/S>::= SUBJECTS
        SUBJECT
<AREA/S>::= AREAS
        AREA
<$MY>::= OUR
<$NEGSTATEMENT>::= <$I> <$UNWANT> TO <$ACQUIRE> <$WHAT>
        <$DON'T> <$GIVE> <$ME> <$WHAT>
<$UNWANT>::= WOULD NOT LIKE
        <$DON'T> <$WANT>
<$NEWEST1>::= LAST
        NEWEST
        <$LAST> <$WRITTEN>
        LATEST
        MOST RECENT
<$NO>::= NO
<$NUMBER2>::= <$TENS>
        <$TENS> <$DIGITS>
<$TEENS>::= NINETEEN
        TEN
        ELEVEN
        TWELVE
        THIRTEEN
        FOURTEEN
        FIFTEEN
        SIXTEEN
        SEVENTEEN
        EIGHTEEN
<$TENS>::= TWENTY
        THIRTY
        FORTY
        FIFTY
```

```
          SIXTY
          SEVENTY
          EIGHTY
          NINETY
<$OLDEST1>::= OLDEST
          FIRST
          EARLIEST
          FIRST <$WRITTEN>
<$OURSELVES>::= <RETRIEVAL/S>
          <$MY> ATTENTION
          MYSELF
          OURSELVES
          ALL <RETRIEVAL/S>
<$WHEN!DATE>::= THIS YEAR
          LAST YEAR
          SINCE LAST YEAR
          <$WHEN> <$DATE>
<STORY/S>::= STORIES
          STORY
<ARTICLE/S>::= ARTICLES
          ARTICLE
<BOOK/S>::= BOOKS
          BOOK
<PAPER/S>::= PAPERS
          PAPER
<ABSTRACT/S>::= ABSTRACTS
          ABSTRACT
<PROCEEDING/S>::= PROCEEDINGS
          PROCEEDING
<REPORT/S>::= REPORTS
          REPORT
<ISSUE/S>::= ISSUES
          ISSUE
<JOURNAL/S>::= JOURNALS
          JOURNAL
<REVIEW/S>::= REVIEWS
<VOLUME/S>::= VOLUMES
<SURVEY/S>::= SURVEYS
          SURVEY
<SUMMARY/S>::= SUMMARIES
          SUMMARY
<STORY/S 2>::= STORIES
          STORY
<ARTICLE/S 2>::= ARTICLES
          ARTICLE
<BOOK/S 2>::= BOOKS
          BOOK
<PAPER/S 2>::= PAPERS
          PAPER
<ABSTRACT/S 2>::= ABSTRACTS
          ABSTRACT
<PROCEEDING/S 2>::= PROCEEDINGS
          PROCEEDING
<REPORT/S 2>::= REPORTS
          REPORT
<ISSUE/S 2>::= ISSUES
          ISSUE
<JOURNAL/S 2>::= JOURNALS
```

```
        JOURNAL
<REVIEW/S 2>::= REVIEWS
<VOLUME/S 2>::= VOLUMES
<SURVEY/S 2>::= SURVEYS
        SURVEY
<SUMMARY/S 2>::= SUMMARIES
        SUMMARY
<$POLITENESS>::= PLEASE
        THANKS
        THANK YOU
<$PRUNE!DATE>::= <$LEMME> <$RESTRICT> <$OURSELVES> TO <$ANY!PIECES>
        <$LEMME> <$RESTRICT> <$OURSELVES> TO <$ANY!NODATE!PIECES> <$WRITTEN1> <$WHEN!DATE>
        <$I'M> INTERESTED IN <$ANY!NODATE!PIECES> <$WRITTEN1> <$WHEN!DATE>
        <$CHOOSE> <$FROM> <$ANY!NODATE!PIECES> <$WHEN!DATE>
<$RESTRICT>::= CONFINE
        RESTRICT
        LIMIT
<$PRUNE!LIST>::= <$PRUNE!DATE>
        <$PRUNE!LIST!TOPIC>
        <$PRUNE!LIST!AUTHOR>
        <$PRUNE!LIST!TITLE>
        <$PRUNE!LIST!CITATION>
        <$PRUNE!LIST!DATE>
        <$PRUNE!LIST!SOURCE>
        <$PRUNE!LIST!SOURCE!DATE>
        <$PRUNE!LIST!WHERE!WRITTEN>
<$PRUNE!LIST!TOPIC>::= <$DO> <$SOME!OF!THEM> <$ALSO!MENTION!TOPICS>
        <$I'M> ONLY INTERESTED IN <$WHAT>
        <$BE> <$THAT!PIECE> <$RE!TOPICS>
        <$BE> <$SOME!OF!THEM> <$ALSO> <$RE!TOPICS>
        <$HOW!MANY!OF!THEM> <$ALSO!MENTION!TOPICS>
<$PRUNE!LIST!AUTHOR>::= <$BE> <$SOME!OF!THEM> <$WRITTEN!BY> <$AUTHORS>
        <$HOW!MANY!BE> <$WRITTEN!BY> <$AUTHORS>
        <$BE> <$SOME> BY <$AUTHORS>
<$PRUNE!LIST!TITLE>::= <$WHAT!WHICH> <TITLE/S> <$MENTION> <$TOPICS>
<$PRUNE!LIST!CITATION>::= <$DO!> <$SOME!OF!THEM> <$CITE> <$AUTHORS>
        <$BE!> <$AUTHORS> <$CITED> <$IN> <$THAT!PIECE>
        <$HOW!MANY!OF!THEM> <$CITE> <$AUTHORS>
        <$BE!> <$AUTHORS> <$CITED> <$IN> <$SOME!OF!THEM>
        <$HAVE!> <$AUTHORS> BEEN <$CITED> <$IN> <$SOME!OF!THEM>
        <$BE> <$AUTHORS> <$CITED> <$IN> <$SOME!OF!THEM>
<$PRUNE!LIST!DATE>::= <$BE[PAST]> <$SOME1> <$WRITTEN1> <$WHEN!DATE>
        <$I> DEMAND <$ANY!NODATE!PIECES> <$WHEN!DATE>
<$PRUNE!LIST!SOURCE>::= <$HOW!MANY> OF <$THAT!PIECE3> APPEARED <$RECENTLY> IN <$A> <$SOURCE>
        <$BE!> <$SOME!OF!THEM> <$FROM> <$SOURCE2>
        <$BE!> <$SOME!OF!THEM> <$FROM> <$ANY!SOURCE!PIECES>
<$PRUNE!LIST!SOURCE!DATE>::= <$BE1> <$SOME!OF!THEM> <$FROM> <$ANY!SOURCE!PIECES> <$WHEN!DATE>
<$PRUNE!LIST!WHERE!WRITTEN>::= <$HOW!MANY!PIECES> <$BE[PAST]> <$WRITTEN> <$WHERE>
        <$HOW!MANY!BE> <$WRITTEN> <$WHERE>
<$WRITTEN!BY> = BY
        <$WRITTEN 2> BY
<$RECENTLY>::= RECENTLY
        LATELY
        IN RECENT <$TIMES>
        IN RECENT <$PIECES1>
<$RECENTLY 2>::= RECENTLY
        LATELY
        IN RECENT <$TIMES>
        IN RECENT <$PIECES1 2>
<$RE!TOPICS>::= <$RE> <$TOPICS> <$WHEN!DATE>
        <$RE> <$TOPICS>
        <$WHEN!DATE> <$RE!TOPICS>
<$QUERY>::= <$QUERY1>
        <$QUERY1> <$RECENTLY 2>
<$QUERY1>::= <$QUERY!AUTHOR>
        <$QUERY!AUTHOR!AT!PLACE>
        <$QUERY!AUTHOR!DATE>
        <$QUERY!AUTHOR!TOPIC>
        <$QUERY!TOPIC>
        <$QUERY!CITATION>
        <$QUERY!WHERE!CONFERENCE>
        <$QUERY!DATE>
        <$QUERY!DATE!OF!ARTICLE!TITLE>
        <$QUERY!LAST!BY!AUTHOR>
        <$QUERY!NEWEST!TOPIC>
        <$QUERY!REFERENCED!PIECE>
        <$QUERY!SOURCE>
        <$QUERY!SOURCE!AUTHOR>
        <$QUERY!SOURCE!CITATION>
        <$QUERY!SOURCE!DATE>
        <$QUERY!SOURCE!REFERENCED>
        <$QUERY!SOURCE!TOPIC>
        <$QUERY!TITLE!SOURCE>
        <$QUERY!TOPIC!DATE>
<$QUERY!AUTHOR>::= <$BE[THERE]!ANY!PIECES> <$WRITTEN!BY> <$AUTHORS>
        DID <$AUTHORS> <$WRITE> <$ANY!NODATE!PIECES> <$RECENTLY>
        DID <$AUTHORS> <$WRITE> <$ANY!PIECES>
        WHAT <$HAVE> <$AUTHORS> <$WRITTEN>
        WHO WROTE <$ANY!NODATE!PIECES> <$RE> <$TOPICS> <$WHEN!DATE>
        <$HOW!MANY!PIECES2> <$BE> <$WRITTEN!BY> <$AUTHORS>
        WHAT ABOUT <$AUTHORS>
        <$HOW!MANY!PIECES2> <$HAVE> <$AUTHORS> <$WRITTEN>
        <$HAVE> <$AUTHORS> <$WRITTEN 2> <$ANY!PIECES>
        <$PROVIDE> <$ANY!PIECES> <$WRITTEN!BY> <$AUTHORS>
        <$HAVE!> <$ANY!PIECES> <$WRITTEN!BY> <$AUTHORS> APPEARED
        <$HAVE!> <$ANY!PIECES> BEEN <$WRITTEN!BY> <$AUTHORS>
<$WRITE>::= WRITE
        PUBLISH
<$QUERY!AUTHOR!AT!PLACE>::= <$HOW!MANY> <AUTHOR/S> WORK <$WHERE>
<$QUERY!AUTHOR!DATE>::= DID <$AUTHORS> <$WRITE> <$ANY!NODATE!PIECES> <$WHEN!DATE>
        <$HAVE> <$AUTHORS> <$WRITTEN> <$WHEN!DATE>
        <$HOW!MANY!PIECES2> <$BE> <$WRITTEN!BY> <$AUTHORS> <$WHEN!DATE>
        <$HOW!MANY!PIECES2> <$HAVE> <$AUTHORS> <$WRITTEN> <$WHEN!DATE>
<$QUERY!AUTHOR!TOPIC>::= WHO WROTE <$ANY!NODATE!PIECES>
        <$QUERY!TOPIC> <$WRITTEN!BY> <$AUTHORS>
        <$HOW!MANY!AUTHORS> <$MENTION> <$TOPICS>
        <$QUERY!AUTHOR> <$RE!TOPICS>
        WHO <$HAVE> <$WRITTEN> <$RE!TOPICS>
<$QUERY!TOPIC>::= <$BE!TOPICS!MENTIONED>
        WHAT ABOUT <$TOPICS>
        <$BE!> <$ANY!PIECES> <$WRITTEN> <$RE!TOPICS>
        <$BE[PAST]> <$TOPICS> WRITTEN UP <$RECENTLY>
        <$BE[THERE]!ANY!PIECES> <$RE!TOPICS> <$ALSO> <$RE!TOPICS>
        WHEN <$BE[PAST]> <$TOPICS> LAST <$MENTIONED>
        <$SOME!PIECES> <$RE!TOPICS>
        <$HOW!MANY!PIECES> <$MENTION> <$TOPICS>
```

```
     <$WHAT!SORTS!OF> <$TOPICS> <$BE> <$WRITTEN>
     WHEN <$BE1> <$TOPICS> <$LAST> <$MENTIONED[PP]>
     <$HOW!MANY!PIECES> <$RE!TOPICS> <$ALSO!MENTION!TOPICS>
     WHERE <$BE!TOPICS!MENTIONED>
     <$BE!TOPICS!MENTIONED> <$SOMEWHERE 2>
     <$BE!TOPICS!MENTIONED> <$SOMEWHERE 2> <$RECENTLY>
     <$HAVE!> <$ANY!PIECES> <$RE!TOPICS> BEEN <$WRITTEN>
     <$BE[THERE]!ANY!PIECES> <$RE!TOPICS>
     <$BE!TOPICS!MENTIONED> <$IN> <$ANY!PIECES>
     <$HAVE!> <$ANY!PIECES> APPEARED <$WHICH> <$MENTION> <$TOPICS>
     <$HOW!MANY!PIECES2> <$RE!TOPICS> <$BE> THERE
     <$HOW!MANY!PIECES2> <$RE!TOPICS> <$BE> <$WRITTEN>
     <$DO!> <$ANY!PIECES> <$RE!TOPICS> EXIST
<$QUERY!CITATION>::= <$HOW!MANY!PIECES> <$CITE> <$AUTHORS>
     <$BE> <$AUTHORS> <$MENTIONED[PP]> <$SOMEWHERE>
     <$WHAT!WHICH> <$PIECES1> <$WRITTEN!BY> <$AUTHORS> <$BE> <$CITED>
     <$BE[THERE]!ANY!PIECES> <$WHICH> <$MENTION> <$ANY!PIECES> <$WRITTEN!BY> <$AUTHORS>
     <$BE!> <$AUTHORS> <$CITED> <$IN> <$ANY!NODATE!PIECES> <$WRITTEN1> <$WHEN!DATE>
     <$HAVE> <$ANY!PIECES> <$CITED> <$AUTHORS>
     <$HAVE> <$AUTHORS> BEEN <$CITED> <$IN> <$ANY!PIECES>
<$WHICH>::= WHO
     WHICH
     THAT
<$QUERY!WHERE!CONFERENCE>::= <$HOW!MANY> <CONFERENCE/S> <$BE[PAST]> <$WHERE>
     <$BE[THERE]> <$SOME!> <CONFERENCE/S> <$WHERE>
<$QUERY!DATE>::= <$HOW!MANY> <$PIECES1> <$BE[PAST]> <$WRITTEN1> <$WHEN!DATE>
     <$WHAT!WHICH> <$BE!> THE <$NEWEST> <$WRITTEN!BY> <$AUTHORS>
     <$BE!THERE> <$ANY!NODATE!PIECES> <$WHEN!DATE>
     <$GIMME> <$ANY!NODATE!PIECES> <$WRITTEN1> <$WHEN!DATE>
<$QUERY!DATE!OF!ARTICLE!TITLE>::= WHEN WAS <$ARTICLE!TITLE> <$WRITTEN1>
<$QUERY!LAST!BY!AUTHOR>::= WHEN WAS THE LAST <$PIECES1> <$WRITTEN!BY> <$AUTHORS> <$WRITTEN1>
<$QUERY!NEWEST!TOPIC>::= <$PROVIDE> THE <$NEWEST> <$RE!TOPICS>
<$QUERY!REFERENCED!PIECE>::= <$HOW!MANY!PIECES> <$CITE> <$THAT!PIECE3>
<$QUERY!SOURCE>::= <$BE[THERE]!ANY!PIECES> <$FROM> <$SOURCE2>
     <$DO!SOME!> <$CONFERENCE> PUBLISH PROCEEDINGS
<$QUERY!SOURCE!AUTHOR>::= <$HOW!MANY!SOURCE!PIECES> CONTAINED <$ANY!PIECES> <$WRITTEN!BY> <$AUTHORS>
     <$HOW!MANY!SOURCE!PIECES> <$CONTAIN> WINOGRAD'S ARTICLE
     DID <$AUTHORS> PRESENT <$ANY!NODATE!PIECES> AT <$CONFERENCE3>
     DID <$AUTHORS> PRESENT <$ANY!NODATE!PIECES> AT <$CONFERENCE3> <$WHEN!DATE>
<$QUERY!SOURCE!CITATION>::= <$HOW!MANY!SOURCE!PIECES> <$CITE> <$AUTHORS>
<$QUERY!SOURCE!DATE>::= DID <$SOURCE2> PUBLISH <$SOMETHING> <$WHEN!DATE>
     <$BE!THERE> <$ANY!SOURCE!PIECES> <$WHEN!DATE>
<$QUERY!SOURCE!REFERENCED>::= <$GIMME> <$ANY!SOURCE!PIECES> <$CITED> BY <$AUTHORS>
<$QUERY!SOURCE!TOPIC>::= <$GIMME> <$ANY!PIECES> <$FROM> <$SOURCE2> <$RE!TOPICS>
     DID ANYONE PUBLISH <$RE!TOPICS> IN <$SOURCE2>
     <$HOW!MANY!SOURCE!PIECES> <$MENTION> <$TOPICS>
     <$BE!TOPICS!MENTIONED> IN <$SOURCE2>
<$QUERY!TITLE!SOURCE>::= <$WHAT!BE> THE <TITLE/S> <$FROM> <$SOURCE2>
     <$PROVIDE> <$ITS!TITLE> <$FROM> <$SOURCE!PIECES>
<$QUERY!TOPIC!DATE>::= <$HOW!MANY> <$PIECES1> <$WHEN!DATE> <$MENTIONED> <$TOPICS>
<RELATE/S>::= RELATE
     RELATES
<$REQUEST>::= <$COMMAND>
     <$NEGSTATEMENT>
     <$QUERY>
     <$STATEMENT>
<$STATEMENT>::= <$GIMME> <$WHAT>
     TELL <$ME> <$RE!TOPICS>
```

```
<$SELECTION>::= <$WHAT!IS> <$SOME!> <$MENU!MENU> <$FROM> <$SUPER!MENU>
        <$I!BE> INTERESTED IN <$SUPER!MENU>
        <$WHAT!WHICH> <$MENU!MENU> <$BE[PRES]> RELATED TO <$WHAT!MENU>
        <$I!BE> ONLY INTERESTED IN <$PIECES1> <$RE> <$WHAT!MENU>
        THE <$MENU!MENU> <$I'M> INTERESTED IN <$BE[PRES]> <$WHAT!MENU>
        <$I'M> INTERESTED IN <$WHAT!MENU>
        <$CHOOSE> <$FROM> <$WHAT!MENU>
<$WHAT!MENU>::= <$SUPER!MENU>
        <$ANY!PIECES> <$RE> <$SUPER!MENU>
        <$WHAT!MENU> <$CONJUNCTION> <$WHAT!MENU>
<$SEMANTIC!NETS>::= <$UNDERSTANDING>
        SEMANTIC NETWORKS
        A SEMANTIC NETWORK
        SEMANTIC NETS
<$UNDERSTANDING>::= HEARSAY
        LANGUAGE UNDERSTANDING
        NATURAL LANGUAGE
        ENGLISH
        NATURAL LANGUAGE UNDERSTANDING
        SPEECH UNDERSTANDING
        SYNTAX
<$SENTENCE>::= <$CONTENTS!MENU>
        <$GET!INFO>
        <$GRIPE>
        <$HELP>
        <$LIST!THEM>
        <$MAKE!FILE>
        <$NO>
        <$PRUNE!LIST>
        <$REQUEST>
        <$SELECTION>
        <$YES>
        <$STOP!LISTING>
<$YES>::= YES
        OK
        SURE
<$STOP!LISTING>::= <$I'M> <$FINISHED>
        NO MORE
        <$I'VE> <$FINISHED>
        <$STOP> <$LISTING>
        <$STOP> THE <$LISTING>
<$SENTENCE1>::= <$SENTENCE>
        <$POLITENESS> <$SENTENCE>
        <$SENTENCE> <$POLITENESS>
<$THAT!PIECE4>::= <$THAT> <$PIECES1>
        <$THEM>
<$SORTS>::= <SORT/S>
        <KIND/S>
        <TYPE/S>
        <VARIETY/S>
<SORT/S>::= SORTS
        SORT
<KIND/S>::= KINDS
        KIND
<TYPE/S>::= TYPES
<VARIETY/S>::= VARIETY
<TRANSACTION/S>::= TRANSACTIONS
        TRANSACTION
```

```
<$STOP>::= STOP
        CEASE
        TERMINATE
        KILL
        FINISH
        QUIT
<$THAT>::= THIS
        THAT
        THESE
        THOSE
<$THESE>::= IT
        <$THAT>
        THEY
        EACH
<$THAT!PIECE2>::= <$THAT> <$PIECES1>
        <$THAT> <ONE/S>
<$THEM>::= <$THAT>
        THEM
<$TIME!SPACE>::= TIME
        SPACE
        TIME <$CONJUNCTION> SPACE
        SPACE <$CONJUNCTION> TIME
<$TOPIC>::= <$AI>
        PROBLEM SOLVING
        GIPS
        <$CHESS>
        <$LEARNING>
        INFERENCE
        <$SEMANTIC!NETS>
        CYBERNETICS
        COMPUTATIONAL LINGUISTICS
        PSYCHOLOGY
        CONTROL
        ADAPTATION
        INTERACTIVE DESIGN
        DESIGN
        AUTOMATIC PROGRAMMING
        HYPOTHESIS FORMATION
        DEDUCTIVE RETRIEVAL
        GEOMETRIC MODELING
        INTERACTIVE KNOWLEDGE SYSTEMS
        KNOWLEDGE SYSTEMS
        COGNITIVE SCIENCE
        COGNITION
        AUTOMATION
        DATA STRUCTURES
        FORMAL SEMANTICS
        A TASK ORIENTED DIALOGUE
        THE TECH-II CHESS PROGRAM
        SYNTHESIS OF LINE DRAWINGS
        TELEOLOGICAL REASONING
        TEMPORAL SCENE ANALYSIS
        TEXTURE ANALYSIS
        A THAUMATURGIST
        SHAPE TOPOLOGY
        THREE DIMENSIONAL MODELS
        A TUTOR OR TUTORING ON TV
        THE WEAK LOGIC OF PROGRAMS
```

THE DATES OF THE WORLD COMPUTER CHESS CONFERENCE
NEWSLETTER REPORTERS
OBJECT LOCATIONS AND MOVEMENTS IN NATURAL IMAGES
PARALLELISM IN PROBLEM SOLVING
THE PERFORMANCE OF PATTERN MATCHING RULES
A PROGRAM SYNTHESIZER FOR NETWORK PROTOCOLS
A PROGRAMMING APPRENTICE
A PROOF CHECKER FOR PROTOCOL TERMINATION EXPRESSIONS
A RADIO INTERVIEW ON SCIENCE FICTION
A TIME DOMAIN ANALYZER
INVARIANCES IN THE PERCEPTION OF FACES
THE LOCATION OF OBJECTS IN MAGAZINES
THE LOGICAL REDUCTION OF LISP DATA BASES
DATA BASES
A LOSING MOVE
MACHINE INTELLIGENCE IN MEDICAL DIAGNOSIS
MANAGEMENT INFORMATION SYSTEMS
OBJECT MANIPULATING ROBOTS
AUTOMATIC MANTRA GENERATION
SYMBOL MAPPING IN BASEBALL
THE STOCK MARKET
THE META-SYMBOLIC SIMULATION OF MULTIPROCESS SOFTWARE
THE METAMATHEMATICS OF MLISP OR MLISP2
MINIMAL SPANNING FORESTS OR TREES
MOTION IN SCENE DESCRIPTION
A MULTILEVEL ORGANIZATION
THE NOMINATION OF NOMINEES BY A NATIONAL NOMINATING COMMITTEE
NONDETERMINISTIC PROGRAMMING
MACRO PROCESSING FOR AN ON-LINE NEWSLETTER
THE ONTOGENY OF NON-INDEPENDENT SUBPROBLEMS
OPERATIONAL REASONING
LANGUAGE PARAPHRASE
OPTIMAL PROBLEM SOLVING SEARCH
OPTIMIZED CODE FOR THE TRANSFER OF COMMENTS
A PACKET BASED APPROACH TO NETWORK COMMUNICATION
THE PARRY SIMULATION OF PARANOIA
LINEAR LEXICOMETRY
MEANS FOR COMPUTER MOVIES
LOW ORDERS OF RECOGNITION PERFORMANCE
A TV REPORTER
A THEOREM PROVER PLANNING FOR PROGRESS
THE STRUCTURE OF ANY VARIETY OF COMPUTER TERMINAL
A CAI MONITOR
A COMMON SENSE ALGORITHM
ACQUISITION OF KNOWLEDGE
ACTIVE KNOWLEDGE
CYCLIC AND ACYCLIC ISOMERS
ADAPTIVE PRODUCTION SYSTEMS
PRODUCTION SYSTEMS
ADVISING PHYSICIANS
ALGEBRAIC REDUCTION
ALGOL
ALGORITHMIC AESTHETICS
ALL-OR-NONE SOLUTIONS
AN ADAPTIVE NATURAL LANGUAGE SYSTEM
AN ASSEMBLY ROBOT
AN AXIOMATIC SYSTEM
ANALOGY IN PROBLEM SOLVING

ANALYSIS OF CONTEXT
CONTEXT
ANALYSIS OF SENTENCES
ASSIMILATION OF NEW INFORMATION
AUGMENTED TRANSITION NETWORKS
AUTOMATED DEDUCTION
DEDUCTION
AUTOMATIC CODING
AUTOMATIC COMPUTATION
AUTOMATIC PROGRAM SYNTHESIS FROM EXAMPLE PROBLEMS
AUTOMATIC PROGRAM WRITING
AUTOMATIC PROOF OF CORRECTNESS
AUTOMATIC THEOREM PROVING
AXIOMATIC SEMANTICS
BACKGAMMON
BELIEF SYSTEMS
BINDINGS
BIOMEDICINE
BRAIN THEORY
BUSINESS PROBLEM SOLVING
CARTOGRAPHY
CASE SYSTEMS
CAUSAL REASONING
CHECKING PROOFS
CHESS PLAYING PROGRAMS
CIRCUIT ANALYSIS
COGNITIVE ROBOTIC SYSTEMS
COMMON SENSE
COMMON SENSE THEORY FORMATION
COMPLEX WAVEFORMS
COMPUTER ART
COMPUTER BASED CONSULTATIONS
COMPUTER CONTROLLED MANIPULATORS
COMPUTER GRAPHICS
COMPUTER MUSIC
COMPUTER VISION
CONCEPTUAL DESCRIPTIONS
CONCEPTUAL INFERENCE
CONCEPTUAL OVERLAYS
CONSTRAINT SATISFACTION
CONSTRUCTING PROGRAMS FROM EXAMPLES
CONSTRUCTION OF PROGRAMS
CONTINUOUS PROCESSES
COOPERATING SOURCES OF KNOWLEDGE
COPYING LIST STRUCTURES
CURVED OBJECTS
DATA BASES FOR INTERACTIVE DESIGN
DECISION THEORY
THE DEDUCTIVE PATHFINDER
DENOTATIONAL SEMANTICS
DEPTH PERCEPTION
DERIVATION PLANS
DESIGN AUTOMATION
DESIGN IN THE ARTS
DETECTION OF LIGHT SOURCES
DISPLAY TERMINALS
DRAGON
DRIVING A CAR

DYNAMIC BINDING
DYNAMIC PROGRAMMING
ELECTRONIC CIRCUITS
ELECTRONICS
THE ENVIRONMENT
EXPERT SYSTEMS
EXPLANATION CAPABILITIES
FABLES OR FAIRY TALES
FEATURE-DRIVEN SYSTEMS
THE FEDERAL JUDICIAL SYSTEM
FIRST ORDER LOGIC
FRAMES
FRAMES AND THE ENVIRONMENT
FUZZY KNOWLEDGE
FUZZY PROBLEM SOLVING
A GAME MODEL
GENERAL PURPOSE MODELS
GENERATION OF NATURAL LANGUAGE
GO OR GO-MOKU
GOAL SEEKING COMPONENTS
GRAPH INTERPRETABLE GAMES
HETEROSTATIC THEORY
HEURISTIC PROGRAMMING
HEURISTIC TECHNIQUES
HUMAN BEHAVIOR
HUMAN MEMORY
HUMAN VISION
IMPROVING PROGRAMS
INDUCTIVE ASSERTIONS
INDUSTRIAL APPLICATION
INEXACT REPRESENTATION
INFERENCES
INFERENTIAL QUESTION ANSWERING
INFORMATION PROCESSING UNIVERSALS
INHERITANCE OF PROPERTIES
INTELLIGENT MACHINES
INTENTIONS
INTERACTIVE PROGRAM SYNTHESIS
INTERPRETIVE SEMANTICS
INTONATION
INVARIANCE FOR PROBLEM SOLVING
INVESTMENT ANALYSIS
ITERATION
KNOWLEDGE BASED SYSTEMS
LAMBDA CALCULUS
LANGUAGE DESIGN
LANGUAGE PRIMITIVES
LARGE DATA BASES
THE BAY AREA CIRCLE
THE BERKELEY DEBATE
THE DREYFUS DEBATE
THE HISTORY OF AI
THE HUNGRY MONKEY
THE INSANE HEURISTIC
AXIOMS FOR GO
COMPUTER BASED CONSULTANT
IMAGE INTENSITY UNDERSTANDING
TROUBLE SHOOTING

```
        LANGUAGE COMPREHENSION
        <$TIME!SPACE> BOUNDS
        PERCEPTRONS
        COMPUTER NETWORKS
        GRAPH MATCHING
        ASSOCIATIVE <MEMORY/S>
        UNIFORM PROOF PROCEDURES
        PLANNER-LIKE LANGUAGES
        HILL CLIMBING
        <$TIME!SPACE> COMPLEXITY
        EVALUATION FUNCTIONS
        PROGRAM VERIFICATION
        FRAME THEORY
        PREDICATE CALCULUS
        GRAIN OF COMPUTATION
        PATTERN MATCHING
        RECOGNITION DEVICES
        PATTERN RECOGNITION
        STRUCTURED PATTERN RECOGNITION
        PATTERN DIRECTED FUNCTION INVOCATION
        RESOLUTION THEOREM PROVING
        MEDICAL CONSULTATION
        VISUAL COMMUNICATION
        A PARTIAL EVALUATOR
        THE LANGUAGE PASCAL
        PHOTOGRAMMETRY
        PICTURE RECOGNITION
        VISUAL PLANES IN THE RECOGNITION OF POLYHEDRA
        PREFERENTIAL SEMANTICS
        THE GAME OF POKER
        PROCEDURAL EVENTS
        PRICE'S TUTORIAL
        PRODUCTIVITY TECHNOLOGY
        A REGION ANALYSIS SUBSYSTEM
        REPRESENTING REAL-WORLD KNOWLEDGE IN RELATIONAL PRODUCTION SYSTEMS
        ROBOTICS COOPERATION AND RESOURCE LIMITED PROCESSES
        USING S-L-GRAPHS
        RULE ACQUISITION CAPABILITIES
        SCENE SEGMENTATION
        SERIAL PATTERN ACQUISITION
        THE SIX SEVEN EIGHT NINE GAME
        SNARING DRAGONS
        SENTENCE MEANING IN CONTEXT
        SOFTWARE INTERRUPTS
        SEVERAL GOALS SIMULTANEOUSLY
        SHAPE GRAMMARS
        SIMULTANEOUS ACTIONS
        STATE DESCRIPTION MODELS
        STOCHASTIC MODELING
        A STEREO PAIR OF VIEWS
        STORAGE REDUCTION
        SYNTACTIC METHODS
        SYNCHRONIZATION OF CONCURRENT PROCESSES
        AI LECTURES
        THE COMPUTERS AND THOUGHT AWARD
<MEMORY/S>::= MEMORY
        MEMORIES
<$WHAT2>::= <$ANY!PIECES> <$RE!TOPICS>
```

```
<$WHAT1>::= <$REITOPICS>
        <$WHAT2>
<$WHERE1>::= AT <$WORKPLACE>
        IN <$WORKPLACE2>
        WITH SUMEX
<$WORKPLACE>::= CMU
        THE GM RESEARCH LABS
        THE INSTITUTE FOR SEMANTIC AND COGNITIVE STUDIES
        MASSACHUSETTS
        NRL
        NIH
        ROCHESTER
        RUTGERS
        SMC
        SRI
        STANFORD
        SUSSEX
        WATSON RESEARCH
        ILLINOIS
        HAMBURG
        EDINBURGH
<$WORKPLACE2>::= THE SUNSHINE STATE
        THE U.S.
        THE USSR
```

Appendix III-C-2. AI Retrieval Language Grammar: AIX15

```
<SENT>::= [ <SS> ]
<SS>::= <$ANY.PAPERS> <$ABOUT.TOPIC>
      <$ARE.THERE> <$ANY.JOURNALS> <$ABOUT.TOPIC>
      <$ARE.THERE> <$ANY.PAPERS> <$ABOUT.TOPIC>
      <$ARE.THERE> <$ANY.PAPERS> IN <$JOURNAL>
      <$ARE.THERE> <$ANY.PAPERS> SINCE <$DATE>
      <$ARE.THERE> <$ANY.PAPERS> THAT MENTION THE <$DATES.OF.THE.CONFERENCE>
      <$ARE.THERE> <$ANY.PAPERS> WHICH <$CITE.AUTHOR>
      <$ARE.THERE> <$PAPERS> <$ABOUT.TOPIC>
      <$ARE> <$ANY.JOURNALS> <$ABOUT.TOPIC> BUT NOT <$TOPICS>
      <$ARE> <$ANY.PAPERS> <$ABOUT.TOPIC>
      <$ARE> <$ANY.PAPERS> <$ABOUT.TOPIC> <$ALSO.ABOUT.TOPIC>
      <$ARE> <$ANY.PAPERS> <$BY.AUTHOR>
      <$ARE> <$ANY.PAPERS> FROM <$A.CONFERENCE>
      <$ARE> <$ANY.PAPERS> FROM <$JOURNAL>
      <$ARE> <$ANY.PAPERS> FROM <$THE.CONFERENCE?S> IN THE MONTH OF <$DATE>
      <$ARE> <$AUTHOR?S> CITED BY <$ANY.PAPERS>
      <$ARE> <$AUTHOR?S> CITED IN <$ANY.PAPERS>
      <$ARE> <$TOPICS> <$MENTIONED> ANYWHERE
      <$ARE> <$TOPICS> <$MENTIONED> IN <$A.PAPER>
      <$ARE> <$TOPICS> <$MENTIONED> IN <$JOURNAL?S>
      <$ARE> ANY <$BY.AUTHOR>
      <$ARE> YOU <$ALWAYS> <$THIS.SLOW>
      <$DO!DID> <$ANY.CONFERENCE?S> <$MENTION.TOPIC>
      <$DO!DID> <$ANY.CONFERENCE?S> PUBLISH <$JOURNAL?S>
      <$DO!DID> <$ANY.JOURNALS> <$MENTION.TOPIC>
      <$DO!DID> <$ANY.PAPERS> <$ABOUT.TOPIC> <$ALSO.MENTION.TOPIC>
      <$DO!DID> <$ANY.PAPERS> <$ABOUT.TOPIC> <$MENTION.TOPIC>
      <$DO!DID> <$ANY.PAPERS> <$ABOUT.TOPIC> EXIST
      <$DO!DID> <$ANY.PAPERS> <$ALSO.MENTION.TOPIC>
      <$DO!DID> <$ANY.PAPERS> <$CITE.AUTHOR>
      <$DO!DID> <$ANY.PAPERS> <$MENTION.TOPIC>
      <$DO!DID> <$ANY.PAPERS> <$MENTION.TOPIC> BUT NOT <$TOPICS>
      <$DO!DID> <$ANY.PAPERS> <$THIS.YEAR> <$CITE.AUTHOR>
      <$DO!DID> <$AUTHOR?S> PRESENT <$A.PAPER> AT <$THE.CONFERENCE?S>
      <$DO!DID> <$AUTHOR?S> PRESENT <$A.PAPER> AT <$THE.CONFERENCE?S> IN <$DATE>
      <$DO!DID> <$AUTHOR?S> PRESENT <$PAPERS> AT <$THE.CONFERENCE?S>
      <$DO!DID> <$AUTHOR?S> PUBLISH <$A.PAPER>
      <$DO!DID> <$AUTHOR?S> WRITE <$A.PAPER>
      <$DO!DID> <$AUTHOR?S> WRITE <$A.PAPER> <$LATELY>
      <$DO!DID> <$AUTHOR?S> WRITE <$A.PAPER> <$THIS.YEAR>
      <$DO!DID> <$THE.AUTHORS> <$MENTION.TOPIC>
      <$DO!DID> <$THE.JOURNAL> PUBLISH ANYTHING IN <$DATE> OR <$DATE>
      <$DO!DID> <$THE.PAPER> <$CITE.AUTHOR>
      <$DO!DID> ALL QUERIES TAKE THIS LONG
      <$DO!DID> ANYONE PUBLISH <$ABOUT.TOPIC> IN <$THE.JOURNAL>
      <$DO!DID> RESPONSES EVER COME FASTER
      <$DO.THEY.WORK> AT <$WORKPLACE>
      <$DOES!DOESN'T> <$THE.PAPER> <$MENTION.TOPIC>
      <$DOES!DOESN'T> <$THE.PAPER> REFERENCE <$A.JOURNAL>
      <$DOES!DOESN'T> <$TOPICS> <$GET.ME> <$MENTIONED> ANYWHERE
      <$DOES!DOESN'T> IT <$ALWAYS> TAKE THIS LONG TO ANSWER ME
      <$DON'T.GET.ME> <$ANY.PAPERS> <$ABOUT.TOPIC>
      <$GET.ME> <$A.JOURNAL> REFERENCED <$BY.AUTHOR>
      <$GET.ME> <$A.PAPER> AFTER <$DATE>
      <$GET.ME> <$ANY.PAPERS> <$ABOUT.TOPIC>
```

```
<$GET.ME> <$ANY.PAPERS> <$ABOUT.TOPIC> BUT NOT <$TOPICS>
<$GET.ME> <$ANY.PAPERS> <$ABOUT.TOPIC> FROM <$DATE> TILL <$DATE>
<$GET.ME> <$ANY.PAPERS> <$BY.AUTHOR>
<$GET.ME> <$PAPERS> PRINTED IN <$TIME!PERIOD>
<$GET.ME> <$QUANTITY> <$PAPERS> <$ABOUT.TOPIC>
<$GET.ME> <$QUANTITY> MORE PLEASE
<$GET.ME> EVERYTHING <$ABOUT.TOPIC>
<$GET.ME> SOME REVIEWS <$ABOUT.TOPIC>
<$GET.ME> SOMETHING <$ABOUT.TOPIC>
<$GET.ME> SOMETHING FROM <$JOURNAL> <$ABOUT.TOPIC>
<$GET.ME> THE <$AND!OR!AUTHOR!DATE!TITLE> FROM <$THE.JOURNAL>
<$GET.ME> THE <$AND!OR!AUTHOR!DATE!TITLE> OF <$THE.PAPER>
<$GET.ME> THE <$AND!OR!AUTHOR!DATE!TITLE> OF EACH
<$GET.ME> THE MENUS
<$HOW.MANY.PAPERS> <$ALSO.MENTION.TOPIC>
<$HOW.MANY.PAPERS> <$MENTION.TOPIC>
<$HOW.MANY.PAPERS> <$THIS.YEAR> <$MENTION.TOPIC>
<$HOW.MANY.PAPERS> <$WERE> <$BY.AUTHOR>
<$HOW.MANY.PAPERS> <$WERE> <$BY.AUTHOR> AND NOT <$AUTHOR%S>
<$HOW.MANY.PAPERS> <$WERE> <$WRITTEN!PUBLISHED> FROM <$DATE> TO <$DATE>
<$HOW.MANY.PAPERS> FROM <$DATE> THROUGH <$DATE> <$MENTIONED.TOPIC>
<$HOW.MANY.PAPERS> HAVE <$AUTHOR%S> <$WRITTEN!PUBLISHED> SINCE <$DATE>
<$HOW.MANY> <$JOURNAL%S> <$MENTION.TOPIC>
<$HOW.MANY> REFERENCES <$ARE> GIVEN
<$IS.THERE> <$A.CONFERENCE> IN <$GEOPLACE>
<$IS.THERE> <$A.JOURNAL> FROM <$DATE> OR <$DATE>
<$IS.THERE> <$A.PAPER> <$ABOUT.TOPIC>
<$IS.THERE> ANYTHING NEW <$ABOUT.TOPIC>
<$IS> <$AUTHOR%S> BUT NOT <$AUTHOR%S> CITED IN <$ANY.PAPERS>
<$IS> <$AUTHOR%S> CITED BY <$ANY.PAPERS> ISSUED IN <$TIME!PERIOD>
<$IS> <$AUTHOR%S> CITED BY <$THESE.PAPERS>
<$IS> <$AUTHOR%S> CITED IN <$ANY.PAPERS>
<$IS> <$AUTHOR%S> CITED IN <$THE.PAPER>
<$IS> <$TOPICS> <$MENTIONED>
<$IS> <$TOPICS> <$MENTIONED> <$LATELY>
<$IS> <$TOPICS> <$MENTIONED> ANYWHERE
<$IS> <$TOPICS> <$MENTIONED> IN <$A.PAPER>
<$IS> <$TOPICS> <$MENTIONED> SOMEWHERE
<$IS> <$TOPICS> <$MENTIONED> SOMEWHERE <$LATELY>
<$IS> IT <$WRITTEN!PUBLISHED> BY <$THE.ASSOCIATION.FOR.COMPUTATIONAL.LINGUISTICS>
<$IS> IT <$WRITTEN!PUBLISHED> BY <$THE.JOURNAL>
<$IS> THAT <$ABOUT.TOPIC>
<$KILL>
<$QUANTITY>
<$QUANTITY> PLEASE
<$WE'RE.INTERESTED.IN> <$JOURNAL%S> AFTER <$DATE>
<$WE'RE.INTERESTED.IN> <$PAPERS> <$ABOUT.TOPIC>
<$WE'RE.INTERESTED.IN> <$PAPERS> <$WRITTEN!PUBLISHED> IN <$TIME!PERIOD>
<$WE'RE.INTERESTED.IN> <$PAPERS> ISSUED SINCE <$DATE>
<$WE'RE.INTERESTED.IN> <$PAPERS> SINCE <$DATE>
<$WE'RE.INTERESTED.IN> <$TOPICS>
<$WERE> <$ANY.PAPERS> <$BY.AUTHOR>
<$WERE> <$ANY.PAPERS> <$WRITTEN!PUBLISHED> <$ABOUT.TOPIC>
<$WERE> <$ANY.PAPERS> <$WRITTEN!PUBLISHED> IN <$GEOPLACE> OR IN <$GEOPLACE>
<$WERE> ANY <$WRITTEN!PUBLISHED> AFTER <$DATE>
<$WHAT.ABOUT> <$AUTHOR%S>
<$WHAT.ARE> SOME OF THE AREAS OF <$TOPICS>
<$WHAT.ARE> THE <$AND!OR!AUTHOR!DATE!TITLE> OF THE RECENT <$JOURNAL>
```

```
<$WHAT.ARE> THE KEY PHRASES
<$WHAT.ARE> THEIR AFFILIATIONS
<$WHAT.HAS> <$AUTHOR?S> <$WRITTEN!PUBLISHED> <$LATELY>
<$WHAT.IS> <$HER!HIS> AFFILIATION
<$WHAT.IS> KNOWN ABOUT EVERY ARTICLE
<$WHAT.IS> THE <$AND!OR!AUTHOR!DATE!TITLE> OF <$QUANTITY>
<$WHAT.IS> THE <$AND!OR!AUTHOR!DATE!TITLE> OF <$THE.PAPER>
<$WHAT.IS> THE <$AND!OR!AUTHOR!DATE!TITLE> OF THAT PIECE
<$WHAT.IS> THE SIZE OF THE DATA BANK
<$WHEN.WAS> <$HUMAN.PROBLEM.SOLVING> <$WRITTEN!PUBLISHED>
<$WHEN.WAS> <$THE.PAPER> <$WRITTEN!PUBLISHED>
<$WHEN.WAS> <$TOPICS> <$MENTIONED>
<$WHEN.WAS> IT <$WRITTEN!PUBLISHED>
<$WHEN.WAS> THE LAST PAPER <$BY.AUTHOR> <$WRITTEN!PUBLISHED>
<$WHERE.IS> <$TOPICS> <$MENTIONED>
<$WHICH.AUTHORS> WORK AT <$GEOPLACE> OR AT <$GEOPLACE>
<$WHICH.AUTHORS> WORK AT <$WORKPLACE> OR AT <$WORKPLACE>
<$WHICH.AUTHORS> WORK WITH <$WORKPLACE> OR AT <$GEOPLACE>
<$WHICH.OF.THESE> <$ABOUT.TOPIC> <$ALSO.MENTION.TOPIC>
<$WHICH.OF.THESE> <$ABOUT.TOPIC> <$MENTION.TOPIC>
<$WHICH.OF.THESE> <$ABOUT.TOPIC> <$WERE> <$WRITTEN!PUBLISHED> <$LATELY>
<$WHICH.OF.THESE> <$ARE> <$BY.AUTHOR>
<$WHICH.OF.THESE> <$BY.AUTHOR> <$ARE> REFERENCED
<$WHICH.OF.THESE> <$CITE.AUTHOR>
<$WHICH.OF.THESE> <$CONTAINED> <$THE.PAPER> <$BY.AUTHOR>
<$WHICH.OF.THESE> <$CONTAINED> <$TOPICS>
<$WHICH.OF.THESE> <$MENTION.TOPIC>
<$WHICH.OF.THESE> <$MENTIONED.TOPIC>
<$WHICH.OF.THESE> <$WERE> <$BY.AUTHOR>
<$WHICH.OF.THESE> <$WERE> <$BY.AUTHOR> SINCE LAST YEAR
<$WHICH.OF.THESE> <$WERE> <$WRITTEN!PUBLISHED> AT <$WORKPLACE> OR AT <$WORKPLACE>
<$WHICH.OF.THESE> APPEARED <$LATELY> IN <$THE.JOURNAL>
<$WHICH.OF.THESE> CITES <$AUTHOR?S>
<$WHICH.OF.THESE> MENTIONS <$TOPICS>
<$WHICH.OF.THESE> REFER TO THESE
<$WHICH.OF.THESE> WAS <$BY.AUTHOR>
CAN I HAVE <$THESE.PAPERS> LISTED
CAN YOU HELP ME
CHOOSE AMONG <$JOURNAL?S> BEFORE <$DATE>
DURING WHAT MONTHS <$WERE> THEY <$WRITTEN!PUBLISHED>
GENERATE A COPY OF THOSE
HAS <$AUTHOR?S> <$WRITTEN!PUBLISHED> <$ANY.PAPERS> <$THIS.YEAR>
HAS <$AUTHOR?S> <$WRITTEN!PUBLISHED> ANYTHING <$LATELY>
HAS <$AUTHOR?S> BEEN REFERENCED IN <$ANY.PAPERS>
HASN'T <$A.PAPER> <$ABOUT.TOPIC> BEEN RELEASED
HASN'T <$TOPICS> BEEN CONSIDERED IN <$JOURNAL>
HAVE <$ANY.PAPERS> <$BY.AUTHOR> APPEARED
HAVE <$ANY.PAPERS> APPEARED <$ABOUT.TOPIC>
HAVE <$AUTHOR?S> <$WRITTEN!PUBLISHED> <$THIS.YEAR>
HAVEN'T YOU FINISHED
HELP
HOW BIG IS THE DATA BASE
HOW CAN I USE THE SYSTEM EFFICIENTLY
HOW LONG <$DOES.IT.TAKE>
I'D LIKE TO KNOW THE <$AND!OR!AUTHOR!DATE!TITLE> OF <$THE.PAPER>
LIST <$QUANTITY> HUNDRED
LIST BETWEEN <$QUANTITY> AND <$QUANTITY> OF THEM
LIST THE <$PAPERS> <$BY.AUTHOR>
```

```
NO MORE PLEASE
NO THANKS
OK
PLEASE HELP ME
PLEASE LIST <$THE AUTHORS>
PLEASE MAKE ME A FILE OF THOSE
PRINT <$QUANTITY>
PRODUCE A COPY OF <$QUANTITY> <$PAPERS>
SELECT FROM <$PAPERS> <$ABOUT TOPIC>
SHOW ME <$QUANTITY>
SHOW ME ITS <$AND!OR!AUTHOR!DATE!TITLE>
SUBSELECT FROM <$TOPICS>
SURE THANKS
TELL ME <$WHAT TO DO>
TELL ME THE <$AND!OR!AUTHOR!DATE!TITLE> OF <$QUANTITY>
THANK YOU <$WE'RE> DONE
TRANSMIT <$QUANTITY>
WHAT <$ABOUT TOPIC>
WHAT <$CAN I DO> TO SPEED YOU UP
WHAT <$DO.I HAVE.TO.DO>
WHAT <$IS> ITS <$AND!OR!AUTHOR!DATE!TITLE>
WHAT <$JOURNAL7S> DURING <$DATE> AND <$DATE> <$MENTION.TOPIC>
WHAT <$PAPERS> <$MENTION TOPIC>
WHAT <$SORT OF SUMMARY> IS AVAILABLE
WHAT ADDRESS IS GIVEN FOR <$THE AUTHORS>
WHAT ADDRESSES ARE GIVEN FOR <$THE AUTHORS>
WHAT CAN <$THE SYSTEM DO>
WHAT CONFERENCE WAS AT <$WORKPLACE> OR AT <$GEOPLACE>
WHAT CONFERENCE WAS AT <$WORKPLACE> OR AT <$WORKPLACE>
WHAT FACTS <$ARE> STORED
WHAT KEY WORD RELATES TO <$TOPICS>
WHAT KEY WORDS SHOULD I USE FOR <$TOPICS>
WHAT KIND OF MENUS <$ARE THERE>
WHAT KINDS OF SUBJECTS <$ARE> STORED
WHAT MUST I ASK
WHAT SHOULD I ASK
WHAT SHOULD I SAY
WHAT SORTS OF <$TOPICS> <$ARE> <$MENTIONED>
WHAT SUBJECT CAN I REQUEST
WHAT TOPIC MENU CAN I CHOOSE
WHAT TOPICS <$ARE> RELATED TO <$TOPICS>
WHAT TYPES OF <$RETRIEVAL CAN HEARSAY.DO>
WHEN WILL YOU HAVE THE ANSWER
WHERE <$ARE> <$TOPICS> <$MENTIONED>
WHERE <$DO THEY WORK>
WHERE DID <$THE PAPER> APPEAR
WHICH <$AI TEXT> <$CONTAINED> <$TOPICS>
WHICH AUTHORS <$MENTION.TOPIC>
WHICH CONFERENCES WERE AT <$GEOPLACE> OR AT <$GEOPLACE>
WHICH IS <$QUANTITY>
WHICH NOTES <$ABOUT.TOPIC> <$ALSO MENTION TOPIC>
WHICH ONES
WHICH SORT OF <$RETRIEVAL KEYS> CAN I SEEK
WHICH TITLES <$MENTION TOPIC>
WHICH WAS THE LAST ARTICLE <$BY.AUTHOR>
WHO
WHO HAS <$WRITTEN!PUBLISHED> <$ABOUT.TOPIC>
WHO WAS QUOTED IN <$THE.PAPER>
WHO WAS THE AUTHOR
WHO WERE <$THE.AUTHORS> OF <$THE.PAPER>
WHO WROTE <$PAPERS> <$ABOUT.TOPIC> <$THIS.YEAR>
WHO WROTE IT
WHY IS THE SYSTEM <$THIS.SLOW>
WOULD YOU LIST <$QUANTITY>
WRITE A FILE OF THOSE
YES PLEASE
```

```
<$RETRIEVAL.CAN.HEARSAY.DO>::= <$RETRIEVAL.CAN.HEARSAY> DO
<$DOES.IT.TAKE>::= DOES IT TAKE
<$DATES.OF.THE.CONFERENCE>::= DATES OF <$THE.CONFERENCE%S>
<$WHAT.TO.DO>::= WHAT TO DO
<$CAN.I.DO>::= CAN I DO
<$THE.SYSTEM.DO>::= THE SYSTEM DO
<$DO.I.HAVE.TO.DO>::= DO I HAVE TO DO
<$THE.AUTHORS>::= THE AUTHORS
       ANY AUTHORS


<$KILL>::= <CEASE.PRINTING>
       PLEASE <CEASE.PRINTING>
       <CEASE.PRINTING> PLEASE
<CEASE.PRINTING>::= <CEASE> <PRINTING>
<CEASE>::= CEASE
       STOP
       TERMINATE
       FINISH
       QUIT
       KILL THE
<PRINTING>::= PRINTING
       LISTING
       TRANSMITTING
```

```
<$HOW.MANY>::= HOW MANY
<$HOW.MANY.PAPERS>::= HOW MANY <$PAPERS>
        HOW MANY OF THESE
<$ARE.THERE>::= <ARE!WERE> THERE
        <$DO!DID> YOU HAVE
        <$DO!DID> YOU HAPPEN TO HAVE
<ARE!WERE>::= <$ARE>
        <$WERE>
<$WERE>::= WERE
        WEREN'T
        WERE NOT
<$DO!DID>::= DO
        DON'T
        DID
        DIDN'T
<$DOES!DOESN'T>::= DOES
        DOESN'T

<$GET.ME>::= <GET!GIVE> ME
        <GET!GIVE>
        TRY TO GET
        TRY TO GET ME
        COULD YOU RETRIEVE
        <I!WE> <DEMAND!WANT>
        <I!WE> <DEMAND!WANT> TO <SEE!GET>
        <I'D!WE'D> LIKE TO <SEE!GET>

<GET!GIVE>::= GET
        GIVE
<I!WE>::= I
        WE
<DEMAND!WANT>::= DEMAND
        DESIRE
        WISH
        WANT
<I'D!WE'D>::= I'D
        WE'D
<SEE!GET>::= SEE
        GET

<$DON'T.GET.ME>::= DON'T <$GET.ME>

<$WHERE.IS>::= WHERE IS
<$IS>::= IS
        ISN'T
        WAS
        WASN'T
<$ARE>::= ARE
        ARE NOT
        AREN'T
<$IS.THERE>::= <$IS> THERE
<$HER!HIS>::= HER
        HIS
<$WHAT.HAS>::= WHAT <HAS!HAVE>
<HAS!HAVE>::= HAS
        HAVE
<$WHEN.WAS>::= WHEN WAS
        WHEN WERE
```

```
<$DO.THEY.WORK>::= <DO.THEY> WORK
<DO.THEY>::= <$DO!DID> THEY
        <$DOES!DOESN'T> <HE!SHE>
<HE!SHE>::= HE
        SHE

<$WE'RE.INTERESTED.IN>::= <$WE'RE> <INTERESTED.IN>
        <$WE'RE> ONLY <INTERESTED.IN>
        THE AREA <$WE'RE> <INTERESTED.IN> IS
        THE ONLY AREA <$WE'RE> <INTERESTED.IN> IS
        <LET'S> <RESTRICT> <OURSELVES> TO
<$WE'RE>::= WE'RE
        WE'VE BEEN
        WE HAVE BEEN
        <I'M>
<I'M>::= I'M
        I AM
<INTERESTED.IN>::= INTERESTED IN
<LET'S>::= LET'S
        LET <US!ME>
<US!ME>::= US
        ME
<RESTRICT>::= RESTRICT
        CONFINE
        LIMIT
<OURSELVES>::= OURSELVES
        OUR ATTENTION
        MYSELF

<$WHAT.ABOUT>::= WHAT ABOUT
<$WHAT.ARE>::= WHAT ARE
<$WHAT.IS>::= WHAT IS
        WHAT'S
<$WHICH.AUTHORS>::= WHICH AUTHORS
<$WHICH.OF.THESE>::= WHICH OF <THESE!THEM>
        WHICH PAPER
        WHICH <$PAPERS>
        WHICH <$JOURNAL>
        WHICH <$JOURNAL?S>
<THESE!THEM>::= THESE
        THEM
```

```
<$WORKPLACE>::= CMU
        NIH
        NRL
        RUTGERS
        SMC
        SRI
        STANFORD
        SUMEX
        THE GM RESEARCH LABS
        THE INSTITUTE FOR SEMANTIC AND COGNITIVE STUDIES
        WATSON RESEARCH
<$GEOPLACE>::= EDINBURGH
        HAMBURG
        ILLINOIS
        MASSACHUSETTS
        ROCHESTER
        SUSSEX
        THE SUNSHINE STATE
        THE U.S.
        THE USSR

<$LATELY>::= LATELY
        RECENTLY
        IN RECENT TIMES
<$WRITTEN!PUBLISHED>::= WRITTEN
        PUBLISHED
        PRODUCED
<$ALWAYS>::= ALWAYS
        REGULARLY
        USUALLY
<$THIS SLOW>::= <THIS!SO> SLOW
<THIS!SO>::= THIS
        SO
<$CONTAINED>::= CONTAINED
        CONTAINS

<$SORT.OF SUMMARY>::= SORT OF SUMMARY
        SORTS OF SUMMARIES
```

```
<$ALSO.CITE.AUTHOR> := ALSO <$CITE.AUTHOR>
        <$CITE.AUTHOR> <IN.ADDITION>
<$CITE.AUTHOR> := <CITE> <$AUTHOR%S>
        REFER TO <$PAPERS> BY <$AUTHOR%S>
<CITE> := CITE
        QUOTE
        REFERENCE
        DISCUSS

<IN.ADDITION> := IN ADDITION
        ALSO
        SIMULTANEOUSLY

<$ALSO.BY.AUTHOR> := ALSO <$BY.AUTHOR>
        <$BY.AUTHOR> <IN.ADDITION>
<$BY.AUTHOR> := <WRITTEN.BY> <$AUTHOR%S>
<WRITTEN.BY> := BY
        WRITTEN BY
```

```
<$DATE>::= <YEAR>
       <MONTH> <YEAR>
       <MONTH> OF <YEAR>
       <MONTH> OF <$THIS.YEAR>
       <MONTH>
<YEAR>::= <CENTURY> <$NUMBER1-99>
       <CENTURY> HUNDRED <$NUMBER1-99>
       <CENTURY> HUNDRED
<CENTURY>::= NINETEEN
       EIGHTEEN
       SEVENTEEN
       SIXTEEN
<MONTH>::= JANUARY
       FEBRUARY
       MARCH
       APRIL
       MAY
       JUNE
       JULY
       AUGUST
       SEPTEMBER
       OCTOBER
       NOVEMBER
       DECEMBER
<$TIME!PERIOD>::= <$QUANTITY> <DAYS!MONTHS!YEARS>
<DAYS!MONTHS!YEARS>::= MONTHS
       DAYS
       YEARS

<$THIS.YEAR>::= THIS YEAR
```

```
<$QUANTITY>::= THE <LAST.> <$NUMBER1-99>
       THE <LATEST.> <$NUMBER1-99>
       THE <LATEST.>
       <$NUMBER1-99>
       UP TO <$NUMBER1-99>
<LAST.>::= LAST
       NEXT
       FIRST
<LATEST.>::= EARLIEST
       LATEST
       NEWEST
       OLDEST
       MOST RECENT

; < NUMBER> ::= <$NUMBER1-99>
;       < HUNDREDS> <$NUMBER1-99>
; < HUNDREDS> ::= < DIGITS> HUNDRED
;       A HUNDRED
<$NUMBER1-99> ::= < NUMBER2>
       < TEENS>
       < DIGITS>
< NUMBER2>::= < TENS>
       < TENS> < DIGITS>
< TEENS> ::= NINETEEN
       TEN
       ELEVEN
       TWELVE
       THIRTEEN
       FOURTEEN
       FIFTEEN
       SIXTEEN
       SEVENTEEN
       EIGHTEEN
< TENS> ::= TWENTY
       THIRTY
       FORTY
       FIFTY
       SIXTY
       SEVENTY
       EIGHTY
       NINETY
< DIGITS> ::= ONE
       TWO
       THREE
       FOUR
       FIVE
       SIX
       SEVEN
       EIGHT
       NINE
```

```
<$AND!OR!AUTHOR!DATE!TITLE>::= AUTHORS
        DATES
        PUBLISHERS
        TITLES
        <AUTHOR!DATE!TITLE>
        <AUTHOR!DATE!TITLE> <AND!OR 3> <AUTHOR!DATE!TITLE>
<AUTHOR!DATE!TITLE> ::= AUTHOR
        DATE
        PUBLISHER
        TITLE
<AND!OR 3>::= AND
        OR
```

```
<$ALSO.ABOUT.TOPIC>::= <IN.ADDITION> <$ABOUT.TOPIC>
        <$ABOUT.TOPIC> <IN.ADDITION>
        WHICH <IN.ADDITION> <$MENTION.TOPIC>
        WHICH <MENTION.TOPIC?WHICH> <IN.ADDITION>
<$ABOUT.TOPIC>::= <ABOUT.> <$TOPICS>
        <WHICH!THAT> <MENTION.TOPIC?WHICH>

<WHICH!THAT>::= WHICH
        THAT

<$ALSO.MENTION.TOPIC>::= <IN.ADDITION> <$MENTION.TOPIC>
        <$MENTION.TOPIC> <IN.ADDITION>
<$MENTION.TOPIC>::= <MENTION.TOPIC?WHICH>
        <$ABOUT.TOPIC> <$ARE.THERE>
<MENTION.TOPIC?WHICH>::= <MENTION.> <$TOPICS>
        <$ARE.THERE> <$ABOUT.TOPIC>
        <ARE!HAVE.BEEN> <$ABOUT.TOPIC>

<ABOUT.>::= ABOUT
        <MENTIONING.>
        ON
<MENTION.>::= CONCERN
        CONSIDER
        CONTAIN THE <PHRASE?S!WORD?S.>
        DESCRIBE
        DISCUSS
        DISCUSSES
        MENTION
        REFER TO
        RELATE TO
<MENTIONING.>::= CONCERNING
        DISCUSSING
        MENTIONING
        REGARDING
        REFERRING TO
<PHRASE?S!WORD?S.>::= <PHRASE!WORD>
        <PHRASES!WORDS>
<PHRASE!WORD>::= PHRASE
        WORD
<PHRASES!WORDS>::= PHRASES
        WORDS

<ARE!HAVE.BEEN>::= ARE
        HAVE BEEN

<$MENTIONED.TOPIC>::= <$MENTIONED> <$TOPICS>
<$MENTIONED>::= <$MENTIONED!DISCUSSED>
        HAVE <$MENTIONED!DISCUSSED>
        LAST <$MENTIONED!DISCUSSED>
        WRITTEN UP
<$MENTIONED!DISCUSSED>::= MENTIONED
        CONCERNED
        DISCUSSED
        REFERRED TO
```

```
<$ANY.PAPERS>::= <ANY!MANY!SOME> <$PAPERS>
       <ANY!MANY!SOME> OF <THESE!THOSE>
       <ANY!MANY!SOME> OF <THESE!THOSE!THE> <$PAPERS>
<$A.PAPER>::= A <PAPER%C>
       A <ADJ@PAPER%C> <PAPER>
       AN <PAPER%V>
       AN <ADJ@PAPER%V> <PAPER>
       <$A.CONFERENCE> <PAPER>
       ANOTHER <PAPER>
       ANOTHER <ADJ@PAPER> <PAPER>
<PAPER>::= <PAPER%C>
       <PAPER%V>
<PAPER%C>::= BOOK
       PAPER
       REPORT
       STORY
<PAPER%V>::= ABSTRACT
       ARTICLE
       SUMMARY
       SURVEY

<ADJ@PAPER>::= <ADJ@PAPER%C>
       <ADJ@PAPER%V>
<ADJ@PAPER%C>::= TECHNICAL
       COMPUTING SURVEY
       <RECENT!CURRENT>
       <RECENT!CURRENT> <ADJ@JOURNAL>
;      <ADJ@JOURNAL%C>
;      <ADJ@JOURNAL%C> <JOURNAL>
       <RECENT!CURRENT> <$JOURNAL>
       <JOURNAL%C>
       <NAME@JOURNAL%C>
       <RECENT!CURRENT> <ADJ@JOURNAL> <JOURNAL>
<ADJ@PAPER%V>::= <ADJ@JOURNAL%V>
       <ADJ@JOURNAL%V> <JOURNAL>
       <NAME@JOURNAL%V>
       <$AI.JOURNAL>

<$THE.PAPER>::= <THIS!THAT!THE> <PAPER>
       <THIS!THAT!THE> <ADJ@PAPER> <PAPER>

<$THESE.PAPERS>::= <THESE!THOSE> <$PAPERS>

<$PAPERS>::= <PAPERS>
       <PAPERS> ON AI
       <ADJ@PAPER> <PAPERS>
       <PAPERS> IN THE SIGART NEWSLETTER
;      <$JOURNAL%S> <$ABOUT.TOPIC>
<PAPERS>::= ABSTRACTS
       ARTICLES
       BOOKS
       PAPERS
       REPORTS
       STORIES
       SUMMARIES
       SURVEYS

<THIS!THAT!THE>::= THIS
```

```
       THAT
       THE
<THESE!THOSE>::= THESE
       THOSE
<THESE!THOSE!THE> ::= THE
       THESE
       THOSE
<ANY!MANY!SOME>::= ANY
       MANY
       SOME
```

```
<$ANY.JOURNALS>::= ANY <$JOURNAL?S>
        ANY <RECENT!CURRENT> <$JOURNALS>
<$A.JOURNAL>::= A <JOURNAL?C>
        A <JOURNAL?C> <OF.THE.ADJ-CONFERENCE>
        A <NAME@JOURNAL?C>
;       A <ADJ@JOURNAL?C> <JOURNAL>
;       A <ADJ@JOURNAL?C> <CONFERENCE.> <JOURNAL>
        AN <JOURNAL?V>
        AN <JOURNAL?V> <OF.THE.ADJ-CONFERENCE>
        AN <NAME@JOURNAL?V>
        AN <ADJ@JOURNAL?V> <JOURNAL>
        AN <ADJ@JOURNAL?V> <CONFERENCE.> <JOURNAL>
<$JOURNAL>::= <JOURNAL>
        <$NAME@JOURNAL>
<JOURNAL>::= <JOURNAL?C>
        <JOURNAL?V>
<JOURNAL?C>::= JOURNAL
        PROCEEDING
        PROCEEDINGS
        SUMMARY
        TRANSACTION
<JOURNAL?V>::= ISSUE

<$NAME@JOURNAL>::= <NAME@JOURNAL?C>
        <NAME@JOURNAL?V>
<NAME@JOURNAL?C>::= CACM
        <$COGNITIVE.PSYCHOLOGY>
        COMPUTING SURVEYS
        SURNOTES
        SIGART NEWSLETTER
        COMPUTING REVIEWS
<NAME@JOURNAL?V>::= ARPA SURNOTES
        <$INFORMATION.AND.CONTROL>

<ADJ@JOURNAL>::= <ADJ@JOURNAL?V>
;       <ADJ@JOURNAL?C>
<ADJ@JOURNAL?V>::= AI
        IJCAI
        ACM
        ACL
        IEEE
        IFIP

<$THE.JOURNAL>::= THE <$JOURNAL?S>
        THE <$NAME@JOURNAL>
        THE <ADJ@JOURNAL> <$JOURNAL?S>
        THE <ADJ@JOURNAL> <CONFERENCE.> <$JOURNAL?S>
        THE <$JOURNAL?S> <OF.THE.ADJ-CONFERENCE>
        <$JOURNAL?S> <OF.THE.ADJ-CONFERENCE>
<$JOURNAL?S>::= <JOURNALX>
        <RECENT!CURRENT> <JOURNALX>
<JOURNALX>::= <JOURNAL>
        <$JOURNALS>
<$JOURNALS>::= <JOURNALS?V>
        <JOURNALS?C>
<JOURNALS?C>::= JOURNALS
        COMMUNICATIONS
        PROCEEDINGS
```

```
      TRANSACTIONS
      VOLUMES
<JOURNALS%V>::= ISSUES

<OF.THE.ADJ.CONFERENCE>::= OF THE <ADJ&JOURNAL>
      OF THE <ADJ&JOURNAL> <CONFERENCE.>
```

```
<$A.CONFERENCE>::= AN <ADJ@CONFERENCE%V> <CONFERENCE.>
        ANOTHER <ADJ@CONFERENCE> <CONFERENCE.>
        A <RECENT.ADJ.CONFERENCE>
<RECENT.ADJ.CONFERENCE> ::= <RECENT!CURRENT> <ADJ@CONFERENCE> <CONFERENCE.>
        <RECENT!CURRENT> <CONFERENCE.>
; NEXT LINE SHOULD BE <ADJ@CONFERENCE%C> <CONFERENCE.>
        <CONFERENCE.>
<ADJ@CONFERENCE>::= <ADJ@CONFERENCE%V>
<ADJ@CONFERENCE%V>::= AI
        IJCAI
        ACM
        IEEE
        IFIP
<CONFERENCE.>::= CONFERENCE
        CONVENTION
        MEETING
        SESSION
<CONFERENCES.>::= CONFERENCES
        CONVENTIONS
        MEETINGS
        SESSIONS
<RECENT!CURRENT>::= RECENT
        CURRENT
        NEW

<$ANY.CONFERENCE%S> ::= ANY <RECENT.ADJ.CONFERENCE%S>
<RECENT.ADJ.CONFERENCE%S>::= <RECENT!CURRENT> <ADJ@CONFERENCE> <CONFERENCE%S>
        <RECENT!CURRENT> <CONFERENCE%S>
        <ADJ@CONFERENCE> <CONFERENCE%S>
<CONFERENCE%S>::= <CONFERENCE.>
        <CONFERENCES.>

<$THE.CONFERENCE%S> ::= THE <RECENT.ADJ.CONFERENCE%S>
        IJCAI
        IFIP
```

```
<$INFORMATION AND CONTROL>::= INFORMATION AND CONTROL
<$COGNITIVE PSYCHOLOGY>::= COGNITIVE PSYCHOLOGY
<$AI.JOURNAL>::= AI JOURNAL
<$AI.TEXT>::= AI TEXT
<$THE ASSOCIATION.FOR COMPUTATIONAL LINGUISTICS>::= THE ASSOCIATION FOR COMPUTATIONAL LINGUISTICS
<$RETRIEVAL.CAN HEARSAY>::= RETRIEVAL CAN HEARSAY
<$HUMAN.PROBLEM SOLVING>::= HUMAN PROBLEM SOLVING
<$RETRIEVAL.KEYS>::= RETRIEVAL KEYS
```

```
<$AUTHOR?S>::= <AUTHOR>
      <AUTHOR> <AND/OR 1> <AUTHOR>
<AND/OR 1>::= AND
      OR

<AUTHOR>::= ALLEN COLLINS
      ALLEN NEWELL
      ANN RUBIN
      ANTHONY MARTELLI
      AZRIEL ROSENFELD
      BERNARD MELTZER
      BERT RAPHAEL
      BILL WOODS
      BONNIE NASH-WEBBER
      BRUCE BUCHANAN
      CARL HEWITT
      CHRISTOPHER RIESBECK
      CHUCK RIEGER
      DANNY BOBROW
      DAVE RUMELHART
      DAVID MARR
      DAVID MICHIE
      DICK SELTZER
      DONALD NORMAN
      DOUG LENAT
      DREW MCDERMOTT
      DREYFUS
      EARL HUNT
      EARL SACERDOTI
      ED FEIGENBAUM
      ED RISEMAN
      ELLIOT SOLOWAY
      ERIK SANDEWALL
      EUGENE CHARNIAK
      FEIGENBAUM
      FELDMAN
      GARY HENDRIX
      GEORGE ERNST
      GIPS
      HANS BERLINER
      HARRY BARROW
      HERB SIMON
      HERBERT BLOCK
      HILARY PUTNAM
      HOLLAND
      HUGH NAGEL
      IRV SOBEL
      ISSAC ASIMOV
      JACK MINKER
      JACK MOSTOW
      JAMES SLAGLE
      JEAN SAMMET
      JEFFREY ULLMAN
      JERRY FELDMAN
      JOHN GASCHNIG
      JOHN HOLLAND
      JOHN MCCARTHY
      JOHN NEWCOMER
```

JOSEPH WEIZENBAUM
JUDEA PEARL
KARL PINGLE
KEITH PRICE
KEN COLBY
KEN RALSTON
KING SUNG FU
LAURENT SIKLOSSY
LEE ERMAN
LEONARD UHR
LES EARNEST
LINDA MASINTER
MADELINE BATES
MARVIN MINSKY
MARY NEWBORN
MARY SHAW
MICHAEL ARBIB
MIKE RYCHENER
MINSKY
MITCHELL NEWEY
NEWELL
NILS NILSSON
NILSSON
NORI SUZUKI
PAMELA MCCORDUCK
PAT WINSTON
PERRY THORNDYKE
PETER KUGEL
RAJ REDDY
RANAN BANERJI
RAYMOND SPROULL
REDDY
RICH FIKES
RICH SMITH
RICHARD MICHALSKI
RICHARD WALDINGER
RICK HAYES-ROTH
ROBERT REITER
ROGER SCHANK
RON OHLANDER
ROSENFELD
SCOTT FAHLMAN
SEYMOUR PAPERT
SIMON
STEVE COLES
STEVE REED
STEVE ZUCKER
TED SHORTLIFFE
TERRY WINOGRAD
THOMAS MARSLAND
THOMAS SYKES
UHR
VIC LESSER
WALLY RHOMBERG
WOODS
WOODY BLEDSOE
YORICK WILKS
ZOHAR MANNA

```
<$TOPICS>::= <AND!OR!TOPICS>
      WINOGRAD'S ARTICLE
<AND!OR!TOPICS>::= <TOPIC>
      <TOPIC> <AND!OR 2> <TOPIC>
<AND!OR 2>::= AND
      OR
<TOPIC>::= A CAI MONITOR
      A COMMON SENSE ALGORITHM
      A GAME MODEL
      A LOSING MOVE
      A MULTILEVEL ORGANIZATION
      A PACKET BASED APPROACH TO NETWORK COMMUNICATION
      A PARTIAL EVALUATOR
      A PROGRAM SYNTHESIZER FOR NETWORK PROTOCOLS
      A PROGRAMMING APPRENTICE
      A PROOF CHECKER FOR PROTOCOL TERMINATION EXPRESSIONS
      A RADIO INTERVIEW ON SCIENCE FICTION
      A REGION ANALYSIS SUBSYSTEM
      A STEREO PAIR OF VIEWS
      A TASK ORIENTED DIALOGUE
      A THAUMATURGIST
      A THEOREM PROVER PLANNING FOR PROGRESS
      A TIME DOMAIN ANALYZER
      A TUTOR OR TUTORING ON TV
      A TV REPORTER
      ABSTRACTION
      ACQUISITION OF KNOWLEDGE
      ACTIVE KNOWLEDGE
      ACYCLIC ISOMERS
      ADAPTATION
      ADAPTIVE PRODUCTION SYSTEMS
      ADVISING PHYSICIANS
      AI
      AI LECTURES
      ALGEBRAIC REDUCTION
      ALGOL
      ALGORITHMIC AESTHETICS
      ALL-OR-NONE SOLUTIONS
      AN ADAPTIVE NATURAL LANGUAGE SYSTEM
      AN ASSEMBLY ROBOT
      AN AXIOMATIC SYSTEM
      ANALOGY IN PROBLEM SOLVING
      ANALYSIS OF CONTEXT
      ANALYSIS OF SENTENCES
      ARTIFICIAL INTELLIGENCE
      ASSIMILATION OF NEW INFORMATION
      ASSOCIATIVE MEMORIES
      ASSOCIATIVE MEMORY
      AUGMENTED TRANSITION NETWORKS
      AUTOMATED DEDUCTION
      AUTOMATIC CODING
      AUTOMATIC COMPUTATION
      AUTOMATIC MANTRA GENERATION
      AUTOMATIC PROGRAM SYNTHESIS FROM EXAMPLE PROBLEMS
      AUTOMATIC PROGRAM WRITING
      AUTOMATIC PROGRAMMING
      AUTOMATIC PROOF OF CORRECTNESS
      AUTOMATIC THEOREM PROVING
```

AUTOMATION
AXIOMATIC SEMANTICS
AXIOMS FOR GO
BACKGAMMON
BELIEF SYSTEMS
BINDINGS
BIOMEDICINE
BRAIN THEORY
BUSINESS PROBLEM SOLVING
CARTOGRAPHY
CASE SYSTEMS
CAUSAL REASONING
CELL ASSEMBLY THEORY
CHECKING PROOFS
CHESS
CHESS PLAYING PROGRAMS
CIRCUIT ANALYSIS
COGNITION
COGNITIVE ROBOTIC SYSTEMS
COGNITIVE SCIENCE
COMMON SENSE
COMMON SENSE THEORY FORMATION
COMPLEX WAVEFORMS
COMPUTATIONAL LINGUISTICS
COMPUTER ART
COMPUTER BASED CONSULTANT
COMPUTER BASED CONSULTATIONS
COMPUTER CONTROLLED MANIPULATORS
COMPUTER GRAPHICS
COMPUTER MUSIC
COMPUTER NETWORKS
COMPUTER VISION
CONCEPTUAL DESCRIPTIONS
CONCEPTUAL INFERENCE
CONCEPTUAL OVERLAYS
CONSTRAINT SATISFACTION
CONSTRUCTING PROGRAMS FROM EXAMPLES
CONSTRUCTION OF PROGRAMS
CONTEXT
CONTINUOUS PROCESSES
CONTROL
COOPERATING SOURCES OF KNOWLEDGE
COPYING LIST STRUCTURES
CURVED OBJECTS
CYBERNETICS
CYCLIC
DATA BASES
DATA BASES FOR INTERACTIVE DESIGN
DATA STRUCTURES
DECISION THEORY
DEDUCTION
DEDUCTIVE RETRIEVAL
DENOTATIONAL SEMANTICS
DEPTH PERCEPTION
DERIVATION PLANS
DESIGN
DESIGN AUTOMATION
DESIGN IN THE ARTS

DETECTION OF LIGHT SOURCES
DISPLAY TERMINALS
DRAGON
DRIVING A CAR
DYNAMIC BINDING
DYNAMIC CLUSTERING
DYNAMIC PROGRAMMING
ELECTRONIC CIRCUITS
ELECTRONICS
ENGLISH
EVALUATION FUNCTIONS
EXPERT SYSTEMS
EXPLANATION CAPABILITIES
FABLES OR FAIRY TALES
FEATURE-DRIVEN SYSTEMS
FIRST ORDER LOGIC
FORMAL SEMANTICS
FRAME THEORY
FRAMES
FRAMES AND THE ENVIRONMENT
FUZZY KNOWLEDGE
FUZZY PROBLEM SOLVING
GAME OF POKER
GAME PLAYING
GENERAL PURPOSE MODELS
GENERATION OF NATURAL LANGUAGE
GEOMETRIC MODELING
GO OR GO-MOKU
GOAL SEEKING COMPONENTS
GRAIN OF COMPUTATION
GRAMMATICAL INFERENCE
GRAPH INTERPRETABLE GAMES
GRAPH MATCHING
HEARSAY
HETEROSTATIC THEORY
HEURISTIC PROGRAMMING
HEURISTIC TECHNIQUES
HILL CLIMBING
HUMAN BEHAVIOR
HUMAN MEMORY
HUMAN VISION
HYPOTHESIS FORMATION
IMAGE INTENSITY UNDERSTANDING
IMPROVING PROGRAMS
INDUCTIVE ASSERTIONS
INDUSTRIAL APPLICATION
INEXACT REPRESENTATION
INFERENCE
INFERENCES
INFERENTIAL QUESTION ANSWERING
INFORMATION PROCESSING UNIVERSALS
INHERITANCE OF PROPERTIES
INTELLIGENT MACHINES
INTENTIONS
INTERACTIVE DESIGN
INTERACTIVE KNOWLEDGE SYSTEMS
INTERACTIVE PROGRAM SYNTHESIS
INTERPRETIVE SEMANTICS

INTONATION
INVARIANCE FOR PROBLEM SOLVING
INVARIANCES IN THE PERCEPTION OF FACES
INVESTMENT ANALYSIS
ITERATION
KNOWLEDGE BASED SYSTEMS
KNOWLEDGE SYSTEMS
LAMBDA CALCULUS
LANGUAGE COMPREHENSION
LANGUAGE DESIGN
LANGUAGE PARAPHRASE
LANGUAGE PASCAL
LANGUAGE PRIMITIVES
LANGUAGE UNDERSTANDING
LARGE DATA BASES
LEARNING
LINEAR LEXICOMETRY
LOW ORDERS OF RECOGNITION PERFORMANCE
MACHINE INTELLIGENCE IN MEDICAL DIAGNOSIS
MACRO PROCESSING FOR AN ON-LINE NEWSLETTER
MANAGEMENT INFORMATION SYSTEMS
MEANS FOR COMPUTER MOVIES
MEDICAL CONSULTATION
MINIMAL SPANNING FORESTS OR TREES
MOTION IN SCENE DESCRIPTION
NEURAL NETWORKS
NEWSLETTER REPORTERS
NONDETERMINISTIC PROGRAMMING
OBJECT LOCATIONS AND MOVEMENTS IN NATURAL IMAGES
OBJECT MANIPULATING ROBOTS
OPERATIONAL REASONING
OPTIMAL PROBLEM SOLVING SEARCH
OPTIMIZED CODE FOR THE TRANSFER OF COMMENTS
PAPERS BY BILL WOODS
PARALLELISM IN PROBLEM SOLVING
PARTIAL EVALUATOR
PATTERN DIRECTED FUNCTION INVOCATION
PATTERN MATCHING
PATTERN RECOGNITION
PERCEPTRONS
PHOTOGRAMMETRY
PICTURE RECOGNITION
PLANNER-LIKE LANGUAGES
PREDICATE CALCULUS
PREFERENTIAL SEMANTICS
PRICE'S TUTORIAL
PROBLEM SOLVING
PROCEDURAL EVENTS
PRODUCTION SYSTEMS
PRODUCTIVITY TECHNOLOGY
PROGRAM VERIFICATION
PSYCHOLOGY
RECOGNITION DEVICES
REPRESENTING REAL-WORLD KNOWLEDGE IN RELATIONAL PRODUCTION SYSTEMS
RESOLUTION THEOREM PROVING
RESOURCE LIMITED PROCESSES
RETRIEVAL
ROBOTICS COOPERATION

RULE ACQUISITION CAPABILITIES
SCENE SEGMENTATION
SEMANTIC NETS
A SEMANTIC NETWORK
SEMANTIC NETWORKS
SENTENCE MEANING IN CONTEXT
SENTENCE MEANING IN CONTEXT
SERIAL PATTERN ACQUISITION
SEVERAL GOALS
SHAPE GRAMMARS
SHAPE TOPOLOGY
SIMULTANEOUS ACTIONS
SNARING DRAGONS
SOFTWARE INTERRUPTS
SPEECH UNDERSTANDING
STATE DESCRIPTION MODELS
STOCHASTIC MODELING
STORAGE REDUCTION
STRUCTURED PATTERN RECOGNITION
SYMBOL MAPPING IN BASEBALL
SYNCHRONIZATION OF CONCURRENT PROCESSES
SYNTACTIC METHODS
SYNTAX
SYNTHESIS OF LINE DRAWINGS
TELEOLOGICAL REASONING
TEMPORAL SCENE ANALYSIS
TEXTURE ANALYSIS
THE ARTICLE BY ALLEN NEWELL
THE BAY AREA CIRCLE
THE BERKELEY DEBATE
THE COMPUTERS AND THOUGHT AWARD
THE DATES OF THE WORLD COMPUTER CHESS CONFERENCE
THE DEDUCTIVE PATHFINDER
THE DREYFUS DEBATE
THE ENVIRONMENT
THE FEDERAL JUDICIAL SYSTEM
THE GAME OF POKER
THE HISTORY OF AI
THE HUNGRY MONKEY
THE INSANE HEURISTIC
THE LANGUAGE PASCAL
THE LOCATION OF OBJECTS IN MAGAZINES
THE LOGICAL REDUCTION OF LISP DATA BASES
THE META-SYMBOLIC SIMULATION OF MULTIPROCESS SOFTWARE
THE METAMATHEMATICS OF MLISP OR MLISP2
THE NOMINATION OF NOMINEES BY A NATIONAL NOMINATING COMMITTEE
THE ONTOGENY OF NON-INDEPENDENT SUBPROBLEMS
THE PARRY SIMULATION OF PARANOIA
THE PERFORMANCE OF PATTERN MATCHING RULES
THE SIX SEVEN EIGHT NINE GAME
THE STOCK MARKET
THE STRUCTURE OF ANY VARIETY OF COMPUTER TERMINAL
THE TECH-II CHESS PROGRAM
THE WEAK LOGIC OF PROGRAMS
THREE DIMENSIONAL MODELS
TIME COMPLEXITY
TIME OR SPACE BOUNDS
TROUBLE SHOOTING

UNDERSTANDING
UNIFORM PROOF PROCEDURES
USING S-L-GRAPHS
VISUAL COMMUNICATION
VISUAL PLANES IN THE RECOGNITION OF POLYHEDRA

Appendix III-C-3. AI Retrieval Language Grammar: AIX05

```
<SENT>::= [ <SS> ]
<SS>::= ANY ABSTRACTS REFERRING TO <$TOPICS>
        ARE <$AUTHOR/S> CITED BY ANY OF THOSE
        ARE <$AUTHOR/S> CITED IN ANY RECENT PAPERS
        ARE <$TOPICS> DISCUSSED IN RECENT JOURNALS
        ARE <$TOPICS> MENTIONED ANYWHERE
        ARE <$TOPICS> MENTIONED IN AN ABSTRACT
        ARE ANY ARTICLES ABOUT <$TOPICS>
        ARE ANY ARTICLES BY <$AUTHOR/S>
        ARE ANY BY <$AUTHOR/S>
        ARE ANY NEW BOOKS BY <$AUTHOR/S>
        ARE ANY OF THE PAPERS ON <$TOPICS> ALSO ABOUT <$TOPICS>
        ARE ANY OF THESE BY <$AUTHOR/S>
        ARE ANY OF THESE FROM AN ACM SESSION
        ARE ANY OF THESE FROM THE IFIP SESSIONS IN THE MONTH OF JUNE
        ARE ANY PAPERS ABOUT <$TOPICS>
        ARE ANY RECENT ISSUES ABOUT <$TOPICS> BUT NOT <$TOPICS>
        ARE NOT SOME OF THESE FROM COMPUTING SURVEYS
        ARE THERE ANY ABSTRACTS WHICH REFER TO <$TOPICS>
        ARE THERE ANY ABSTRACTS WHICH REFER TO PAPERS BY <$AUTHOR/S>
        ARE THERE ANY ARTICLES ABOUT <$TOPICS>
        ARE THERE ANY ISSUES ABOUT <$TOPICS>
        ARE THERE ANY NEW ISSUES CONCERNING <$TOPICS>
        ARE THERE ANY NEW PAPERS ON <$TOPICS>
        ARE THERE ANY PAPERS THAT MENTION <$TOPICS>
        ARE THERE ANY RECENT ARTICLES IN CACM
        ARE THERE ANY RECENT BOOKS ABOUT <$TOPICS>
        ARE THERE SOME PAPERS ON <$TOPICS>
        ARE YOU ALWAYS THIS SLOW
        ARE YOU REGULARLY THIS SLOW
        ARE YOU USUALLY SO SLOW
        AREN'T THERE ANY ABSTRACTS SINCE NINETEEN SEVENTY FIVE
        CAN I HAVE THESE ABSTRACTS LISTED
        CAN YOU HELP ME
        CEASE PRINTING
        CHOOSE AMONG VOLUMES BEFORE NINETEEN SIXTY
        COULD YOU RETRIEVE SOMETHING FROM <$INFORMATION+AND+CONTROL> DISCUSSING <$TOPICS>
        DID <$AUTHOR/S> PRESENT A PAPER AT IJCAI
        DID <$AUTHOR/S> PRESENT A PAPER AT THE IFIP MEETINGS IN SEPTEMBER
        DID <$AUTHOR/S> PRESENT PAPERS AT IFIP
        DID <$AUTHOR/S> PRESENT PAPERS AT IJCAI
        DID <$AUTHOR/S> PUBLISH A PAPER
        DID <$AUTHOR/S> WRITE A BOOK
        DID <$AUTHOR/S> WRITE A BOOK RECENTLY
        DID <$AUTHOR/S> WRITE A PAPER THIS YEAR
        DID ANY <$AI+JOURNAL> PAPERS CITE <$AUTHOR/S>
        DID ANY ACL PAPERS CITE <$AUTHOR/S>
        DID ANY IEEE CONVENTIONS PUBLISH PROCEEDINGS
        DID ANY OF THOSE PAPERS CITE <$AUTHOR/S>
        DID ANYONE PUBLISH ABOUT <$TOPICS> IN COMMUNICATIONS OF THE ACM
        DID THE SIGART NEWSLETTER PUBLISH ANYTHING IN OCTOBER OR NOVEMBER
        DIDN'T THAT PAPER QUOTE <$AUTHOR/S>
        DO ALL QUERIES TAKE THIS LONG
        DO ANY ARTICLES ON <$TOPICS> IN ADDITION CONSIDER <$TOPICS>
        DO ANY ARTICLES ON <$TOPICS> MENTION <$TOPICS>
        DO ANY ARTICLES REFER TO <$TOPICS>
DO ANY AUTHORS DESCRIBE <$TOPICS>
DO ANY NEW ARTICLES MENTION <$TOPICS>
DO ANY OF THE ABSTRACTS MENTION <$TOPICS>
DO ANY OF THESE ALSO DISCUSS <$TOPICS>
DO ANY OF THESE ALSO MENTION <$TOPICS>
DO ANY OF THESE CITE <$AUTHOR/S>
DO ANY OF THESE MENTION <$TOPICS>
DO ANY OF THOSE PAPERS MENTION <$TOPICS>
DO ANY PAPERS ABOUT <$TOPICS> ALSO CONSIDER <$TOPICS>
DO ANY PAPERS CITE <$AUTHOR/S>
DO ANY PAPERS DISCUSS <$TOPICS>
DO ANY PAPERS DISCUSS <$TOPICS> BUT NOT <$TOPICS>
DO ANY PAPERS ON <$TOPICS> EXIST
DO ANY PAPERS THIS YEAR CITE <$AUTHOR/S>
DO ANY RECENT ACM CONFERENCES CONSIDER <$TOPICS>
DO ANY RECENT BOOKS CITE <$AUTHOR/S>
DO ANY RECENT BOOKS MENTION <$TOPICS>
DO ANY RECENT JOURNALS DISCUSS <$TOPICS>
DO ANY RECENT SUMMARIES DISCUSS <$TOPICS>
DO MANY ABSTRACTS DISCUSS <$AUTHOR/S>
DO MANY ABSTRACTS DISCUSS <$TOPICS>
DO RESPONSES EVER COME FASTER
DO THEY WORK AT THE GM RESEARCH LABS
DO YOU HAPPEN TO HAVE ANY RECENT PAPERS ON <$TOPICS>
DO YOU HAVE ANY ARTICLES ON <$TOPICS>
DO YOU HAVE ANY NEW PAPERS ON <$TOPICS>
DO YOU HAVE ANY RECENT PAPERS ON <$TOPICS>
DO YOU HAVE ANY SUMMARIES ABOUT <$TOPICS>
DO YOU HAVE NEW PAPERS ON <$TOPICS>
DOES <$TOPICS> GET DISCUSSED ANYWHERE
DOES <$TOPICS> GET MENTIONED ANYWHERE
DOES HE WORK AT CMU
DOES IT ALWAYS TAKE THIS LONG TO ANSWER ME
DOES SHE WORK AT THE INSTITUTE FOR SEMANTIC AND COGNITIVE STUDIES
DOES THAT ARTICLE MENTION <$TOPICS>
DOESN'T THIS PAPER REFERENCE AN IEEE TRANSACTION
DON'T GET ME ANY ARTICLES WHICH MENTION <$TOPICS>
DURING WHAT MONTHS WERE THEY PUBLISHED
FINISH PRINTING
GENERATE A COPY OF THOSE
GET ME ANY BOOKS WRITTEN BY <$AUTHOR/S>
GET ME EVERYTHING ON <$TOPICS>
GIVE ME ANY ABSTRACTS MENTIONING <$TOPICS> BUT NOT <$TOPICS>
GIVE ME ANY ARTICLES ABOUT <$TOPICS>
GIVE ME ANY PAPERS ON <$TOPICS> FROM JUNE TILL AUGUST
GIVE ME ONE MORE PLEASE
GIVE ME SOMETHING MENTIONING <$TOPICS>
GIVE ME THE DATE OF THAT ABSTRACT
GIVE THE AUTHOR AND DATE OF EACH
HAS <$AUTHOR/S> BEEN REFERENCED IN ANY OF THOSE
HAS <$AUTHOR/S> PUBLISHED ANY PAPERS THIS YEAR
HAS <$AUTHOR/S> PUBLISHED ANYTHING RECENTLY
HASN'T <$TOPICS> BEEN CONSIDERED IN COMPUTING REVIEWS
HASN'T A CURRENT REPORT ON <$TOPICS> BEEN RELEASED
HAVE <$AUTHOR/S> PUBLISHED THIS YEAR
HAVE ANY ARTICLES APPEARED WHICH MENTION <$TOPICS>
HAVE ANY NEW PAPERS BY <$AUTHOR/S> APPEARED
HAVEN'T YOU FINISHED
```

HELP
HOW BIG IS THE DATA BASE
HOW CAN I USE THE SYSTEM EFFICIENTLY
HOW LONG DOES IT TAKE
HOW MANY ABSTRACTS ARE THERE ON <$TOPICS>
HOW MANY ABSTRACTS REFER TO <$TOPICS>
HOW MANY ARTICLES DISCUSS <$TOPICS>
HOW MANY ARTICLES ON <$TOPICS> ARE THERE
HOW MANY ARTICLES WERE WRITTEN BY <$AUTHOR/S> AND NOT <$AUTHOR/S>
HOW MANY BOOKS DISCUSS <$TOPICS>
HOW MANY BOOKS WERE PRODUCED FROM MARCH TO DECEMBER
HOW MANY BOOKS WERE WRITTEN BY <$AUTHOR/S>
HOW MANY OF THESE ALSO DISCUSS <$TOPICS>
HOW MANY PAPERS ARE ABOUT <$TOPICS>
HOW MANY PAPERS CONSIDER <$TOPICS> SIMULTANEOUSLY
HOW MANY PAPERS DISCUSS <$TOPICS>
HOW MANY PAPERS FROM APRIL THROUGH AUGUST CONCERNED <$TOPICS>
HOW MANY PAPERS HAVE <$AUTHOR/S> WRITTEN SINCE JANUARY
HOW MANY PAPERS REFER TO <$TOPICS>
HOW MANY PAPERS THIS YEAR DISCUSS <$TOPICS>
HOW MANY PAPERS WERE WRITTEN BY <$AUTHOR/S>
HOW MANY RECENT ISSUES CONCERN <$TOPICS>
HOW MANY REFERENCES ARE GIVEN
HOW MANY SUMMARIES DISCUSS <$TOPICS>
I AM INTERESTED IN <$TOPICS>
I AM ONLY INTERESTED IN PAPERS ON <$TOPICS>
I DEMAND ANOTHER ARTICLE AFTER AUGUST NINETEEN THIRTEEN
I'D LIKE TO KNOW THE PUBLISHERS OF THAT STORY
I'D LIKE TO SEE THE MENUS
IS <$AUTHOR/S> BUT NOT <$AUTHOR/S> CITED IN SOME OF THOSE ARTICLES
IS <$AUTHOR/S> CITED BY THOSE ABSTRACTS
IS <$AUTHOR/S> CITED IN ANY OF THESE
IS <$TOPICS> DISCUSSED ANYWHERE
IS <$TOPICS> DISCUSSED IN A RECENT SUMMARY
IS <$TOPICS> MENTIONED
IS <$TOPICS> MENTIONED ANYWHERE
IS <$TOPICS> MENTIONED IN AN ABSTRACT
IS <$TOPICS> REFERRED TO
IS <$TOPICS> REFERRED TO ANYWHERE
IS THAT ABOUT <$TOPICS>
IS THERE A RECENT ARTICLE ABOUT <$TOPICS>
IS THERE A RECENT PAPER ABOUT <$TOPICS>
IS THERE A RECENT PAPER MENTIONING <$TOPICS>
IS THERE AN ARTICLE ABOUT <$TOPICS>
IS THERE AN IFIP CONVENTION ISSUE FROM MAY OR JUNE
IS THERE ANYTHING NEW REGARDING <$TOPICS>
ISN'T <$TOPICS> MENTIONED IN AN ABSTRACT
ISN'T THERE AN ARTICLE ABOUT <$TOPICS>
KILL THE LISTING
LET ME LIMIT MYSELF TO REPORTS ISSUED SINCE NINETEEN FIFTEEN
LET US CONFINE OURSELVES TO JOURNALS AFTER FEBRUARY NINETEEN FIFTY
LET'S RESTRICT OUR ATTENTION TO PAPERS SINCE NINETEEN SEVENTY FOUR
LIST BETWEEN TWELVE AND TWENTY OF THEM
LIST THE ABSTRACTS BY <$AUTHOR/S>
LIST THE NEXT FOURTEEN HUNDRED
NO MORE PLEASE
NO THANKS
OK

PLEASE HELP ME
PLEASE LIST THE AUTHORS
PLEASE MAKE ME A FILE OF THOSE
PLEASE TERMINATE TRANSMITTING
PRINT THE NEXT ONE
PRODUCE A COPY OF THE NEWEST EIGHTY ARTICLES
QUIT LISTING PLEASE
SELECT FROM ARTICLES ON <$TOPICS>
SHOW ME ITS PUBLISHER
SHOW ME THE LATEST ELEVEN
STOP TRANSMITTING PLEASE
SUBSELECT FROM <$TOPICS>
SURE THANKS
TELL ME THE TITLES OF THE EARLIEST TEN
TELL ME WHAT TO DO
THANK YOU I'M DONE
THE AREA I AM INTERESTED IN IS <$TOPICS>
THE AREA I'M INTERESTED IN IS <$TOPICS>
THE FIRST TWO
THE LATEST SIXTEEN PLEASE
TRANSMIT THE NEXT EIGHTEEN
TRY TO GET SURVEYS PRINTED IN THE LAST EIGHTY MONTHS
WAS <$AUTHOR/S> CITED BY ANY REPORTS ISSUED IN THE LAST NINETY YEARS
WAS <$AUTHOR/S> CITED IN THAT SUMMARY
WAS <$TOPICS> MENTIONED SOMEWHERE IN RECENT TIMES
WAS <$TOPICS> WRITTEN UP RECENTLY
WAS IT PUBLISHED BY <$THE+ASSOCIATION+FOR+COMPUTATIONAL+LINGUISTICS>
WAS IT PUBLISHED BY THE JOURNAL OF THE ACM
WAS THERE A CONFERENCE IN THE USSR
WASN'T <$TOPICS> MENTIONED RECENTLY
WASN'T <$TOPICS> REFERRED TO SOMEWHERE
WE DESIRE A PROCEEDING OF THE ACM MEETING REFERENCED BY <$AUTHOR/S>
WE WANT SOME REVIEWS CONCERNING <$TOPICS>
WE WISH TO GET THE LATEST FORTY ARTICLES ON <$TOPICS>
WE'D LIKE TO SEE THE TITLES FROM PROCEEDINGS OF THE ACM CONFERENCE
WE'RE INTERESTED IN <$TOPICS>
WE'RE INTERESTED IN ARTICLES PUBLISHED IN THE LAST THIRTY YEARS
WE'VE BEEN INTERESTED IN <$TOPICS>
WERE ANY OF THESE ARTICLES WRITTEN BY <$AUTHOR/S>
WERE ANY OF THESE PUBLISHED IN THE SUNSHINE STATE OR IN THE U.S.
WERE ANY OF THESE WRITTEN BY <$AUTHOR/S>
WERE ANY PUBLISHED AFTER JUNE NINETEEN SIXTY FIVE
WERE THERE ANY ARTICLES ABOUT <$TOPICS>
WEREN'T SOME ARTICLES PUBLISHED ON <$TOPICS>
WHAT ABOUT <$AUTHOR/S>
WHAT ABOUT <$TOPICS>
WHAT ADDRESS IS GIVEN FOR THE AUTHORS
WHAT ADDRESSES ARE GIVEN FOR THE AUTHORS
WHAT ARE SOME OF THE AREAS OF <$TOPICS>
WHAT ARE THE KEY PHRASES
WHAT ARE THE TITLES OF THE RECENT ARPA SURNOTES
WHAT ARE THEIR AFFILIATIONS
WHAT BOOKS MENTION <$TOPICS>
WHAT CAN I DO TO SPEED YOU UP
WHAT CAN THE SYSTEM DO
WHAT CONFERENCE WAS AT RUTGERS OR AT SRI
WHAT CONFERENCE WAS AT WATSON RESEARCH OR AT ILLINOIS
WHAT DO I HAVE TO DO

```
WHAT FACTS ARE STORED
WHAT HAS <$AUTHOR/S> WRITTEN LATELY
WHAT HAS <$AUTHOR/S> WRITTEN RECENTLY
WHAT HAVE <$AUTHOR/S> WRITTEN LATELY
WHAT IS HER AFFILIATION
WHAT IS HIS AFFILIATION
WHAT IS KNOWN ABOUT EVERY ARTICLE
WHAT IS THE SIZE OF THE DATA BANK
WHAT IS THE TITLE OF THAT PAPER
WHAT IS THE TITLE OF THE EARLIEST ONE
WHAT IS THE TITLE OF THE MOST RECENT ONE
WHAT ISSUES DURING JANUARY AND JULY CONCERN <$TOPICS>
WHAT KEY WORD RELATES TO <$TOPICS>
WHAT KEY WORDS SHOULD I USE FOR <$TOPICS>
WHAT KIND OF MENUS ARE THERE
WHAT KINDS OF SUBJECTS ARE STORED
WHAT MUST I ASK
WHAT PAPERS ON <$TOPICS> ARE THERE
WHAT SHOULD I ASK
WHAT SHOULD I SAY
WHAT SORT OF SUMMARY IS AVAILABLE
WHAT SORTS OF <$TOPICS> ARE WRITTEN UP
WHAT SUBJECT CAN I REQUEST
WHAT TOPIC MENU CAN I CHOOSE
WHAT TOPICS ARE RELATED TO <$TOPICS>
WHAT TYPES OF <$RETRIEVAL+CAN+HEARSAY> DO
WHAT WAS ITS TITLE
WHAT'S THE PUBLISHER OF THAT PIECE
WHEN WAS <$HUMAN+PROBLEM+SOLVING> WRITTEN
WHEN WAS <$TOPICS> LAST MENTIONED
WHEN WAS <$TOPICS> LAST REFERRED TO
WHEN WAS IT PUBLISHED
WHEN WAS THAT BOOK WRITTEN
WHEN WAS THAT PAPER PUBLISHED
WHEN WAS THE LAST PAPER BY <$AUTHOR/S> PUBLISHED
WHEN WERE <$TOPICS> LAST REFERRED TO
WHEN WILL YOU HAVE THE ANSWER
WHERE ARE <$TOPICS> REFERRED TO
WHERE DID THAT ARTICLE APPEAR
WHERE DO THEY WORK
WHERE DOES HE WORK
WHERE IS <$TOPICS> MENTIONED
WHICH <$AI+TEXT> CONTAINED <$TOPICS>
WHICH <$COGNITIVE+PSYCHOLOGY> CONTAINED <$TOPICS>
WHICH <$COGNITIVE+PSYCHOLOGY> CONTAINS <$TOPICS>
WHICH ABSTRACTS CONCERN <$TOPICS>
WHICH ABSTRACTS REFER TO <$TOPICS>
WHICH ARTICLES CONCERN <$TOPICS>
WHICH ARTICLES HAVE CONCERNED <$TOPICS>
WHICH ARTICLES ON <$TOPICS> ALSO CONCERN <$TOPICS>
WHICH ARTICLES REFER TO THESE
WHICH AUTHORS WORK AT HAMBURG OR AT EDINBURGH
WHICH AUTHORS WORK AT NIH OR AT STANFORD
WHICH AUTHORS WORK WITH SUMEX OR AT SUSSEX
WHICH BOOKS ON <$TOPICS> WERE PUBLISHED RECENTLY
WHICH BOOKS WERE WRITTEN BY <$AUTHOR/S> SINCE LAST YEAR
WHICH COMPUTING SURVEY ARTICLES RELATE TO <$TOPICS>
WHICH COMPUTING SURVEYS CONTAINED THE ARTICLE BY <$AUTHOR/S>
WHICH CONFERENCES WERE AT MASSACHUSETTS OR AT ROCHESTER
WHICH IS THE OLDEST
WHICH NOTES ON <$TOPICS> ALSO DISCUSS <$TOPICS>
WHICH OF THEM DISCUSSES <$TOPICS>
WHICH OF THESE APPEARED RECENTLY IN THE IEEE TRANSACTIONS
WHICH OF THESE ARE BY <$AUTHOR/S>
WHICH OF THESE CITES <$AUTHOR/S>
WHICH OF THESE WAS WRITTEN BY <$AUTHOR/S>
WHICH OF THESE WERE WRITTEN BY <$AUTHOR/S>
WHICH ONES
WHICH PAPER MENTIONS <$TOPICS>
WHICH PAPERS ARE ON <$TOPICS>
WHICH PAPERS BY <$AUTHOR/S> ARE REFERENCED
WHICH PAPERS CITE <$AUTHOR/S>
WHICH PAPERS DISCUSS <$TOPICS>
WHICH PAPERS HAVE MENTIONED <$TOPICS>
WHICH PAPERS ON <$TOPICS> ALSO CONCERN <$TOPICS>
WHICH PAPERS ON <$TOPICS> ALSO DISCUSS <$TOPICS>
WHICH PAPERS ON <$TOPICS> ARE ABOUT <$TOPICS>
WHICH PAPERS WERE WRITTEN AT NRL OR AT SMC
WHICH PAPERS WERE WRITTEN BY <$AUTHOR/S>
WHICH RECENT JOURNALS REFER TO <$TOPICS>
WHICH SORT OF <$RETRIEVAL-KEYS> CAN I SEEK
WHICH STORIES IN THE SIGART NEWSLETTER HAVE BEEN DISCUSSING <$TOPICS>
WHICH SUMMARIES ON <$TOPICS> CONSIDER <$TOPICS> IN ADDITION
WHICH TECHNICAL PAPERS WERE WRITTEN BY <$AUTHOR/S>
WHICH TITLES CONTAIN THE PHRASE <$TOPICS>
WHICH WAS THE LAST ARTICLE BY <$AUTHOR/S>
WHO
WHO HAS WRITTEN ABOUT <$TOPICS>
WHO WAS QUOTED IN THAT ARTICLE
WHO WAS THE AUTHOR
WHO WERE THE AUTHORS OF THAT BOOK
WHO WROTE IT
WHO WROTE PAPERS ON <$TOPICS> THIS YEAR
WHY IS THE SYSTEM SO SLOW
WOULD YOU LIST UP TO SEVENTEEN
WRITE A FILE OF THOSE
YES PLEASE
```

```
<$INFORMATION+AND+CONTROL>::= INFORMATION AND CONTROL
<$COGNITIVE+PSYCHOLOGY>::= COGNITIVE PSYCHOLOGY
<$THE+WORLD+COMPUTER+CHESS+CONFERENCE>::= THE WORLD COMPUTER CHESS CONFERENCE
<$AI+JOURNAL>::= AI JOURNAL
<$AI+TEXT>::= AI TEXT
<$THE+ASSOCIATION+FOR+COMPUTATIONAL+LINGUISTICS>::= THE ASSOCIATION FOR COMPUTATIONAL LINGUISTICS
<$RETRIEVAL+CAN+HEARSAY>::= RETRIEVAL CAN HEARSAY
<$HUMAN+PROBLEM+SOLVING>::= HUMAN PROBLEM SOLVING
<$RETRIEVAL+KEYS>::= RETRIEVAL KEYS
```

```
<$AUTHOR/S>::= <AUTHOR>
      <AUTHOR> <AND!OR 1> <AUTHOR>
<AND!OR 1>::= AND
      OR

<AUTHOR>::= ALLEN COLLINS
      ALLEN NEWELL
      ANN RUBIN
      ANTHONY MARTELLI
      AZRIEL ROSENFELD
      BERNARD MELTZER
      BERT RAPHAEL
      BILL WOODS
      BONNIE NASH-WEBBER
      BRUCE BUCHANAN
      CARL HEWITT
      CHRISTOPHER RIESBECK
      CHUCK RIEGER
      DANNY BOBROW
      DAVE RUMELHART
      DAVID MARR
      DAVID MICHIE
      DICK SELTZER
      DONALD NORMAN
      DOUG LENAT
      DREW MCDERMOTT
      DREYFUS
      EARL HUNT
      EARL SACERDOTI
      ED FEIGENBAUM
      ED RISEMAN
      ELLIOT SOLOWAY
      ERIK SANDEWALL
      EUGENE CHARNIAK
      FEIGENBAUM
      FELDMAN
      GARY HENDRIX
      GEORGE ERNST
      GIPS
      HANS BERLINER
      HARRY BARROW
      HERB SIMON
      HERBERT BLOCK
      HILARY PUTNAM
      HOLLAND
      HUGH NAGEL
      IRV SOBEL
      ISSAC ASIMOV
      JACK MINKER
      JACK MOSTOW
      JAMES SLAGLE
      JEAN SAMMET
      JEFFREY ULLMAN
      JERRY FELDMAN
      JOHN GASCHNIG
      JOHN HOLLAND
      JOHN MCCARTHY
      JOHN NEWCOMER
```

JOSEPH WEIZENBAUM
JUDEA PEARL
KARL PINGLE
KEITH PRICE
KEN COLBY
KEN RALSTON
KING SUNG FU
LAURENT SIKLOSSY
LEE ERMAN
LEONARD UHR
LES EARNEST
LINDA MASINTER
MADELINE BATES
MARVIN MINSKY
MARY NEWBORN
MARY SHAW
MICHAEL ARBIB
MIKE RYCHENER
MINSKY
MITCHELL NEWEY
NEWELL
NILS NILSSON
NILSSON
NORI SUZUKI
PAMELA MCCORDUCK
PAT WINSTON
PERRY THORNDYKE
PETER KUGEL
RAJ REDDY
RANAN BANERJI
RAYMOND SPROULL
REDDY
RICH FIKES
RICH SMITH
RICHARD MICHALSKI
RICHARD WALDINGER
RICK HAYES-ROTH
ROBERT REITER
ROGER SCHANK
RON OHLANDER
ROSENFELD
SCOTT FAHLMAN
SEYMOUR PAPERT
SIMON
STEVE COLES
STEVE REED
STEVE ZUCKER
TED SHORTLIFFE
TERRY WINOGRAD
THOMAS MARSLAND
THOMAS SYKES
UHR
VIC LESSER
WALLY RHOMBERG
WOODS
WOODY BLEDSOE
YORICK WILKS
ZOHAR MANNA

```
<$TOPICS> :→ <AND/OR/TOPICS>
      WINOGRAD'S ARTICLE
<AND/OR/TOPICS> :→ <TOPIC>
      <TOPIC> <AND/OR 2> <TOPIC>
<AND/OR 2> :→ AND
      OR
<TOPIC> :→ A CAI MONITOR
      A COMMON SENSE ALGORITHM
      A GAME MODEL
      A LOSING MOVE
      A MULTILEVEL ORGANIZATION
      A PACKET BASED APPROACH TO NETWORK COMMUNICATION
      A PARTIAL EVALUATOR
      A PROGRAM SYNTHESIZER FOR NETWORK PROTOCOLS
      A PROGRAMMING APPRENTICE
      A PROOF CHECKER FOR PROTOCOL TERMINATION EXPRESSIONS
      A RADIO INTERVIEW ON SCIENCE FICTION
      A REGION ANALYSIS SUBSYSTEM
      A STEREO PAIR OF VIEWS
      A TASK ORIENTED DIALOGUE
      A THAUMATURGIST
      A THEOREM PROVER PLANNING FOR PROGRESS
      A TIME DOMAIN ANALYZER
      A TUTOR OR TUTORING ON TV
      A TV REPORTER
      ABSTRACTION
      ACQUISITION OF KNOWLEDGE
      ACTIVE KNOWLEDGE
      ACYCLIC ISOMERS
      ADAPTATION
      ADAPTIVE PRODUCTION SYSTEMS
      ADVISING PHYSICIANS
      AI
      AI LECTURES
      ALGEBRAIC REDUCTION
      ALGOL
      ALGORITHMIC AESTHETICS
      ALL-OR-NONE SOLUTIONS
      AN ADAPTIVE NATURAL LANGUAGE SYSTEM
      AN ASSEMBLY ROBOT
      AN AXIOMATIC SYSTEM
      ANALOGY IN PROBLEM SOLVING
      ANALYSIS OF CONTEXT
      ANALYSIS OF SENTENCES
      ARTIFICIAL INTELLIGENCE
      ASSIMILATION OF NEW INFORMATION
      ASSOCIATIVE MEMORIES
      ASSOCIATIVE MEMORY
      AUGMENTED TRANSITION NETWORKS
      AUTOMATED DEDUCTION
      AUTOMATIC CODING
      AUTOMATIC COMPUTATION
      AUTOMATIC MANTRA GENERATION
      AUTOMATIC PROGRAM SYNTHESIS FROM EXAMPLE PROBLEMS
      AUTOMATIC PROGRAM WRITING
      AUTOMATIC PROGRAMMING
      AUTOMATIC PROOF OF CORRECTNESS
      AUTOMATIC THEOREM PROVING
```

AUTOMATION
AXIOMATIC SEMANTICS
AXIOMS FOR GO
BACKGAMMON
BELIEF SYSTEMS
BINDINGS
BIOMEDICINE
BRAIN THEORY
BUSINESS PROBLEM SOLVING
CARTOGRAPHY
CASE SYSTEMS
CAUSAL REASONING
CELL ASSEMBLY THEORY
CHECKING PROOFS
CHESS
CHESS PLAYING PROGRAMS
CIRCUIT ANALYSIS
COGNITION
COGNITIVE ROBOTIC SYSTEMS
COGNITIVE SCIENCE
COMMON SENSE
COMMON SENSE THEORY FORMATION
COMPLEX WAVEFORMS
COMPUTATIONAL LINGUISTICS
COMPUTER ART
COMPUTER BASED CONSULTANT
COMPUTER BASED CONSULTATIONS
COMPUTER CONTROLLED MANIPULATORS
COMPUTER GRAPHICS
COMPUTER MUSIC
COMPUTER NETWORKS
COMPUTER VISION
CONCEPTUAL DESCRIPTIONS
CONCEPTUAL INFERENCE
CONCEPTUAL OVERLAYS
CONSTRAINT SATISFACTION
CONSTRUCTING PROGRAMS FROM EXAMPLES
CONSTRUCTION OF PROGRAMS
CONTEXT
CONTINUOUS PROCESSES
CONTROL
COOPERATING SOURCES OF KNOWLEDGE
COPYING LIST STRUCTURES
CURVED OBJECTS
CYBERNETICS
CYCLIC
DATA BASES
DATA BASES FOR INTERACTIVE DESIGN
DATA STRUCTURES
DECISION THEORY
DEDUCTION
DEDUCTIVE RETRIEVAL
DENOTATIONAL SEMANTICS
DEPTH PERCEPTION
DERIVATION PLANS
DESIGN
DESIGN AUTOMATION
DESIGN IN THE ARTS

DETECTION OF LIGHT SOURCES
DISPLAY TERMINALS
DRAGON
DRIVING A CAR
DYNAMIC BINDING
DYNAMIC CLUSTERING
DYNAMIC PROGRAMMING
ELECTRONIC CIRCUITS
ELECTRONICS
ENGLISH
EVALUATION FUNCTIONS
EXPERT SYSTEMS
EXPLANATION CAPABILITIES
FABLES OR FAIRY TALES
FEATURE-DRIVEN SYSTEMS
FIRST ORDER LOGIC
FORMAL SEMANTICS
FRAME THEORY
FRAMES
FRAMES AND THE ENVIRONMENT
FUZZY KNOWLEDGE
FUZZY PROBLEM SOLVING
GAME OF POKER
GAME PLAYING
GENERAL PURPOSE MODELS
GENERATION OF NATURAL LANGUAGE
GEOMETRIC MODELING
GO OR GO-MOKU
GOAL SEEKING COMPONENTS
GRAIN OF COMPUTATION
GRAMMATICAL INFERENCE
GRAPH INTERPRETABLE GAMES
GRAPH MATCHING
HEARSAY
HETEROSTATIC THEORY
HEURISTIC PROGRAMMING
HEURISTIC TECHNIQUES
HILL CLIMBING
HUMAN BEHAVIOR
HUMAN MEMORY
HUMAN VISION
HYPOTHESIS FORMATION
IMAGE INTENSITY UNDERSTANDING
IMPROVING PROGRAMS
INDUCTIVE ASSERTIONS
INDUSTRIAL APPLICATION
INEXACT REPRESENTATION
INFERENCE
INFERENCES
INFERENTIAL QUESTION ANSWERING
INFORMATION PROCESSING UNIVERSALS
INHERITANCE OF PROPERTIES
INTELLIGENT MACHINES
INTENTIONS
INTERACTIVE DESIGN
INTERACTIVE KNOWLEDGE SYSTEMS
INTERACTIVE PROGRAM SYNTHESIS
INTERPRETIVE SEMANTICS

INTONATION
INVARIANCE FOR PROBLEM SOLVING
INVARIANCES IN THE PERCEPTION OF FACES
INVESTMENT ANALYSIS
ITERATION
KNOWLEDGE BASED SYSTEMS
KNOWLEDGE SYSTEMS
LAMBDA CALCULUS
LANGUAGE COMPREHENSION
LANGUAGE DESIGN
LANGUAGE PARAPHRASE
LANGUAGE PASCAL
LANGUAGE PRIMITIVES
LANGUAGE UNDERSTANDING
LARGE DATA BASES
LEARNING
LINEAR LEXICOMETRY
LOW ORDERS OF RECOGNITION PERFORMANCE
MACHINE INTELLIGENCE IN MEDICAL DIAGNOSIS
MACRO PROCESSING FOR AN ON-LINE NEWSLETTER
MANAGEMENT INFORMATION SYSTEMS
MEANS FOR COMPUTER MOVIES
MEDICAL CONSULTATION
MINIMAL SPANNING FORESTS OR TREES
MOTION IN SCENE DESCRIPTION
NEURAL NETWORKS
NEWSLETTER REPORTERS
NONDETERMINISTIC PROGRAMMING
OBJECT LOCATIONS AND MOVEMENTS IN NATURAL IMAGES
OBJECT MANIPULATING ROBOTS
OPERATIONAL REASONING
OPTIMAL PROBLEM SOLVING SEARCH
OPTIMIZED CODE FOR THE TRANSFER OF COMMENTS
PAPERS BY BILL WOODS
PARALLELISM IN PROBLEM SOLVING
PARTIAL EVALUATOR
PATTERN DIRECTED FUNCTION INVOCATION
PATTERN MATCHING
PATTERN RECOGNITION
PERCEPTRONS
PHOTOGRAMMETRY
PICTURE RECOGNITION
PLANNER-LIKE LANGUAGES
PREDICATE CALCULUS
PREFERENTIAL SEMANTICS
PRICE'S TUTORIAL
PROBLEM SOLVING
PROCEDURAL EVENTS
PRODUCTION SYSTEMS
PRODUCTIVITY TECHNOLOGY
PROGRAM VERIFICATION
PSYCHOLOGY
RECOGNITION DEVICES
REPRESENTING REAL-WORLD KNOWLEDGE IN RELATIONAL PRODUCTION SYSTEMS
RESOLUTION THEOREM PROVING
RESOURCE LIMITED PROCESSES
RETRIEVAL
ROBOTICS COOPERATION

RULE ACQUISITION CAPABILITIES
SCENE SEGMENTATION
SEMANTIC NETS
A SEMANTIC NETWORK
SEMANTIC NETWORKS
SENTENCE MEANING IN CONTEXT
SENTENCE MEANING IN CONTEXT
SERIAL PATTERN ACQUISITION
SEVERAL GOALS
SHAPE GRAMMARS
SHAPE TOPOLOGY
SIMULTANEOUS ACTIONS
SNARING DRAGONS
SOFTWARE INTERRUPTS
SPEECH UNDERSTANDING
STATE DESCRIPTION MODELS
STOCHASTIC MODELING
STORAGE REDUCTION
STRUCTURED PATTERN RECOGNITION
SYMBOL MAPPING IN BASEBALL
SYNCHRONIZATION OF CONCURRENT PROCESSES
SYNTACTIC METHODS
SYNTAX
SYNTHESIS OF LINE DRAWINGS
TELEOLOGICAL REASONING
TEMPORAL SCENE ANALYSIS
TEXTURE ANALYSIS
THE ARTICLE BY ALLEN NEWELL
THE BAY AREA CIRCLE
THE BERKELEY DEBATE
THE COMPUTERS AND THOUGHT AWARD
THE DATES OF THE WORLD COMPUTER CHESS CONFERENCE
THE DEDUCTIVE PATHFINDER
THE DREYFUS DEBATE
THE ENVIRONMENT
THE FEDERAL JUDICIAL SYSTEM
THE GAME OF POKER
THE HISTORY OF AI
THE HUNGRY MONKEY
THE INSANE HEURISTIC
THE LANGUAGE PASCAL
THE LOCATION OF OBJECTS IN MAGAZINES
THE LOGICAL REDUCTION OF LISP DATA BASES
THE META-SYMBOLIC SIMULATION OF MULTIPROCESS SOFTWARE
THE METAMATHEMATICS OF MLISP OR MLISP2
THE NOMINATION OF NOMINEES BY A NATIONAL NOMINATING COMMITTEE
THE ONTOGENY OF NON-INDEPENDENT SUBPROBLEMS
THE PARRY SIMULATION OF PARANOIA
THE PERFORMANCE OF PATTERN MATCHING RULES
THE SIX SEVEN EIGHT NINE GAME
THE STOCK MARKET
THE STRUCTURE OF ANY VARIETY OF COMPUTER TERMINAL
THE TECH-II CHESS PROGRAM
THE WEAK LOGIC OF PROGRAMS
THREE DIMENSIONAL MODELS
TIME COMPLEXITY
TIME OR SPACE BOUNDS
TROUBLE SHOOTING

UNDERSTANDING
UNIFORM PROOF PROCEDURES
USING S-L-GRAPHS
VISUAL COMMUNICATION
VISUAL PLANES IN THE RECOGNITION OF POLYHEDRA

IV. COLLECTED PAPERS

A collection of papers, all of which appeared in the Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, Hartford, Connecticut, May 9-11, 1977, with the exception of the last paper, "A halting condition and related pruning heuristic for combinatorial search", which is an unpublished working paper.

A FUNCTIONAL DESCRIPTION OF THE HEARSAY-II SPEECH UNDERSTANDING SYSTEM

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ABSTRACT

A description of the September, 1976, version of the Hearsay-II system is given at the knowledge-source level, indicating the actions of each knowledge-source and their interactions.

INTRODUCTION

The Hearsay-II system has been described elsewhere in terms of its system organization, including the model which has driven that design [LeHs75, ErMu75, FePa76]. Also, the individual knowledge sources (KSs) have been separately reported on in detail. In this paper, a description of the September, 1976, version of the system is given in terms of the functions and interactions of the KS.[2] This does *not* include a description of how this configuration is realized within the general Hearsay model and Hearsay-II system, nor does it include many details of the inner workings of the KSs, or comparisons of Hearsay-II with any other systems.

The task for the system is to answer questions about and retrieve documents from a collection of computer science abstracts (in the area of artificial intelligence). Example sentences are:

"Which abstracts refer to theory of computation?"
"List those articles."
"What has Minsky written since nineteen seventy-four?"

The vocabulary contains 1011 words (in which each extended form of a root, e.g., the plural of a noun, is counted separately, if it appears). The grammar which defines the legal sentences is context free and includes recursion. The style of the grammar is such that there are many more non-terminals than in conventional syntactic grammars; the information contained in the greater number of nodes provides semantic and pragmatic constraint within the grammatical structure. For example, in place of 'Noun' in a conventional grammar, this grammar includes such non-terminals as 'Topic', 'Author', 'Year', 'Publisher', etc.

The grammar allows each word, on the average, to be followed by seventeen other words of the vocabulary. The standard deviation of this measure is very high (about 51), since some words can be followed by many others (up to 300 in several cases). For the sentences used for performance testing, the average length is seven words and the average number of words that can follow any initial portion of the sentence is thirty-four.

The September, 1976, configuration of the system recognizes about 80% of its test utterances (run blind) word-for-word correctly, with about 90% of the utterances being interpreted semantically correct.

SIGNAL ACQUISITION, PARAMETER EXTRACTION, SEGMENTATION, and LABELLING

An input utterance is spoken into a medium-quality Electro-Voice RE-51 close-speaking headset microphone in a fairly noisy environment (>65 db). The audio signal is low-passed filtered and 9-bit sampled at 10 KHz. All subsequent processing, as well as controlling the A/D converter, is digital and is done on a time-shared PDP-10 computer. Four parameters (called "ZAPDASH") are derived by simple algorithms operating directly on the sampled signal [GoZa77]. These parameters are extracted in real-time and are initially used to detect the beginning and end of the utterance.

The ZAPDASH parameters are next used by the *SEG* knowledge-source as the basis for an acoustic segmentation and classification of the utterance. This segmentation is accomplished by an iterative refinement technique: First, silence is separated from non-silence; then, the non-silence is broken down into the sonorant and non-sonorant regions, etc. Eventually, five classes of segments are produced: silence, sonorant peak, sonorant non-peak, fricative, and flap. Associated with each classified segment is its duration, absolute amplitude, and amplitude relative to its neighboring segments (i.e., local peak, local value, or plateau). The segments are contiguous and non-overlapping, with one class designation for each.

Finally, the SEG KS does a finer labelling of each segment. The labels are allophonic-like; there are currently 98 of them. Each of the 98 labels is defined by a vector of autocorrelation coefficients [ItMi75]. These templates are generated from speaker-dependent training data that have been hand-labelled. The result of the labelling process, which matches the central portion of each segment against each of the templates using the Itakura metric, is a vector of 98 numbers; the i'th number is an estimate of the (negative log) probability that the segment represents an occurrence of the i'th allophone in the label set.

[1] This work was supported by the Defense Advanced Research Projects Agency (F44620-73-C-0074) and is monitored by the Air Force Office of Scientific Research.

[2] Henceforth, all descriptions are understood to apply to the September, 1976, system.

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WORD SPOTTING

The initial generation of words, bottom-up, is accomplished by a three-step process.

First, using the labelled segments as input, the *POM* knowledge source [SmWo76] generates hypotheses for likely syllable classes. This is done by first identifying syllable nuclei and then "parsing" outward from each nucleus. The syllable-class parsing is driven by a probabilistic "grammar" of "syllable-class -> segment" productions; the rules and their probabilities are learned by an offline program which is trained on hand-labelled utterances. (The current training, which is speaker-dependent, is over 60 utterances containing about 360 word tokens.) For each nucleus position, several competing syllable-class hypotheses are generated -- typically three to eight.

The syllable classes are used to hypothesize words. Each of the 1011 words in the vocabulary is specified by a pronunciation description. For word hypothesization purposes, an inverted form of the dictionary is kept, in which there is associated with each syllable-class all the words which have some pronunciation containing that syllable-class. The *MOW* KS [SmWo76] looks up each hypothesized syllable class and generates word candidates from among those words containing that syllable-class. For each word that is multi-syllabic, all of the syllables in one of the pronunciations must match above a threshold. Typically, 50 words of the 1011-word vocabulary are generated at each syllable nucleus position.

Finally, the generated word candidates are rated and their begin- and end-times adjusted by the *WIZARD* knowledge source [McWo77]. For each word in the vocabulary, WIZARD has a network which describes the possible pronunciations. This rating is calculated by finding the path through the network which best matches the labelled segments, using the distances associated with each label for each segment; the rating is then based on the difference between this best path and the segment labels.[3]

The result of the word processing so far is a set of words. Each word includes a begin-time, an end-time, and a confidence rating. A policy KS, called *WORD-CTL* ("word control"), selects a subset of these words, based on their times and ratings, to be hypothesized; it is these selected word hypotheses that form much of the base for the "top-end" processing that now begins. Typically, these selected hypotheses include about 75% of the words actually spoken (i.e., "correct" word hypotheses) and with each correct hypothesis having a rating which ranks it on the average about three, as compared to the five to twenty-five or so hypotheses which compete with it (i.e., which significantly overlap it in time). The non-selected words are retained internally by WORD-CTL for possible later hypothesization.

TOP-END PROCESSING

Word-Island Generation

The *WOSEQ* knowledge source [LeSe77] has the job of generating, from the word hypotheses generated bottom-up, a small set (about three to ten) of word sequence hypotheses. Each of these sequences, or ***islands***, can be used as the basis for expansion into larger islands, hopefully culminating in an hypothesis that spans the entire utterance. Multi-word islands are used rather than single-word islands because of the relatively poor reliability of ratings of single words as well as the limited syntactic constraint supplied by single words.

WOSEQ uses two kinds of knowledge to generate multi-word islands:

> A table derived from the grammar indicates for every ordered pair of words in the vocabulary (1011 x 1011) whether that pair can occur in that order in some sentence of the defined language. This binary table (which contains about 1.7% "1"'s) thus defines "language-adjacency".
>
> Acoustic-phonetic knowledge, embodied in the *JUNCT* KS, is applied to pairs of word hypotheses and is used to decide if that pair might be considered to be time-adjacent in the utterance. JUNCT uses the dictionary pronunciations and examines the segments at their juncture (gap or overlap) in making its decision.

WOSEQ takes the highest-rated single words and generates multi-word sequences by expanding them with other hypothesized words that are both time- and language-adjacent. This expansion is controlled by heuristics based on the number and ratings of competing word hypotheses. The best of these words sequences (which occasionally includes single words) are hypothesized.

The top-end processing is started by the creation of these word-sequence hypotheses. Subsequently, WOSEQ may generate additional hypotheses if the recognition process seems not to be making progress based on those already hypothesized. These additional hypotheses may include shorter, decomposed versions of some of the original ones.

Word-Sequence Parsing

Because the syntactic constraints used in the generation of the word sequences are only pair-wise, a sequence longer than two words may not be syntactically acceptable. A component of the *SASS* [HaSy77, HaUn77] knowledge source can parse a word sequence of arbitrary length, using the full constraints given by the language. This parsing does not require that the word sequence form a complete non-terminal in the grammar nor that the sequence be sentence-initial or sentence-final, only that the words occur contiguously somewhere in some sentence of the language. If a sequence hypothesis does not parse, the hypothesis is marked as "rejected". Otherwise, a phrase hypothesis is created. Associated with the phrase hypothesis is the word sequence of which it is composed, as well as information about the way (or ways) the words parsed.

[3] WIZARD is, in effect, a miniature version of the HARPY speech recognition system [LoHa76], except that it has one network for each word, rather than one network with all words and all sentences.

Word Predictions from Phrases

Another component of the SASS knowledge source can, for any phrase hypothesis, generate predictions of all words which can immediately precede and all which can immediately follow the phrase in the language. In doing the computation to generate these predictions, this KS uses the parsing information attached to the phrase hypothesis by the parsing component.

Word Verification

An attempt is made to verify the existence of or reject each such predicted word, in the context of its predicting phrase. If verified, a confidence rating for the word must also be generated. First, if the word has been hypothesized previously and passes the test for time-adjacency (by the JUNCT KS), it is marked as verified and the word hypothesis is associated with the prediction. (Note that a single word may thus become associated with several different phrases.) Second, a search is made of the internal store of WORD-CTL to see if the candidate can be matched by a previously generated candidate which had not been hypothesized. Again, JUNCT makes a judgment about time-adjacency. Finally, WIZARD compares its word-pronunciation network to the segments in an attempt to verify the prediction.

For each of these different kinds of verification, the approximate begin-time (end-time) of the word being predicted to the right (left) of the phrase is taken to be the end-time (begin-time) of the phrase. The end-time (begin-time) of the predicted word is not known and, in fact, one requirement of the verification step is to generate an approximate end-time (begin-time) for the verified word. In general, several different "versions" of the word may be generated which differ primarily in there end-times; since no context to the right (left) of the predicted word is given, several different estimates of the end (beginning) of the word may be plausible based solely on the segmental information.

Word-Phrase Concatenation

For each verified word and its predicting phrase, a new and longer phrase may be generated. This process, accomplished by a component of SASS similar to the Word-Sequence recognition component, involves parsing the words of the original phrase augmented by the newly verified word. The extended phrase is then hypothesized and includes a rating based on the ratings of the words that compose it.

Complete Sentences and Halting Criteria

Two unique "word" hypotheses are generated before the first and after the last segment of the utterance to denote begin and end of utterance, respectively. These same "words" are included in the syntactic specification of the language and appear as the first and last terminals of every complete sentence. Thus, any verified phrase that includes these as its extreme constituents is a complete sentence and spans the entire utterance. Such a sentence becomes a candidate for selection as the system's recognition result.

In general, the control and rating strategies do not guarantee that the first such complete spanning hypothesis found will have the highest rating of all possible spanning sentence hypotheses that might be found if the search were allowed to continue, so the system does not just stop with the first one generated. However, the characteristics of such an hypothesis are used to prune from further consideration other partial hypotheses which, because of their low ratings, are unlikely to be extendable into spanning hypotheses with ratings higher than the best already-discovered spanning sentence. This heuristic pruning procedure is based on the form of the ratings function (i.e., how the rating of the phrase is derived from its constituent words). The pruning procedure considers each partial phrase and uses the ratings of other word hypotheses in the time areas not covered by the phrase to determine if the phrase might be extendable to a phrase rated higher than the spanning hypothesis; if not, the partial phrase is pruned. This pruning process and the rating and halting policies are discussed in [HaPo77].

The recognition processing finally halts in one of two ways: First, there may be no more partial hypotheses left to consider for predicting and extending. Because of the combinatorics of the grammar and the likelihood of finding some prediction that is rated at least above the absolute rejection threshold, this form of termination happens when the pruning procedure has been effective and has eliminated all competitors. Second, the expenditure of a predefined amount of computing resources (time or space) also halts the recognition process; the actual thresholds used are set according to the past performance of the system on similar sentences (i.e., of the given length and over the same vocabulary and grammar)

Once the recognition process is halted, a selection of one or more phrase hypotheses is made to represent the result. If at least one spanning sentence hypothesis was found, the highest-rated such hypothesis is chosen; otherwise, a selection of several of the highest-rated of the partial phrase hypotheses is made, biasing the selection to the longest ones which tend to overlap (in time) the least.

Attention Focussing

The top-end processing operations include (a) word-island generation, (b) word sequence parsing, (c) word prediction from phrases, (d) word verification, and (e) word-phrase concatenation. Of these, (b), (c), and (d) are the most frequently performed. In general, there are a number of these actions waiting to be performed at various places in the utterance. The selection at each point in the processing of which of these actions to perform is a problem of combinatoric control, since the execution of each action will, in general, generate more such actions to be done.

To handle this problem, the Hearsay-II system has a statistically-based scheduler [HaFo77] which calculates a priority for each action and selects, at each time, the waiting action with the highest priority. The priority calculation attempts to estimate the usefulness of the action in fulfilling the overall system goal of recognizing the utterance. The calculation is based on information specified when the action is triggered. For example, the word verifier is triggered whenever words are predicted from a phrase hypothesis; the information passed to the scheduler in order to help calculate the priority of this instantiation of the verifier includes such things as the time and rating of the predicting phrase and the number of words predicted. In addition to the action-specific information, the scheduler keeps track of the overall state of the system in terms of the kinds and quality of hypotheses in each time area.

INTERPRETATION and RESPONSE

The *SEMANT* knowledge-source [HaDi77] accepts the word sequence(s) result of the recognition process and generates an interpretation in an unambiguous format for interaction with the data base that the speaker is querying. For example, the spoken sentence

"What has Minsky written since 1974?"

is represented in this format as

Type: $REQUEST
Subtype: $QUERY!AUTHOR!DATE
[Date: >1974; Author: "MINSKY"]

The interpretation is constructed by actions associated with "semantically interesting" non-terminals in the parse tree(s) of the recognized sequence(s). If recognition results in two or more partial sequences, SEMANT constructs a consistent interpretation based on all of the partial sentences, taking into account for each partial sentence its rating, temporal position, and consistency (or competitiveness) as compared to the other partial sentences.

The *DISCO* knowledge-source [HaDi77] accepts the formatted interpretation of SEMANT and produces a response to the speaker. This response is often the display of a selected portion of the queried data base. In order to retain a coherent interpretation across sentences, DISCO has a finite-state model of the discourse which is updated with each interaction.

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SELECTION OF WORD ISLANDS IN THE HEARSAY-II SPEECH UNDERSTANDING SYSTEM

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ABSTRACT

In Hearsay-II, a word recognizer hypothesizes words bottom-up from acoustic data. Usually many competing words are hypothesized for each time interval of speech, with the correct word rarely top-ranked. Due to the unreliable ratings of words and the limited syntactic constraint supplied by single words, the use of single-word islands would cause the recognition system to explore many blind alleys before abandoning an incorrect island. In addition, the multiplicity of words makes the parsing of all possible word sequences extremely time-consuming. The Hearsay-II island selection strategy uses (1) knowledge of what word adjacencies are allowed by the grammar, (2) analysis of acoustic data at the junctures between word hypotheses, and (3) heuristics based on the number of competing word hypotheses, to form multi-word islands which the syntax-level knowledge source first checks for grammatically and then attempts to extend to form a complete recognition.

INTRODUCTION

Conventional strategies for controlling the search in a continuous speech understanding system fall into two major categories: left-to-right (HARPY [Lowerre, 1976], Hearsay-I [Reddy, 1973]) and island-driven (SRI [Paxton, 1975], SPCHLIS [Woods, 1975], Hearsay-II [Lesser, 1975]) strategies. In the left-to-right strategy, as the name implies, the search always begins at the start of the utterance and continues to extend in a left-to-right manner each partially hypothesized phrase that appears plausible. In contrast, the island-driven strategy, before beginning the process of phrase hypothesization and extension, first performs a scan of the entire utterance in an attempt to spot likely words [Smith 1976, Klovstad 1976]. The best words found in this phase are chosen as the initial phrasal hypotheses for the second phase of the search. In this second phase, a partial phrase chosen for further extensions can be extended by prediction of grammatically legal word extensions on either the left or right or in both directions, depending, for instance, on the constraints given by the grammar about which direction has fewer extensions (see Hayes-Roth and Lesser 1976, Paxton and Robinson 1975, and Woods 1976 for a discussion of techniques for choosing the next hypothesis to extend); this strategy allows the phrasal hypothesis to be concatenated with existing partial phrases to construct new, enlarged hypotheses.

The advantages of the left-to-right strategy over the more sophisticated island-driven strategy are mainly in the area of efficiency: (1) the computationally expensive word-spotting phase is bypassed and (2) the application of grammatical knowledge and the overhead for controlling the search is much less expensive. The major disadvantage of the left-to-right scheme is that the beginning of the utterance may not contain very good acoustic data and thus lead to initial word predictions that are very poor; in this case, it may be very difficult or impossible (if the correct word was not hypothesized) to recognize the utterance. The major advantage of island-driven strategy is its robustness; there may be hypothesized more than one correct initial island, and thus there exists more than one sequence of steps to achieve the correct recognition. In addition, the island-driven strategy would seem to have a higher probability of starting the search with an initial island that is valid because of its word-spotting phase. However, this word-spotting search may not in practice produce results as valid as would be expected because words are predicted based only on acoustic constraints; neither grammatic nor co-articulation constraints are used except at the beginning and end of the utterance. Another advantage of the island-driven strategy is that it can use variations in the branching factor of the grammar at different points in the utterance to reduce the space needed to be searched.

The major disadvantage of both of these search strategies is that they are particularly sensitive to major rating "errors" on single words--cases where a valid word is rated lower than an invalid word in the same time area. If the correct word in the starting area is very poorly rated, a best-first search from the higher-rated alternatives will develop a very large search space, and backtracking all the way to the initial incorrect decision will be very expensive and unlikely.

Two means of overcoming this shortcoming exist. First, in the limited-breadth-first search, the N top rated words in an area are used to begin searches, and as long as one of these is correct, recognition is not precluded. The second alternative is to identify multi-word sequences of word hypotheses that are most probably correct as the

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starting islands in an island-driven strategy. In comparison with single-word islands or left-to-right single-word starting hypotheses, multi-word sequences are more reliable for two reasons: under certain generally applicable conditions, the credibility of a sequence hypothesis exceeds that of a single word hypothesis and, secondly, the reliability of a validity rating for a sequence is greater than that of a single word hypothesis.

To substantiate this conjecture, consider the following average rank order statistics for initial islands based on the three different approaches. These data were collected over 34 training utterances, with each island generation strategy applied to all utterances. The average sentence length was 5.5 words. The left-to-right and the single-word island-driven strategies have the same rank order statistic which is 2.6 (i.e., there are on the average 1.6 islands with ratings better than the correct one). It is interesting to note that in none of the 34 utterances did the left-to-right strategy not hypothesize the correct word in the initial utterance position; the average number of words hypothesized for the initial position was eleven words. The average rank order statistic for the multi-word island strategy, if one utterance is eliminated in which the rank order is 30, is 2.0; the average length of the best correct multi-word island is 2.3 words, where the average number of correct words hypothesized bottom-up is 3.0;

A MULTI-LEVEL ISLAND-DRIVEN STRATEGY

The strategy found to be most effective in the Hearsay-II system (as applied to a 1000-word vocabulary with an average word fanout of 33) is to select multi-word sequences of word hypotheses as starting islands for syntax-level processing. This strategy introduces a new level of hypothesis, the word sequence, between the conventional lexical and phrase levels. A word-sequence hypothesis is a concatenation of one or more word hypotheses. In contrast with a phrasal hypothesis, a word-sequence hypothesis is created before the syntax-level knowledge source begins its work, and may not be grammatical (i.e., it may represent a sequence of words which does not appear in any sentence in the language defined by the grammar).

The decision to create word-sequence hypotheses arose from the realization that the combinatorial space of all possible sequences of word hypotheses, generated as a result of the word-spotting scan, can be reduced sharply by applying a computationally inexpensive filter to the data. This filter is based on simple kinds of grammatical and co-articulation knowledge about which word pairs are possible. The grammatical constraints are specified through a square bit matrix, whose order is the size of the vocabulary; each entry (i,j) in the matrix indicates whether word j can follow word i in the grammar. If two words can follow each other, they are called "language-adjacent". The co-articulation constraints are specified through another square matrix, whose order is the size of the number of phonemes. Each entry (i,j) in the matrix indicates what type of acoustic segments are allowed in the juncture between two words, the first word ending with the phoneme i and the second word beginning with phoneme j. The appendix contains a more detailed description of how the co-articulation constraints are implemented. If two words pass these co-articulation constraints, they are said to be "time-adjacent". A word-sequence hypothesis always consists of word hypotheses which are pair-wise language-adjacent and time-adjacent.

Consider a pair of word hypotheses that are language- and time-adjacent. If there is a third hypothesis that is language- and time-adjacent, either to the left of the first word of the pair or to the right of the second, it can be concatenated onto the pair to form a three word hypothesis. This action of extending could be repeated (leftward and rightward) until there were no more possible extensions. If there were many alternative extensions at each point, this process would result in the creation of a larger number of partially similar word sequences. However, it is clear that a sequence of more than two words may not be grammatical, since language-adjacency is defined only between successive two word pairs. The determination of the grammaticality of a sequence by the syntax-level knowledge source is a relatively expensive operation (between .1 and 1 seconds on a PDP-10 KA10); thus, there is a bias against creating word sequences which have a high probability of being incorrect.

The factors which are of interest in deciding whether a word sequence is good are the length of the sequence, the ratings of its individual word hypotheses, and the number of other word hypotheses competing (overlapping in time) with each of them. The best starting island is the longest one which has a very high probability of being correct, with correctness taking precedence over length; correctness is a function of both individual word validity rating and the lack of similar alternative sequences. These considerations led to the following algorithm for sequence creation:

(1) The 30 highest-rated word hypotheses anywhere in the utterance are chosen as initial one word sequences. Those with ratings less than some cutoff are discarded unless doing so would leave less than five, in which case the five top words are kept.

(2) Each initial sequence is assigned a competing sequence count (CSC) of 1.

(3) For each current sequence, the sets of all word hypotheses left-(right) language- and time-adjacent to the beginning (ending) words of the sequence are found. If the current sequence has CSC=N, and R right-adjacent words are found, then a right extension would have CSC=N*R.

(4) Only those extensions whose average word ratings exceed a cutoff proportional to the square root of N*R are formed. The direction chosen for extension is a function of CSC count for the direction and the validity of the highest word that remains to be extended in the specific direction.

(5) Steps 3 and 4 are repeated in a recursive manner until no more extensions can be formed.

All sequences that are generated as a result of this process which are subsequences of another sequence are discarded.

This algorithm produces a large number of potential word sequences, usually between 10 and 100. The cost of validating them all for grammaticality is expensive. Thus, another level of filtering is performed, based on a rating attached to each word sequence. The rating of a sequence is an increasing function of these quantities: (1) the duration-weighted average word rating, AVGRATE, computed by summing the product (word's rating)*(number of syllables it contains) over all words in the sequence and then dividing by the number of syllables in the sequence; (2) the duration, DUR, computed as the percent of the utterance's syllables contained in the sequence; (3) the number of words in the sequence, NWORDS. The rating function is

$$\text{RATE} = \text{AVGRATE} + 0.1 * \text{NWORDS} * \text{AVGRATE} + 0.5 * \text{DUR}$$

The highest rated word sequence plus word sequences whose rating is some epsilon away from the highest are chosen as candidates for further evaluation. In addition, another criteria is employed to choose sequences for further evaluation: if at all possible, there should be at least one word sequence for each area of utterance; the time areas not covered by the highest rated word-sequences are the areas that are attempted to be covered by lesser rated word-sequences. Word sequences not chosen by this filtering are not discarded but rather are held in abeyance until either processing later on stagnates, or an existing word sequence candidate has been found to be ungrammatical or cannot be successfully extended; in these cases, these poorer-rated sequences are hypothesized for consideration by the rest of the system. This process of word sequence generation for the 34 utterances results in an average of 8.1 initial candidates, with an average of 6.6 more candidates being generated during the run.

The basic result of this algorithm is the identification of sequences of time-adjacent and language-adjacent words whose credibility is high. Although a large proportion of these sequences may not be grammatical, very few highest-rated sequences are ever incorrect (unless no successive correct word pairs are hypothesized). Furthermore, the computation of CSC biases against forming long sequences except where the chance occurrence of a language-adjacent pair is small; thus, in only ten percent of utterances does a highly-rated incorrect sequence contain a correct subsequence of length greater than one which does not occur in a longer correct sequence. In such a case, if the grammaticality of the incorrect long sequence is rejected by the syntax knowledge source, a decomposition of the sequence into two maximal subsequences occurs; these decompositions will be hypothesized subsequently if rated sufficiently high. This is a form of backtracking and, therefore, is subject to the same weaknesses as other backtracking search algorithms. In this case, however, the probability of a false initial island has been greatly reduced. As a result, the chance of a totally fruitless search is correspondingly reduced.

The effectiveness, in terms of both total system error rate and amount of search performed, of this multi-word island approach over both the left-to-right and single-word island-driven strategies is indicated by following statistics; the overall error rate for the three strategies is 67%, 47% and 54%, respectively. In the ten sentences that were recognized correctly by all three strategies, the average number of phrases hypothesized are 47, 68 and 68, respectively.

CONCLUSION

The multi-word sequence generation procedure is a key knowledge sources in Hearsay-II. By exploiting the redundancy of the language to identify plausible word sequences and, incidentally, increasing the probability that a valid starting island hypothesis will be more highly rated than an incorrect one, this source of knowledge provides very reliable and useful knowledge to direct the overall search. In our opinion, this knowledge source is a paradigmatic example of the effective use of redundancy and statistical sampling to achieve a reduction of uncertainty in problems characterized by fuzzy and partial information.

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APPENDIX

This appendix describes the word pair adjacency acceptance procedure (JUNCT) developed for Hearsay-II, the knowledge it uses, and the current results. Such a procedure must be computationally inexpensive, making decisions on hundreds of pairs of hypothesized words. It must rely upon knowledge of word junctures and upon the information contained in the segmental transcription of the spoken utterance. And it must reject as many incorrect pairs (word pairs not actually spoken) as possible, without rejecting any of the correct pairs.

As input, JUNCT receives a pair of word hypotheses. If it determines, based upon the times associated with the hypotheses, the juncture rules contained in the procedure, and the segmental description of the spoken utterance, that the words are adjacent, the pair is accepted as a valid sequence; otherwise it is rejected.

The word junctures upon which JUNCT must make its decisions fall within three distinct cases: (1) Time-contiguous hypotheses: Words which are time contiguous are immediately accepted by JUNCT as a possible sequence; no further tests for adjacency are performed. (2) Overlapping hypotheses: When two words overlap in time, juncture rules are applied in the context of the segmental interpretation of the utterance to determine if such a juncture is allowable for the word pair. (3) Separated hypotheses: When the words are separated by some interval of time, rules are applied, as in the overlap case, to determine whether the pair can be accepted as a valid sequence in the utterance.

The juncture rules used by JUNCT are of two types: (1) allowable overlaps of word end- and begin-phonemes, and (2) tests for disallowed segments within the word juncture. A bit matrix of allowable overlaps is precompiled into the procedure, and is indexed by the end- and begin-phonemes of the word pair. Any overlap juncture involving phonemes which are not allowed to share segments is rejected by JUNCT. In the separation case, as in allowed overlaps, the segmental description of the spoken utterance is examined in the context of the end- and begin-phonemes of the word pair to determine if any disallowed segments are present in the juncture. If such segments are found, the word pair is rejected. Only when a word pair passes all rule tests which apply in the segmental context of its juncture is it accepted as a valid sequence.

Examples of allowable phoneme overlaps are the following:

(1) Allow words to share a flap-like segment if one of the juncture phonemes is a stop. (2) Allow nasal-like segment overlaps in nasal-stop phoneme junctures. (3) In a fricative-stop phoneme juncture, allow sharing of aspirations, fricatives, silences, and flap-like segments.

Examples of non-allowed segments in a juncture are the following: (1) Do not allow a vowel segment in any juncture (overlap or separation), unless it is a vowel-vowel phoneme juncture. (2) Do not allow a fricative segment in any non-fricative juncture.

Current Results

Stand-alone performance evaluation runs were made over 60 utterances using words generated from files produced by the Hearsay-II word hypothesizer. Syntactically adjacent pairs of words whose ratings were 40 and above (on a scale from 0 to 100) and whose times (left-word end time and right-word begin time) were within a 200 millisecond interval were considered. All of the words used for testing the procedure were hypothesized "bottom-up" in Hearsay-II; no grammatically based predictions were used in the evaluation runs. Table 1 summarizes the performance of the JUNCT procedure.

It is expected that, as lower-level sources of knowledge provide more accurate times for word hypotheses, the rules for acceptance of valid word pairs may be tightened, further increasing the speed and performance of Hearsay-II.

	CORRECT WORD PAIRS	INCORRECT WORD PAIRS	TOTAL
ACCEPTED	188 (95.4%)	2891 (41%)	3079 (42%)
REJECTED	5 (2.5%)	4224 (59%)	4233 (58%)
TOTAL	197	7115	7312

Table 1. JUNCT performance (60 utterances)

Word Verification in the HEARSAY II Speech Understanding System

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ABSTRACT

A key problem for speech understanding systems is the verification of word hypotheses generated by various knowledge sources in the system. In this paper we will discuss the general problem of word verification in speech understanding systems. A description of our matching algorithm for word verification which is based on that used in the HARPY system, a general connected speech recognition system (Lowerre, 1976), is given. An example of the verification of a word hypothesis using this algorithm is presented. Problems which arose in applying this technique to verification of individual words in a connected speech understanding system and their solutions are discussed. A performance analysis of the verifier in terms of accuracy and speed is given and directions for future work are indicated.

INTRODUCTION

Word verification is the evaluation of word hypotheses in speech understanding or recognition systems. The aim of this evaluation is to decide which hypotheses are worthy of further processing by other parts of the system. This evaluation is generally performed by measuring how closely a given word matches its predefined representation. The representation and the match of the acoustic signal may be performed at various representational levels such as the parametric, phonetic and syllabic. Since errors are introduced and propagated as information is encoded from the parametric to the syllabic level, accurate matching becomes increasingly difficult at each successive level of abstraction. However the computation time for matching decreases since there are fewer match elements each containing more information.

Words may be hypothesized from many diverse sources of knowledge not solely based upon acoustic evidence. If 5% to 8% of the vocabulary is hypothesized for each word position in the utterance (the current HEARSAY bottom-up performance), the verifier must distinguish between 50 to 80 competing word candidates in a 1000 word vocabulary. Even with significant improvements in word hypothesization (ie. decreasing the effective vocabulary hypothesized to .5% per word position), as we move to systems with large vocabularies (~100,000 words see Smith 1977) the number of potential verifiable words remains quite large.

The verifier must assign a likelihood score which is commensurate with the match between the underlying acoustic data and the phonetic description of the word. The goodness of a score may be only temporarily significant so the scores should rank order the competitive words in any time area such that the correct word is high in the ordering.

Besides this acceptance criteria, it is also necessary for the verifier to reject absolutely a large percentage of the hypothesized words, without rejecting significant numbers of correct words, in order to constrain the combinatoric explosion of hypotheses at higher levels.

THE HEARSAY ENVIRONMENT

Word verification is performed within HEARSAY II in the following environment. Word candidates may be supplied from a bottom-up word hypothesizer (POMOW) based on acoustic information or from a top-down syntax and semantics knowledge source (SASS) based on syntactic information and constraints provided by the grammar. POMOW (Smith 1976) provides word hypotheses which have reasonable underlying acoustic support over a definite portion of the utterance. The times supplied are used to guide verification but do not preclude change. SASS (Hayes-Roth 1977) provides words which can be characterized as being syntactically plausible in a particular time area of the utterance. No pruning is performed according to the credibility of the underlying acoustic information. Since these words are always hypothesized based on a previously verified word or from the boundaries of the utterance, only one time is known. This requires that the verifier must not only rate the hypothesis, but must also predict the missing time. In addition, since words may be predicted to the left or right of a verified word, the verifier must have the ability to match words in both directions.

HEARSAY operates under the hypothesize-and-test paradigm to produce many competing hypotheses which overlap in time. Each word hypothesis must be verified and assigned a rating before it can be used by other sources of knowledge. Each of these verified hypotheses can in turn be used as seeds to generate new sets of syntactically plausible words. A measure of the fan-out from each word is the effective branching factor of the HEARSAY II grammar (Goodman 1976) which is is between 5 and 15. Thus regardless of the scoring performance, a verifier must be computationally efficient in order to be useful in this type of system.

VERIFICATION MODEL

WIZARD can be decomposed into three major parts: word networks, a segmentation of the utterance, and a control structure which implements the matching algorithm. First, each word in the lexicon is represented by a statically defined network which embodies alternate pronunciations of the word. Each node in the word network represents a phone and arcs indicate successor/predecessor relationships between phones.

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Figure 1 gives an example of the network for the word ABSTRACT. These networks are stored as a static data structure in a packed format. The uniform representation of words by a single network which embodies all speech dependent knowledge gives several advantages over other approaches. First, the generation of proper network descriptions can be handled on a case by case basis without the need of a general theory for all. This also eliminates the need for special case solutions when the general theory fails or is found incomplete. Tools are also available to generate word descriptions and tune the acoustic-phonetic templates (Lowerre, 1976).

The acoustic information is a segmentation of the utterance where each segment is represented as a vector of phone probabilities. WIZARD benefits from the use of the same templates and segmentation as the HARPY system (Lowerre, 1976). As in HARPY the phone probabilities are distance measures between each segment and acoustic-phonetic templates in the phonetic dictionary. This value is a scaled log likelihood measure (since the probabilities do not sum to 1) and is used directly in computing the word match score over the given segments. WIZARD uses approximately 90 templates to cover all phonetic variations in its 1024 word vocabulary.

The last component is the dynamic matching algorithm. Although there is no speech dependent knowledge embodied in this module, several heuristics are employed to find optimal starting points and to choose the best final segment. These heuristics are discussed in the following section on implementation issues.

Figure 3 illustrates the matching of the word ABSTRACT to ten segments of an utterance. The match score for any phone *I* in the *Tth* segment can be calculated from the following:

$$M_{I,T} = Min(M_{J,T-1}) + P_{I,T}$$

Where $M_{J,T-1}$ is the best match score in the previous segment for phone J where

J = I or

J precedes I in the network

and $P_{I,T}$ is the acoustic match score of phone I in segment T

Figure 2 gives the phone probabilities for each phone in the network in each of the segments over which the match is performed.

Those scores in Figure 3 marked with * indicate the best path through the mapping. The begin time of each segment is given, along with the segment number, on the top of the figure. The left side is labeled with each phone in the network. Entries in the table of ∞ indicate that a phone mapping to that segment is not allowed. The final mapping is given at the bottom of the figure. The final match score of 40 is the score of the best phone which transitions into the final state] plus the acoustic match probability of] which is defined to be zero. This represents the score of the best path through the network. This score would be normalized (by the number of segments mapped -1) to 4 and would receive a HEARSAY score of 90 out of a possible 100. Other paths can be found by tracing back from the other four possible ending phones: ← (48), - (46), DX (66), and - (46).

IMPLEMENTATION ISSUES

Initially several problems arose while integrating this knowledge source into HEARSAY II. The following is a discussion of the problems addressed during the implementation of the verifier. First, since we were dealing with single words and attempting to verify them as if they existed in isolation, many of the constraints provided by word juncture rules and syntactic knowledge were unavailable for use. In light of the power that these constraints give to similiar systems (Lowerre 1976) would verification be tractable?

Words could be hypothesized bottom-up with incorrect times. This meant that procedures had to be employed to search the segmentation for the local best starting and ending point around the given points. Words predicted top-down always had a missing time, and procedures for predicting these times accurately had to be developed. Problems in the generation of end and begin times of words which share vowels often cause valid word pairs to be rejected by higher level knowledge sources.

The conversion of internal match scores to HEARSAY II ratings while maintaining consistency of the ratings proved to be a major concern when it was noticed that the average internal ratings for words varied considerably depending on where in the utterance the words occurred. The notion of rank order of the word with respect to its competitors rather than absolute score proved to be unimplementable in practice. While useful in static tests outside of the system as a measure of performance, a rank order scheme which assumed all competitors in a particular time area were available to be rated at the same time, or remembered at some later time, proved intractable.

It has been noticed by other researchers that short function words such as on, the, of, to, in, tend to be hypothesized at many places in the utterance, with good ratings and are most often false alarms. Our experience was much the same and we chose to attempt to handle this problem directly rather than pass it on to the higher level knowledge sources.

SOLUTIONS

Several modes of verification are supported within WIZARD. Each represents a partial solution to one or more of the problems outlined. Non-pad mode uses no heuristics to determine the boundaries of the match. The predicted begin/end times are mapped directly into their respective segments and verification is performed across those segments. It takes approximately 60 milliseconds of CPU time on a PDP-KA10 to perform matching in this mode.

Pad mode was added to handle the problem that bottom-up times may be incorrect. This mode is currently used to verify all bottom-up hypothesis. In this mode the begin/end times are mapped into segments as in non-pad mode. Then a one segment uncertainty is allowed during the matching. Thus if *B* is the begin segment, *E* is the end segment, segments *B-1/B/B+1* are allowable starting points for the match and *E-1/E/E+1* are the allowable ending points. The nine paths between the boundary segments are evaluated in parallel by modifying the boundary conditions in the matching algorithm. As a result WIZARD must backtrack from each of the final end segments in order to find the correct begin segment associated with the path. This is necessary so that the begin time of the segment can be returned as the begin time of the word and to determine the path length (number of phones on the path) for scoring. This mode takes about 100 milliseconds of CPU time on the PDP-KA10 and is about 3.5 times faster than exploring each of the nine paths in non-pad mode.

As we have mentioned before it is necessary to perform verification where only one of the word times is known. Two prediction modes are implemented in WIZARD, one where the end time is unknown (right) and the other predicts a missing begin time (left). As in pad mode a one segment window is evaluated around the given starting segment. Then each successive segment is matched and the match score is computed as if the match were ending in that segment. The scores are ordered and the score for the best path is returned along with the missing time. Several heuristics are used to prune the number of end segments actually looked at as possible end states. This is the most computationally expensive of the verification modes taking about 160 milliseconds per verification on a PDP-KA10 processor.

Several experiments were performed to determine the best way to normalize the match scores. The technique employed was to verify approximately 10000 bottom-up word hypotheses from 60 utterances, normalize the scores and calculate the average rank order of the correct words. The rank order gives the number of incorrect words that were rated as high as, or higher than, the correct word. This ordering is a measure of how many words per word position must be considered by the top level knowledge sources in order to have confidence that the correct word is present, assuming it has been hypothesized. Normalizing the scores by the time duration of the word amplified the problem of function words receiving unusually good scores. More complex normalizations based on non-linear time scaling were also rejected. Segmental normalizations employing penalties for mapping the same phone into many successive segments proved to be too time consuming in light of the benefit derived. Currently, predict mode scores are normalized by the number of segments in the match path *N* while the other modes are normalized by *N-1*. These normalizations are computationally simple and embellishments tried to date have not performed significantly better.

The conversion of internal WIZARD scores to HEARSAY II hypothesis ratings was accomplished by conducting a statistical analysis of correct/incorrect word ratings over approximately 50000 verifications. By knowing the distribution of correct and incorrect words over each of the internal score values (dynamic range of 64), a corresponding distribution of HEARSAY scores was calculated. The HEARSAY score distribution allows for the absolute rejection of verified words. This threshold was set so as to reject no correct words. Scores above that threshold were distributed so as to capitalized on the distributions of the correct words. Several tradeoffs are possible here. If one requires that no potential correct words be rejected then WIZARD was able to reject 12% to 19% of the incorrect words hypothesized. On the other hand if it were possible for the system to perform with a small number of the correct words being rejected, a higher percentage of incorrect words could be rejected. Allowing a 6% rejection rate of correct words approximately 51% of the incorrect words can be eliminated from consideration by the higher level knowledge sources.

To aid in compensating for the apparent temporal difference in word scores, the acoustic match probabilities generated by the segmenter were normalized such that the score of the best phone in a segment had the absolute best match score. This alleviated the problem and improved the reliability of the normalized match score while leaving the rank order statistics unchanged.

RESULTS

The results summarized in Figure 4 are for five data sets, containing 100 utterances, in which 332 correct words were hypothesized bottom-up by POMOW. In addition, 13053 incorrect words were generated. The vocabulary size for POMOW and WIZARD was approximately 550 words. WIZARD rated each of the words using pad mode verification. For each rating threshold (15,10) the number of correct and incorrect words that were accepted or rejected is tabulated. From this data the number of words hypothesized per word position, and the percent of the vocabulary per word position, can be calculated. These numbers give a vocabulary independent measure of performance, allowing comparisons between various system configurations. An average rank order of the correct word is provided which measures, at each threshold, the number of words in each word position that must be examined in order to include the correct word. The range of rank orders between the data sets (20 utterances/set) is also noted.

DISCUSSION

The major direction of this work is the application of the HARPY network representations to the verification of single words in a connected speech understanding system. This includes the modifications to allow the various verification modes dictated by the HEARSAY II system strategies. We feel that WIZARD makes an important contribution to the overall performance of HEARSAY II and forms a groundwork upon which more sophisticated verifiers can be developed.

Several problems with the current word verification system can not be solved within the existing framework. Future work is required in the following areas. New schemes for normalization of scores have been proposed to improve the performance in segmentations having many very short transition segments. These segments in general have poor ratings and often degrade the composite word score.

Although we felt that the matching algorithm was computationally efficient when first implemented, as system strategies evolved it was found that a significant portion of recognition time was being spent in verification. A sizable increase in speed can be obtained by coding certain of the inner loops in assembly language. Other implementation oriented optimizations may be needed.

A most useful addition to WIZARD would be the ability to verify sequences of words by dynamic generation of multiple word networks. These networks would embody the appropriate word juncture rules and would allow WIZARD to rate phrasal hypotheses directly rather than having other knowledge sources calculate a composite score from the individual word scores. Along these lines, perhaps as a first step, it is necessary to handle word juncture problems which cannot be statically encoded in the single word networks themselves. These juncture problems are a major cause of incorrect times on word hypotheses.

It will be necessary to augment this word verification system with a component to perform more direct signal matching. The purpose of this addition is to disambiguate competing words which have good WIZARD scores in the same time area. We propose to extract word templates at the parametric level and perform matching using Itakura's method (Itakura, 1975). The philosophy here is to store templates for a small number of potentially difficult words rather than synthesize the templates by a rule-based system. This time consuming matching would be performed when indicated by higher sources of knowledge.

ACKNOWLEDGEMENTS

The original idea to implement a word verifier using a network representation was that of Raj Reddy who made continuing suggestions for refinements to the basic algorithm and for improvements to its performance. Bruce Lowerre cheerfully shared his dictionary and network generation expertise. Lee Erman and Richard Smith aided in integrating WIZARD into HEARSAY and provided the impetus for many of its interesting features.

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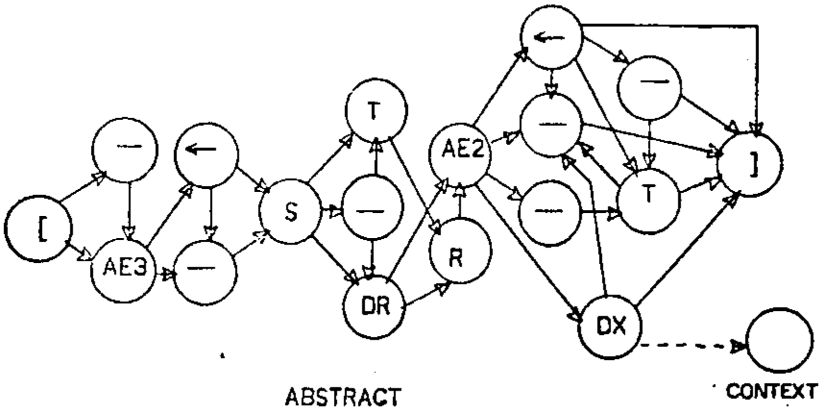

(-,0) AE3 (←(-,0),-) S (-,0) (DR (R,0), T R) AE2! ((←(-,0),-) (T,0), DX)

Figure 1

SEG#	20	21	22	23	24	25	26	27	28	29	30
-	27	29	12	16	26	26	36	42	24	0	14
AE3	2	0	37	34	33	17	23	6	6	23	12
←	14	10	1	27	35	20	34	20	11	2	20
S	45	45	45	0	18	42	36	42	42	25	20
DR	40	42	37	27	24	9	36	42	31	14	6
R	18	14	19	43	35	32	7	17	7	28	41
T	36	38	35	0	13	21	36	42	31	11	8
AE2	7	8	29	43	35	16	10	4	8	29	29
DX	0	12	18	35	31	14	19	17	3	27	7

FIGURE 2

TIME		93	99	100	112	118	123	128	136	145	148	160	
SEG#		20	21	22	23	24	25	26	27	28	29	30	
[	*0	*	*	*	*	*	*	*	*	*	*	*	*
]	*	*	*	*	*	*	*	*	*	*	*	*	40
-	*	27	56	68	84	110	136	172	214	238	238	252	*
AE3	*	*2	*2	39	73	106	123	146	152	158	181	193	*
←	*	*	12	*3	38	65	91	125	153	163	160	188	*
-	*	*	31	14	19	45	71	107	149	173	158	172	*
S	*	*	*	57	*3	*21	63	99	141	183	188	178	*
-	*	*	*	*	73	29	47	83	125	149	149	163	*
DR	*	*	*	*	84	27	*21	57	99	130	144	150	*
R	*	*	*	*	*	98	40	*20	45	52	80	121	*
T	*	*	*	*	63	16	37	73	115	146	157	157	*
AE2	*	*	*	*	*	119	43	31	*32	*32	61	90	*
←	*	*	*	*	*	*	145	77	59	43	34	54	*
-	*	*	*	*	*	*	*	181	119	83	43	48	*
-	*	*	*	*	*	*	145	79	73	56	*32	46	*
T	*	*	*	*	*	*	*	181	119	90	54	*40	*
DX	*	*	*	*	*	*	133	62	48	35	59	66	*
-	*	*	*	*	*	*	145	79	73	56	32	46	*
	[	AE3	AE3	←	S	S	DR	R	AE2	AE2	-	T	]

FIGURE 3

```
THR 15           # HYPED BY POHON     ACCEPTED       REJECTED      5.6 RANK ORDER
       CORRECT        332            326 (98%)       6 ( 2%)      (3.0 - 7.1)
     INCORRECT      13053          10426 (80%)    2627 (20%)
         TOTAL      13385          10752 (80%)    2633 (20%)
    #/WORD POS         40 (8%)        32 ( 6%)       8 ( 2%)

THR 10           # HYPED BY POHON     ACCEPTED       REJECTED      4.5 RANK ORDER
       CORRECT        332            312 (94%)      20 ( 6%)      (3.4 - 5.0)
     INCORRECT      13053           6462 (49%)    6591 (51%)
         TOTAL      13385           6774 (51%)    6611 (49%)
    #/WORD POS         40 (8%)        20 ( 4%)      20 ( 4%)
```

FIGURE 4

The d' Model of Signal Detection Applied to Speech Segmentation

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Abstract The statistical measure, d', from Signal Detection Theory, [Swe64] has been shown to parametrize the "detectability" of signal over noise in a wide variety of perceptual situations. Its usefulness is extended to the problem of quantifying error rates for segmentation of continuous speech. It has often been impossible to accurately compare different machine techniques for segmentation since errors occur as either missing or extra segment boundaries whose rates are related by internal decision thresholds. The basic d' model is shown to accurately (>95% confidence) describe the missing versus extra segment trade-off found in at least one, non-trivial, speech segmentation program. [Gol75]

Introduction The last few years of computer speech recognition research have produced, among other things, a number of techniques for machine segmentation of the speech signal into phonetic (or acoustic) units. [e.g. Dix75, Bak75, Gol75] The difficulties involved in evaluating and comparing the performance of segmenters seem to occur in two areas. First, one must acquire a definition of the "correct" segments for some large set of data. This is usually done by hand, although some automatic techniques are available.* Since the production of "correct" segmentations and their comparison with macnine segmentations (e.g. What amount of mis-alignment, etc. should one allow?) involve a number of linguistic as well as recognition system-specific issues, we will not deal further with these problems here.

However, a second problem is that segmentation errors occur in two types: missed boundaries (segments) and extra boundaries (segments). There is clearly a trade-off between these two types of error, but we have not understood it well enough in a quantitative sense to compare different segmenters (or even the same segmenter "tuned" to a different point of the M/E trade-off). What was needed was a model of this trade-off which yielded a single, comparable measure of segmentation efficacy for any set of data with errors marked missing or extra. Such a model is provided by Signal Detection Theory. We will show that the theory agrees quite well with the results of a set of segmentation trials run to explore the M/E trade-off.

Signal Detection Theory The theory of Signal Detection, as formulated by Tanner, Swets, and Green, [Tan64, Lic64] is primarily applied to detection trials which may be considered similar to the segmentation process. A detection trial presents a stimulus, which may be composed of noise or of noise and some known signal, and requires a decision to be made about the presence of the signal. This is not unlike the decision process resulting in the placement of a segment boundary based upon local information only. It is assumed that the a priori likelihoods and costs of various errors are known to a decision process which senses and possibly transforms the stimulus into some internal signal space before it yields a decision on the presence of the signal. The detector's sensory data is considered, in this model, to be reduced to a single decision parameter. An optimal one, according to decision theory, is the ratio of the probabilities of two hypotheses -- that the input stimulus was signal plus noise or that it was noise alone. A simple threshold on this single parameter may be placed to optimize the expected costs given a priori likelihoods, costs of misses, false alarms, etc. Figure 1 represents such a hypothetical internal decision parameter, L.

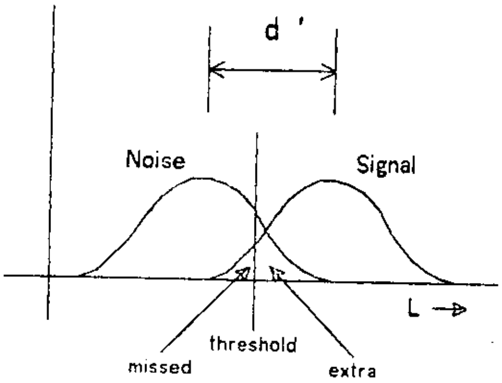

Figure 1: Signal Detection Model

Very simply stated, the model assumes a single decision parameter, L, which may be any sensory measurement one wishes. The distribution of L values for the two types of stimuli, signal-plus-noise and noise-alone, are assumed to be normal (with equal variance in the simplest version of the model). Their means differ by d' times the standard deviation. Rates of "hit" and "false

*The Harpy speech recognition system [Low76] can be forced to the correct words. This produces a "best" fit of the system's acoustic and phonological knowledge to the signal. When a very fine grained fit is made (average acoustic segment duration, 30 ms.), the resulting phonetic segments are very close to those produced by humans.

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alarm" -- Pr{accept|signal} and Pr{accept|noise} respectively -- are sufficient to determine the least d' for which an optimal decision process can display the observed rates. When the hit and false alarm rates are plotted against one another for a number of sets of trials where the detector's acceptance threshold has been altered, a response operator characteristic (ROC) curve is obtained (see figure 2).

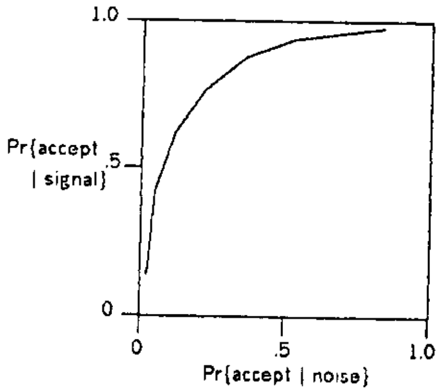

Figure 2: Typical ROC Plot

The theory states that the curve is totally determined by d'. When the axes of the ROC curve are transformed by the inverse function of the Normal distribution function, the curve is approximately a straight line with slope=sigma(noise)/sigma(signal) and x-intercept=d'. [Ega64]

This theory has been most often applied to detection trials to provide estimates of the detectability of the signal as it appears in a human perceiver's internal sensory signal space. The estimate of d' provided by the signal detection model may then be compared with well known properties of visual or auditory signals to provide a bound on the efficacy of the perceiver's transduction process -- the sensory channel. While the main thrust of its application is not relevant here, the signal detection model and the dimensionless measure d' can be used as a normalized measure of segment boundary detection that is relatively unaffected by adjustments in the proportion of missing versus extra segment errors. Furthermore, the d' value, once estimated, may be used to predict the entire response-operator characteristic.

Segmentation The results reported here are, for the most part, obtained from a segmentation program written for a comparison study of parametric representations [Gol75] and used for a while as the initial signal-to-symbol stage of the Hearsay II speech understanding system. [Erm74] A short description of the segmenter is therefore called for.

The signal amplitude, and measures of signal and of amplitude change,** (each measured over both 10 and 30 ms. intervals), are input. Speech is separated from silence and from near-silence, and flaps are detected by their amplitude contours. Then the measures of change are inspected for significant peaks (possible boundaries). The union of all such detections is processed by a correction routine to merge multiple boundaries caused by the same underlying phonetic change. The program has two advantages for this study. First, the input parametric representation is easily changed, and second, the internal, segment detection process is easily tuned along the M/E trade-off.

Results from this program were compared with a "corrected" hand segmentation. That is, the machine segmentation was compared to a phonemic-level human segmentation for discovering missing segments, and to a finer-grained phonetic-level segmentation for discovering extra segment errors.

Results The first experiment validates the Signal Detection model assumption of two (nearly) normal distributions in a signal, hypothetical decision variable. A set of 40 sentences with 1093 phonemes and 1541 phonetic segments was segmented seven times. Internal thresholds were varied to produce segmentations performing over a wide range of the M/E trade-off. The resultant error rates are plotted on a normal-normal grid in Figure 3. A least-squares regression fit a line with slope=1.00 (Noise standard deviation / Signal standard deviation), and x-intercept=2.25 (d' -- the separation of the means of the two distributions).

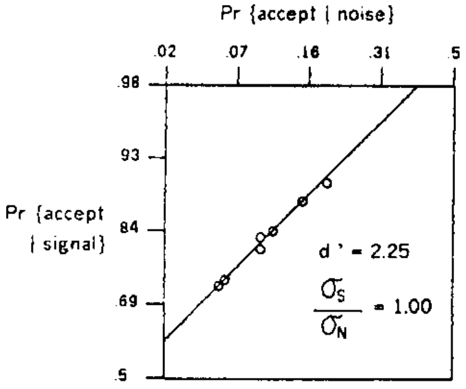

Figure 3: The M/E Trade-off

The line is the ROC of the segmenter with this particular parametric representation, "correct" segment definitions, etc. for all M/E trade-off tuning.

A second experiment, run with different input parameters, gives a measure of confidence in the d' estimates. When the 40 sentence were divided into 10 groups, and estimates of d' made for each group, the 95% confidence interval in d' was found to be +- 0.14 (i.e. the estimate from 4 sentences fits the d' computed from all 40 within the confidence interval). Since this interval is considerably smaller than the differences found between segmentation programs, or between input parametric

**Signal change is typically a pattern recognition match score.

representations, we feel such comparisons are meaningful using d'. For example, four representation of the signal were tested [Gol75] yielding d' values from 1.29 to 2.38. Furthermore, published results of two other segmenters [Bak75, Dix75] allowed estimates of d' to be made of 2.26 and 2.73. The ordering of all these segmentation runs agrees very well with our intuitions about the programs, as well as with the (somewhat sparse) results of speech recognition use of them.

Conclusions We believe that the model provided by Signal Detection Theory, and particularly the d' parameter of that model, offer a highly suitable and attractive measure of segmentation efficacy, and a means of better understanding the M/E trade-off. Different segmenters, conforming to needs of different speech recognition systems, can be quantitatively compared, and their performance under different "tuning" of the M/E trade-off can be predicted.

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AN APPLICATION OF CONNECTED SPEECH TO THE CARTOGRAPHY TASK

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ABSTRACT

This paper summarizes initial development of a system for visual and verbal data acquisition in the cartography task. Visual input and output is provided by a graphics tablet in conjunction with a graphic display terminal. Verbal input consists of sequences of commands and map feature descriptors which are recognized by the Harpy speech recognition system. An important and interesting aspect of this research involves the design and analysis of vocabularies and grammars for tasks of this nature.

INTRODUCTION

The cartography task is an interesting application in man-machine communication combining several forms of input. It is a practical task, used daily by map makers, and has a well defined protocol. In this task features are selected and traced from a map and further described by a sequence of descriptor phrases. The graphical input is obtained using an x-y coordinate input device, such as a graphics tablet. In currently used cartography systems, the textual descriptions are entered via keyboard. This paper describes the VICS system, a cartography system in which connected speech input replaces keyboard input. VICS stands for Voice Input Cartography System.

This project was undertaken because it represented a practical and useful application for speech input of sufficient size to be interesting, but small enough to be feasible. An important aspect of the research is the pursuit of a methodology for language design for man-machine voice communication. Interaction with the user is sufficiently flexible to allow the investigation of several different methods of language structure, from little or no constraint to highly constrained sequences. Further, since a smoothly interacting system with adequate response would have immediate application, there is great potential for study of the many problems associated with man-machine systems.

In order to combine voice and graphical input in a practical system, one needs 1) a speech recognition system capable of recognizing utterances from a language as complex as required by the task, 2) a graphic system sufficiently flexible to allow graphical input and visual feedback as necessary for the task, and 3) some method of interfacing them so the system behaves in a way which appears as natural as possible to the user. Two systems designed at Carnegie-Mellon University provide the necessary tools. The Harpy speech recognition system [Lowerre, 1976 and 1977] recognizes live voice input with the ability to apply grammatical constraints. The SPACS graphic system [Greer, 1976], originally built as a stand alone interactive graphics editor, uses a tablet input device in conjunction with a graphics display terminal. Its capabilities include free-hand line drawing and the ability to create tables, flow charts, logic diagrams, and other schematic diagrams. The interfacing problem is solved by the use of a task module in the Harpy system.

Other systems for speech input are available. The isolated word recognition system developed by Threshold Technology [Martin, 1975] and the Bell Labs connected speech system [Sambur and Rabiner, 1976] are accurate systems, but at present lack the desired flexibility in structuring the grammar. Other successful systems, such as Hearsay-II [Erman et.al., 1976 and Lesser et.al., 1975], HWIM [Woods, 1976], and the IBM system [Jelinek, et.al., 1975 and Bahl, et.al., 1976], have much more elaborate control structures and were designed for larger tasks. The overhead involved in these systems is considered unacceptable for tasks such as this one.

THE HARPY CONNECTED SPEECH RECOGNITION SYSTEM

In the Harpy system the recognition process consists of searching for the best path through a precompiled network, given the acoustic evidence present in the utterance. The search scheme uses heuristics to reduce the number of paths considered, resulting in only a few "best" paths being searched in parallel. The recognized utterance

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is then turned over to a task module, a program whose purpose is to respond to the user in a way appropriate to the task. The simplest task module would simply type the recognized utterance on some output device such as a CRT. In more complicated cases, such as the AI abstract retrieval task, the task module would extract the intent (meaning) of the utterance, consult its data base, and supply an appropriate response, eg. "There are 17 articles on that topic".

The recognition process in Harpy uses a precompiled network which integrates syntactic, lexical, and word juncture knowledge. Syntactic knowledge is specified by a context-free grammar defining the input language. Lexical information is embodied in a symbolic phonetic dictionary containing pronunciations and alternate pronunciations for each word in the task language. Word juncture phenomena are characterized by a set of *a priori* juncture rules giving alternate pronunciations of word beginnings and endings based on the context of adjacent words. All these sources of knowledge serve as inputs to a program which compiles a network representing all possible pronunciations of all possible input utterances.

The acoustic evidence used to determine the best path in the network is obtained by segmenting the input and extracting LPC parameters for each segment. These LPC parameters are matched with phone templates to produce a metric between the segments and the symbols (phones) associated with network states. This metric is in the form of the probability that the segment is an instance of the symbol. Probabilities are learned from exemplars taken as training data.

Creating a new task for Harpy consists of defining the language, training the phone templates, and specifying the task module. To define the language one first specifies the grammar for the input language and then obtains from it a list of all the words used in the language. For each of these words a description of its allowed pronunciations is entered into the dictionary. These descriptions are in terms of a standard set of phones.

THE VICS SYSTEM

The task module coordinates verbal and graphical input and controls discourse with the user. Figure 1 shows a user at the graphics display interacting with the VICS system. Verbal input is a sequence of words or phrases which may be commands for the task module or descriptions of the map feature. Graphic input is via a graphics tablet x-y sensor. There are two graphic input modes: point mode and trace mode. The user enters point mode by saying "point" or "point mode". In this mode the user defines one position on the map corresponding to the location of an feature such as a well, pond, or water tank. For more complicated and larger features, such as lakes, islands, shorelines, and harbors, trace mode is entered. In this mode the x-y sensor position is continuously monitored giving a graphical description consisting of a set of lines. In both modes the graphical description is displayed on a CRT for visual verification. Figure 2 shows how the graphics display appears after the user has traced an intermittent stream. At this point the user describes the feature verbally according to the vocabulary and grammatical structure. The display after verbally describing the stream is shown in figure 3. Figure 4 shows the display after another trace-describe cycle describing an adjacent pond. After the description is complete the user may reject or accept it using voice commands. If accepted, the description is stored for future use.

Figure 1. User at graphics display interacting with the VICS system.

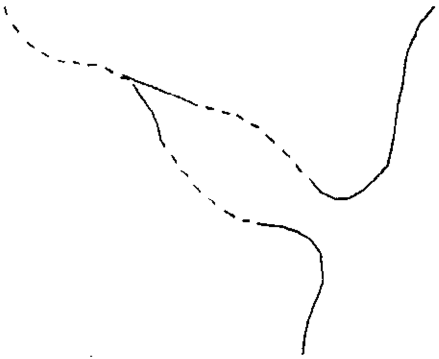

Figure 2. Graphics Display after tracing an intermittent stream.

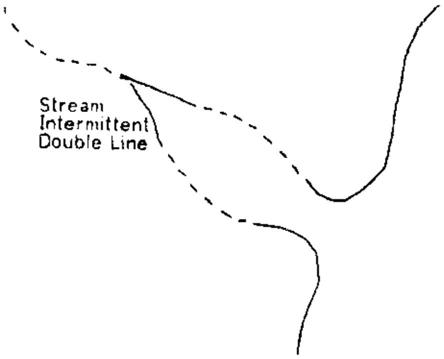

Figure 3. Graphics display after verbally describing tne intermittent stream.

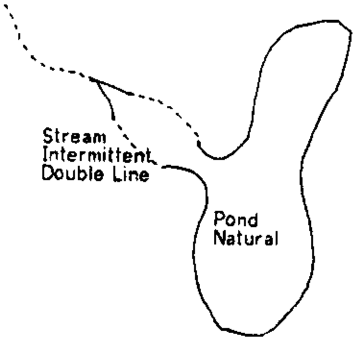

Figure 4. Graphics display after description of both stream and pond.

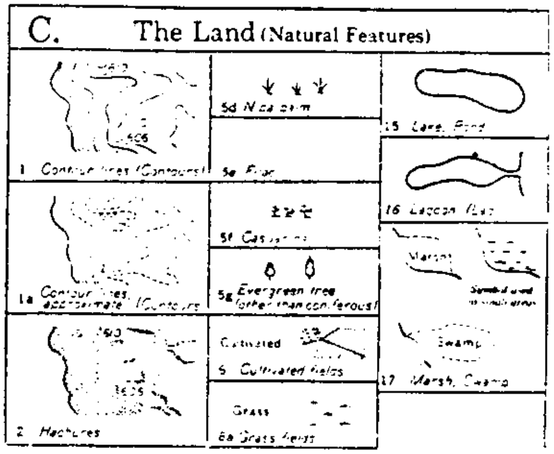
C. The Land (Natural Features)
1 Contour lines (Contours)
1a Contour lines, approximate (Contours)
2 Hachures
5d
5e
5f
5g Evergreen tree (other than coniferous)
Cultivated
5 Cultivated fields
Grass
6a Grass fields
15 Lake, Pond
16 Lagoon
Marsh
Swamp
17 Marsh, Swamp

Figure 5. Examples from cartography feature charts.

```
ABOVE    (-,0) (AH2,AX) (+(-,0),-) (B,0) AA! V
ACCEPT   (-,0) AE! (+(-,0),-) S EH (+(-,0),-) (P,0)
AIDS     (EYL,0) EYC! (EYR,0) (+(-,0),-) S
BED      (+(-,0),-) (B,0) EH! (+(-,0),-) (D,0)
BELOW    (+(-,0),-) ((B,0) (IH3,IY),B) L! OW
BOG      (+(-,0),-) (B,0) AA! (+(-,0),-) (G,0)
CANAL    (+(-,0),-) K IH5 N! AE EL
COASTAL  (+(-,0),-) K OW! S - T (AH2,0) EL
CULTURE  (+(-,0),-) K UH! EL (+(-,0),-) SH ER
DOUBLE   (+(-,0),-) D AH (+(-,0),-) (B,0) EL!
DRAIN    (+(-,0),-) DR R (EYL,0) EYC! (EYR,0) N
```

Figure 6. Example showing dictionary format for the cartography task.

Roads
Populated Places
Railroads
Culture
Boundaries
Relief
Drainage
Coastal/Hydro
Vegetation
Navigational Aids
Ports/Harbors
Marine Dangers

Figure 7. First menu presented to the user after tracing map feature..

The vocabulary for the VICS system consists of task module commands and words or phrases for describing the map feature. These phrases are familiar content phrases used by map makers and are contained in a document produced jointly by the Department of Commerce and the Department of Defense [U.S. Dept. of Commerce, 1975]. Some examples from this document are shown in figure 5. We have chosen, in cooperation with RADC, 691 phrases from this document. A 77 phrase subset, used in the description of features in the class drainage, has been chosen for test purposes. The first few lines of the task dictionary are shown in figure 6.

The choice of grammar is dictated both by the nature of the task, eg. the description of map features, and by the desired user interactions, eg. user commands. A factor relating to user satisfaction is grammatical constraint. A grammar with high constraint implies, in general, fewer recognition errors and therefore greater satisfaction. Care must be taken, however, to not constrain the grammar so much that interaction becomes unnatural for the user.

There are several ways of imposing grammatical structure on the phrases which make up the verbal description. We are currently experimenting with two methods, which represent the extremes of constraint. The first method is unstructured where any phrase may be followed by any phrase, i.e. not constraint. This gives the user complete freedom to describe the map feature in the most natural way. Since there are other methods which allow the naturalness but also have some constraint, this mode is used for the investigation of what accuracies are attainable in the worst case. If accuracy is adequate in this case, then it will be more than adequate in situations with greater constraint. The second method is complete constraint, or tree-like, where each description is represented by a path from the root of a tree to the one of its leaves. In this method menues representing all possible choices at a node of the tree are shown to the user. After one of these possible utterances is spoken and recognized, the system uses the recognized phrase to move to the appropriate new node and presents the next menu according to the choices at the new node. The first menu (top or root node) presented to the user is shown in figure 7. This menu describes the major classification of the feature being described. Each menu contains "restart" and "backup" as possible verbal commands. Restart means go back to the root node of the grammar tree and start the current description again. Backup means move back to the previous node of the tree. This command be used when a error was encountered. As the description is entered verbally, the recognized phrases are placed on the display, near the graphical description, for verification. The final menu contains "ok", "accept", "backup", and "restart" as possible inputs.

Neither of these methods for grammatical structure is viewed as being entirely appropriate to the task. Another method which we intend to investigate is an unordered tree-like scheme where each description is a path thru a tree structure, but phrases can be entered in any order and the user need supply only enough of the path to make it unique. A variation allows features to have certain default attributes, eg. "river" implies "natural". The default would be used to construct the unique description unless some other counteracting choice, such as "man-made" were mentioned.

The VICS system was first demonstrated in September 1976 after less than a man-month of effort. Recent emphasis has been on investigation of various language studies. While no extensive accuracy studies have been made, it appears that 98% accuracies are attainable with moderate grammatical constraint.

DISCUSSION

The research reported represents initial progress toward the development of a system combining visual and verbal data acquisition for the cartography task. We have shown that a new task can be constructed in a relatively short time. The system is still in its infancy and many interesting research problems remain in vocabulary analysis and design, language analysis and design [Goodman, 1976], effects of language structure and user discourse, interactive techniques, and the investigation of recognition characteristics under various vocabulary and grammatical complexities. We look forward to pursuing these areas of research.

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Dynamic Speaker Adaptation in the Harpy Speech Recognition System

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ABSTRACT

The Harpy speech recognition system works optimally when it "knows" the speaker, i.e. when it has learned the speaker dependent characteristics (speaker dependent parameters) of the speaker. There are three methods of learning these parameters. One way is to generate them from a set of training data which covers all the allophones that occur in the task language. A second method is to use "speaker independent" parameters with a resulting reduction in accuracy performance. Since it is inconvenient for a "new" speaker to say a set of training data before using the system and the low accuracy with speaker independent parameters is unacceptable, a third method has been devised to allow the system to dynamically learn the speaker dependent parameters while using the system. The new speaker starts with a set of speaker independent parameters. These parameters are then altered after correct recognition (which can be forced if necessary) to match the spoken utterance.

INTRODUCTION

This paper presents a method by which the Harpy is able to adapt to non-familiar speakers. The first section gives a short description of the Harpy system, its data structures, and its current performance. The following sections discuss the speaker variability issue and several approaches that have been taken towards its solution. These approaches include speaker specific tuning, speaker independent tuning, and dynamic speaker adaptation. The last section discusses how these averaging techniques can also be used in isolated word recognition systems.

THE HARPY SYSTEM

The Harpy system is the first system to be demonstrated with a vocabulary of over 1000 words. The system was demonstrated at the completion of the five year Advanced Research Projects Agency (ARPA) speech research project in September, 1976. It had a sentence accuracy, across five speakers (both male and female), of 91% and ran in about 30 MIPSS (a MIPSS is millions of machine instructions executed per second of speech). Since that time, improvements have been made in the speed of the system. The current system runs in less than 7 MIPSS. The system is a recognition system rather than an understanding system since it uses no semantic knowledge about the task in decoding the utterance. However, there are several other sources of knowledge in the system such as syntactic, lexical, word juncture phenomena, speaker characteristics, and intrinsic phoneme durations (see Lowerre, 1976 for complete details).

In the Harpy system, the syntactic, lexical, and word juncture knowledge are combined together into one integral network representation similar to that of the Dragon system (Baker, 1975). The syntactic knowledge is specified by a context free set of production rules for the task language. A dictionary is used to represent the lexical knowledge. The dictionary contains symbolic phone spellings and specifies alternate pronunciations of the words in the task language. Word juncture rules are also included in the network to account for inter-word phonetic phenomena. The network consists of a set of states and inter-state pointers. Each state has associated with it phonetic, lexical, and duration information. The pointers indicate what states may follow any given state. Two special states in the network, the initial state and the final state, indicate the starting point and ending point for all utterances respectively. The network is, therefore, a complete (and pre-compiled) representation of all possible pronunciations of all possible utterances in the task language. This network is used to guide the recognition process.

The recognition process of the Harpy system is based on the Locus model of search. The Locus model rejects all but a narrow beam of paths around the most likely path through the network. These "best" paths are searched in parallel with one pass through the speech data and therefore does not require backtracking.

The following is a short description of the recognition process: The utterance is digitized at 10 KHz. This continuous signal is segmented into consecutive acoustically similar sound units (based on distance measures of the data) and autocorrelation values and linear predictor coding (LPC) coefficients are extracted for each segment. The segments are then mapped to the network states based on the probability of match (distance match) of the LPC data and the expected phones of each state. The matching of the LPC's and the network states is accomplished by use of phone templates. The templates contain the idealized parameters for each phone that occurs in the network states and they may be either speaker specific or speaker independent. The metric used for this matching is Itakura's minimum prediction residual error (see Itakura, 1975).

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The mapping scheme used is a modified graph search in which heuristics are used to reduce the number of paths that are checked. The result is that only a few "best" paths are searched in parallel during the recognition processes thus greatly reducing the computational overhead.

Results The current system achieves a sentence accuracy of 90.0% and a word accuracy of 94.3% on a 1011 word task and runs in 6.8 MIPSS.

SPEAKER ADAPTATION IN THE HARPY SYSTEM

Speaker variability Speaker variability generally occurs in three forms, dialectic, contextual, and acoustic. Dialectic variability involves changes in the pronunciation of words among speakers. Contextual variability involves changes in word pronunciation do to the context of the words. Acoustic variability results from vocal tract changes among speakers. Either or all types of variability can occur when changing speakers. The Harpy system attempts to recognize these different variabilities and to separate the effects made by each. Dialectic variability is an effect across a broad group of speakers and the variability is encoded into the lexicon. Many dialects can be encoded into the lexicon or different lexicons can be used for different dialects. The current Harpy system uses the "mid-western American" dialect of English. The contextual variability is handled in the word juncture phenomena rules and, to a lesser extent, in the lexicon itself. The acoustic variability is a speaker dependent phenomenon and can be separated from the other types of variability.

Approach to speaker variability Many proposals and attempts have been made, from such groups as SDC, BBN, Lincoln Labs, etc., as to how to handle the speaker variability problem. These proposals include such ideas as vowel formant normalizations as an attempt to determine speaker independent characteristics of the speech signal. The Harpy system handles speaker variability by the use of phone templates to capture the vocal tract characteristics. We achieve this by identifying all the unique sounds that occur in the task language (called phones). It is important to realize that these phones may or may not bear a resemblance to what may be usually thought of as a phonetic sound in the English language. For example, there are usually several occurrences of one vowel (allophones) in our set of phones each of which has a unique name. Also, there could be a single phone which represents what is usually thought of as a combination of phones (e.g. the phone "WH" represents the characteristics of the aspiration sound when pair "K W" that occures together as in the word "queen"). Each of the phones used in the Harpy system represents one unique phonetic sound.

Phonetic knowledge in the Harpy system The Harpy system uses a phonetic dictionary (along with word juncture rules) to represent the lexicon of the task language. The spellings in the dictionary are strings of phones (along with a special syntax) which are used to represent primary and alternate pronunciations of the words in the lexicon. The phonetic dictionary is a representation of the actual realizations of the task language words rather than a pronunciation dictionary. A set of speaker dependent phone templates (one per phone) is used to match the symbolic lexicon to the actual acoustic signal. The phones of the lexicon represent all the unique phonetic sounds that occur in the task language. Since the lexicon contains symbolic spellings which are speaker independent and there is a one to one mapping of the templates to the phones, the acoustic speaker variability can be handled effectively by using a unique set of templates for each speaker. The templates model speaker dependent vocal characteristics. For example, the dictionary spelling for "CONCERN" is "(← (-,0),-) (K,0) (IH7,IH3) N S ER (N,DX)". Optional paths are enclosed within parenthesis and are separated by commas (the "0" represents the null option). The spelling is interpreted as either a voice bar ("←") followed by an optional silence ("-") or just a silence, followed by an optional "k", followed by either a "IH7" or "IH3", followed by an "N", followed by a "S", followed by an "ER", followed by either an "N" or "DX". See McKeown, 1977, for an example network.

Averaging of template exemplars The success of the speaker dependent phonetic templates depends of the ability to average many exemplars of each phone together to generate each template. This averaging enables the automatic cancelation of errors (provided they are small). Since the template is an average, there is no need to find the single "ideal" exemplar that best fits all occurrences of the phone. The averaged template will usually match all exemplars of the phone in the training data to a high degree of accuracy. If a match of an exemplar in the training data is too far from the average template, then this indicates a missing phone.

The metric used by the Harpy system is Itakura's minimum prediction residual error of the LPC data. A method was needed to average samples together that could be used for generating the templates for this metric. The method we use is to sum the autocorrelation data of the samples that are used in generating the template. The justification of this is that the LPC's are independent of the number of autocorrelation samples that are used to generate them. The obvious danger is that non-similar sounds may be averaged resulting is a poor spectrum. This is a real problem and is handled by a semi-automatic procedure for generation of the phones, templates, lexicon, and word juncture rules described below.

Speaker specific tuning The phones, templates, lexicon, and word juncture rules are generated from a set of training data that contains occurrences (and hopefully all contexts) of all the words in the lexicon. A semi-automatic iterative procedure is used to generate (or more precisely, update) these knowledge sources. There is a "chicken-egg" problem with this iterative procedure in that the data sources must already exist in order to update them. The generation of the initial knowledge sources is a tedious manual boot-strapping procedure. The training data must be carefully hand labeled (both at the word level and the phone level) and initial guesses are made about what phones, word spellings, juncture rules, etc. are needed. This manual effort is the main bottle-neck for developing larger vocabulary systems. Automatic methods must be developed before larger systems can be attempted.

The following is the semi-automatic procedure used to update the data sources: The Harpy system is run in a forced recognition mode with a previously generated set of templates (which can be from some other speaker) to produce a parsing of the phones to the acoustic data. This forced recognition can be done either by using a unique network for each utterance (which represents only the one utterance) or by considering only paths in a large network that represent each single utterance. The parsings generated from the forced recognition runs are used to locate the autocorrelation data for the averaging of the templates. After the averaging is completed, a new set of templates is generated and used to again run the training cycle. This cycle is run several times until the templates converge. If the templates do not converge, then this indicates an error in either the lexicon or word juncture rules or a missing phone which must be manually analyzed and corrected.

Speaker independent tuning The speaker dependent templates are an averaging of many phone exemplars for each template. Since there is a unique set of templates for each speaker, they capture the individual vocal tract characteristics. This idea of capturing vocal tract characteristics by the use of templates can be extended to multiple speakers. When a number of these speaker dependent sets of templates are generated, another set of templates can be generated from all of them by a similar averaging technique. This set of templates, since they are an averaging of several speakers, will be speaker independent. The performance with speaker independent templates will of course be lower than with the speaker dependent templates. For example, one experiment done with connected digits gave the following result: Ten speakers (including males and females) were used to produce ten speaker dependent sets of templates. The average word accuracy for all ten speakers (when tested on the speaker dependent templates with a total of 1000 three word utterances) was 98%. These ten template sets were then used to generate a set of speaker independent templates. These same ten speakers plus ten new speakers were then tested with the system. The word accuracy for all 20 speakers (on 1200 utterances) was 93%. An interesting observation is that there was no significant difference between the accuracies of the ten speakers whose templates were used to generate the speaker independent set and the ten new speakers.

Dynamic speaker adaptation The high error rate (7%) with the speaker independent templates makes this alternative to the handling of acoustic variability unacceptable. Further, the training cycle mentioned earlier to generate the speaker dependent templates is inconvenient do to the large amount of training data needed and is computationally expensive. A third scheme was devised which allows a new user the immediate use of the system but also allows for the speaker dependent vocal characteristics. This is the dynamic tuning of the speaker templates. A new speaker to the system starts with the set of speaker independent templates. The system will, upon all correct recognitions, automatically average the autocorrelation data with the corresponding templates and update the template parameters. The first occurrence of a phone spoken by the speaker will replace the speaker independent template. Further occurrences of the same phone will add to the average of the template. This will result in the phone template being altered quickly for the first occurrences of a phone and a gradual fine tuning of the template by additional occurrences of the phone. In this method, the system quickly adapts itself to the speaker's acoustic characteristics. If the system makes an error in recognition, one can either speak the same utterance again with the hope that it will be recognized correctly the second time or the system can be rerun on the same utterance and forced to recognize the utterance. To force a recognition, the appropriate switch is set and the correct utterance is typed to the system. The system will then only consider paths in its network which represent the spoken utterance.

The error rate when first starting is, of course, 7% but quickly drops off towards the 2% error rate of the speaker dependent templates. The time needed for the updating of the templates is zero during the actual recognition but requires up to one times real time after recognition depending on the number of templates that are updated. Therefore, the overhead of doing the dynamic speaker adaptation is minimal.

DISCUSSION

Summary In this paper we have considered several sources of variability in the connected speech signal, i.e. dialectic, contextual, and speaker dependent variability, and described how the Harpy system attempts to cope with all these sources of variability. The dialectic and contextual variability are encoded into the lexicon and word juncture rules. The speaker dependent sources of variability are handled by averaging phone parameters (i.e., the autocorrelation coefficients, not the LPC's) from among several exemplars of a given phone by the same speaker (for speaker specific templates) or from many speakers (for speaker independent templates). In the case of dynamic adaptation, a set of speaker independent templates are used initially and the system automatically alters the templates during use to adapt to the specific speaker.

It appears straight forward to adopt the above techniques for isolated word recognition systems also. Given several training samples of the same word, one can align the speech signal by dynamic programming techniques and average the autocorrelation coefficients as in the connected speech case. Since this averaging would be independent of word representation used, i.e. whether one uses segmentation and phone templates to represent words or the conventional brute force word templates, one can still use the above averaging technique to generate better templates.

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USE OF SEGMENTATION AND LABELING IN ANALYSIS-SYNTHESIS OF SPEECH

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ABSTRACT

We have been attempting to produce further bandwidth reduction in LPC based analysis-synthesis techniques by using the segmentation and labeling algorithms used in the Harpy and Hearsay-II systems. Preliminary results indicate that a factor of 3 to 5 further reduction in bandwidth might be possible using segmentation and labeling in conjunction with LPC vocoders.

INTRODUCTION

An important application of speech analysis-synthesis is digital voice transmission. Real-time transmission at low bandwidths can only be achieved through efficient analysis and encoding techniques. While present analysis methods, based on signal processing techniques, have been used successfully to obtain bandwidth reductions of over an order of magnitude, further improvement is possible if higher level properties of speech are also taken into account. In this paper, we demonstrate how segmentation and labeling, two techniques commonly used in connected speech recognition, can be applied to vocoder systems as a means of improving coding efficiency.

In the remaining sections, we describe segmentation and labeling techniques, and their use in vocoder systems. Results from three different vocoder simulations based on these techniques are presented and evaluated. We then consider some of the practical aspects of real-time speech transmission using these methods. Finally, the advantages and disadvantages of high level speech processing as applied to vocoders are discussed.

APPROACH

Our goal in this study was to evaluate the usefulness of segmentation and labeling as techniques for improving vocoder coding efficiency. To accomplish this, two vocoder simulations using each of these techniques separately, and a vocoder simulation which combined the techniques, were run. The results were compared with those obtained using conventional parameter encoding methods, and evaluated in terms of bandwidth reduction and quality of synthetic speech.

Of the several techniques for speech analysis that exist, this paper considers only those based on the autocorrelation method of linear prediction. A complete vocoder simulation based on this technique has already been developed by Markel and Gray[Markel and Gray, 1974]. Since a detailed discussion can be found in this reference, we consider only those aspects relevant to the bandwidth problem here.

Analysis parameters in autocorrelation based linear prediction systems consist of pitch period, a voiced/unvoiced decision, amplitude information, and parcor coefficients. These parameters are generally encoded into a minimal bit representation and transmitted at a constant frame rate. The system on which our comparisons are based uses a frame rate of 100 frames/sec, where each frame consists of 200 speech samples. A total of 64 bits are allocated to the 14 parcor parameters, which are quantized as described in [Markel and Gray, 1974]. Pitch period and the voiced/unvoiced decision are encoded together in 6 bits, and the amplitude is coded into 5 bits.

SEGMENT-CODER

Classically, information concerning the vocal tract shape is transmitted in the form of parcor parameters once per analysis frame. Speech, however, can be segmented into events, for the duration of which, vocal tract shape may be considered approximately constant. Cases where this is not true, such as glides and diphthongs, may be approximated by a series of shorter segments. Therefore, it should be possible, without significant degradation in synthetic speech quality, to transmit parcor parameters once per segment, rather than once per frame. Since segment duration is relatively long compared with analysis frame length, a savings in the number of bits needed to encode the analysis parameters should result. A vocoder simulation based on this hypothesis was developed.

Segmentation is preformed using algorithms developed for the Hearsay speech recognition system[Goldberg and Reddy, 1976]. Three stages are involved in the overall process: parametrization, segmentation, and classification. The first step in parametrization is to generate smoothed and differenced waveforms from the sampled speech. Next, peak to peak amplitudes and zero crossing counts are extracted from each waveform once per centisecond of speech. Segmentation is based on these parameters.

Segment boundaries are determined by successive subdivision of the waveform. First, silences and unvoiced fricatives are detected by a thresholding technique. Next, the remaining segments are divided where significant dips in the smoothed peak to peak parameter occur. A region growing technique is then applied to further subdivide the segments. Finally, the resulting segments may optionally be classified in terms of manner of articulation. Decision rules based on the averaged parameter values for each segment are used for this purpose.

Operation of the vocoder is relatively straightforward. Speech is segmented as it enters the system. When a segment boundary occurs, parcor parameters for that segment are calculated. By definition, all frames within a segment should have similar spectral properties, however

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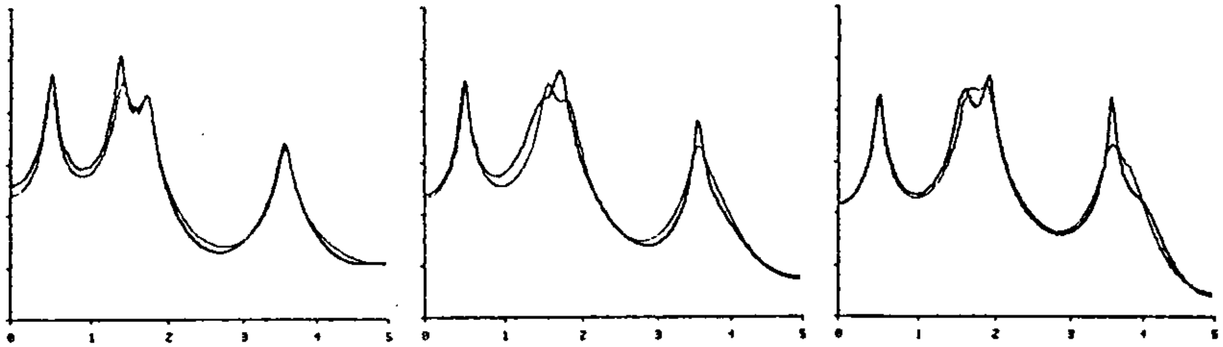

Figure 1. Spectral mismatch resulting from interpolation of parcor coefficients at segment boundaries.

this is not always the case. Near segment boundaries, the vocal tract is changing, and cannot be assumed to have constant resonances. To eliminate possible errors due to these changes, the parcor coefficients are computed at the segment midpoint. Once calculated, these coefficients, along with the segment duration, are transmitted. Pitch and amplitude are then extracted from each frame in the segment, encoded, and transmitted. Thus, with this scheme, pitch and amplitude are still transmitted at the constant rate of once per frame, but parcor coefficients are transmitted at the rate of once per segment, which is not necessarily constant.

Except at its boundaries, the same set of parcor coefficients is used to synthesize speech for each frame within a segment. Near boundaries variation in the parcor coefficients due to vocal tract changes must be taken into account. Good results have been obtained using simple linear interpolation. For most segments it is adequate to interpolate over 5 centiseconds, from 2 centiseconds before the segment boundary, to 2 centiseconds after. For shorter segments, indicating rapid changes in the spectral structure, interpolation is done from the segment midpoint.

The effects of parcor coefficient interpolation are illustrated in Figure 1. This figure shows the spectral envolopes for a transition from one segment to the next. The darker curve represents the conventional synthetic speech, the lighter represents the speech synthesized from interpolated parcor coefficients. Note that although the peak amplitude and shape differ slightly, the peak locations are nearly identical.

Figure 3 shows a digital spectrogram for the utterance "The area I'm interested in is understanding," synthesized with the Segment-coder. For comparison purposes, a digital spectrogram of the utterance synthesized with conventional methods is shown in Figure 2. As can be seen, the spectrograms resemble each other closely. In informal listening tests, the synthetic speech generated with parcor parameters transmitted only once per segment was nearly indistinguishable from that generated with parcor parameters transmitted every frame.

The degree of improvement in coding efficiency will vary from system to system, depending on frame rate, and the precision to which each of the parameters are encoded. For the system described earlier, a total of (6+5+64)x100=7500 bits/sec are required to encode the analysis parameters. Using segmentation, pitch period and amplitude information are still transmitted for each frame, but parcor coefficients are transmitted only once per segment. Another parameter, the segment duration, must also be transmitted with each segment. Allocation of 4 bits for this parameter allows for segment lengths up to 16 centiseconds. Segments exceeding this length are rarely encountered, and can easily be split into multiple segments. On average, the segmentation algorithm produces 15 segments per second of speech. Thus, the total bit rate needed for this scheme is (6+5)x100+(4+64)x15=2120 bits/sec. This represents improvement by a factor of about 3.5 over the conventional method.

Reductions of this order have been obtained in conventional vocoders by using reduced frame rate. Rather than transmitting one frame per centisecond, these vocoders might transmit one frame every 3 centiseconds, indiscriminately ignoring data between frames. This has a smoothing effect which results in the loss of short events that may be perceptually significant. Thus, the overall quality of the synthetic speech should be lower than that obtained with the segmentation scheme.

LABEL-CODER

A second technique makes use of an assumption that all speech, regardless of its complexity, can be formed by combinations of a small number of basic sounds. The VORTRAX speech synthesizer is an example of one such system based on this assumption. Associated with each sound is unique formation of the vocal tract, and associated with each vocal tract formation is a set of parcor coefficients. If speech at each analysis frame can be identified and classified as one of these sounds, then it would only be necessary to transmit a label identifying the sound, rather that the entire set of parcor parameters. Since the number of sounds is small, significantly fewer that 64 bits are needed to encode the label, and an improvement in coding efficiency would result.

Prior to the development of a vocoder simulation, the properties of each sound must be determined and represented in a format usable by the system. A procedure to accomplish this was developed for use with the Harpy system[Lowerre, 1976]. Segments from several utterances, spoken by a particular speaker, are identified and grouped according to their sound class. Autocorrelation coefficients for each segment are computed and averaged over all segments in the same class. For each averaged autocorrelation sequence, hereafter referred to as a template, linear prediction coefficients, parcor coefficients,

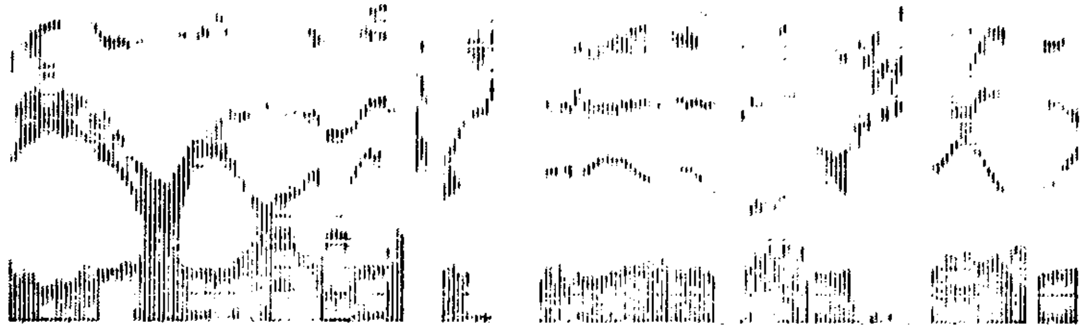

Figure 2. Digital spectrogram of synthetic speech for the utterance "The area I'm interested in is understanding," generated using conventional signal encoding techniques.

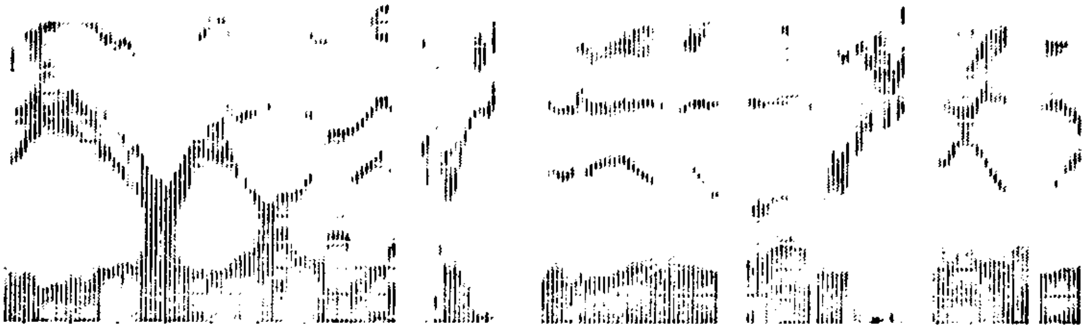

Figure 3. Spectrogram of the synthetic speech generated by the Segment-coder.

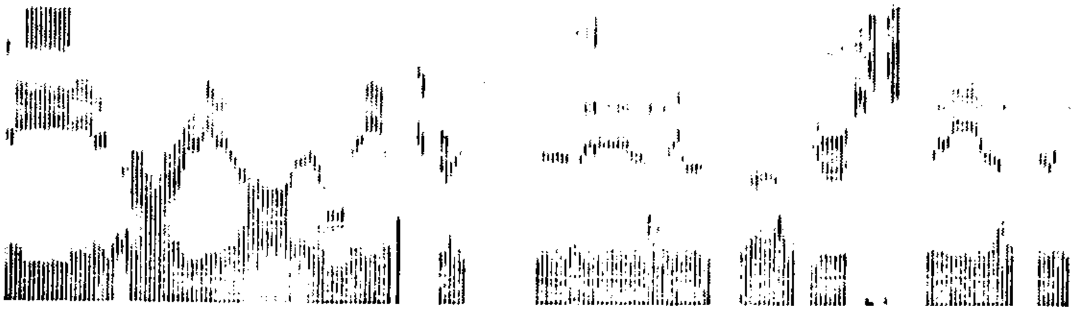

Figure 4. Spectrogram of the synthetic speech generated by the Label-coder.

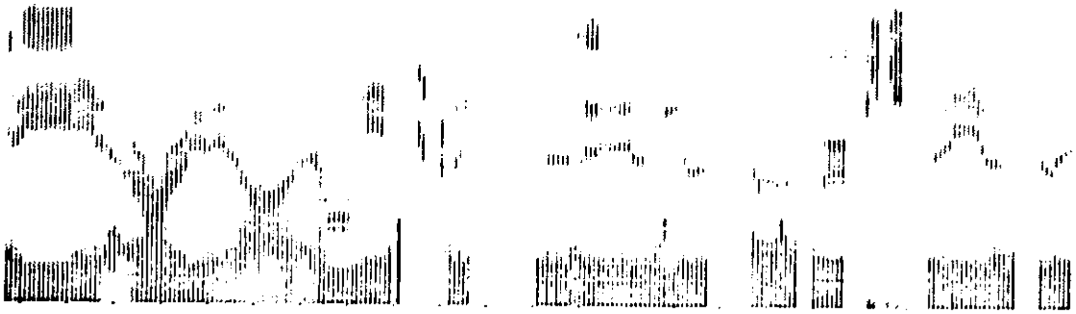

Figure 5. Spectrogram of the synthetic speech generated by the Segment-label-coder.

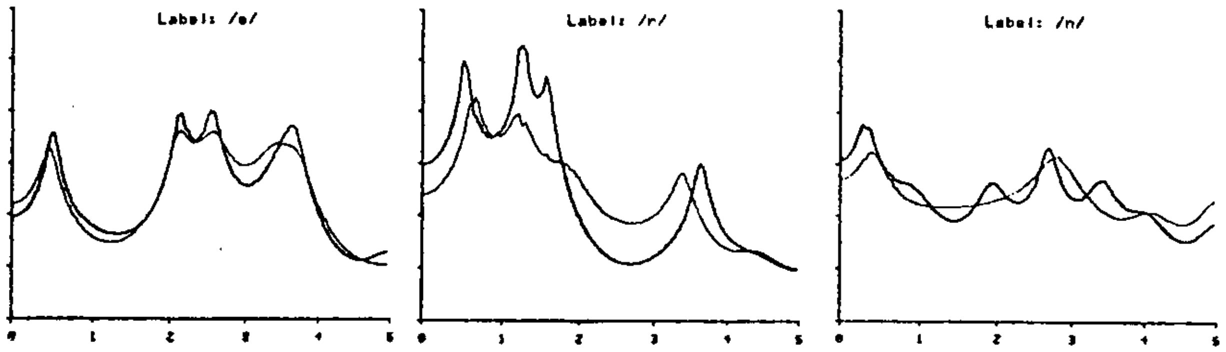

Figure 6. Spectral mismatch resulting from replacing parcor coefficients by a single phone label.

and b-coefficients[Itakura, 1975] are computed. This information is made available to both the transmitter and receiver portions of the vocoder.

The task of the vocoder, then, is to determine, for each analysis frame, which template best matches the speech signal. The LPC matching technique developed by Itakura[Itakura, 1975] has been used for this purpose. A distance metric is applied between each frame and all templates. The best template, in terms of minimum distance, is selected. A label identifying this template, along with pitch and amplitude information is transmitted. At the receiver, a simple table lookup, using the label as an index, is preformed to determine the parcor parameters of each frame. From this point on, synthesis proceeds normally.

Figure 6 shows the spectral mismatch between original spectra and the labels assigned to them. The darker curve corresponds to the original speech, the lighter to speech synthesized with the labeling method. The curves illustrate typical spectral errors that occur with the labeling method.

Displayed in Figure 4 is a digital spectrogram of the test utterance, synthesized with the Label-coder. This may be compared with the spectrogram of the conventional synthetic speech in Figure 2. Although the synthetic speech was intelligible, there was considerable distortion. We believe that this can be eliminated by changes in the template generation and matching algorithms.

Again, the bandwidth reduction afforded by this technique depends on how accurately the parameters are quantized, but in this case it is independent of frame rate. As before, we base our comparison on the system described earlier. For this system a total of 6+5+64=75 bits/frame are needed to encode the speech. For the system with labeling, a label, along with the encoded pitch and amplitude, is transmitted for each frame. To uniquely identify each of the 96 templates used in this simulation, 7 bits were allocated for the label. Thus, with labeling, only 6+5+7=18 bits are needed to encode each frame. This represents a bandwidth reduction by a factor of 4.

SEGMENT-LABEL-CODER

Clearly, if only one set of parcor coefficients is necessary to encode the spectral structure of each segment, and if each spectral structure can be identified by a label, then it should be possible to transmit only one label per segment. Examination of the analysis parameters from the labeling system reveals that this is indeed the case. Most frames within a segment were found to be labeled with the same label. Those that were not, were labeled with an acoustically similar label. Once again, a vocoder simulation to test the hypothesis was developed.

The separate use of segmentation and labeling has already been discussed. This system is merely a combination of the two previous ones. After segmentation, the labeling algorithm is applied at the midpoint of each segment. The label which best characterizes the spectral properties of that segment, and the segment duration are encoded for transmission. Of course, pitch and amplitude information are still transmitted for every frame. Received labels are first used determine the parcor parameters associated with each segment, which in turn are used to synthesize speech for all frames within that segment. Interpolation at segment boundaries is carried out as previously described.

The spectrogram for speech synthesized by this system is shown in Figure 5. Note its similarity to the spectrogram for speech synthesized by the labeling system. This is to be expected, since it was already determined that segmentation causes no significant degradation. The differences between this and the other spectrograms are due to degradation introduced by labeling.

Again, we calculate coding efficiency by comparison with the conventional system. With this encoding scheme, a total of 6 bits for pitch, and 5 bits for amplitude are transmitted every frame. An additional 4 bits for segment duration, and 7 bits to identify the template are transmitted for each segment. Using a frame rate of 100 frames/sec, and an average of 15 segments per second of speech, a data rate of (6+5)x100+(4+7)x15=1265 bits/second is obtained. This is approximately 5.9 times smaller than the 7500 bits/sec of the conventional system.

DISCUSSION

We have shown that segmentation and labeling can be used as a means of reducing bandwidth in speech analysis-synthesis systems. Since the primary application of such systems is secure voice communications, it is appropriate to mention some of the practical aspects of a vocoder based on these techniques.

A problem arises when the vocoder is converted to real-time operation. Since analysis parameters for each segment are not transmitted until the entire segment has been spoken, it is possible for the synthesizer to complete synthesis of one segment before it receives parameters for the next. If this happens, a pause in the synthesizer output will occur. To avoid these pauses it is necessary define a maximum segment duration, and delay the synthesis by this amount. We have already indicated that 16 centiseconds is a reasonable choice for maximum segment duration. If the synthesizer lags the transmitter by this amount, plus an additional 2 centiseconds to allow for interpolation, continuous synthetic speech can be guaranteed. In practice, this is not a serious drawback. Delays of this magnitude are secondary in nature to those normally encountered in satellite based transmission systems.

From the discussion of labeling it should be clear that both transmitter and receiver must access to the same set of templates. Since the templates vary from speaker to speaker, it is impractical to make them a permanent part of the system. Rather, at the beginning of a conversation, templates for each speaker could be loaded into the corresponding transmitter and transmitted to the connecting receiver. Another possibility would be to use a single set of templates which has been averaged over many speakers. However, lower quality synthesis can be expected with this method.

In addition to the obvious reduction in bit rate, there are other advantages to the use of these techniques. At first, the additional processing needed to segment and classify speech would seem to result in slower vocoder operation, however this is not the case. Once the segments are known, the time consuming autocorrelation analysis need be preformed only once per segment. Thus, overall vocoder operation is actually faster. Furthermore, since gross segment classifications are obtained during the segmentation process, specialized processing, depending on the segment class can be preformed. For example, silences can be dismissed with no processing, and low coefficient LPC analysis can be preformed for fricatives. This should result in a more accurate synthesis.

The main point should be clear: through the use of specialized knowledge of the nature of speech, and higher level signal-to-symbol transformation techniques, incrementally better vocoders can be obtained. We have demonstrated two steps in this progression. The first was the transition from systems based solely on spectral analysis, to a system that combined knowledge of segments with spectral analysis. The next step was the use of labeling in addition to segmentation to give even further bandwidth reduction. As speech recognition systems evolve, better and better encodings will become practical. Eventually, it should be possible to transmit syllable sized units.

Finally, improvement in coding efficiency is obtained at the expense of generality. As more specialized knowledge of speech and language is used, the variety of sounds that can be transmitted is reduced. At the lowest level is the system that transmits sampled speech directly. With this system, arbitrary sounds can be represented accurately. The step to conventional vocoders limits those sounds which can be transmitted to speech. Greater restrictions occur as the vocoder becomes more and more language oriented.

CONCLUSIONS

We have presented two techniques, based on algorithms developed for the Hearsay and Harpy speech recognition systems, which use knowledge about speech phenomena, to yield reductions in vocoder bandwidth. While the degree of improvement varies from system to system, typical reduction factors ranging from 3 to 4 can be expected from each method. Furthermore, improvements by a factor of 5 or more can be realized if the techniques are combined.

Use of segmentation caused no noticeable degradation in the synthetic speech quality. With labeling, considerable degradation occured, however it is felt that this can be eliminated with better templates.

Some of the practical aspects of vocoder implementation based on these techniques, along with the advantages and disadvantages to the use of specialized knowledge, were discussed. On the basis of arguments presented then, we believe that speech analysis-synthesis using segmentation and labeling is worthy of further research.

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A HALTING CONDITION AND RELATED PRUNING HEURISTIC FOR COMBINATORIAL SEARCH

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ABSTRACT

Many combinatorial search problems can be viewed within the "Chinese restaurant menu selection paradigm" of "choose one from Column A, one from Column B, ..." A solution to such a problem consists of a set of selections which are mutually consistent according to some set of constraints. The overall value of a solution is a composite function of the value of each individual selection. The goal of the search is to find the best (highest-rated) solution. Examples of such search problems occur in the domains of speech understanding, vision, and medical diagnosis.

This paper describes a search-pruning heuristic and a halting condition which are conservative in that they will not miss the best solution by pruning it out of the search or by terminating the search before it is found. The method exploits information about already-found solutions in order to prune the search and decide when to terminate it. An implementation of the halting condition and pruning heuristic within the Hearsay-II speech understanding system is described and evaluated, and the conditions governing its applicability and performance are discussed.

INTRODUCTION: SOME EXAMPLES

A frequently-occurring problem in AI involves finding the best combination of choices for a set of interdependent multiple-choice decisions. The possible combinations form a combinatorial search space. Each decision corresponds to a data element which can be labelled (explained, interpreted) in several alternative ways, some of which may be preferable to (more appropriate than) others. Legal solutions (combinations of labels) must satisfy certain domain-specific consistency constraints governing the interdependencies between the various elements to be labelled.

One example of combinatorial search occurs in the domain of speech understanding. A spoken utterance can be viewed as a set of contiguous points in time. The combinatorial search task of a speech understanding system is to label each time interval with the word apparently spoken during that interval. Several labels may appear plausible due to the uncertainty of the speech signal and the word recognition process [7]. A solution consists of a transcription of the utterance, i.e., a sequence of word labels, which is syntactically and semantically consistent. The credibility (probability of correctness) of such a solution depends on the overall goodness of fit between the labels and their time intervals.

Another example comes from the domain of vision. The contour detection

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problem can be described as follows: given a scene represented by an array of pixel gray levels, label each pixel with a vector corresponding to the apparent intensity gradient at that point in the image [9]. A consistent interpretation of the scene assigns parallel gradients to contiguous pixels on a contour and null gradients to pixels in the interior of a region. The accuracy of an interpretation depends on the overall degree to which the labels match the visual data they attempt to describe.

A third example can be found in the domain of medical diagnosis. Here the data elements to be explained are the patient's symptoms. A diagnosis provides consistent explanations for all the symptoms. The plausibility of a diagnosis depends on the overall plausibility with which the individual symptoms are accounted for [1].

PROPERTIES OF COMBINATORIAL SEARCH

Let us now examine these search problems in order to discover common properties which can be exploited in designing halting conditions and pruning heuristics. In each example, the set of data elements (points in time, pixels, symptoms) to be explained or labelled is known at the beginning of the search. (Actually, this assumption does not hold for systems like MYCIN which collect data during the course of the search. However, as we shall see, it is sufficient for the set of elements to be determined anytime before the first solution is found.)

A partial solution consists of consistent explanations for a subset of the elements. Combinatorial search algorithms typically extend and combine such partial solutions. In fact, each step in the search can be characterized as examining a collection of partial solutions I_1, ..., I_k, and then possibly creating a new partial solution I'. We can use rating information about partial solutions in order to decide when to halt the search once some solution has been found. For example, suppose we examine the ratings of all existing partial solutions and conclude that none of them can be extended into a complete solution rated higher than the best one found so far. Under this condition, it is safe to halt the search; the best solution found is the best one possible. This condition is the desired conservative halting condition.

A similar technique can be used to prune the search. If a partial solution cannot possibly be extrapolated into a complete solution superior to the best existing one, it can be ***rejected*** -- i.e., all efforts to extend it or combine it with other partial solutions can safely be abandoned. This pruning heuristic is conservative but also rather weak. A more powerful heuristic depends on certain properties of the function used for rating solutions. Let us consider this function in more detail.

THE RATING FUNCTION

A complete solution consistently explains all the elements[1] and is rated according to how well each element is explained. I.e., if the rating function R(I,S) measures how well the interpretation I explains the elements of the set S, then R(I,S) = f{R(I,e) | e in S}, where R(I,e) measures how well I explains the element e. R(I,S) is assumed to be an increasing function of the terms R(I,e). The interpretation I is a set of labels for the elements of S, i.e., for all e in S I:e -> $l_I(e)$. The rating R(I,e) may be context-sensitive, i.e., depend on how other elements besides e are labelled (e.g., its neighbors, if e is a pixel). A considerable

[1] This condition could be relaxed by allowing complete solutions to label some elements "IGNORED." The rating function would then have to reflect the relative significance of explaining or ignoring a given element, so as to allow meaningful comparison between solutions accounting for different subsets of the element set.

simplification is possible if $R(I,e)$ is context-free, i.e., $R(I,e) = R(l_I(e),e)$, where $l_I(e)$ is the label assigned by I to e, and $R(l,e)$ measures the goodness of fit between the label l and the element e. In this case, $R(I,S) = f\{R(l_I(e),e) \mid e \text{ in } S\}$. If f is a simple averaging function, then $R(I,S) = \text{Average}\ \{R(l_I(e),e) \mid e \text{ in } S\}$.

The best solution I maximizes $R(I,S)$ subject to the consistency constraints. Note that the function R may produce higher values if applied to inconsistent interpretations (non-solutions). For example, the interpretation Imax:e -> Imax(e), where Imax(e) is the highest-rated label for e, will in general maximize $R(I,S)$ but is not in general consistent.

A HALTING CONDITION AND PRUNING HEURISTIC

We can now precisely define our halting condition and pruning heuristic in terms of the rating function R. Let S' be a subset of the element set S, and let I' be a partial solution which explains S'. Let I be the highest-rated solution found so far during the search.

I' can be extended into a complete (not necessarily consistent!) interpretation I" by assigning Imax(e) to every e in S-S'. I" is the highest-rated possible complete extrapolation of I'. Thus if $R(I'',S) \leq R(I,S)$, I' cannot be extended into a solution better than I, and it is *safe* to reject I' and all its potential extensions. Unfortunately, this condition is too strong and is not often satisfied. A more powerful (but still conservative) pruning heuristic is made possible by assuming that R is context-free in the sense defined earlier.

A MORE POWERFUL PRUNING HEURISTIC

Suppose that R is context-free and that a solution I has been found. If a better solution is possible, there must exist a partial solution I' which is ***locally superior*** to I. I' is locally superior to I over domain S' if $R(I',S') > R(I,S')$. Intuitively, I' explains some subset S' better than I does. If no such I' exists, then I is the best solution, and it is safe to halt the search.

This reasoning requires some justification. We consider all individual element labels to be one-element partial solutions, and assume that they are available to the search algorithm as such. If some potential complete solution I" is better than I, then there must exist at least one element e in S such that $R(I'',e) = R(l_{I''}(e),e) > R(l_I(e),e) = R(I,e)$. (Otherwise $R(I'',S) \leq R(I,S)$.) This one-element partial solution can be extended step by step into I" so that the partial solution I' at each step is locally superior to I. We assume that such a sequence of partial solutions can be found by the search algorithm. This is a strong assumption. Many sequences of partial solutions may lead by stepwise extension and combination to the same solution, but not all will maintain local superiority at each step, and not all may be realizable by the search algorithm being used.

With this caveat, we now observe a happy property of context-free rating functions: once a solution has been found, only partial solutions which are locally superior to it need be considered. All others may be ***deactivated***, i.e., ignored except for combination with active partial solutions.

We can now express a powerful conservative pruning condition: A proposed search operation based on partial solutions I_1, ..., I_k may safely be cancelled if

(1) Any of the I_i has been ***rejected***, or

(2) All of the I_i have been ***deactivated.***

The halting condition is trivial: halt when all pending search operations have been cancelled.

UNDERLYING ASSUMPTIONS

Let us now re-examine some of the assumptions on which this method is based, and the motivations for making them.

(1) The rating function is context-free. Otherwise the local superiority criterion is not valid.

(2) The labels lmax(e) are known at the beginning of the search, and exist as one-point partial solutions. Otherwise correct but low-rated partial solutions might be erroneously rejected. Actually, in order to avoid erroneous rejection, it is only necessary to know an upper bound function $Rmax(e) \geq R(I,e)$ for all e in S. The tighter this upper bound, the more partial solutions can be rejected. The Rmax function used by the HWIM speech understanding system is defined by the score of the best phonetic label for each segment [8]. Since this score is based on the best possible word match for each segment rather than on the best actual word match, it provides a poor (over-optimistic) upper bound on the actual word ratings, and produces mediocre results. The Rmax function used in Hearsay-II is defined by the score of the highest-rated hypothesized word at each point in the utterance, and produces good results.

(3) If a potential solution I" is better than an existing solution I, the search algorithm must be capable of building I" in such a way that each partial solution I' in the derivation sequence is locally superior to I. Otherwise the derivation of I" might require operating on a set of deactivated partial solutions and be blocked by the deactivation pruning heuristic.

EXAMPLE FROM HEARSAY-II

The Hearsay-II speech understanding system [2] segments a spoken utterance into syllable-length time intervals. These are the elements. The labels for each element are taken from a 1,000-word vocabulary. A complete solution is a grammatical transcription spanning the utterance. A partial solution is a grammatical phrase spanning part of the utterance. The rating function is a simple average of label fit goodness. A (partial) solution I covers a time interval [first!syl:last!syl]. Its rating is its average word rating weighted by the number of syllables in each word. I.e., $R(I,[first!syl:last!syl]) = Average \{ R(W_I(syl) \mid A(syl))) \}$, where $first!syl \leq syl \leq last!syl$, $A(syl)$ represents the acoustic data in the interval syl, $W_I(syl)$ is the word label assigned by I to syl, and $R(W \mid A)$ measures how closely the word W matches the acoustic data A. $R(W \mid A)$ is computed by the word verifier [6].

In Hearsay-II, partial solutions are explicitly represented as ***hypotheses*** on a global data structure called a ***blackboard***. Search operations are proposed by various ***knowledge sources*** which monitor the data on the blackboard. The operations relevant to the discussion at hand are [5]

(1) ***Recognition***: given a sequence of words, parse it and record it as a partial solution if it is grammatical.

(2) ***Prediction***: given a recognized phrase, propose words which can grammatically precede or follow it. Predictions which are rated above a specified threshold by the word-verifier are recorded on the blackboard as one-word hypotheses. Thus prediction

dynamically assigns extra labels to elements, and could potentially violate our earlier assumption that Rmax(e) is known before the rejection pruning heuristic is applied. This is not a problem in practice, however, since most label assignment (word recognition) is done at the beginning of the search or before the first complete solution is found, and predicted words are seldom rated higher than the best previously-recognized words.

(3) ***Concatenation***: given two temporally adjacent phrases (or a phrase and a word predicted next to it and subsequently verified), concatenate them and record the result as a partial solution if it is grammatical.

These search operations are performed in order of their priorities, which are assigned by a central focus-of-attention module [3]. The focus module tries to order the search in a best-first manner, and succeeds about 50% of the time on the corpus tested for this paper. This figure seems to increase as the constraints on grammatical consistency are increased, i.e., as the branching factor of the language is reduced. For a best-first search, the best halting policy is to terminate the search as soon as a solution is found. Note that the rejection and deactivation pruning heuristics are inapplicable if this policy is used, since these heuristics do not become applicable until some solution is found.

EVALUATION

The deactivation and rejection heuristics were evaluated on a corpus of 34 utterances drawn from a 262-word vocabulary. Utterance length ranges from 3 to 9 words, with an average of 6. The fanout (number of grammatical word successors in each word position) averages 27 for the corpus.

Each utterance was processed in 5 modes. Mode N uses neither heuristic; mode R uses rejection; mode D uses deactivation; and mode B uses both. In mode F, the system accepts the first solution it finds and immediately halts. The results of the experiment are shown in Table 1.

The simple accept-the-first-solution policy used in mode F is fastest, but at a considerable cost in accuracy, since it fails for those runs (about 50%) in which the highest-rated solution is not the first one found. A more conservative policy finds these solutions at the cost of extra search in those runs where the best solution is found first. The correct choice of policy (simple versus conservative) depends on a tradeoff between efficiency and accuracy. Since accuracy is very important in speech understanding, the conservative policy is preferred despite its extra cost.

The heuristics can be evaluated according to two criteria. First, how fast is the best solution found once the first solution is found? As Table 1 shows, deactivation is about twice as powerful as rejection in speeding up this phase of the search. The combination of heuristics is only slightly more effective than using deactivation alone.

Mode:	N	R	D	B	F
Average number of search operations (Hearsay-II knowledge source and precondition executions) to find first solution:[1]	153	157	145	152	152
Average number of (percent) extra search operations to find the best solution once the first solution has been found:	71	58	30	26	0
	46%	37%	21%	17%	0%
Speedup in this phase of the search relative to mode N:	1	1.2	2.4	2.7	infinity
Average total number of search operations to find best solution:	223	215	175	178	152
Average number of (percent) extra search operations to satisfy halting condition[2] once the best solution has been found (excluding runs in which time or space is exhausted):[3]	241	153	89	52	0
	108%	71%	51%	29%	0%
Average total number of search operations until halting condition is satisfied:	286	282	253	226	152
Number (percent) of utterances in which halting condition is satisfied before system exceeds predefined limits on time (800 search operations) or space (193K):	4	17	32	32	34
	12%	50%	94%	94%	100%

Table 1. Results of experimental evaluation of pruning heuristics.

[1] Ideally these numbers should be equal, since the heuristics are not applied until the first solution is found. The variation in these figures is caused by some randomness in the Hearsay-II scheduler in choosing between equally promising search operations.

[2] The halting condition is satisfied when no more search operations are pending, or when all the pending operations are considered unpromising by the system.

[3] Speedup ratios between different modes are not meaningful here since the set of excluded utterances varies from mode to mode.

Second, how fast is the halting condition satisfied once the best solution is found? An ideal policy would halt as soon as the best solution was found. The deviation of an actual policy from this ideal can be measured by its "halting overhead," i.e., the amount of extra search performed after the best solution is found. When neither heuristic is used, the halting condition is satisfied in only 12% of the runs (time or space bounds are exceeded in the others) and the halting overhead in those runs is 108%. The rejection heuristic succeeds in satisfying the halting condition in 50% of the runs, with an overhead of 71%. Deactivation leads to halting in 94% of the runs, with 51% overhead. The combination of both heuristics also causes halting in 94% of the runs, but reduces overhead to only 29%.

These results can be summarized as follows:

(1) Deactivation is about twice as powerful as rejection in accelerating the search for the best solution once the first solution has been found. This difference in empirical performance substantiates the intuitive notion that the conditions for deactivating a partial solution are substantially easier to satisfy than the conditions for rejecting it. The combined heuristics speed up this phase of the search by a significant factor (2.7).

(2) The combined heuristics succeed most (94%) of the time in satisfying the halting condition, at a reasonable cost (29%) compared to the time it takes to find the best solution. The large variance in this cost and the failure to satisfy the halting condition in the other 6% of the runs suggest that other techniques are needed to further streamline the search without eliminating the best solution.

DISCUSSION OF APPLICABILITY

What properties of Hearsay-II make this method applicable?

(1) Most of the word labelling is performed before the first solution is found and the heuristics are applied. Seldom is a new word subsequently hypothesized with a rating higher than all the other words in its time interval. Thus the necessary information (the Rmax function) is determined before the heuristics are applied. Exceptions do not automatically cause erroneous rejection, since the Rmax function generally provides a safety margin by overestimating the rating of the best possible solution.

(2) A solution must account for the whole time interval of the utterance, i.e., for every element (syllable). This facilitates the comparison of extrapolated potential solutions with already-found solutions.

(3) The rating function for evaluating solutions is context-free. This facilitates the local comparison of partial solutions with complete solutions.

The context-free property is somewhat counter-intuitive since the consistency criteria are in general context-sensitive, i.e., the admissibility of a label depends on the labels assigned to other elements. The rating function might be expected to rate solutions (consistent interpretations) higher than inconsistent explanations, but a context-free rating function does not have this intuitively satisfying trait. Our approach separates two properties of a solution:

(1) satisfaction of consistency constraints.

(2) goodness of fit between labels and data.

Consistency is considered to be an all-or-none property and is guaranteed by the form of the search. Relative goodness of fit is assumed to be *local,* rather than context-sensitive. When this assumption approximates the truth, it becomes possible to apply the powerful deactivation heuristic.

CONCLUSIONS

Conservative pruning heuristics for combinatorial search have been presented. They operate by eliminating branches of the search which cannot lead to solutions better than those found already. In this respect, they can be thought of as alpha-beta pruning heuristics in a one-player game. The pruning heuristics and associated halting condition have been implemented in Hearsay-II and shown to be effective in the real-world problem domain of speech understanding.

When the object of a search is to find the best solution (not just any solution), there is an important tradeoff between speed and accuracy. The simplest halting policy accepts the first solution found. This policy is correct if the search is always best-first; the closer the search is to best-first, the more attractive such a simple policy becomes. More sophisticated policies increase accuracy at the expense of prolonging the search so as to guarantee that the best solution is not missed.

In a nearly-best-first search, the discovery of a solution changes the purpose of the search from one of finding the best possible solution to one of verifying that there is no better solution than the one found. This change of purpose should be reflected in the search-guiding policies.

The approach described exploits certain assumptions about the search.

(1) The search space can be represented by a set of elements (data) each of which can be labelled in several ways. A solution labels all the elements and satisfies specified consistency constraints.

(2) A rating function evaluates how well a given label fits a given element. An upper bound on the best label rating for each element should be determined by the time the first solution is found. The tighter the bound, the better the performance of the pruning heuristics.

(3) The rating of a solution should be a function of the ratings of its individual labels. It should be possible to compute an upper bound on the rating of the best possible extrapolation of a given partial solution. The tighter the bound, the better the performance.

(4) The better the found solution relative to the best (generally inconsistent) interpretation Imax (which assigns each element its highest-ranked label), the more pruning can be done. The stronger the consistency constraints, the lower a solution will tend to be rated compared to Imax, and the worse the performance.

Many search problems (e.g., speech and image understanding, medical diagnosis) appear to fit the paradigm of "choose one from Column A, one from Column B," i.e., given alternative choices for a set of decision points, find the best-rated consistent set of choices. When efficient best-first search algorithms are infeasible, some mechanism is needed for deciding when to halt the search and accept the best solution found so far. Such a mechanism should terminate the search as soon as possible without ignoring better solutions. This paper has shown how such a mechanism can exploit information about already-found solutions to accelerate the search conservatively, i.e., without ignoring better solutions.

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Re71Sm Reddy, D. R., Bell, C. G. and Wulf, W. A. Speech recognition in a multiprocessor environment. *Proc. 1971 IEEE Conf. on Automatic Control*, Miami, Florida, 1971. Also appeared in CM72W1.

Re71Sp Reddy, D. R. Speech recognition: prospects for the seventies. *Proc. IFIP 1971*, Ljubljana, Yugoslavia, 1971, I.5-I.13. Also appeared in CM72W1. Invited paper.

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Gd70Am Goodman, G. Ambiguity in phonetic grammars. *Proc. of the 3rd Hawaii Inter. Conf. System Sciences*, Honolulu, Hawaii, 1970.

Re70Cm Reddy, D. R., Erman, L. D. and Neely, R. B. The CMU speech recognition project. *Proc. 1970 IEEE System Sciences and Cybernetics Conf.*, Pittsburgh, PA, 1970. Also appeared in CM72W1.

Re70Sp Reddy, D. R. Speech input terminals for computers: problems and prospects. *IEEE Computer Conference*, Washington, D.C., 1970. Also appeared in CM72W1.

(The following earlier papers were done at Stanford and are included here for reference.)

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Ne69Ex Neely, R. B. Experimental conversational computer system. *J. Acous. Soc. Amer. 46* (July 1969) 89. (Abstract only)

Re69Co Reddy, D. R. and Neely, R. B. Contextual analysis of phonemes of English. Tech. Report, Stanford University, AI Memo 79, Stanford, CA, 1969.

Re69Se Reddy, D. R. Segment-synchronization problem in speech recognition. *J. Acous. Soc. Amer. 46* (July 1969) 89. (Abstract only)

Re69Us Reddy, D. R. On the use of environmental, syntactic, and probabilistic constraints in vision and speech. Tech. Report, Stanford University, AI Memo 78, Stanford, CA, 1969.

Vi69As Vicens, P. J. Aspects of speech recognition by computer. Tech. Report, Stanford University, AI Memo 85, Stanford, CA, 1969. Ph.D. Dissertation. The "Vicens-Reddy" system.

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Mc68Co McCarthy, J., Earnest, L., Reddy, D. R. and Vicens, P. J. A computer with hands, eyes and ears. *Proc. FJCC*, 1968, 329-337.

Re68Cn Reddy, D. R. Consonantal clusters and connected speech recognition. *Proc. 6th Inter. Congress on Acoustics*, Tokyo, Japan, 1968, 57-60.

Re68Co Reddy, D. R. On computer transcription of phonemic symbols. *J. Acous. Soc. Amer. 44* (Feb. 1968) 638-639.

Re68Ph Reddy, D. R. and Robinson, A. E. Phoneme to grapheme translation of English. *IEEE Trans. Audio and Electroacoustics 16* (Feb. 1968) 240-246.

Re68Pr Reddy, D. R. and Vicens, P. J. A procedure for segmentation of connected speech. *J. Audio Engr. Soc. 16* (Apr. 1968) 404-412.

Vi68Pr Vicens, P. Preprocessing for speech analysis. Tech. Report, Stanford University, AI Memo 71, Stanford, CA, 1968.

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Re67Co Reddy, D. R. Computer recognition of connected speech. *J. Acous. Soc. Amer. 42* (Aug. 1967) 329-347.

Re67Ph Reddy, D. R. Phoneme grouping for speech recognition. *J. Acous. Soc. Amer. 41* (May 1967) 1295-1300.

Re67Pi Reddy, D. R. Pitch period determination of speech sounds. *Comm. ACM 10* (June 1967) 343-348.

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Re66Ap Reddy, D. R. An approach to computer speech recognition by direct analysis of the speech wave. Tech. Report, Stanford University, AI Memo 43, Stanford, CA, 1966. Ph.D. Dissertation.

Re66Se Reddy, D. R. Segmentation of speech sounds. *J. Acous. Soc. Amer. 40* (Aug. 1966) 307-312.

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Re64Ex Reddy, D. R. Experiments on automatic speech recognition by a digital computer. Tech. Report, Stanford University, AI Memo 26, Stanford, CA, 1964.

Abbreviations:
ASSP -- Acoustics, Speech and Signal Processing.
CMUCSD -- Department of Computer Science, Carnegie-Mellon University, Pittsburgh, PA, 15213. (412) 621-2600 x. 141.
IJCAI -- International Joint Conferences on Artificial Intelligence.
JASA -- Journal of the Acoustical Society of America.