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A NON-COGNITIVE FORMAL APPROACH TO
KNOWLEDGE REPRESENTATION IN
ARTIFICIAL INTELLIGENCE

DISSERTATION

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Major, USAF

AFIT/DS/ENG/86J-1

DEPARTMENT OF THE AIR FORCE

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Wright-Patterson Air Force Base, Ohio

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IN ARTIFICIAL INTELLIGENCE

DISSERTATION

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

Jim A. McMannama, B.S., M.S.

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A NON-COGNITIVE FORMAL APPROACH TO KNOWLEDGE REPRESENTATION
IN ARTIFICIAL INTELLIGENCE

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Preface

The purpose of this study was to add formality to knowledge representation in the Artificial Intelligence (AI) field. Because knowledge representations could be considered analogous to abstract data types, I felt that there must be a variety of formal analysis techniques already developed by computer scientists that could be applied directly to my formalization task. In pursuit of this general concept, I found that formal language researchers had developed such a set of techniques. By showing the usefulness of these existing techniques in this dissertation, I feel that AI researchers can now be prevented from "re-inventing the wheel" in their search for formal techniques to use in analyzing knowledge representations.

Because of the numerous articles I reviewed in search of the techniques, I chose only to cite a representative sample within the body of the dissertation. However, my views on the dissertation subject could not help but be swayed by all the articles I did review. Therefore, to provide you with a better understanding of my position, I placed in Appendices A and B my extensive bibliography on formal language theory and AI knowledge representation. I make no claims as to the completeness of the lists.

Literature articles were not the only help I received. I wish to thank my entire advisory committee for the encouragement they provided me, especially when a different approach I had taken failed to produce results. I am particularly indebted to my committee chairman, Prof. Gary B. Lamont, for the ideas that we generated during our weekly brainstorming sessions and for his understanding and guidance during some of the personal tribulations that I experienced during my AFIT tour. Additionally, I wish to thank my office mates, Capt Edward McCall, Capt Timothy Kearns and Capt Charles Matson for the informative interchanges of opinions on my topic.

Because of the extensive literature search that I performed, I wish also to acknowledge the outstanding efforts of the AFIT engineering library staff for their rapid responses to my requests for books and articles from other libraries. Also, many thanks go out to my wife Karyle and my daughters Wendi and Tiffany for the many sacrifices that they made so that I would have sufficient study time. Finally, I want to thank my parents Loren (deceased) and Hilma for the financial and emotional support they provided so that I could obtain my initial college education without which this dissertation could never have been undertaken.

Jim A. McMannama

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Abstract

With the entry of Artificial Intelligence (AI) into real-time applications (e.g. Defense Department's Pilot's Associate Program), a rigorous analysis of AI expert systems is required in order to validate them for operational use. This analysis effort should include the formal mathematical analysis of the individual computer program elements contained within these expert systems. Included in this set of elements are the various knowledge representation schemes used for the knowledge-base.

To satisfy this requirement for analysis of knowledge representations, the techniques of formal language theory are used. A combination of theorems, proofs and problem-solving techniques from formal language theory are employed, either directly or in a modified form, to analyze language equivalents of the more commonly used AI knowledge representations of production rules (excluding working memory or situation data) and semantic networks.

This analysis reveals specific characteristics about these two representations such as their formal language-type, representation set-size, closure properties, special-case equivalences, special-case transformations and special representation-variations. Because of the complexity of formal language theory, many examples are provided to help clarify these characteristics.

By studying several of these characteristics in combination, two major results are identified that affect the use of these two representations. The first result stems from the characteristic that there is a countably infinite number of possible knowledge-languages (the sets of antecedent/consequent words, node-label words and relation-words) that can be contained in either a production-rule or a semantic-network structure. Using this characteristic, no single support-tool or automatic-programming tool can ever be constructed that will be able to handle all possible production-rule or semantic-network variations.

The second result stems from the characteristic that while the set of all finite production-rule languages and the set of all finite semantic-network languages are not equivalent, there are unique subsets of these languages that can be transformed into each other by a single transformation. Using this transformation, the entire set of finite production-rule languages is shown to be able to be stored in and retrieved from some of the finite semantic-network languages. In effect, the semantic-network structure is a viable candidate for a centralized database of knowledge.

A NON-COGNITIVE FORMAL APPROACH TO KNOWLEDGE
REPRESENTATION IN ARTIFICIAL INTELLIGENCE

I. Introduction

Background

One of the oldest subjects of interest to philosophers, linguists, psychologists, etc., is human intelligence. In the past, they have attempted to define intelligence as various collections of observed human behaviors. Based on the characteristics of these behaviors, they proposed theories and models that could generate the same "intelligent" behavior patterns. For example, the behavioral psychologists' stimulus-response pair model is used extensively in their research (1:4).

Because these older models of human intelligence were based on example observations, many questions were raised regarding the ability of the models to accurately simulate all human beings. As advances in medical technology provided increased knowledge about the human brain, these questions of accuracy were handled by expanding the older models to include known brain operations. These more advanced models are known as the neural networks (2). However, the brain operations that are being simulated are still based on nondestructive observations. Therefore,

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these more advanced models are still relying on example
observations and are now at a lower modeling level than was
previously possible.

Intelligent Computers. As these advances in knowledge
about the brain were being made, another technology was
being developed which would significantly impact all of the
models of human intelligence. That was the development of
the digital computer. Various sequential processes that
were thought to generate intelligent behavior patterns could
also be modeled via computer programs. For example,
Newell's and Simon's Logic Theorist model was implemented in
a computer program and studied via that medium (1:3). Of
course, the use of computers assumes that human intelligence
is a logical process.

At the same time these more advanced psychological
models were being studied, a specialty area was developing
which studied computer programs that exhibited "intelligent
behavior": Artificial Intelligence (AI). The psychological
models and the computer program models appeared to come
together when Quillian's computer program model called a
semantic network was classified as a psychological model of
human memory (1:8).

Quillian's tie between psychological models and computer
programs led to the generation of the term "Cognitive
Science." Cognitive Science involves the study of computer
models of human thinking (1:4). Examples of such models
that have been studied to date are given in Table I.

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Table I. Cognitive Models (1:Section XI)

```
Problem Solvers: General Problem
                 Solver.

                 Opportunistic
                 Problem Solver.

Memory Models: Semantic Network

               Human Associative
               Memory.

               MEMOD.

               ACT.

Learning:  Elementary Perceiver
           and Memorizer (EPAM).

Belief Systems: PARRY.
```

An outstanding characteristic of these cognitive models is that they are developed from a macro-level point of view. That is, cognitive models use high level abstract definitions of the internal brain structure and perform functions based on that definition. For example, Figure 1 shows a semantic network representation of the relationship of Golf_Bag to Bags and Bags to Containers. The semantic-network model uses an abstraction of nodes and links to model how the brain stores information. How an individual symbol, node or link is actually stored within memory is not of direct importance to the model definition. Only the node/link string names and the existence of link ties are of concern (see the subsection on semantic networks in Section I for more details on this model).
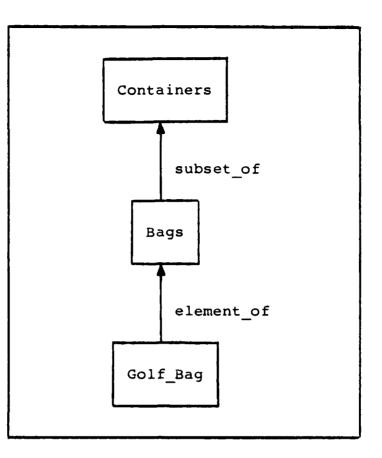
Figure 1. Semantic Network Bag Model

In contrast, neural-network models operate at the micro-level by using various interconnection patterns of neurons to model functions. For example, the word Bags could be modeled in a neural network as shown in Figure 2. Each letter symbol is modeled by a single neuron. To operate, the letter-neurons each fire when stimulated (e.g. reading the letters). By receiving the proper electrical inputs, a word-neuron at a second level is then stimulated and fires. This word-neuron could then be the same word, Bags, used in the semantic network of Figure 1.

From Figure 1 and Figure 2, interesting analogies can be drawn. One is that the micro-level model is analogous to
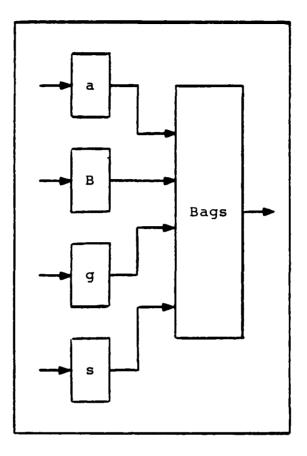
Figure 2. Neural Network Word-Model

the hidden implementation details of an abstract data type

(3). Another is that the macro-level models which deal with

memory modeling (see Table I) are analogous to atomic

abstract data type constructs. Another analogy is that any

macro-level model which uses a memory model is analogous to

an object level computer program (4). These analogies are

not unexpected since cognitive models have been implemented

on computers.

Artificial Intelligence Definition. Because of this

relationship between AI and psychology, extremists' views

have caused difficulties in defining artificial intelli-

gence. Some argue, without proof, that these two fields are

indeed equivalent. That is, humans are equivalent to logic devices. Others argue that the fields are entirely unrelated because human creativity does not always follow a logical path. While these different positions exist, the proponents of each position are really arguing the existence of a single model which would account for human intelligence.

To keep from being involved in the issues surrounding the existence of a single human intelligence model, a definition of AI which handles both extremes is used. While this definition is a combination of ideas from the AI handbook (2; 5), it is not so stated within the body of that text. The definition of AI used here is as follows:

Definition 1.01: AI is the study of encoding human knowledge into abstract data types and the development of computer procedures to manipulate the encoded knowledge into an output form which, when decoded, exhibits aspects of intelligent human behavior.

This definition encompasses the views of both sets of extremists as a result of the encoding of the knowledge and the decoding of the output. If humans are logical devices, then the encoding/decoding is a moot point. If not, then the level of the behavior exhibited rests entirely on the encoding/decoding external to the machine.

In addition, this definition is capable of encompassing the specialty areas of planning, theorem proving, problem

solving, learning, knowledge representation, robotics, pattern recognition and expert systems within the field of AI research. For example, the manipulating procedures identified in Definition 1.01 can be considered as the procedures used in the problem solving models as given in Table I.

Formal Language Theory. Besides these relationships among AI, psychology and computer programs, there is another field where AI associations are strong: formal language theory. To better understand these ties, some background on formal language theory is presented. Because formal language theory is well developed, only a very limited background is given. The reader is referred to text books such as Revesz (6) or Ginsburg (7) for detailed background and to Appendix A for additional formal language references.

Definitions and Characteristics. Formal language theory received attention when Chomsky proposed his four types of grammar (8). In general, a grammar is defined as follows (6:2):

Definition 1.02: A generative grammar is an ordered four-tuple, G:=(NT,T,S,P). NT is a finite set of nonterminal symbols. T is a finite set of terminal symbols (alphabet). S is a special nonterminal start symbol subset contained in NT. P is a set of Post rewrite production-rules of the form a->b.

Each production rule in P takes a single nonterminal symbol and rewrites it into a new combination of terminal and/or nonterminal symbols. The production rules are applied nondeterministically beginning with the start symbol and ending when the string (word) being generated contains only terminal symbols. A single grammar is capable of generating all the possible words in a language.

Chomsky's four types of grammar are defined via variations of their production rules.

Definition 1.03: A type-0 grammar, $G(0):=(NT,T,S,P)$, is a generative grammar which contains unrestricted production rules of the form a->b where $a \in (NT \cup T)^{+}$ and $b \in (NT \cup T)^{*}$. The "+" and "*" indicate the Kleene closure of the elements of the indicated set without the empty word and with the empty word, respectively (8:142).

Definition 1.04: A type-1 grammar (context-sensitive), $G(1):=(NT,T,S,P)$, is a type 0 grammar with the added restriction that each string produced after applying a single production rule must be greater than or equal to the length of the string before the application of that rule. That is, mjv->mkv where $j \in NT$, $k \in (NT \cup T)^{+}$ and $m,v \in (NT \cup T)^{*}$ (8:142).

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Definition 1.05: A type-2 grammar (context-free),

G(2):=(NT,T,S,P), is a type 1 grammar which
has only productions of the form j->k where
$j \in NT$ and $k \in (NT \cup T)^+$ (8:142).

Definition 1.06: A type-3 grammar (regular),

G(3):=(NT,T,S,P), is a type 2 grammar which
has all production rules in one of two
forms: j->pn or j->p where $j,n \in NT$ and
$p \in T$ (8:142).

The inheritance of restrictions shown explicitly in the
previous definitions of the grammar-types was proven by
Chomsky:

Theorem 1.01: Type $0 \supset$ Type $1 \supset$ Type $2 \supset$ Type 3 (8:152).

Chomsky also proved that the type-0 languages are
equivalent to recursively enumerable sets (the set of
languages accepted by Turing machines). Chomsky and others
continued research and showed that type-1 languages are a
subset of the recursive sets. Also, type-2 languages were
proven to be those languages accepted by a nondeterministic,
finite machine with one pushdown-store. In addition, type-3
languages were found to be regular sets (languages accepted
by a finite automaton) (9:43).

Languages and Grammars. From these initial defini-
tions and characteristics, language theory research spread
out in several directions. In one direction, many languages
were defined and studied. Examples include real-time
languages (10), one-way list-storage languages (11), time-

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bounded languages (12), tally languages (13), counter languages (14), left-derivation bounded languages (15) and languages constructed from the sentential forms (interim words containing both terminals and nonterminals) called Szilard languages (16).

One of the most studied classes of languages is the regulated languages. These languages use a context-free grammar along with a set of rules that control when a specific rewrite production-rule can be applied. These languages are part of the set used for compiler applications. Examples of these languages include those generated by programmed grammars (17), scattered context grammars (18), attribute grammars (19) and indexed grammars (20).

In another research direction, grammars were studied abstractly. Some examples are grammar schemata (21), compound grammars (22) and grammar forms (23).

Not being satisfied with studying individual varieties of languages, language researchers found certain common characteristics existed among different languages (e.g. closure under intersection with regular sets). These findings led Ginsburg and Greibach to develop the concept of Abstract Families of Languages (AFL) (24). An AFL is a collection of sets of finite words (languages) each of which was generated from some finite alphabet. By definition, an AFL is closed under union, product, empty-word free Kleene closure, inverse homomorphism, empty-word free homomorphism and intersection with regular sets.

One of the unique characteristics of AFLs is that the contained languages can be generated from different alphabets by different types of grammars. Note that regular sets, context-free languages, context-sensitive languages, recursive sets and type-∅ languages, all over the same alphabet, each form an AFL by itself (24).

While an AFL is restricted to the six closures specified, the study of AFLs, in general, is not bounded by those closures. For example, a full-AFL is one which is closed under all possible homomorphisms (25). An additional example is the pre-AFL where the member languages do not meet some of the six closure properties (26). On the other hand, a super-AFL is a full-AFL which exhibits additional closure relationships beyond the six specified (25).

While AFLs contain many languages, special families exist where the theorist only has to study a single language in order to obtain the characteristics of the entire family: principal-AFLs (27). In these families, a single language exists from which all other members can be obtained by applying the six closure operations on this "base" language (24). The closure relationships pass the characteristics of the base language to all descendants.

In addition to studying specific families of languages researchers investigated hierarchies of languages. For example, ordering languages by the time needed to accept them forms a language hierarchy (28). A different language hierarchy is formed by ordering the languages based on the

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number of nonterminal symbols allowed on the right hand side of the rewrite production-rules (29).

Perhaps one of the most important language characteristics that AFL theory has yielded is the existence of infinite hierarchies of families of languages. For example, an infinite hierarchy of context-sensitive AFLs has been shown to exist (30). Another infinite hierarchy of AFLs can be generated by applying the substitution operator to any full-AFL that is not closed under substitution (25). Even infinite hierarchies of AFLs, each of which is an infinite hierarchy of AFLs, has been shown to exist (31).

Language Problems. Formal language theory involves more than the study of different varieties of languages. It also involves the study of the solvability of language related problems. For example, given two type-3 grammars, it is possible to determine if they generate the same language without having to enumerate all the words in each language and compare them (weak equivalence). However, for type-2 grammars, this is not possible (unsolvable)(9:54-67).

Since some cases of weak equivalence were found to be unsolvable, variations on the equivalence definition were made in the search for solvable equivalence. One example variation for language equivalence is structural equivalence. Structural equivalence exists when languages use the same derivational tree structure (32). An example variation for grammar equivalence is transformational equivalence. There, grammars which are able to be translated into one

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another by application of homomorphisms are considered equivalent (33).

Other investigations involved the study of the solvability of the word membership problem. That is, proving that a word belongs to a given language. For example, given a word and a grammar, it is unsolvable for any type-0 grammar whether or not the word is in the language generated by the grammar (9:63). The word membership problem, however, is solvable for type-1 grammars (9:54).

Because the existence of these unsolvable problems caused concern for those investigating using languages to model other problems, language theorists searched for special classes of languages where these problems could be solved. For example, context-free grammars which have rewrite production-rules that can be used either forward or backward without changing the set of sentential forms (interim words) have a solvable equivalence problem (34). A similar result was proven for languages generated by parenthesis grammars (35).

Studying language problems as a theoretical curiosity did not satisfy language theorists. Because of the symbolic nature of languages, some theorists teamed with others from different academic fields to attempt to solve problems in those fields by using formal language theory techniques. For example, by using rewrite production-rules in parallel, biological growth could be modeled and studied (36). In another field, graphs were studied via graph grammars (37).

In another example, solutions to mathematical equations were studied via formal language representations (38). A further example is investigation of computer networks and time sharing systems via formal language theory (39).

Relationship of AI and Formal Languages. Given this background on formal language theory, the relationships of AI and formal languages can now be approached. These relationships currently can only be indicated via example cases because no supporting proofs exist in the literature which show that the relationship of formal languages and AI exists for all the AI systems. However, the mere existence of these example cases show that some formal relationships may exist.

To keep from getting involved in the details of these example applications, only a short description of the informal ties between the AI system and formal languages is given initially. Also, a few examples are provided to motivate the development of formal relationships. The reader is referred to the references in Appendix B for additional examples. For more details on the AI systems mentioned, the reader is referred to the AI handbook (2; 5).

In this set of example applications, there are several cases where the tie between AI production systems and formal languages can be seen. One example is the use by Vere of a type-0 grammar to develop a relational production system (40). Another example is the technique used to infer the

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control structure for a programmed grammar production system (41).

In addition to these AI production systems, formal languages have several direct relationships with AI learning systems. For example, grammatical inference is considered to be one of the tasks performed by learning machines (42). Formal language theory was also used to prove the nonexistence of an ideal learning machine (43). A further example is a learning robotic system which uses a hierarchy of grammars between the man-machine interface and the robot (44).

Of all the ties between AI systems and formal languages, the relationship between pattern recognition and language theory is the best known. The most familiar example is the use of Web grammars to generate patterns for picture recognition (45). In another case, Attributed grammars have been used in shape recognition (46). A further example is the Plex languages. They were developed to model physical systems like printed characters and circuit diagrams (47).

Recognizing these relationships between AI and formal languages, many questions arise regarding the models of human intelligence that AI computer programs simulate. Are the proposed human intelligence models a sentence in some higher level programming language or an entire programming language themselves? Are there countably infinite versions of a single model? Does a countably infinite number of unique human intelligence models exist? Can any model of

human intelligence be proven to truly represent intelligent behavior?

While answers to these questions may be debated for many years to come, one component of these models can be investigated in regard to these questions. That component is the form of knowledge representation used to simulate the human storage of knowledge.

Individual Knowledge Representations. In general, knowledge representations can be considered as abstract data types (3). This characteristic can be identified from the definition of AI (see Definition 1.01). The first part of the AI definition involves encoding human knowledge into abstract data types (standard computer science practice for program data). In the past, AI knowledge representations have been defined as a combination of data structures and interpretative procedures that, if used in the right way in a program, will lead to "knowledgeable" behavior (5). Depending on where one assumes the split to occur between the main program's control procedures and the data structure's interpretative procedures, the abstract data types referred to in the AI definition can be considered to coincide with the definition of knowledge representation. The results of this dissertation are based in part on this separation.

Because of this abstract nature of AI knowledge representations, there is a wide variety of abstract data types that compete for membership in the class of AI knowledge

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representations. In general, a representation is referred
to by the name of its underlying data structure and the
data-structure accessing procedures are usually called the
inference mechanisms. In this subsection, examples of the
more popular individual representations are presented. The
discussion on each representation contains, in order,
descriptions of the representation's structure, the
applicable inference mechanism and a specific example. For
the sake of brevity, only a limited description of each
representation will be provided. Cited references can
provide the reader more detailed descriptions. For more
information regarding such areas as applications,
advantages/disadvantages, variations, etc., the reader is
referred to reference 5 and to the references contained in
Appendix B.

<u>Predicate Calculus</u>. Logic has been one of the
strongest foundations for philosophers over hundreds of
years. This strength comes from the consistency that logic
provides as a formal mathematical system. These same
characteristics lead AI researchers to consider logic as a
knowledge representation scheme.

Of all the different variations of logic (e.g. modal,
intuitionist, predicate), AI researchers selected predicate
calculus as a candidate representation. Because of the
hierarchy of predicate-calculus types (e.g. propositional
calculus, quantified propositional calculus, equality
calculus, first-order predicate calculus, second-order

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predicate calculus), the name "predicate calculus" is insufficient to describe the representation (9: Chapter 2). The actual representation uses first-order predicate calculus with equality.

The primary reason that first-order predicate calculus was chosen is that Church proved that the validity of first-order predicate calculus statements is partially solvable while for second-order predicate calculus statements it is not solvable (48). This means that algorithms exist which will verify that true first-order statements are indeed true without having to generate all possible true statements.

Secondary reasons for the selection of first-order calculus involve the "expressibility" of the representation. The n-ary function constants provide the capability to represent more than just true/false knowledge. For example, the function Father(Joe) can return the name John. Equality provides the capability for function results to be tested as well as the normal true/false values. For example, the test Father(Joe)=Bill? returns false.

As noted previously, a knowledge representation scheme's usefulness comes from the ability to retrieve information from the structure via the inference mechanisms. Robinson's computer algorithm based on the resolution principle provides the primary inference mechanism for first-order predicate calculus (49). His algorithm applies individual procedures that generate new true statements from previous

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```
(Vx)[Clubmember(x)=>Fathername(John,Father(x))]
```

Figure 3. Predicate Calculus Example

ones in an ordered manner. This ordered approach provides a
capability to obtain a solution to a query without gener-
ating all true statements. However, Robinson's approach is
still combinatorial in nature so the number of true state-
ments the algorithm generates is not necessarily the
absolute minimum.

Figure 3 contains an example of the following statement
in first-order predicate calculus: all members of the club
have a father named John. The variable x can represent a
club member name or ID number. The predicate constant,
Fathername, returns true if the function, Father, returns
the name John. The equality test is embedded within the
Fathername predicate.

Production Rules. One of the most influential
developments in mathematics of this century was the
production-rule system introduced by Post (50). Moreover,
psychologists had been modeling human actions as a series of
stimulus-reaction pairs. Recognizing the relationship of
Post's system to these models, Newell and Simon developed
production-rule models of human intelligence (51).

In these rule-models, a production rule consists of an
antecedent-consequent pair. This pair is tied together in
the form of an implication statement. That is, if the

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antecedent is true then the consequent is true. The

antecedent-consequent pair may contain declarative

knowledge. However, the pair is not restricted to that type

of knowledge. The consequent part may be complex proce-

dures. With the added concept of "procedural attachment,"

the antecedent part may also entail execution of a procedure

before determining its truth value.

Even though knowledge is represented in a logical

formalism for which a limited set of the predicate calculus

inference mechanisms would apply, production-rule inference

mechanisms are just a restricted form of "generate and test"

algorithms. That is, instead of generating a rule, these

algorithms search the already established rule-set and test

for rules which have their antecedent condition met. The

most popular inference mechanisms are backward-chained and

forward-chained search (5).

One of the unique features of production-rule systems is

the close tie the individual rules have with the working

memory during operation. Production rules only represent

conditions that could be true about a given situation. For

example, the set of production rules may contain one rule

that has the consequent that a fact is true while another

rule may have the consequent that the same fact is false.

To determine the correct answer for a given situation, a

production-rule system has to make use of a working memory

that contains information unique to the particular situ-

ation. That is, the set of production rules alone may not

```
                    ┌─────────────────┐
          ┌────────▶│  User Interface │◀────────┐
          │         └─────────────────┘         │
          │                  │                  │
          │                  ▼                  │
          │         ┌─────────────────┐         │
          │    ┌────│ Situation Data  │         │
          │    │    └─────────────────┘         │
  ┌───────────▼─┐            ▲                  │
  │ Explanation │            │                  │
  └─────────────┘            ▼                  │
          ▲    ▲    ┌─────────────────┐         │
          │    └────│    Control      │◀────────┘
          │         │   Structure     │
          │         └─────────────────┘
          │                  ▲
          │                  │
          │         ┌─────────────────┐
          └─────────│ Knowledge-Base  │
                    └─────────────────┘

              Arrows indicate
              information flow.

  Total database contains
  situation data and knowledge-base.
```
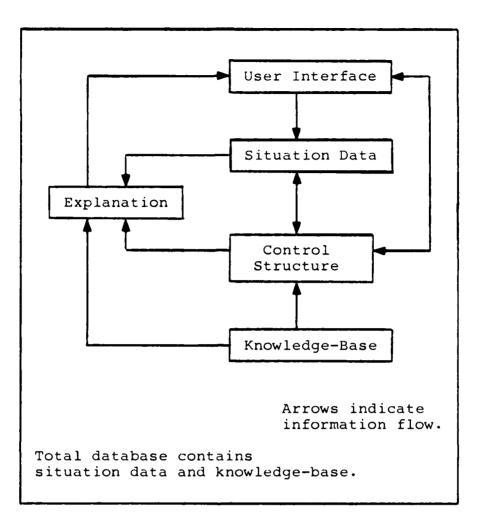
Figure 4.   Expert System Functional Diagram

represent the complete knowledge about an event. A

production-rule system has to use a working memory in

conjunction with the production rules to reach a conclusion.

This working memory has to contain the information needed to

determine which antecedent is true so that the correct

consequent can be applied for the given situation.

To better understand the relationship of this working

memory in a production-rule system, Figure 4 shows a

functional diagram of an expert system. The production

rules reside in the knowledge-base and the working memory is

```
If (?patient fever>104) and
   (situation data contains patient lab results)
  Then
   (assign lab results to patient) and
   (call rule 37)
```

Figure 5. Production Rule Example

contained in the situation data. Therefore, as the expert
system operates, the control structure uses both the pro-
duction rules and the situation data to eventually reach a
conclusion.

Because of this close tie with the working memory,
individual production rules are allowed to interact with the
working memory. This interaction can involve viewing the
contents of working memory as an entity and modifying the
contents of the memory as needed.

Figure 5 contains an example production-rule represen-
tation for a medical production-rule system. While the rule
does not represent a simple English language statement, it
does reflect the tie of the working memory to the production
rules as well as the complexity of the rules. In the first
antecedent clause, the unit variable "?patient" allows for
the use of the rule with a specific patient's name. In some
implementations the fever value could be an attribute
assigned to the specific patient's name. Then, the
"greater-than" computation could be accomplished by a
procedure call that retrieves the fever attribute-value pair
and performs the greater-than test. The second antecedent

clause allows the situation data to be searched for the list of lab results. This list can be entered separately by lab technicians that are not directly involved in the execution of the overall production system.

Once these two antecedent clauses are determined to be true, the consequent is activated. The first clause of the consequent assigns the lab results as attribute-value pairs to the patient's name. This is actually a procedure call. Then, the second clause directs the inference algorithm to select the next rule to be tested.

Semantic Networks. The semantic memory model (see Figure 6) developed by Quillian was an attempt to handle word meaning in a computer by using a hierarchy of syntax pointers similar to a dictionary (52). The model was made up of nodes connected by directed arcs (associative links). The nodes consisted of two kinds: type (TP) and token (TK). A "type" node contained a single word whose definition was obtained by following the associative links attached to it to other word nodes. In memory, only a single type-node was assigned to each word. In Figure 6, the type-node TP1 represents the definition of word A. By following the links, two other nodes are reached that contain words B and C. These two additional words provide the definition of word A.

The "token" node was a place holder for words that were used in the definition of another word. From a given type-node, associative links were connected to token-nodes.

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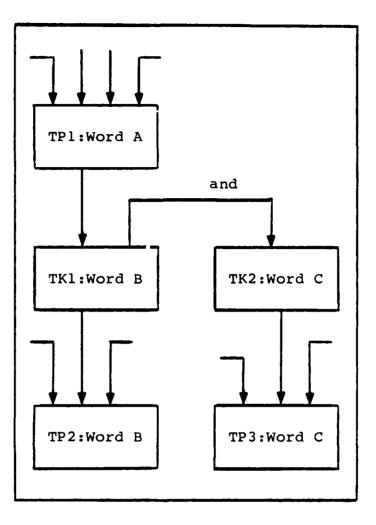
Figure 6. Quillian's Semantic Memory

To keep from reproducing the type-node and all its links
every time a word was used in a definition, a token-node was
used which pointed to the single type-node for this embedded
word.   Therefore, there may be many common named token-nodes
throughout memory but each points only to its respective,
single, type-node.   In Figure 6, nodes TK1 and TK2 represent
the token-nodes for words B and C.   By following the links
leaving these token-nodes, their type-nodes, TP2 and TP3,
can be reached.

The associative links that interconnected the nodes handled a limited set of primitive relations among the nodes. These included set/subset, a form of attribute-value representation, the token-to-type pointer, conjunction and disjunction. More complex relationships between two nodes were handled by dual associative links with the relationship name residing in the node.

The inference procedures associated with the network stem from Quillian's spreading activation procedure which "drew" inferences about two concepts (words). His procedure is based on the inheritance capability of the network. The procedure "activated" the two type-nodes representing the concepts. Their links were then followed to other nodes. These nodes were activated and their links were followed. The process was repeated until a common node was activated by following paths from both concept-nodes. The common node then described the connection between the original concepts.

From this beginning, the knowledge representation of a semantic network evolved (53). Nodes now represent words, concepts, objects, etc. With the advent of procedural attachment, the nodes can represent calls to selected procedures. The associative links now represent many complex relationships (54).

In the simplest form, the inference procedures for a semantic network operate on a basic matching routine. The routine constructs a data structure that represents the information being sought. Then, the semantic network is

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Clyde → is-a → Elephant → is-a → Mammal

Joe → is-a → (Elephant)

has_color

Ehas_color

White   Gray
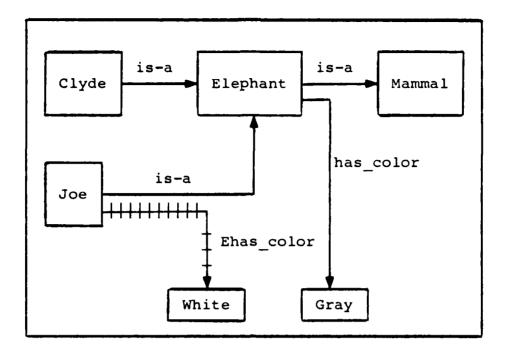
Figure 7. Semantic Network Example

searched for a matching structure and the information is retrieved. Exact matches are not necessary since the inheritance capability can be used to locate common information that may be stored at a higher level in the network.

Unlike the production rules, a semantic network contains information that is always true independent of a given event. The working memory (situation data of Figure 4) provides only a local storage function for the query and its data structure equivalent. In effect, a semantic-network representation contains all the true information about the world that it represents. On the other hand, production rules are usually combined with the situation data to generate world truths.

Figure 7 contains an example of a semantic network representation of the statement: Clyde is a gray elephant,

Joe is a white elephant and both are mammals. The associative links "is_a" show the relationship of Joe and Clyde to elephants and the inherited relationship of mammals. The "has_color" link shows the normal color of elephants. The "Ehas_color" link shows the exception link indicating that Joe is white instead of gray. In the operation of a semantic-network system, the exception link would dominate the inherited has_color link for a query involving Joe.

Frames. Frames were originally proposed quite informally by Minsky to handle the evidence that people use previous experience to interpret new situations. To use Minsky's own words (55:212):

> A frame is a data-structure for representing a stereotyped situation, like being in a certain kind of living room, or going to a child's birthday party.

For each generic type of frame (room, party, automobile), slots exist which are filled either with pointers to other frames, terminal data or default data (see Figure 8). The frame may even contain information about how to use it or what to do if it does not exactly fit the situation. Essentially, frames are tables of relations where the values of the attributes are either explicit or implicit.

The inference mechanisms are basically pattern matching operations. A frame is selected which matches the input requested information. In case no exact match is possible, a metric such as the maximum number of slots matched may be used so that at least a related but not necessarily correct

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frame may be found. Using the information contained within the selected frame (e.g. sequence to follow, inheritance pointers, defaults, procedural attachment), the answer to a request can then be generated.

Figure 8 contains an example frame representation of the statement: Joe lives in a two-story frame house at 955 Mann, Larned, Kansas and the house has 1000 square feet and cost $50,000. To incorporate this information into the frame-system, a house-frame would be selected and filled in as shown. Since there is no missing data in this example, the only default occurring is the ancestor slot in the house-frame. The square foot cost slot is a procedure call which can compute the value if it is needed. See reference 56 for several examples of frame-systems shown pictorially.

Scripts. In the Minsky paper on frames, the work of Schank and Abelson was characterized in relationship to frames (55). In reaction to this characterization, Schank and Abelson countered that the frame description was too general for use. They proposed that their work be considered as a specialization of a frame idea. They called their approach "scripts" (57).

Scripts define a sequence of events which normally occur in association with another event. The idea is that if a given event can be predicted with regularity, only the variations from the norm need be identified in a definition of the event. Therefore, the stored information is a

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```
+--------------------------------------------------+
|  +--------------------------------------------+  |
|  |                                            |  |
|  |  Title: Joe's house                        |  |
|  |                                            |  |
|  |  Ancestor: (Default=none)                  |  |
|  |                                            |  |
|  |  Location: Pointer to Joe's                |  |
|  |               address-frame                |  |
|  |                                            |  |
|  |  Type: Pointer to Joe's                    |  |
|  |          house-type frame                  |  |
|  |                                            |  |
|  +--------------------------------------------+  |
|                                                  |
|     +-----------------------------------------+  |
|     |                                         |  |
|     |  Title: Joe's address                   |  |
|     |                                         |  |
|     |  Ancestor: Joe's house                  |  |
|     |                                         |  |
|     |  Street Number: 955                     |  |
|     |                                         |  |
|     |  Street name: Mann                      |  |
|     |                                         |  |
|     |  Town Name: Larned                      |  |
|     |                                         |  |
|     |  State: Kansas                          |  |
|     |                                         |  |
|     +-----------------------------------------+  |
|                                                  |
|  +--------------------------------------------+  |
|  |                                            |  |
|  |  Title: Joe's house-type                   |  |
|  |                                            |  |
|  |  Ancestor: Joe's house                     |  |
|  |                                            |  |
|  |  Construction: Wood frame                  |  |
|  |                                            |  |
|  |  Stories: 2                                |  |
|  |                                            |  |
|  |  Size: 1000                                |  |
|  |                                            |  |
|  |  Cost: 50000                               |  |
|  |                                            |  |
|  |  Square foot cost: (compute)               |  |
|  |                                            |  |
|  +--------------------------------------------+  |
+--------------------------------------------------+
```

Figure 8. Frame Representation Example

generic sequence of events which contain certain default slots for variations.

The inference mechanisms for scripts are the same as for frames for the initial frame selection. However, once the frame is selected, the system remains within that frame for all information retrievals. A sequence of events is followed to obtain the requested information.

The restaurant script is the most famous example of this knowledge representation scheme. Figure 9 contains a limited version of this script. Even though this is a simple example, statements like "Joe ate a hamburger in the restaurant" will instantiate the script. Then questions like "did Joe pay the check?" can be answered by investigating the departing sequence contained in the script. The defaults in the departing sequence allow for a case when the food is bad and Joe refused to pay the check.

Conceptual Dependency. As with all the knowledge representation approaches, the goal is to represent knowledge in a machine usable form. In addition to the machine-form, the question arises as to the form of the knowledge itself. Since knowledge is usually described by "natural" language, initial research into the primitive structure of natural language was conducted by Schank and Tesler (58). From this early work, Schank developed a conjecture known as "conceptual dependency" (59).

Schank's conjecture was that the "meaning" obtained from a natural language statement can be represented

```
Title: Restaurant Script

Customer: (default=customer)

Players: Waitress, Chef,
         Cashier

Entry: 1. Customer enters
       2. Customer waits to
          be seated
       3. Customer sits down
       4. Waitress gives
          customer a menu

Order: 1. Waitress arrives to
          take order
       2. Customer orders
          (default=hamburger)

Eating: 1. Waitress delivers
           order
        2. Customer eats

Depart: 1. Waitress brings
           check
        2. (default=customer
           leaves tip)
        3. (default=customer
           pays cashier)
        4. Customer leaves
```

Figure 9. Script Example

(defined) by a primitive set of actors (ACTs) acting on the

objects in the statement. Hence, equivalent sentences would

translate into the same combination of ACTs.

While the number of ACTs is not fixed, the original

primitive set consisted of eleven members. Five of the ACTs

were associated with physical actions: PROPEL, MOVE, INGEST,

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```
            p            O            D   ┌──►window
        I◄──►PROPEL◄──ball◄───┤
                                          └─◄I
```
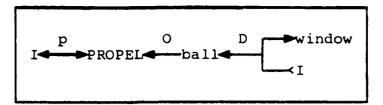
Figure 10. Conceptual Dependency Example (60)

EXPEL AND GRASP. Two other ACTs dealt with mental actions:

MTRANS and MBUILD. Another two ACTs handled the sight and

sound senses: ATTEND and SPEAK. The last two ACTs covered

physical and abstract state changes: PTRANS and ATRANS.

Later extensions added planning, script and goal

actors (60).

The literature does not clearly differentiate between

inference mechanisms in general and those used for a spe-

cific natural language understanding system. Therefore, the

mechanisms are introduced via the operation of a system

known as MARGIE (60). In general, natural language state-

ments are translated into the primitive conceptual

dependency structure. Then, applying some sixteen different

classes of inferences, conclusions are obtained which are

either supported by existing facts in the structure or

cannot be disproved by facts already in the structure.

Figure 10 contains an example of a conceptual dependency

representation of the statement: I threw the ball at the

window. The double arrow denotes a mutual dependency

between actor and action. The p indicates past tense. The

O means the object of the act. The arrow under the O points

to the act. The D combined with the "C" shaped arrow

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denotes the physical direction of the action; from I to window. The arrow under the D points to the object that is involved in the act.

Combined Representations. AI researchers have found that using only a single knowledge representation, such as one of those described previously, in complex systems is not always advantageous for a given application. For example, a representation may be able to represent all the domain knowledge (Representation Adequacy) but be unable to help direct the attention of the inference mechanism during system operation (Inferential Efficiency) (61:201-202). To try to overcome these types of performance problems, researchers have investigated combining several knowledge representations to gain the advantages each representation can offer. Several examples follow.

A system which combines semantic networks and frames was investigated by Hayes (62). The frame was used as a high-level description of a low-level semantic network. Although more complex in this application, the frame can be seen to represent the "planes" proposed by Quillian (52). Referring to Figure 6, in each type-word plane, the token-words used to define the type-word are obtained by following the links within the plane (filled terminal slots in this combined semantic-network/frame structure). For the token-word nodes, pointers have to be followed to their planes for definition (pointer slots).

In addition to semantic networks, frames have also been combined with predicate calculus. For example, the Krypton representation uses a frame-structure to hold terms that are organized taxonomically (63). Then, first-order sentences are applied to obtain the predicates from the frame-representation. In another example, Charniak proposes a representation that incorporates both first-order sentences and predicates within a frame-structure (64).

Combined representations are not restricted to just the dual systems mentioned previously. For example, a combination of semantic networks, frames and procedures has been used as a method for representing knowledge in an instructional system (65). The frame involves the overall subject while the semantic network shows the relationship of topics. The procedural aspects handle the control of such items as questions, frame control, etc.

In addition to frames and semantic networks, procedural knowledge has also been combined with production rules. For example, a scheme for incorporating procedural knowledge within a production-rule system has been proposed which allows the rules to remain independent of each other (66). A production system can represent the procedural sequences by incorporating the sequences into rules that call rules. That is, the consequent of each rule performs a step and then calls the next rule in the sequence. However, this scheme proposes to use a Recursive Transition Network (RTN)

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for the sequencing portions so that the rules remain independent of each other (56:169-170).

Knowledge Representation Relationships. In addition to combining representations, researchers have investigated mapping one scheme into another in search of equivalent representations. There are several reasons that researchers search for equivalence. One reason is they want to show consistency of various representations by mapping them into predicate calculus. Another reason is they want to show that a given representation can "express" the same knowledge as other representations. A further reason is they want to convert one representation into another form so that the advantages of various representations can be used when the particular problem-solving situation warrants. This search for equivalence resulted in the controversial procedural versus declarative knowledge issue (67). While that issue was never resolved, the work involved in attempting to show equivalence of various schemes provides insight into the knowledge representation approaches. Some examples of these mapping efforts follow:

In the previous subsection on individual knowledge representations, the definition of knowledge representation was shown to be analogous to an Abstract Data Type (ADT). While several approaches have attempted to provide ADT definitions for knowledge representations, the most complete one was the semantic network proposed by Dilger and Womann

(68). Their definition required 35 generic axioms to describe an entire abstract network.

Abstract data types were not the only schemes investigated. One mapping that generated the most interest was translating a representation into the predicate calculus scheme. For example, using the KRL-∅ frame-language, Hayes provided a translation of KRL-∅ frames into predicate calculus (69). In another example, Simmons and Bruce developed an algorithm which converts a version of a semantic network into predicate calculus (70).

Predicate calculus formulations were also translated into other representations. For example, the combined work of Sandewall and Hendrix provided an approach to translate predicate calculus into a special form of semantic networks called a partitioned semantic network (71; 72). Sandewall provided the individual clause relationships while Hendrix developed the quantification relationship into a partitioned semantic network.

Hendrix's partitioned semantic network was also involved with translations of production rules. For example, Duda and others translated production rules into a partitioned semantic network (73).

Representations were also translated into production rules. For example, Rychener implemented unique frames via production rules in his Instructable PMS Language system (74). As a concluding example, frames can be used to

implement scripts. This relationship was pointed out by Minsky in his original definition of frames (55).

The Problem

From this extensive background research on formal language theory and knowledge representations, one major conclusion can be reached. The conclusion is that given all the research heretofore performed by all the philosophers, psychologists, linguists, computer scientists, etc., there still does not exist an acceptable model for human intelligence. Because a human model hinges on our ability to nondestructively investigate the internal workings of a living human being, there are risks that a true model of human intelligence may never be found.

The same risk is passed down to the cognitive scientists in two forms. First, there is a risk that the human cannot be simulated by a computer program. Second, assuming that a computer model exists, there is a risk that it may never be found (see Section IX for more details on these risks).

Because of this lack of a model of human intelligence, there still is no acceptable theory of knowledge representation (5). From the higher level theories of those like Bobrow (75) and Newell (76), through the individual schemes already described previously, no single approach has been found which will handle intelligent tasks. However, knowledge representation research still continues.

Problem Background. As with any computer simulation
task where the underlying model is unknown, research on
knowledge representations involves the development of
experimental versions. These versions will be implemented,
evaluated, revised, re-implemented, re-evaluated, etc.
Finally, when a representation is actually implemented in an
operational system, the selected version will need to be
formalized and validated as a general representation scheme.

For a given representation, this validation effort
includes providing detailed definition of the representa-
tion, determining the scheme's limitations, identifying its
computational efficiencies, investigating its relationships
with other representations, etc. However, this does not
include verification of the model's applicability to humans.
The elusive nature of the human model prevents the gener-
ation of the necessary verification procedures.

With the AI field's entry into actual real-time applica-
tions (e.g. Defense Department's Pilot's Associate Program),
knowledge representations are requiring a rigorous evalu-
ation stage. Without the backing of detailed analyses,
there are high risks in selecting an acceptable representa-
tion for a real-time application. As an example of these
risks, a representation could be selected that can only
handle a special set of knowledge. But, as the system using
this representation ages, new knowledge has to be added to
the representation in order to keep the overall system
current. When the new knowledge is attempted to be added,

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it may be the case that the representation cannot accommodate all the new information efficiently. In the extreme case, the modified system may no longer be able to operate within the necessary time constraints. This could force a complete redesign of the system including selection of a different knowledge representation (61:201-202).

Some of these real-time applications involve expert systems. Associated risks involve the obtaining of the expert's knowledge in a form that can be properly implemented in several knowledge representations. Without supporting comparison analyses, there is a risk that the knowledge gained from an expert may be stored in a form that cannot be effectively translated into other knowledge representations. If this is the case, there is a risk that the particular storage form may only be useful in a limited number (if any) of real-time applications.

While these examples of risks point out the negative aspects of not performing the needed analyses, there are positive side effects that can occur from such analyses. For example, the comparison analysis may reveal the existence of a translation algorithm which could be used to automate the transformation between knowledge representations.

Problem Statement. Even though knowledge representation researchers recognizes this need for rigorous evaluation, they still have not taken the necessary and sufficient steps towards defining, analyzing and comparing knowledge repre-

sentations. Probably the most critical support for the problem statement is that there are no acceptable formal definitions for most of the common knowledge representation schemes. Except for predicate calculus, the individual knowledge representations previously described are not rigorously defined. Because of this lack of definitions, the authors of many published articles begin by providing their own definition of the original representation that they used as the basis for developing their specific representation variant (77; 78). This lack of formal definition has led to the generation of so many variations of these common schemes that it has become difficult to determine where the variation starts and the original definition ends. For example, Brachman addresses the definition issue for semantic networks in reference 79. In the case of production rules, Davis and King point out that the variations have become more an issue of style than differences (80).

An additional support for the problem statement is that while the literature abounds with articles on knowledge representation applications, the majority of these articles fail to present any supporting analysis (see Appendix B for references). Even where some analysis has been accomplished, the results are often in a form that is not compatible for comparisons with the results of other analyses (81; 82). Furthermore, articles identifying and analyzing representation models which failed entirely are notably absent.

Further support for the problem statement is that there is no acceptable common approach for comparing representations. In addition to mapping between representations, there are other approaches for comparing representations such as constructing "expressibility" metrics (83). However, knowledge representation researchers still cannot agree on a basic set of characteristics for comparing representations (84). No existing approach can handle the over one-hundred dimensions suggested in reference 84.

Having identified the problem, the next step is to determine an approach to solve the problem which is done in the next section. Also, the next section contains an overview for the remainder of this document.

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II. Dissertation Approach

General Concept

Recognizing the lack of analyses and the controversial issues surrounding comparison characteristics, the goal of this dissertation is not to develop another knowledge representation as a solution to the problem. The goal is to develop general insights about existing representations and provide an approach by which future representations can be compared. The conjecture is that formal language theory can be used as the basis from which to generate compatible comparisons of knowledge representations. For the validation tasks associated with knowledge representation (see Section I), there are analogous studies associated with formal language theory. For example, the task of determining the relationships among representations is analogous to the task of determining language/grammar equivalence. Other analogous tasks are the identification of hierarchies of representations (languages) and determining membership of a representation (language) in the hierarchy.

Supporting Rationale. Even though the previous examples in Section I implied the existence of a representation-language tie, stronger rationale supporting the conjecture is required. Therefore, before proceeding with the development of the formal language approach, two additional cases of this tie are examined in detail.

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The first case involves Feder's use of a two-dimensional language to describe line pattern images (85). Using this language, he studied the characteristics of the patterns via formal language theory. He used the hierarchical relationships of complement, union and intersection to expand simple, easy-to-study languages into more complex ones. While not presented in detail, he suggests the use of known relationships in formal language theory to determine time and size limitations, solvability of the recognition problem, etc.

The second case involves the formal language relationship of a subset of predicate calculus, known as quantified propositional calculus. Hamblin proved that all the individual statements of quantified propositional logic form a context-sensitive language (86). Therefore, many characteristics of context-sensitive languages could be used in analyzing this subset of predicate calculus. For example, the equivalence problem for a context-free language is unsolvable (9:63). From the Chomsky language hierarchy (see Theorem 1.01 of Section I), context-free languages are contained within the context-sensitive languages. By inclusion, it follows that the equivalence problem for context-sensitive languages is also unsolvable. From this unsolvability characteristic, it follows that it may not be possible to prove that Hamblin's representation is equivalent to any other type-1 representation-language.

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The word "may" has to be used in this equivalence conclusion because the equivalence finding for context-sensitive languages is for the general case of all context-sensitive languages. Because formal language theorists have proven the existence of special classes of languages where equivalence is solvable (34), it may be the case that equivalence is solvable for some knowledge representation languages contained in the type-1 language-class. However, Hamblin did not perform any language-class investigations.

Counterpoints. Even with this strong evidence supporting the conjecture, there are several counterpoints to applying formal language theory to knowledge representations. One counterpoint stems from the position that knowledge representations are said to deal with both syntax and semantics (84). The association of semantics with representations cause an "apples and oranges" situation to exist between many representations. An example of this association is represented by the relation between semantic networks and production rules. The semantic-network representation uses symbols to represent all known truths about a given world. But, the production-rule representation uses symbols to represent conflicting truths that can only be resolved by using the working memory (situation data of Figure 4). The fact that the meaning of the symbols represent truths or conflicting truths can only be determined by the semantics assigned to the symbols.

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Smith provides an answer to this semantics concern (87). In an attempt to develop a model of human memory based on five levels, Smith defined the concept that everything below the top level is just syntax. The only way to deal with the top level as syntax is to go outside the human environment.

The conjecture of this dissertation is based on the similar position that knowledge representation schemes are syntactical structures within the computer system. The semantics come into play entirely outside the computer. For example, a semantic-network's relation is represented in the computer as memory locations containing symbols (binary equivalent) and memory pointers. The relation name itself has no internal significance except that an internal pointer can be found stored with the name symbols. The "meaning" of a link name is assigned outside the computer system. The computer process that is applied to determine when to follow a path is nothing more than a syntactical pattern match on a symbolic representation of the link's name.

Similarly, a production-rule's antecedent is stored as a set of symbols and symbolically matched against the situation data. The fact that the antecedent may represent, for example, a person's condition (see Figure 5) can only be determined outside the computer system.

Furthermore, conflicting consequents like "patient has disease A" and "patient does not have disease A" are two different atomic symbol strings within the machine. The

conflicting meaning of the strings can only be identified outside of the computer system.

Also, any processes used to interact with the working memory still involve only the primitive machine operations of symbolic comparison and memory handling. By definition, the meaning of the individual contents of working memory can thus only be determined outside the computing machine.

Another counterpoint involves the handling of explicit procedural knowledge within formal languages. Procedural sequences cannot normally be handled by the unordered word generation that a nondeterministic grammar provides. However, depending on how the procedures are defined, there are ways tc handle this problem. Procedures can be generalized as any arbitrary computer program over a set of computer programming languages. Thus, the computer programming languages are added into the overall knowledge representation languages. That is, computer programming languages are identifiable subsets of words contained in the overall knowledge representation language.

If the allowable procedures are restricted to a special set of computer programs, then the word order of the implementing computer programming languages becomes important. This word order can be handled in the following manner. Each procedure in the set can be represented as an ordered, finite group of words (with repeats) from the associated implementing computer programming language. For each computer programming language, these ordered groups can then

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be considered as a single word in another language. These new languages can then be added to the overall knowledge representation language. Formal language theorists have dealt with procedures defined in this manner via a class of languages called trace languages (88).

A further counterpoint stems from the conjecture that sa's that most of the knowledge representations are already formally equivalent. This argument comes from using representations to model Turing machines. Since representations can be used to model both the knowledge-base and control structure of Turing machines (see Figure 4), equivalence of representations has already been shown to exist. Hence, there is no need to study the equivalence issue any further. The problem with this conjecture is that the equivalence is determined by comparing the results generated by the overall Turing machine model, not comparing the representations themselves. That is, two different representation forms may be used to model the same Turing machine. However, the two representations used to model the knowledge-base part may not be equivalent syntactically to each other.

This dissertation is based on the position that equivalence of knowledge representations should be determined separately from the rest of the components of a system that uses them. That is, the knowledge-base (see Figure 4) should be viewed from a meta-level where the individual characteristics of the representation can be identified. At this meta-level, the syntax of the representation can be

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best studied via formal language theory. Thus, characteristics unique to the representations can be identified regardless of the system implementation. For example, it may be the case that one representation form is easier for users to maintain. However, another form may be more computationally efficient for a certain problem-solving technique. By determining the syntactical equivalences of the representations, it may be possible for users to maintain their representations in one form and perform transformations into other representations when required (centralized database concept).

Approach

Having answered the major concerns with the dissertation's concept, the details of the approach can now be discussed. The approach is to analyze knowledge representations by first converting them into a formal language and then proving characteristics of the representations via techniques of formal language theory.

Scope. Because there are many different knowledge representations and variations given in the literature (see Section I and the references in Appendix B), attempting to analyze every one within the scope of this study is an insurmountable task. In order to reduce this effort to a more manageable size, the scope was initially limited to the set of the six individual representations previously

described (predicate calculus, production rules, semantic networks, frames, scripts and conceptual dependency).

Without a formal theory of knowledge representation, the six individual representations cannot be guaranteed to be members of a basis set of knowledge representation. Therefore, analyzing all of them does not necessarily provide coverage of the entire knowledge representation area. But, credibility of the overall approach can be established by using a few of the schemes from this constrained set.

From this set of six schemes, two were then selected: production rules (excluding working memory or situation data) and semantic networks. Production rules were chosen because they are the most widely used knowledge representations in expert systems. Because of this use, the results should be able to assist a large group of expert system developers.

The production system's working memory is excluded as part of the representation for several reasons. One reason is that the contents of the working memory are unique to the particular problem being solved. As previously noted, the representations are being evaluated at a meta-level where system control operation has been separated from the representation.

Another reason the working memory is excluded is that the production rules themselves already contain antecedent/consequent clauses that involve the working memory. The embedded tests for antecedent truthfulness involve symboli-

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cally matching the contents of working memory with the contents of a production rule. Hence, the working memory will have to contain duplicate information. Furthermore, the procedures that are called from rules to interact with the working memory are already contained symbolically in a production rule.

Semantic networks were chosen because in addition to being used in expert systems, they are representative of a completely declarative knowledge structure. Also the semantic network is the extreme simplification of a frame. In reference 62, this relationship was explicitly noted where each node (frame) represented a subnetwork. In the limit, each frame could represent a single node with the node name contained in one slot, the relation name in another slot and the link pointer in a third slot. Since part of formal language theory deals with hierarchical characteristics of languages, the semantic network provides the foundation language upon which to expand into the frame hierarchy.

The other knowledge representations were not selected for a variety of reasons. Predicate calculus was not chosen for investigation because it has been studied extensively over the years by others and, as pointed out in the subsection on supporting rationale, the initial effort (formal language mapping and typing) has already been completed by Hamblin (86). Frames were not selected because, as noted previously, frames can be considered to be an extension of

the already chosen semantic networks. Scripts were not investigated because they were shown to be just a specialization of the frame representation (55). Conceptual dependency was not selected because it can be considered as a special layered semantic network.

Overview. With the completion of the justification for limiting the scope to production rules and semantic networks, the details of the actual approach used can now be described. As stated previously, the basic approach is to derive the formal language equivalent for each of the selected representations and then evaluate and compare them via formal language techniques. In order to derive their language equivalent, there are some general results that need to be derived from formal language theory first.

Formal language theory relies on the concept of recursively enumerable sets. Because of the word "enumerable", most theorists take for granted that the size of the language space is countably infinite. There do not exist in the literature direct formal proofs of this fact. Therefore, the dissertation begins, in Section III, with the construction of formal language space and the development of theorems proving the countably infinite size of the space.

With this part of formal language theory established, Section IV focuses on the definitions of the two selected knowledge representations. Because of the numerous variations of production-rule and semantic-network definitions given in the literature, an inclusion hierarchy of charac-

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teristics is generated for each representation. The characteristics included in each hierarchy are those used by the knowledge representation community to define particular versions of each representation. Using the lowest level characteristics from each hierarchy, formal definitions for the "category-1" production rules and semantic networks are developed.

By applying these category-1 definitions, a formal language equivalent for each of the two representations is developed in Sections V and VI. Individual characteristics about each of these language equivalents are proven. These include the countably infinite cardinality of each of the languages and their membership in Chomsky's class of type-2 languages. In addition, a word/symbol variation is applied to redefine the specific form of the knowledge contained in these representation-structures. The effects of this variation upon the previously identified type-2 language classification are determined.

In addition to the individual language's characteristics, Sections V and VI also contain proofs of the characteristics of special classes of category-1 languages. These characteristics include the countably infinite cardinality of the classes, the type-2 language-bounds for languages contained in each of these classes, the union and product nonclosure properties of the languages in each of these classes, and the inability of each of these classes to be an Abstract Family of Languages.

With the development of the characteristics of the category-1 languages completed, these characteristics are then used in Section VII to formally compare the two special classes of representation-languages. The comparison techniques used are those for determining equivalence of the representations and determining transformation between the representations (see Section I). For the equivalence case, equivalences between certain subsets of production-rule and semantic-network languages are proven to exist. However, for the arbitrary case, equivalence of production-rule and semantic-network representations at the category-1 level is proven not to exist. For the transformation case, any arbitrary production-rule language contained in the special class of category-1 languages is proven to be transformable into a semantic-network language. However, an arbitrary semantic-network language contained in the special class of category-1 languages is proven to be unable to be transformed into a production-rule language.

Given all of these findings for the production-rule and semantic-network languages, the next step is to expand the representation-definitions according to the inclusion hierarchy developed in Section IV and determine the characteristics for the top-category languages. In Section VIII, the hierarchical expansion is performed with the help of several conjectures. These conjecture focus on the existence of a language equivalent at the top category and the equivalence of the meanings (semantics) of the characteristics tabular-

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ized in Section IV. Using these conjectures, an arbitrary

production-rule or semantic-network language contained in

the top-category classes of languages is shown not to be

contained in Chomsky's class of type-2 languages.

Additionally, the top-category classes of production-rule

and semantic-network languages are shown not to be equiva-

lent. Also, each of these top-category classes is shown not

to be an Abstract Family of Languages. Furthermore, an

arbitrary top-category production-rule language is shown to

be able to be transformed into a semantic-network language.

However, an arbitrary top-category semantic-network language

is shown to be unable to be transformed into a

production-rule language.

Using these characteristics, conclusions are reached in

Section IX regarding the use of the knowledge representa-

tions of production rules and semantic networks.
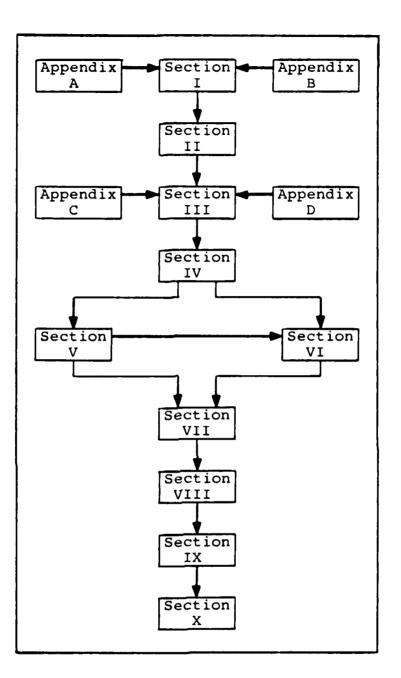
Recommendations are then provided in Section X on how to

expand and apply the results of this analysis. Suggestions

are also presented on how to add additional analysis tech-

niques to the approach. Finally, comments on the

contributions of this effort are discussed.

Reader's Guidance

Because of all of the interrelated findings of this

dissertation, some assistance needs to be provided to help a

reader follow through the dissertation and understand the

information contained within various subsections. For this

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dissertation, this assistance takes the form of a flow diagram, cross-reference lists and examples. Because of the dependence of the theorems and proofs used in one section of this dissertation on those used in a previous section, the dissertation should be read in the order of the section numbers. However, a reader may follow the production-rule or semantic-network language-development alone by referring to Figure 11. The vertical arrows indicate the sequence that should be followed in order to understand a particular section. The horizontal arrows indicate those sections that provide support to a particular section. However, the reader is not required to understand the entire contents of the supporting section in order to understand the particular section that the horizontal arrow indicates.

For example, to understand the semantic-network language-development contained in Section VI, a reader should read Section IV in detail but can refer to portions of the production-rule language-development contained in Section V. However, for the production-rule language-development contained in Section V, Section VI can be ignored.

In addition to this flow diagram, cross-reference lists of definitions, theorems, corollaries, conjectures and propositions are provided in the beginning to help the reader. Many of the proofs refer to other definitions, theorems, etc., by only the item identification number and section. These lists provide the reader a quick page

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```
        ┌─────────┐     ┌─────────┐     ┌─────────┐
        │Appendix │────▶│ Section │◀────│Appendix │
        │    A    │     │    I    │     │    B    │
        └─────────┘     └─────────┘     └─────────┘
                             │
                             ▼
                        ┌─────────┐
                        │ Section │
                        │    II   │
                        └─────────┘
                             │
                             ▼
        ┌─────────┐     ┌─────────┐     ┌─────────┐
        │Appendix │────▶│ Section │◀────│Appendix │
        │    C    │     │   III   │     │    D    │
        └─────────┘     └─────────┘     └─────────┘
                             │
                             ▼
                        ┌─────────┐
                        │ Section │
                        │    IV   │
                        └─────────┘
```

Figure 11. Dissertation Flow Diagram

reference should a review of the identified item be
required.

While the flow diagram and cross-reference lists help
the reader locate needed information, many example cases
help the reader better understand the information that is

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presented. For some of the more complex proofs, example cases are presented within the steps of the proof. Even though these examples occur in the proof, the reader is cautioned not to falsely conclude that the proof was done "by example." If a counter-example type of proof is used, this fact is noted at the beginning of the proof.

With this understanding of the document's structure, the reader may now proceed to the first set of findings: the size of language space.

III. Language Space

After a thorough review of the formal language litera-
ture (see Appendix A), many theorists were found to be using
several unproven assumptions about the size of languages
within the proofs of their own theorems. One assumption
they use is that because all languages are recursively
enumerable, any infinite length language must contain a
countably infinite number of words. Another assumption they
use is that any infinite hierarchy of languages must contain
a countably infinite number of languages. While these
assumptions are not false, the theorists missed related
size-characteristics that could only be revealed by support-
ing proofs of these assumptions. As a result, some of their
own theorems have proofs which are more complex than is
necessary. Since several findings of this work depend
directly on the length and number of languages, these
assumptions were rigorously proven so that all the size
characteristics could be identified.

Because these assumption proofs depend a great deal on
definitions and theorems already provided by other sources,
a subsection is given herein which lists these required
items. For the theorems of others, their proofs are not
provided herein. The reader is referred to the cited
reference for those proofs. Even though supporting details
are provided in the development, the reader is assumed

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to have background in set theory, formal language theory, recursive function theory and Turing machines. Additional information on these subjects can be found in references 8, 9, 89, 90, 91, 92, 93, 94, 95 and 96.

Supporting Definitions and Theorems

The definitions and theorems contained in this subsection are presented in an order which supports their later use. In order to provide sufficient information to understand some of these definitions and theorems, related definitions and theorems are also given. However, only the main definitions and theorems are referred to in the actual proofs. Therefore, a well informed reader may skip to the next subsection and only refer back to the specific definitions and theorems that are cited in the proofs.

Since the definitions of various grammars were previously given in Section I (see Definitions 1.02-1.06), they are not repeated in this subsection. However, for consistency, the same symbols used in the tuple form of the grammar definition, (T, NT, S, P), are also used herein to represent terminals, nonterminals, start symbol and rewrite production-rules, respectively. Because the terms "word" and "language" are associated with grammars, their definitions need to be provided at the outset.

Definition 3.01: Let "Z" be any finite set of symbols called an alphabet. These symbols are called the letters of the alphabet (9:2).

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Definition 3.02: A word (string) over Z is any finite,
concatenated sequence of letters from Z
(with repeats allowed) (9:2).

Definition 3.03: The empty word, "e", is the word consisting
of no letters (9:2).

Definition 3.04: The closure of Z, "Z^*", denotes the set of
all words over Z including e (9:2).

Definition 3.05: The empty set, "ϕ", is the set containing
no words (9:2).

Definition 3.06: A word, "w", that is an element of Z^* is
generated by a grammar, "G", if there is a
finite sequence of words over NT$\cup$Z such
that w(0) is equal to a symbol s$\in$S and
w(n)=w and w(i+1) is obtained from w(i),
$0 \leq i < n$, by application of one of the produc-
tion rules in the production rule set P.
The terminal set of G is equal to Z in this
definition (9:41).

Definition 3.07: The set of all words that can be generated
by G is called the language generated by
G (9:41).

Now that a language has been defined as a set of words,
set-theory definitions and theorems are necessary for
further refinement.

Definition 3.08: Let A be a set. The power set, "PS" of A
is the set of all subsets of A, including A
and ϕ (90:92).

Definition 3.09: Cardinal numbers are the numbers used to
measure the size (number of elements
contained within) of a set (90:279).

Definition 3.10: A set is said to be finite if its cardinal
number is a natural number. A set that is
not finite is said to be infinite (91:103).

Theorem 3.01: The set, "N", of natural numbers is an infi-
nite set (90:276).

Definition 3.11: Aleph null, "NØ", represents the cardinal-
ity of N (90:280).

Definition 3.12: A set A is of cardinality NØ if there is a
bijection (see Definition 3.15) from
N to A (90:280).

Definition 3.13: A set A is countably infinite if the
cardinality of A is NØ. A set is countable
if it is finite or countably infinite. The
set A is uncountable or uncountably infi-
nite if it is not countable (90:280).

Theorem 3.02: The subset of real numbers over [Ø,1] is not
countably infinite (90:284).

Definition 3.14: A set A is of cardinality "c" (uncountably
infinite) if there is a bijection from
[Ø,1] to A (90:286).

Theorem 3.03: Let A be a finite set. Furthermore, let "|A|"
denote the cardinal number of A. Then,
|A|<NØ<c (90:291).

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Theorem 3.04: Any subset of a countable set is
countable (91:39).

Theorem 3.05: The union of a countable set of countable
sets is countable (91:41).

Theorem 3.06: The set Z^* is countably infinite for any
finite alphabet Z (90:282).

Theorem 3.07: If Z is a finite, nonempty alphabet, then the
cardinality of $PS(Z^*)$ is c (90:285).

Theorem 3.08: Every infinite set contains a countably
infinite subset (90:282).

Definition 3.15: A one-one correspondence between two sets
exists if a pairing of the elements of
either set with the elements of the other
set exists. A bijection is a one-one
correspondence (91:36).

Definition 3.16: Two sets, A and B, are said to be equipo-
tent if and only if there exists a one-one
correspondence between them (91:37).

Theorem 3.09: A necessary and sufficient condition for a set
A to be infinite is that there exist at least
one proper subset of A which is equipotent to
A (91:104).

Theorem 3.10: The set of all finite subsets of a given
countably infinite set is countably
infinite (91:42).

This completes the basic supporting information neces-
sary to establish characteristics of a given language. But,

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additional theorems and definitions are required to estab-
lish the relationship of languages. One of the required

theorems is the Chomsky inclusion hierarchy of languages.

Since the Chomsky inclusion hierarchy was given Theorem 1.01

of Section I, this theorem is not repeated again. However,

specific definitions and theorems regarding languages and

Turing machines are provided to complete the background for

the language size proofs.

Definition 3.17: A set of words, A, over a finite alphabet,

Z, is recursively enumerable if there is a

Turing machine which accepts every word in

A and either rejects or loops for every

word in Z^*-A (9:38).

Definition 3.18: A set of words, A, over Z is recursive if

there is a Turing machine which accepts

every word in A and rejects every word in

Z^*-A (9:39).

Definition 3.19: A set of words over Z is a regular set if

the set is generated recursively by a

finite number of applications of the

following steps:

1.   Every finite set of words over Z

(including ϕ) is a regular set.

2.   If U and V are regular sets over Z

so are their union and product.

3.   If U is a regular set, so is its

closure, U^* (9:2).

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Definition 3.20: A set of words over Z is called a type-i language (i=0,1,2,3) if it can be generated by a type-i grammar (8:143).

Theorem 3.11: A set of words over Z is recursively enumerable if and only if it is a type-0 language (8:143).

Definition 3.21: A set is regular over Z if and only if it is accepted by some finite automaton over Z (9:7).

Definition 3.22: A function $f:Z^* \to Z^*$ is Turing realizable if there exists a Turing machine, M, such that M has a halted computation $(e,qI,\#,w) \Rightarrow (\phi,q,\#,v)$ if and only if $f(w)=v$, and M fails to halt for an input tape, $\#w$, if and only if $f(w)$ is undefined (92:445).

Definition 3.23: Let N represent the natural numbers. A function $f:N^m \to N$ is Turing computable if there exist a Turing machine that realizes the function $g:\{\#,1\}^* \to 1^*$, where

$$g(1^{x1}\#\ldots\#1^{xm}) =$$

$$\begin{cases} 1^y \text{ if } f(x1,..,xm) = y \\ \text{undefined if } f(x1,..,xm) \text{ is} \\ \text{undefined} \end{cases} \quad (92:463).$$

Definition 3.24: A subset, K, of the natural numbers, N, is Turing enumerable if either:

    1. $K = \phi$

        or

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2. There exists a Turing computable
    function, $f:N \to K$, that maps N onto
    K. We say f is an enumeration of K
    in this case. Using Godel number-
    ing this can be extended to an
    arbitrary set $X \subseteq Z^*$, where Z is any
    alphabet. Set X is Turing enumer-
    able if the set $\{Gd(w)|w \in X\}$ is
    Turing enumerable. Gd is the Godel
    numbering of Z^* (92:487).

Theorem 3.12: Type 3 languages are the finite state
             languages (8:150).

Theorem 3.13: There exists a Turing computable function,
             $W:NXN \to N$, such that for all x,y,z, $W(z,x)=y$
             if and only if machine M(z) in an enumera-
             tion of Turing machines computes
             $f(x)=y$ (92:491).

Language-Space Size

With this background established, the size of language
space can now be determined. First, the space needs to be
constructed using some of the definitions and theorems of
the previous subsection.

Let Z represent an arbitrary finite alphabet per Defini-
tion 3.01. Then, applying Definitions 3.02, 3.03, 3.04,
3.05, 3.06 and 3.07 and Theorem 3.11, let "L" be defined as
a set which contains all the languages generated by all

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possible grammars over Z. That is, L contains all type-0
languages over Z.

Next, applying Definitions 3.04 and 3.08, let "D" be
defined as a set that contains all possible subsets of Z^*.
That is, $D=\{PS(Z^*)\}$.

By these definitions, $L \subseteq D$ since L is also a set
containing subsets of words from $PS(Z^*)$. At this point, it
cannot be determined whether or not L is a proper subset of
D. However, a size characteristic can be established for
each formal language in L.

<u>Theorem</u> 3.14: The cardinality of every set of words $d \in D$ is
countable.

  Proof: From Theorem 3.06, the set of all finite words
    Z^* is countably infinite. Since D contains
    all possible subsets of these words, Theorem
    3.04 can be applied to conclude that each
    element in D is countable. Q.E.D.

<u>Corollary</u> 3.01: The cardinality of every language $l \in L$ is
countable.

  Proof: By definition, $L \subseteq D$. Therefore, for every
    language $l \in L$ there must exist a $d \in D$ where
    l=d. By Theorem 3.14, each l is also
    countable. Q.E.D.

Instead of working from the uncountably infinite set D
(see Theorem 3.07), the size of L can be determined by
working from the empty set.

Theorem 3.15: The set of formal languages over Z is not
empty.

Proof: From set theory, the cardinality of ϕ is zero
but the cardinality of the set $\{\phi\}$ is one.
From Definition 3.19, ϕ is a regular set.
From Definition 3.21, a regular set must be
accepted by a finite automaton. Applying
Theorem 3.12, ϕ is a type-3 language. There-
fore, if all grammars generated only the empty
set, L must still contain ϕ as a language
member. From Definition 3.08, D also contains
ϕ as a member. Hence, $|L| \neq 0$. Q.E.D.

Theorem 3.16: The cardinality of the set L of languages over
Z is not finite.

Proof: Applying Theorems 3.06 and 3.10, the set of
all finite subsets of Z^* is countably infi-
nite. From Definition 3.19, every finite set
is a regular set. Applying Definition 3.21
and Theorem 3.12, these regular sets are
members of the type-3 languages over Z. From
Chomsky's inclusion hierarchy (Theorem 1.01 of
Section I), type-3 languages are a proper
subset of type-0 languages. Since L contains
all the type-0 languages by definition, L also
contains these finite languages. Therefore,
applying Definitions 3.09 and 3.10, the
cardinality of L cannot be finite. Q.E.D.

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Recognizing that the finite sets have been accounted for in the type-3 languages, a theorem and a corollary regarding the cardinality of the each of the remaining sets of words and languages can be proven.

Theorem 3.17: For each $d \subset D'$ and $d \not\subset$ type-3 languages, then d has countably infinite cardinality.

   Proof: By Theorem 3.14, each d is countable. Applying Definition 3.13, only the countably infinite sets remain. Q.E.D.

Corollary 3.02: For each language $l \subset L$ and $l \not\subset$ type-3 languages, then l has countably infinite cardinality.

   Proof: By definition, $L \subseteq D$. Therefore, for every language $l \subset L$ there must exist a $d \subset D$ where $l = d$. Applying Theorem 3.17, l has countably infinite cardinality. Q.E.D

Even though L and D have been shown to contain a countably infinite subset of languages, conclusions regarding the cardinality of L cannot yet be reached. This is because Theorem 3.08 shows that a countably infinite subset exists in both countably infinite and uncountably infinite sets. Turing machines are needed to resolve this problem.

Theorem 3.18: The cardinality of the set of formal languages L over Z is countably infinite.

   Proof: In the proof of Theorem 3.16, L was found to contain all the finite languages. Applying Theorem 3.10, these finite languages form a

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countably infinite subset of L. Therefore, L
must be at least countably infinite in size.

Now, from Definition 3.17 and Theorem
3.11, Turing machines accept type-0 languages.
Depending on how the reject or loop criteria
is interpreted (e.g. one machine could reject
only one nontype-0 set while another could
reject several different nontype-0 sets), it
is possible for more than one Turing machine
to accept a given type-0 language. However,
Definition 3.17 states that at least one
Turing machine exists for every type-0 lan-
guage. Therefore, applying Theorem 3.13,
there are at most a countably infinite number
of Turing machines that could accept type-0
languages. Hence, there are at most a count-
ably infinite number of type-0 languages.

Since L is bounded both from above and
from below by countably infinite cardinality,
L must be countably infinite in size. Q.E.D.

With L being countably infinite, proper inclusion of L
in D can now be proven.

Theorem 3.19: The set L of formal languages over Z, is a
proper subset of D.

Proof: From Theorem 3.07, D has cardinality c
(uncountably infinite). On the other hand,
Theorem 3.18 has shown L has cardinality N0

(countably infinite). Recalling that L was
defined such that it is a subset of D and
applying Theorem 3.03, it follows that L must
be a proper subset of D. Q.E.D

The proper inclusion of L in D supports the existence of
nonrecursively enumerable sets. Formal language theorists
ha e spent considerable effort in developing nonrecursively
enumerable sets to prove the inclusion of L in D. One
example of such a set is the countably infinite set repre-
senting the class of total recursive functions (92:562).
However, theorists sometimes propose a nonrecursively
enumerable set that is later proven to be recursively
enumerable. Appendix C contains a proof that a nonrecur-
sively enumerable set constructed by Manna is actually
recursively enumerable (9:39).

Now that set of formal languages over a single alphabet
has been proven to be included in D and has countably
infinite cardinality, all that is left to do is to determine
the size of the set of languages over all possible finite
alphabets.

Theorem 3.20: The set of formal languages over all finite
alphabets has countably infinite cardinality.

Proof: From AFL theory, all the finite alphabets for
formal languages are obtained from a countably
infinite alphabet (97:33). From Theorem 3.10,
the set of possible finite alphabets has
countably infinite cardinality. Since every

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set has the empty set ϕ as a finite subset, this countably infinite set of alphabets must contain ϕ. However, by Definition 3.01, an alphabet cannot be the empty set. Therefore, the empty set must be removed from this group of alphabets. By applying the $f(x)=x-1$ mapping on the indexes of the remaining finite sets, there is still a countably infinite number of finite alphabets remaining.

Now, since theorem 3.17 established that for a single, finite alphabet a countably infinite number of type-0 languages exist, let $LL(i)$ represent the countably infinite set of type-0 languages for the ith alphabet. Then, perform the set union operation over the $LL(i)$ language sets. Since there are a countably infinite number of alphabets, i ranges over the natural numbers. Therefore, it follows from Definition 3.12 and Theorem 3.05 that the resulting set has countably infinite cardinality. Q.E.D.

With the size of the set all formal languages established, the formal language space analysis is complete. Because languages and grammars are related, an analysis of the size of grammar space should also be provided. Since the main results of this dissertation do not rely directly on theorems related to grammar space, the grammar-space

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analysis is given in Appendix D for reference. Having
established the size of formal language space, the investi-
gation of the production rules and semantic networks can now
begin.

IV. Representation Definitions

With the size of the language space established as countably infinite, the first step towards developing the formal representation languages is generating definitions for production rules and semantic networks.

Definition of Production Rules

The literature abounds with different descriptions of production rules (see references 5, 40, 41, 50, 51, 56, 66, 73, 74, 80 and Appendix B for examples). Trying to write a definition that would contain all the unique characteristics of each variation could result in numerous pages of confusing and possibly conflicting details. However, it was noted that these characteristics could be grouped into categories based upon the complexity of the knowledge that was to be represented. Each category could then be described by a statement that covered the member characteristics.

The results of this classification for the previously noted references are given in Table II and Table III. Because of the different natures of the "test only" antecedent and the "action" consequent of a rule, separate categorization of each was necessary. Additionally, the categories were ordered from less complex characteristics to more complex. Recalling that inclusion hierarchies are studied in formal language theory, the categories themselves were also established as such a hierarchy to support the

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Table II. Categories of Antecedents of Production Rules

Category	Characterization
1	The antecedent contains a single string of symbols representing a single fact where existence of the fact in the database indicates that the fact is true.
2	The antecedent contains conjunctions of single facts [e.g. (Bill AND Cat)].
3	The antecedent contains conjunctions of total predicates operating on facts. [e.g. Red(ball) AND Owner(Joe, bat)].
4	The antecedent contains Boolean combinations (including nesting) of computationally primitive operations of matching and detecting.
5	The antecedent contains unit (?X in LISP) and segment ($X in LISP) free-variables.
6	The antecedent can test values assigned to facts.
7	The antecedent can call complex functions embedded in the literals to determine the truth value.
8	The antecedent can alter the database of facts without firing any rules.

Note: The categories are specified in an inclusion hierarchy form: 8 ⊃ 7 ⊃ 6 ⊃ 5 ⊃ 4 ⊃ 3 ⊃ 2 ⊃ 1

language development goal. That is, the characteristics of a lower numbered category are properly included in those of a higher numbered category (see Figure 12). Therefore, as the category number increases, the number of characteristics and the complexity of the characteristics that a rule contains also increases. The top category level

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Table III. Categories of Consequents of Production Rules

Category	Characterization
1	The consequent contains a single string of symbols representing a single fact which is added to the database as a true fact when the antecedent is true.
2	The consequent adds multiple facts to the database with use of the AND operator.
3	The consequent contains unit (?X in LISP) and segment ($X in LISP) free-variables.
4	The consequent can perform substring replacement within a given fact.
5	The consequent can perform value assignment actions to facts.
6	The consequent can call procedures and other rules.
7	The consequent can manipulate the database and produce side effects which do not involve the rules.

Note: The categories are specified in an inclusion
      hierarchy form: $7 \supset 6 \supset 5 \supset 4 \supset 3 \supset 2 \supset 1$

indicated in Figure 12 represents category 8 for the antecedent hierarchy and category 7 for the consequent hierarchy.

While this classification effort condensed the set of characteristics, a definition which would cover all the possible combinations of antecedent categories with consequent categories would still be very complex. However, by following the techniques used by Feder (85), this complexity problem can be solved. Feder achieved success by studying a less complex language to determine some of the
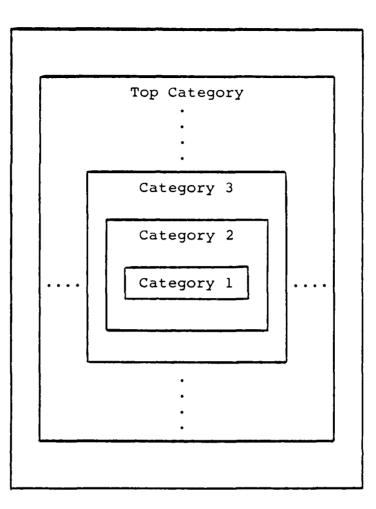
```
                              Top Category
                                   .
                                   .
                                   .
                                   .
                    +--------------------------------+
                    |          Category 3            |
                    |   +------------------------+    |
                    |   |      Category 2        |    |
                    |   |   +----------------+   |    |
              ....  |   |   |   Category 1   |   |    |  ....
                    |   |   +----------------+   |    |
                    |   +------------------------+    |
                    +--------------------------------+
                                   .
                                   .
                                   .
```

Figure 12.   Inclusion Hierarchy

characteristics of more complex members of the same language

hierarchy.   Therefore, the solution is to utilize a similar

approach and develop a definition of production rules based

on the "category-1" characterizations of Tables II and III.

This definition can then be used to generate a less complex

language version.

Having selected the category level of the definition,

the form that is used in the definition to represent the

characteristics needs to be chosen.   While generating the

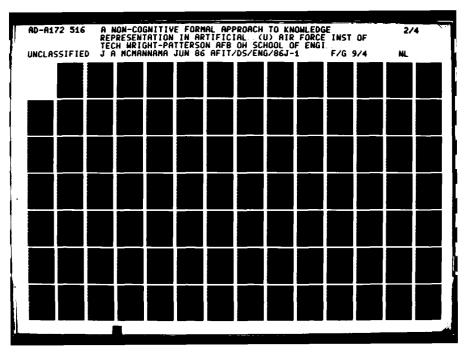categories from the previous references, it was noted that

the most common form used in defining a production rule is a tuple form [e.g. a->b, (a,b)]. Therefore, to maintain compatibility with the literature and formal language theory, a tuple form is chosen.
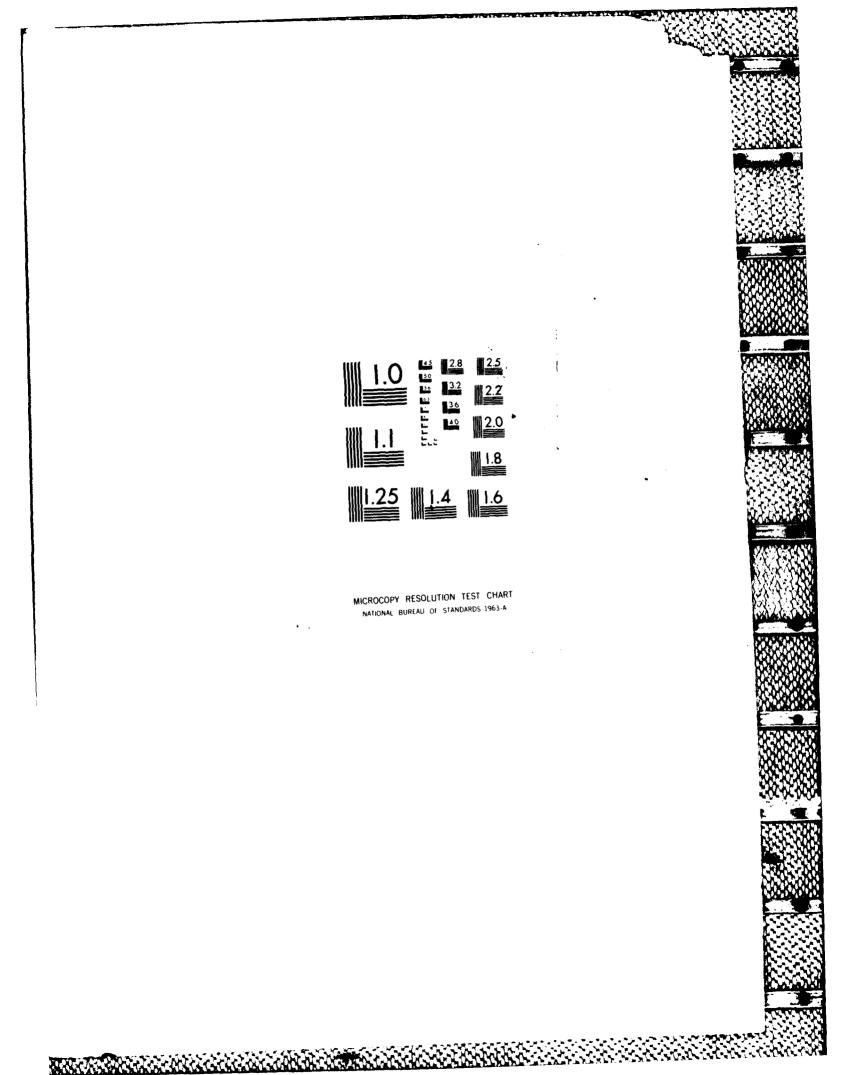
Now that the form selection is complete, the definition of production rules that have only category-1 characteristics is given. The actual number of rules contained within a representation is investigated in Section V.

Definition 4.01: For any nonempty, finite alphabet Z, a production rule that has only category-1 characteristics (see Tables II and III) is defined as a 3-tuple. The 3-tuple is of the form "amb" where "a" and "b" represent individual facts, "m" is a special symbol disjoint from Z which represents the implies operator, $a, b \in Z^+$ and $a \neq b$. The form amb reads "a implies b."

In order to better understand the definition, the specified restrictions need to be explained. The concatenated word-form of the 3-tuple was selected in order to support the later development of a language version. By not using delimiters between the elements of the 3-tuple to show separation, later language development efforts would not have to be involved with blank spaces and commas within a production-rule word. However, by constraining m to be disjoint from Z and to be placed as the center element

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within the 3-tuple, m can act as a separator as well as an operator if necessary.

Within this 3-tuple word-form, several restrictions involving the facts contained in the antecedent and consequent need explanation. First, single facts were not constrained to any limited set of words over Z so that the generality of the definition could be maintained. Because programmers arbitrarily assign symbol strings to represent facts, one may use "car" to represent a specific fact while another may use "auto" to represent the same fact. Therefore, the definition must provide the entire set of symbol strings for the programmers use.

Second, even though all words over Z were represented as facts, the empty word e was not added to the set because of its concatenation property: ea=a or ae=a. Since the 3-tuple was restricted to be a concatenated word-form, a grammar generating the 3-tuple word with an alphabet containing e could produce words such as "mb" or "am" instead of "emb" or "ame." These generated words are not 3-tuples and so are not production rules by definition.

Finally, when using any two of the previously constrained individual facts within a given rule, system operating efficiencies dictate that the facts be disjoint. Rules which have equal antecedent and consequent entries could cause a system to continuously fire the rule after its initial activation. Since a fact is true once it is placed in the database, adding multiple copies of the same fact to

the database does nothing to increase its truth value.
Therefore, this continuous firing and updating action would
cause unnecessary computational overhead during the system's
operation.

Definition of Semantic Networks

Because semantic networks also have widely varying
definitions (see references 5, 52, 53, 54, 62, 65, 68, 70,
71, 72, 73, 74, 78, 79 and Appendix B), the same methodology
that was previously used for developing the production-rule
definition can also be used to develop the semantic-network
definition. Therefore, applying the same categorization
approach, semantic networks can be characterized as shown in
Tables IV, V and VI. Because of the differences between
nodes and links, two separate hierarchies were constructed.
Additionally, a hierarchy was developed to handle the
combinations of links which do not depend on the
characteristics of the links being combined.

Continuing to apply the same methodology, the semantic-
network definition is based on the category-1 characteriza-
tions provided in the three associated tables. However, the
form used in the definition is not based on the most common
form as was the case for production rules. The most common
form used to define a semantic network is a directed graph
which has labeled nodes and links. Another form used is a
tuple form which represents the relationship between only
two nodes [e.g. (node-1, relation, node-2)]. Recalling that

Table IV. Categories of Nodes of Semantic Networks.

Category	Characterization
1	A node contains a single string of symbols representing objects, categories, concepts, sets, etc., but does not contain relations.
2	A node contains a single string of symbols representing relations, predicates, attributes or values.
3	A node contains unit (?X in LISP) and segment ($X in LISP) free-variables in support of quantification representation.
4	A node contains functions, procedure calls, rules or special symbols.
5	A node contains prototypes, depictions, roles or descriptors.

Note: The categories are specified in an inclusion hierarchy form: $5 \supset 4 \supset 3 \supset 2 \supset 1$

the goal of this dissertation is to compare the production-rule and semantic-network languages, the task can be made easier if the words in the languages are of similar form. Therefore, the tuple form is chosen for the semantic-network definition.

With this groundwork completed, the definition of semantic networks that have only category-1 characteristics is given. As was the case for production rules, the size of the semantic network is investigated in Section VI.

Table V. Categories of Individual Links of Semantic
          Networks

Category	Characterization
1	A link represents a binary relation between two nodes where the relation can be thought of as a predicate of the form Relation(tail_node, head_node).
2	A link represents a pointer without any relation such as an attribute-value pointer or a pointer associated with a relation-node.
3	A link represents an n-ary relation.
4	A link represents exception cases.

Note: The categories are specified in an inclusion
      hierarchy form: $4 \supset 3 \supset 2 \supset 1$

Table VI. Categories of Link-Combinations of Semantic
           Networks

Category	Characterization
1	The links are treated as stand-alone independent entities.
2	The links are combined by disjunction, conjunction and negation.
3	The links are combined to represent the antecedent and consequent of implications.

Note: The categories are specified in an inclusion
      hierarchy form: $3 \supset 2 \supset 1$

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Definition 4.02: For any two disjoint, nonempty, finite

alphabets, Y and Z, a semantic network that

has only category-1 characteristics (see

Tables IV, V and VI) is defined as a

collection of 3-tuples. Each 3-tuple is of

the form "arb" where "a" and "b" represent

the node labels, "r" represents the rela-

tion between the nodes, $a,b \in Z^+$, $r \in Y^+$ and

$a \neq b$. The form arb reads "a is related to

b by r." That is, the link arrow goes from

a to b.

As was the case for production rules, the semantic-

network definition can also be better understood if the

restrictions are explained. Except for the naming conven-

tions used, the explanations for the restrictions of the

3-tuple to a concatenated word-form, the placement of r, the

use of all the words over Z for node labels, the use of all

words over Y for the relations and the elimination of the

empty word are identical to those given for similar

restrictions in the definition of a production rule.

Therefore, they will not be repeated here. The reader is

referred to the paragraphs following Definition 4.01 for

these explanations. However, there are two additional

restrictions that need explanation.

The first is the restriction that the node labels and

relations be constructed from disjoint alphabets. This

restriction comes directly from the category-1 characteris-

tics given in Table IV. There, a node was restricted not to contain a relation. By using disjoint alphabets, nodes can be guaranteed not to contain any words that are symbolically identical to the relation-words.

The second and final restriction requiring explanation is the computational efficiency of a≠b within any given 3-tuple. Recall that the inference mechanism of spreading activation (see Section I) relies on the capability to follow links throughout the network. If a node was encountered that was related directly to itself, the activation procedure could loop forever on that path. Therefore, if nodes of this type were allowed, additional computational overhead would have to be expended in order to prevent the activation procedure from entering these loops.

Related Definitions

The definitions of production rules and semantic networks are not the only definitions used herein. According to Definitions 4.01 and 4.02, a production rule requires a set of facts and a semantic network requires a set of node labels and a set of relations. Because the terms "knowledge-words" and "knowledge-languages" are used later when referring to these sets, separate definitions of these terms are needed for clarity.

Definition 4.03: For a production rule, a knowledge-word is a single fact-word contained in the set

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of facts and a knowledge-language is the
entire set of fact-words.

Definition 4.04: For a semantic network, a knowledge-word is
either a single node-label word or a single
relation-word and the knowledge-language is
the union of the node-label and relation
sets.

Having generated the necessary definitions of production
rules and semantic networks, the formal language equivalents
of these two knowledge representations is developed.

V.   Production-Rule Language and Characteristics

Given these category-1 definitions for production rules
and semantic networks, the formal language and characteris-
tics for each of these representations can now be developed.
Because of the extensive effort required to determine
language equivalents, each representation is covered in its
own section. Production rules are covered first.

Production-Rule Language

There are two different approaches that are used to
determine the language membership of this production-rule
representation. The first approach is to investigate a set
of the finite, yet variable length, strings amb generated by
concatenation of the symbols from the alphabet $Z \cup \{m\}$. In
this case, the characteristics (e.g. word membership in the
set of facts, individual consideration of symbols making up
a fact-string, language-type of the fact-set) of the indi-
vidual fact-strings, a and b, are evaluated along with the
representation's amb strings over $Z \cup \{m\}$. In other words, the
representation's structure is not considered to be separated
from the facts it contains.

The second approach that will be applied is to use the
abstract 3-tuple form of the production-rule strings and
consider each of these strings to be of a fixed length,
three. Here, each individual fact is considered as a single
symbol in the language-alphabet. Individual characteristics

of facts are hidden by the abstract nature of this knowledge representation's structure. Only the size of the fact-set is considered.

Case I: Facts are Words. The best place to start the production-rule language development is at the individual word level where consideration is given to the characteristics of the fact-set.

Theorem 5.01: Each production rule amb constructed under the constraints of Definition 4.01 of Section IV is a finite word over $Z \cup \{m\}$.

Proof: From Definitions 3.01 and 3.02 of Section III, a word over any nonempty, finite alphabet is finite in length. From Definition 4.01, Z was defined to be nonempty and finite and m was defined to be a single symbol. From set theory, the union of two finite sets remains finite and so the new alphabet, $Z \cup \{m\}$, is also nonempty and finite.

In addition to this finite alphabet, each a and b are also finite in length (see Definitions 3.03 and 3.04 of Section III). Since the sum of finite numbers remains finite, the length of amb is finite. Therefore, each amb over $Z \cup \{m\}$ meets the requirements for being a finite word. Q.E.D.

Using these individual rule-words, let "PR" represent the set consisting of all these words for a given Z.

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```
          CØ      C1      C2      C3    .....

CØm       XX    CØmC1   CØmC2   CØmC3   .....

C1m     C1mCØ     XX    C1mC2   C1mC3   .....

C2m     C2mCØ   C2mC1     XX    C2mC3   .....

C3m     C3mCØ   C3mC1   C3mC2     XX    .....

  .     ...............................

  .     ...............................

  .     ...............................
```

Figure 13.   PR Word Matrix

That is, PR contains all possible 3-tuples over $Z \cup \{m\}$ meeting

Definition 4.Ø1 of Section IV.   The size characteristic of

this word-set can be determined from the following theorem.

Theorem 5.Ø2: The set PR consists of a countably infinite

number of words.

Proof: From Theorem 3.Ø6 of Section III, the set Z^*

is countably infinite.   Recognizing that

$Z^+ = Z^* - \{e\}$ and using the mapping $f(x) = x-1$ on the

natural numbers, it follows that the set Z^+ is

also countably infinite.

Now, construct the matrix equivalent of

the PR set as shown in Figure 13.   The symbols

CØ,C1,... represent the words contained in Z^+

and the symbol m is the implies relationship.

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The symbol "XX" represents those words which are not contained in PR due to the a≠b constraint.

For this matrix, it follows from the size of Z^+ that there are countably infinite rows. Because there is exactly one word per row where a=b, a set consisting of all the XX words must also be countably infinite. Using the mapping of f(x)=x-1 once again, each row is found to still contain a countably infinite number of entries when the a=b word is removed. Since PR is equivalent to the union of the rows of this matrix with the XXs removed, it follows from Theorem 3.05 of Section III, that PR consists of a countably infinite number of words. Q.E.D.

Now that PR has been shown to contain a countably infinite number of formal words, the next step is to classify PR as a formal language. Recalling that formal language theorists have shown the existence of countably infinite hierarchies of languages within a given language-type (Chomsky) as well as across types (AFLs), trying to establish that PR resides in one of the known hierarchies could take a considerable number of "test and evaluate" actions. Because of the existence of machines (e.g. Turing, finite automata) that accept only the languages of a given type (93), the set PR is only evaluated against the four-

level Chomsky hierarchy (8). Formal language theorists have also developed a significant amount of characteristics about languages residing in this finite hierarchy.

To determine the language placement of PR in this finite hierarchy, the impact on the language-type of PR caused by the constraints on the facts (see Definition 4.01 of Section IV) is investigated. First, all of the constraints are relaxed and the language-type of a set of production rules is determined. Then, the constraints are applied one at a time and the language-type is re-evaluated. To begin, the fact-set is allowed to contain the empty word e and in a given amb string a is allowed to equal b.

Theorem 5.03: The set of all production-rule words, each word of the form amb, where Z is a nonempty finite alphabet, $a, b \in Z^*$ and m is a single symbol disjoint from Z, is a type-3 language.

Proof: With all of the previous restrictions on the set of facts eliminated, the set of production-rule words can be represented as the concatenation of the words of three sets: $Z^*\{m\}Z^*$. Because Z is a finite alphabet and m is a single symbol, it follows from Definition 3.19 of Section III that Z and $\{m\}$ are regular sets and so is Z^*. Applying this regular set definition again, $Z^*\{m\}Z^*$ is found to be a regular set. Finally, applying Definition 3.21 and Theorem 3.12 of Section III to this

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concatenated set, this set of production-rule

words is found to be a type-3 language.

Q.E.D.

Now that the unrestricted case has been proven to be a

type-3 language, the empty word constraint is applied and

the language-type is re-evaluated.

Theorem 5.04: The set of all production-rule words, each

word of the form amb, where Z is a nonempty,

finite alphabet, $a, b \in Z^+$ and m is a single

symbol disjoint from Z, is a type-3 language.

Proof: In this case, the set of production-rule words

can be represented by the concatenation of

three sets: $Z^+\{m\}Z^+$. In reference 94, pages

30-31, Z^+ is proven to be a regular set.

Therefore, applying Definition 3.19 of Section

III, $Z^+\{m\}Z^+$ is a regular set. From Definition

3.21 and Theorem 3.12 of Section III, this set

of production-rule words is a type-3 language.

Q.E.D.

From this theorem, the removal of the empty word from

the set of facts is seen not to affect the language-type of

the set of production rules. However, this is not the case

for the $a \neq b$ constraint as is seen in the next two theorems.

Theorem 5.05: The set of all production-rule words, PR,

where each word amb meets the requirements of

Definition 4.01 of Section IV, is not a type-3

language.

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Proof: The PR set is identical to one of the "center-marker" languages studied by Haines (98):

$CM = \{xcy \mid x,y \in R$, R is a regular set over Z, $x \neq y$, $c \notin Z\}$. However, Haines did not prove directly that some CM languages are not type-3. Therefore, the PR case will have to be proven in detail.

For this proof assume that PR is a regular set. From the regular set closure properties (92:186), if PR is a regular set then so is its complement; $CR = [Z \cup \{m\}]^{*} - PR$. If the complement CR is a regular set, then so is its intersection with the regular set of Theorem 5.03; $IR = CR \cap \{amb \mid a,b \in Z^{*}, m \notin Z\}$.

Now, this last intersection yields $IR = \{xmx \mid x \in Z^{*}\}$. By applying the iteration theorem of regular sets to IR (96:47), if IR is a regular set, it must contain words of the form "xmy" where $|x| \neq |y|$. But, IR contains only words where $|x| = |y|$. Hence, IR cannot be a regular set.

The fact that IR is not a regular set indicates that PR is not a regular set. This is determined by following the steps used to construct IR in reverse. Since IR is not a regular set, then CR cannot be a regular set. Since CR is not a regular set, then PR cannot

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be a regular set. Hence, PR is not a type-3
language. Q.E.D.

Because of the relationship of PR to one of the
centermarker-languages of Haines, the actual language-type
of PR has already been determined by him.

Theorem 5.06: The set of all production-rule words, PR,
where each word amb meets the requirements of
Definition 4.01 of Section IV, is a type-2
language.

Proof: The PR set is identical to one of the
centermarker-languages studied by Haines (98):
$CM = \{xcy \mid x, y \in R$, R is a regular set over Z,
$x \neq y$, $c \not\subset Z\}$. Haines proved that the CM lan-
guages are at least type 2. The details of
his proof will not be repeated here. By
applying Theorem 5.05, PR is found to be
exactly a type-2 language. Q.E.D.

So, PR has been proven to be a type-2, context-free,
language. By considering the facts as a language them-
selves, the production-rule language has been shown to be
dependent on the knowledge-language (see Definition 4.03 of
Section IV) as well as the rule's structure. More is
discussed about the characteristics of PR later. But first,
consider the case where the facts are defined to be symbols
in an alphabet.

Case II: Facts are Symbols. In order to "hide" the
language characteristics of facts in the production-rule

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strings, the facts will need to be treated as arbitrary
entities. To achieve this, each fact is considered to be a
single alphabet symbol of unit length. Because only the
individual characteristics of the facts are to be hidden,
this alphabet of facts remains countably infinite in size.
Otherwise, the set does not contain all the possible facts
in Z^+. The definition of the production-rule word has to be
modified as follows to incorporate these arbitrary facts:

Definition 5.01: For an arbitrary, countably infinite set of
facts F, a production rule that has only
category-1 characteristics (see Tables II
and III) is defined as a 3-tuple. The
3-tuple is of the form "amb" where "a" and
"b" represent individual facts, "m" is a
special symbol disjoint from F which
represents the implies operator, a,b F,
$|a|=|b|=1$ and $a \neq b$. The form amb reads "a
implies b".

With this definition in hand, let "PA" represent the set
consisting of all the 3-tuples meeting Definition 5.01. For
this set, the first step is to determine if each 3-tuple is
a formal word.

Theorem 5.07: Each production rule of the form amb meeting
Definition 5.01 is not a finite word.

Proof: This follows directly from the definition of a
word. While the length of amb is three and
hence finite, the overall alphabet, $F \cup \{m\}$,

that the strings are constructed from is
countably infinite. From Definitions 3.01 and
3.02 of Section III, words are constructed
from only finite alphabets. Therefore, the
amb strings are not finite words. Q.E.D.

This theorem makes a very strong statement at the very
beginning of the investigation of PA. The amb strings were
purposely made finite in length to make these strings meet
the finite length requirement of formal words (see Defini-
tion 3.02 of Section III). Yet, the countably infinite
alphabet prevents the strings from being formal words. The
size of this alphabet also leads to the following theorem
regarding the PA set.

Theorem 5.08: The set of production rules PA consisting of
all possible strings amb meeting the
Definition 5.01 is not a formal language.

Proof: Because languages require finite words as
members, PA can be proven not to be a formal
language immediately by applying Theorem 5.07.
However, to emphasize the critical nature of
the size of the alphabet, an alternate proof
is given.

Recall from Definition 3.07 of Section III
that a language is the set of all words that
can be generated by a grammar. From the
definition of a grammar (Definition 1.02 of
Section I), a grammar has to have a finite set

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T of terminal symbols. The overall alphabet, $F \cup \{m\}$, is this terminal set T for the PA grammar. But, this alphabet is countably infinite. Therefore, a grammar does not exist that generates all the finite strings (words) in the PA set; thus PA cannot be a type-0 formal language. Q.E.D.

Besides establishing that PA is not a language, Theorem 5.09 emphasizes that for strings of symbols, finite length is a necessary but not sufficient condition to make the strings formal words. This is but one of the characteristics that have to be taken into account when attempting to map the knowledge representations into formal language structures. There are other characteristics that impact the PR and PA sets as well.

Production-Rule Characteristics

Even though PA is not a formal language (Theorem 5.08), the characteristics of this set reveal several important facts that affect the class of languages that contains the PR language (see Theorem 5.06). Therefore, the characteristics of PA are covered first. Then, the characteristics of the production-rule set PR are developed.

PA Characteristics. To investigate the PA set further, the number of strings contained in PA is determined.

<u>Theorem</u> 5.09: The set PA consisting of all possible 3-tuples

over F of the form amb meeting Definition 5.01

is countably infinite.

Proof: Because the alphabet F is countably infinite,

the proof of Theorem 5.02 can be applied

directly to this theorem. That is, let the

C0,C1,... be members of F instead of Z^+. Therefore, it

follows that PA is countably infinite. Also, the subset of

words where a=b is countably infinite for the PA case as

well. Q.E.D.

It is important not to try to prove that PA is countably

infinite by applying Theorem 3.17 of Section III. Theorem

3.17 requires, but does not so state, that the strings be

formal words. From Theorem 5.07, PA does not contain these

required formal words. But, PA can be forced to contain

formal words by restricting the set F to be finite.

<u>Theorem</u> 5.10: For an arbitrary, nonempty, finite subset of

F, FS, all of the production rules of the form

amb that meet Definition 5.01 over FS instead

of F are finite words.

Proof: Because FS is nonempty and finite, the overall

alphabet for the production rules, $FS \cup \{m\}$, is

also nonempty and finite. Therefore, these

production-rule strings meet the first of the

two constraints for formal words (see Defini-

tion 3.01 of Section III).

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The second constraint, finite length (see
Definition 3.02 of Section III), is met by the
constraint that $|a|=|b|=|m|=1$. Hence, each
amb string is of length three, a finite
number. Therefore, each amb string is a
finite word over FS $\cup$ {m}. Q.E.D.

Since production-rule words exist for this special case,
the search for a language-type can begin. But this search
is very short in comparison to the previous search for the
PR language.

<u>Theorem</u> 5.11: The set of production rules PF consisting of
all possible strings meeting Definition 5.01,
except that the facts are selected from an
arbitrary, finite subset FS of F, is a finite
set and hence a type-3 language.

Proof: Let the size of FS be a nonzero, finite
number, M. Following the same technique of
matrix construction used in Theorem 5.02,
construct the matrix equivalent of PF as shown
in Figure 14. The symbols C0,C1,...CM
represent the a and b fact-symbols in FS. The
symbol XX represents the a=b cases. The
symbol m is the implies relationship.

From Figure 14, the size of the matrix is
M^2. Because there is only one XX entry per
row, the overall size of PF is M(M-1). Since
M is finite, M(M-1) is also finite.

```
         CØ      Cl      C2    ...   CM
CØm      XX    CØmCl   CØmC2  ...  CØmCM

Clm    ClmCØ     XX    ClmC2  ...  ClmCM

C2m    C2mCØ   C2mCl    XX    ...  C2mCM

...      ...     ...     ...   ...   ...

CMm    CMmCØ   CMmCl   CMmC2  ...    XX
```

Figure 14.   PF Word Matrix

Therefore, PF consists of a finite number of
words.

Using PF's finite size, the fact that the
amb strings are words and applying Definitions
3.19, 3.21 and Theorem 3.12 of Section III, PF
is found to be a type-3 language.   Q.E.D.

Theorem 5.11 only dealt with a single arbitrary case of
converting a subset of strings in PA into some formal
language.   The next theorem expands this into a class of
languages.

Theorem 5.12: There exists a countably infinite number of
              finite production-rule languages where the
              nonempty fact-sets are selected from an
              arbitrary, countably infinite set of symbols.

       Proof: Theorem 5.11 was based on selecting a finite
              subset of facts from F.   Applying Theorem 3.10
              of Section III, there is a countably infinite

                              98

number of finite subsets in F. Because the empty set ϕ is always a finite subset of any set, the nonempty constraint requires that it be removed from this group of subsets. After removing the empty set and applying the $f(x)=x-1$ mapping on the indexes of the remaining subsets, there is still a countably infinite number of nonempty finite subsets available for use in generating finite production-rule languages. Hence, there exists a countably infinite number of finite production-rule languages. Q.E.D.

Because finite languages have been studied extensively by Maurer et al. (99; 100), further investigation of the characteristics of these finite production-rule languages is not accomplished. However, it is important to notice that when the facts are arbitrary, countably infinite, symbols, no single production-rule language exists that can contain all possible rules. See Section IX for discussions on additional affects that the knowledge-languages (see Definition 4.03 of Section IV) have on production rules.

Category 1 Class. Since the PR version of production rules does contain all possible production-rule words for a given Z, the characteristics of the PR language merit further investigation. Due to the fact that the general characteristics of context-free languages have been studied extensively, the "common" characteristics of type-2 lan-

guages (e.g. normal grammar forms, word membership algo-
rithm, parsing algorithm) of PR alone are not investigated
further. The reader is referred to references 6, 92, 93, 94,
95, 96 and the references in Appendix A for information on
how to determine these characteristics.

However, there are characteristics of the class of
languages which contains the PR language that directly
impact later findings. Therefore, the characteristics of
this class are covered in depth.

Theorem 5.13: Any set of production-rule words consisting of
all the words meeting Definition 4.01 of
Section IV, except that the set of facts for
each rule-set is any nonempty regular set over
Z, is at least a type-2 language.

Proof: This proof follows directly from
Haines (98) and Theorems 5.06 and 5.12.
Haines proved that for the centermarker-
languages, the x and y strings of the
centermarker-word xcy can be selected from any
regular set and the resulting language is type
2. Here, the equivalent x and y are selected
from any nonempty regular set over the
fact-alphabet Z. Therefore, each of the
production-rule languages in this theorem is
upper bounded at a type-2 language.

Now, to show the "at least" criterion, the
results of Theorems 5.06 and 5.12 are needed.

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Theorem 5.06 established that the production-rule set PR is exactly a type-2 language. Since PR uses a nonempty regular set Z^+ for the fact-set, PR meets the requirements of this theorem. Hence, a type-2 language exists that meets the constraints of this theorem.

Next, Theorem 5.12 established the existence of a countably infinite set of type-3 production-rule languages where the facts are selected from nonempty, finite, regular sets. If Z^+ is used as the arbitrary, countably infinite set for Theorem 5.12, then these finite language are also contained in the set of languages covered by this theorem.

Therefore, since both type-2 and type-3 production-rule languages are contained in the set of languages covered by this theorem, it follows from Chomsky's language-hierarchy (8) and the type-2 upper bound that these languages are at least type 2. Q.E.D.

As was shown in Theorem 5.13, the production-rule language PR is only one of a number of possible production-rule languages each of which has only category-1 characteristics (see Tables II and III of Section IV). The size of this class of languages provides another important characteristic.

Theorem 5.14: The production-rule language PR consisting of all words meeting Definition 4.01 of Section IV is a member of a countably infinite class of type-2 production-rule languages.

Proof: This proof follows from Theorem 3.18 of Section III and Theorems 5.02, 5.06, 5.12 and 5.13. Theorem 5.13 established that type-2 production-rule languages can be constructed provided the facts are selected from a non-empty regular set. Theorems 5.02 and 5.06 revealed the existence of at least one language containing a countably infinite number of words, PR, that meets the constraints of Theorem 5.13. By using Z^+ as the arbitrary countably infinite set, Theorem 5.12 shows the existence of a countably infinite set of finite production-rule languages that also meet the regular set constraint of Theorem 5.13. Since PR contains a countably infinite number of words, PR is not a member of this countably infinite set of finite languages. Hence, from set theory, the union of a finite set (the single PR language) and a countably infinite set (the finite languages) is countably infinite. So, PR is a member of a set of languages that is at least countably infinite in size.

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To prove the upper bound on this class, the size of language space is needed. Theorem 3.18 of Section III established that the size of language space for a given alphabet is countably infinite. Therefore, the upper bound for this class of production-rule languages is also countably infinite. Since both the upper and lower bounds agree, this class of production-rule languages is countably infinite in size. Q.E.D.

So, at the category-1 level of the definition-hierarchy (see Figure 12 in Section IV) there exist countably infinite numbers of production-rule languages (both finite and countably infinite in size) of which PR is a member. The fact that this class consists of all possible production-rule languages over regular fact-sets yields another characteristic of this class of languages.

Theorem 5.15: The class of category-1 languages consisting of production-rule languages where each language consists of all the words meeting Definition 4.01 of Section IV, except that the set of facts for each language is any nonempty regular set over Z, is not closed under the union operation.

Proof: This proof follows from construction of a counter-example. For this proof, arbitrarily select the Z alphabet as follows: Z={c, d, g,

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h, k}. For this alphabet, arbitrarily select
two finite, regular sets as follows: S1={c, d}
and S2={g, h}. Now, construct the two
production-rule languages for these sets:
L1={cmd, dmc} and L2={gmh, hmg}. Finally, using
these two languages, form a third language by
the union operation: L3={cmd, dmc, gmh, hmg}.

By this construction, L1 and L2 meet the
constraints needed to be members of the
specified class of category-1 languages. That
is, each of these two languages consists of
all the words meeting Definition 4.01 of
Section IV except that the facts are selected
from some nonempty regular set over Z. How-
ever, the language formed from their union,
L3, does not meet these constraints.

The language L3 consists of production-
rule words formed from a regular set of four
individual facts: S3={c, d, g, h}. But, L3 does
not contain all possible production-rule words
over S3. For example, the legal word "cmg" is
not contained in L3. Yet, by the definition
of the production-rule languages contained in
this class, this specific word (and others)
must be contained in the production-rule
language over the S3 set of facts. Therefore,

L3 is a finite language but is not a
production-rule language.

Since the union closure property requires
that the third language L3 also be in the
class, it follows that this class of category-
1 production-rule languages is not closed
under the union operation. Q.E.D.

This union closure property is not the only regular
operation that this class of production-rule languages does
not meet. This class also does not meet the product closure
property. The product of two languages is the concatenation
of a word from the first language to that of a word from the
second language in order to form the words contained in a
third language. To be closed under this operation, the
language formed by the product operation must also be in the
same class as the two original languages.

Theorem 5.16: The class of category-1 languages consisting
of production-rule languages where each
language consists of all of the words meeting
Definition 4.01 of Section IV, except that the
set of facts for each language is any nonempty
regular set over Z, is not closed under the
product operation.

Proof: This proof follows from the construction of a
counter-example. For any two production-rule
languages in this class of category-1 lan-
guages, the product operation generates

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strings of the form "AlmB1A2mB2." Because a production-rule word has only one implies symbol m, the product operation generates illegal rule-words. Hence, the strings generated by the product operation cannot be contained in any production-rule language. So, this class of category-1 production-rule languages is not closed under the product operation. Q.E.D.

These closure properties of this class of production-rule languages lead to another characteristic of this language class. This characteristic is that this class of production-rule languages does not form an Abstract Family of Languages (AFL) (24).

Theorem 5.17: The class of category-1 languages consisting of production-rule languages where each language consists of all words meeting Definition 4.01 of Section IV, except that the set of facts for each language is any nonempty regular set over Z, is not an AFL.

Proof: From reference 24, an AFL contains languages that are closed under six operations: union, product, Kleene closure, e-free homomorphism, inverse homomorphism and intersection with a regular set. From Theorems 5.15 and 5.16, this class of production-rule languages is not closed under either union or product.

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Therefore, this class of category-1 production-rule languages cannot be an AFL. Q.E.D.

The result of Theorem 5.17 presents a major stumbling block to the further study of this class of production-rule languages. Because this class is not an AFL, the determination of additional characteristics of the class has to involve the analysis of the entire set of languages in the class. Thus, the multitude of characteristics already proven about AFLs by formal language theorists cannot be used to help expand the characteristic-set of this class of languages.

The characteristics of AFLs are not the only characteristics that do not apply to this class of languages. The characteristics of the general class of type-2 languages also do not apply. For example, the entire set of Chomsky's type-2 languages form an AFL but this class of category-1 production-rule languages does not. Another example is that the entire set of Chomsky's type-2 languages is closed under the regular operations of union and product (6:12), yet this class of languages is not.

So, while this class of category-1 production-rule languages is a set of type-2 languages, characteristics of the general type-2 languages cannot be used, without proof, when referring to this class of production-rule languages. Even though other characteristics of this class of production-rule languages as well as characteristics of

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other classes of category-1 production-rule languages could be investigated, sufficient characteristics of production-rule languages have been identified for use in later investigations. The time has come to develop the semantic-network language equivalent.

VI. Semantic-Network Language and Characteristics

Since the 3-tuple form of a production-rule representation has been successfully evaluated via formal language theory, the investigation can now turn to the evaluation of the 3-tuple form of a semantic-network representation. Because both representations use a 3-tuple form, some theorems about semantic networks can be proven by arbitrarily mapping the symbol m to a single relation-word in the relation-set. To make extensive use of this mapping, the semantic-network development parallels that of the production-rule effort.

Semantic-Network Language

Following the production-rule methodology, there are two approaches that are used to determine a semantic-network language equivalent: node labels and relations are words; node labels and relations are symbols. However, for a semantic network there are two additional approaches that have to be considered: node labels are words and relations are symbols and vice versa. Because these last two approaches depend on the results of the "node label and relations are symbols" approach, they are addressed under that approach.

Case I: Word Approach. As was the case for the production-rule effort, the semantic-network development begins with analysis at the individual word level.

<u>Theorem</u> 6.01: Each set of semantic-network strings con-
structed under the constraints of Definition
4.02 of Section IV contains finite words of
the form arb.

Proof: From Definitions 3.01 and 3.02 of Section III,
a word over any nonempty, finite alphabet is
finite in length. From Definition 4.02, the
alphabets for the node-label set, Z, and the
relation-set, Y, are each nonempty and finite.
From set theory, the union of two finite sets
remain finite. Therefore, the alphabet over
which each arb string is constructed, $Z \cup Y$, is
nonempty and finite.

Each of the a, r and b components of the
overall string is finite in length (see
Definitions 3.03 and 3.04 of Section III).
Since the sum of finite numbers remains
finite, the length of arb is a finite number.
Therefore, each 3-tuple, arb, over $Z \cup Y$ is a
finite word. Q.E.D.

Now that the individual 3-tuples are known to be finite
words, the set "SN" can be constructed which contains all
the possible words over $Z \cup Y$ that meet Definition 4.02 of
Section IV. The size of this set can be determined by
expanding the proof given for the size of the PR production-
rule language (see Theorem 5.02 of Section V).

<u>Theorem</u> 6.02: The set SN contains a countably infinite

number of words.

Proof: The proof of this theorem follows directly

from Theorem 5.02 of Section V and Theorem

3.05 of Section III. For Theorem 5.02, Figure

12 was constructed for the case of words of

the form amb where m was a single symbol and

$a, b \in Z^+$. In that case, there were found to be

a countably infinite subset of cases for a=b

as well as countably infinite rows. Each row

was also found to contain countably infinite

entries. So, the entire set PR was found to

be countably infinite by application of the

Theorem 3.05: the union of a countable set of

countable sets remains countable.

Using this production-rule case, discard

the "implies" meaning attached to m and rename

the symbol m to be a single relation-word

"R1," where $R1 \in Y^+$. Then, let the fact-

alphabet Z be equated to the node-label

alphabet. Under this mapping, the proof of

Theorem 5.02 shows that there is a countably

infinite number of words of the form "aR1b" in

SN and a countably infinite number of a=b

cases for a given R1.

Now let R1 range over Y^+. Since Y^+ is

countably infinite (see Theorem 5.02 for the

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proof of the size of Z^+), there is a countably

infinite number of subsets of words "aR(i)b"

in SN, each containing countably infinite

words. By applying Theorem 3.05, SN is found

to contain a countably infinite number of

words. Additionally, it follows that the

union of all the countably infinite subsets

where a=b is countably infinite. Q.E.D.

Because the set SN contains a countably infinite number

of finite words, additional effort will be required to

determine if it is a formal language. That is, since SN is

not finite (a type-3 language), additional analysis is

required to determine the language-type (if any) of SN. The

semantic-network development follows the production-rule

approach of using Chomsky's finite language-hierarchy to

classify the languages (8). Additionally, the semantic-

network language is developed by first removing all the

constraints of Definition 4.02 of Section IV on the node

labels and relations. Then, each constraint is applied,

one at a time, so that the affects of these constraints

can be identified.

Theorem 6.03: The semantic network that contains all of

the words of the form arb, where Z and Y are

nonempty, disjoint, finite alphabets and
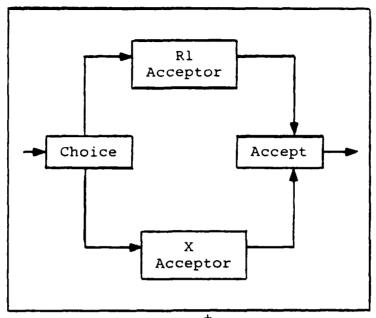
$a,b \in Z^*$, $r \in Y^*$, is a type-3 language.

Proof: The set of semantic-network words for this

case can be represented as the concatenation

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of three sets: $Z^*Y^*Z^*$. Because Y and Z are
finite, they are regular sets by Definition
3.19 of Section III. Applying Definition 3.19
once more, Z^* and Y^* are found to be regular
sets as well. Then, applying the concatenation
rule of Definition 3.19, $Z^*Y^*Z^*$ is found to be
a regular set. Applying Definition 3.21 and
Theorem 3.12 of Section III, this regular set
is proven to be a type-3 language. Q.F.D.

Now that the unrestricted case has been found to be a
type-3 language, let the constraint be applied that the
empty word, e, cannot be contained in either the node-label
or relation set and evaluate again.

Theorem 6.04: The semantic network containing all of the
words of the form arb, where Z and Y are
nonempty, disjoint, finite alphabets and
$a,b \in Z^+$, $r \in Y^+$, is a type-3 language.

Proof: In this case, the set of semantic-network
words can be represented as the concatenation
of three sets: $Z^+Y^+Z^+$. Because Z and Y are
finite alphabets, Z^+ and Y^+ are regular sets
(94:30-31). Applying the concatenation rule
of Definition 3.19 of Section III, $Z^+Y^+Z^+$ is a
regular set. Applying Definition 3.21 and
Theorem 3.12 of Section III, this regular set
is proven to be a type-3 language. Q.E.D.

The proof technique of Theorem 6.04 also applies to the cases where the empty word is allowed in one set (node labels or relations) but not the other. This conclusion follows from the fact that Z^*, Z^+, Y^* and Y^+ are all regular sets. The concatenation process on any mix of these sets still yields a regular set. Because the case proven in Theorem 6.04 already applies directly to the constraints of the semantic-network definition, these other mixed cases are not established as formal theorems.

Even though this empty word constraint does not cause the language-type to change, the $a \neq b$ constraint on the node labels affects the type-3 language finding. The following theorem relies heavily on the results found for the production-rule language.

Theorem 6.05: The semantic network, SN, consisting of all the words arb which meet Definition 4.02 of Section IV is not a type-3 language.

Proof: The proof will be by construction. First, assume that SN is a type-3 language. Then, from Definition 3.21 and Theorem 3.12 of Section III, all of the words in SN must be accepted by a finite automaton. Because the centermarker relation-set is a countably infinite regular set, this finite automaton must contain a finite number of states with looping paths to accept these relation-words. Since these relation-words are over a disjoint

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Figure 15. Y^+ Acceptor

alphabet, the states and interconnecting
paths, including the initial and final states
used to accept the relation-words, can be
identified within the automaton. This set of
states and paths can then be investigated
separately from the set accepting the node-
label words. Using construction techniques,
nondeterministic finite automaton is developed
that will accept the relation-words (see
Figure 15).

First, select a single relation R1 from
the relation-words Y^+. Next, construct a set
X such that $X=Y^+-\{R1\}$. Because Y^+ and $\{R1\}$ are
regular sets over Y, the difference closure
property of regular sets yields that X is also
a regular set (92:186).

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Now, let X-Acceptor and R1-Acceptor be the names of the finite automata that accept X and {R1}, respectively. Next, apply the union closure property of regular sets (92:186) and the equivalence in machine "power" of a nondeterministic finite automaton and a deterministic finite automaton (93:62) and construct an equivalent nondeterministic finite automaton accepting the relation-words Y^+. From Figure 15, this construction is accomplished by connecting the R1-Acceptor and X-Acceptor in a parallel fashion via a common initial state (the "choice" state of nondeterministic machines). Therefore, as words from Y^+ are entered, the equivalent automaton effectively executes both the R1-Acceptor and X-Acceptor in parallel during the acceptance process. The overall automaton halts in the final "accept" state when either the R1-Acceptor or X-Acceptor accepts the input relation-word.

Next, since SN is assumed to be a type-3 language and accepted by some finite automaton, use this equivalent nondeterministic finite automaton as the mechanism that accepts the Y^+ words during SN acceptance (see Figure 16). That is, replace the states and inter-

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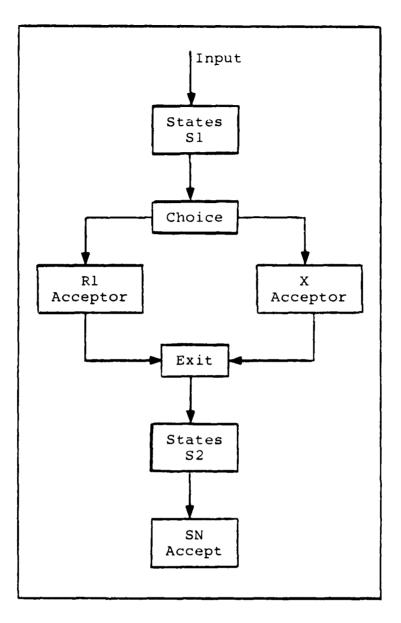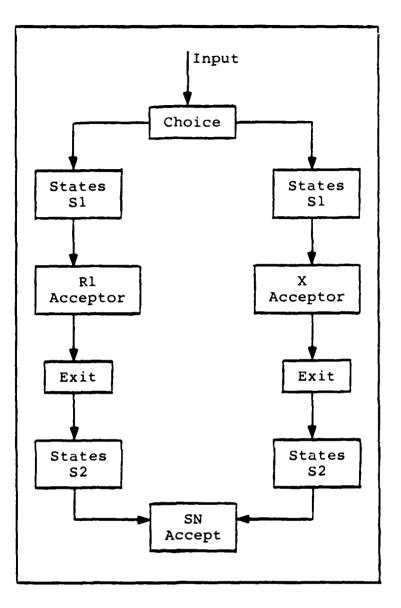
Figure 16. SN Acceptor

connecting paths previously used to accept Y^+

in the SN acceptor with this equivalent

nondeterministic finite automaton. Because

the SN machine does not necessarily halt upon

accepting the relation-word, change the accept

state to an "exit" state from the R1-Acceptor

and the X-Acceptor. Since neither changing

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the number finite states nor adding nondeterminism to a finite automaton changes the overall power of the machine (93), this exchange of Y^+ acceptors does not change the power of the original SN acceptor automaton.

In this exchange of Y^+ acceptors, the initial/final states of the Y^+ acceptor are the final/initial states for the S1 and S2 sets of states, respectively. This has to occur because the incoming and outgoing paths to/from the Y^+ acceptor were not modified.

After this new Y^+ acceptor is in place in the SN acceptor, words from SN are now constrained to follow one of the two paths when being accepted. That is, in operation, the overall SN acceptor can really be considered as passing through two independent sequences of states depending on the relation-word in the overall semantic-network word. For example, words of the form aR1b contained in SN can only be accepted by traversing the states of the R1-Acceptor. Recognizing this true separation of paths, the proof can now be finalized.

Because of this guaranteed separation of paths, this overall SN acceptor (Figure 16) can be replaced by an equivalent acceptor.

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Figure 17. Equivalent SN Acceptor

This equivalent acceptor contains an indepen-
dent path for words of the form aR1b and an

independent path for the words of the form

"aW(i)b" where W(i) X (see Figure 17). This

acceptor is constructed as follows: The

choice state is moved from the relation-word

subautomaton and placed as the initial state

in the overall machine. The original machine
states (finite in number) are then duplicated
in each of the choice paths, except that the
R1-Acceptor is used in one path and the
X-Acceptor is used in the other. Because the
initial choice state was moved, the initial
states in the R1-Acceptor and X-Acceptor
become the new final states for the S1 set of
states. This does not affect the operation of
the acceptors nor the set of S1 states since
the choice state effectively passed the same
set of incoming paths to the initial states
inside the two acceptors anyway. Also, the
exit state is duplicated for both acceptors.
The exit state remains both the final state
for the acceptors and the initial state for
the S2 states as before.

Therefore, this equivalent SN acceptor is
a nondeterministic finite automaton. The
automaton accepts words of the form aR1b by
following one set of independent states and
accepts words of the form aW(i)b by following
another set of independent states. Even
though there are duplicate states in each of
the two paths, these states are not inter-
connected in any manner. Because of the
placement of the choice state in the SN

acceptor, the two paths are effectively each a finite automaton accepting just words of the form aRlb and aW(i)b, respectively. In other words, since SN is assumed to be a regular set, the difference and union closure properties of regular sets can be used to form two other regular sets, {aRlb} and {aW(i)b}, whose union yields SN. Hence, the two separate automata accepting words of the form aRlb and aW(i)b, respectively, can be connected in parallel to accept the overall SN set.

Now, let m=Rl and let the arbitrary fact-alphabet and the arbitrary node-label alphabet be identical. If m is allowed semantically to be the implies relation of PR, this mapping results in this {aRlb} set becoming the PR language. So, this SN acceptor accepts the PR language as a special subset. But, this subset is actually accepted by a finite set of independent states in SN: a finite subautomaton. This PR set was previously proven not to be a type-3 (regular set) language. Hence, PR cannot be accepted by any finite automaton (see Theorem 5.05 of Section V). This is a contradiction of the regular set closure properties used to construct the {aRlb} regular set. Therefore, this finite

automaton (Figure 17) cannot accept all of the words in SN as previously assumed.

While this contradiction was found by constructing only one finite automaton, the contradiction condition also applies to any finite automaton that could be constructed to accept SN. The subautomaton that was constructed to accept Y^+ (see Figure 15) was based on the known closure relationships of the regular sets and the known equivalence of nondeterministic/deterministic finite automata. Hence, it follows that any other finite subautomaton constructed to accept the relation-words Y^+ has to be equivalent to the one constructed for this proof. That is, no matter how the Y^+ regular set is partitioned into regular subsets (subsets must remain regular to be accepted by a finite automaton), there always exists one subset where the difference closure property can be applied to construct the single symbol, {R1}, regular set. Then, using the union closure property and nondeterminism, the equivalent separate path for {R1} acceptance can be shown to exist and the contradiction condition can be identified.

In addition to this equivalence of all possible Y^+ acceptors, the accepting mechanism

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for the node-label words Z^+ and the a≠b

constraint have been adequately handled by the

abstract nature of the construction. That is,

the node-label words Z^+ were not manipulated

in any way by this construction. The accept-

ing mechanism for them was handled abstractly

in that two abstract sets of finite states, S1

and S2, were assumed to perform the recog-

nition of the node-label words as well as the

a≠b criterion. Therefore, all possible

finite automaton acceptors have been con-

sidered and the recognition of the node-label

words as well as the a≠b criterion.

Therefore, all possible finite automaton

acceptors have been considered and so SN has

been proven not to be a type-3 language.

Q.E.D.

The proof that SN is not a type-3 language relied on

SN's relationship to Haines' centermarker-languages (98).

By applying this relationship again, the actual language-

type of SN can be determined.

Theorem 6.06: The semantic network consisting of all the

words that meet Definition 4.02 of Section IV

is a type-2 language.

Proof: The proof of this theorem is by construction.

The construction relies heavily on Haines'

centermarker-languages and the type of machine

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that accepts them (98). First, since SN is
over Z^+, let M be the nondeterministic, single
pushdown-store, machine that accepts the
centermarker-language $CM=\{xcy \mid x,y \in Z^+, x \neq y, c \notin Z\}$. From the work of Haines, this machine
must exist.

Next, make use of the fact that c is a
disjoint, regular set and identify the finite
set of states and interconnecting paths in M
that are used to accept c. Since this center-
marker is only a single symbol, it may be the
case that a single path between two apparently
unrelated states is used for this acceptance.
For example, Haines used the c symbol to
change between the x and y acceptance schemes.
The symbol was effectively accepted by trav-
ersing a path between the states used in the
acceptance of other unrelated words.

However, these apparently unrelated states
are actually the initial and final states of
the subautomaton that accepts c. The key
point is that the initial and final states of
the automaton accepting c may actually perform
dual roles inside M. It is important to
include these dual-function states in the
subautomaton accepting c.

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Putting aside for the moment this mechanism that accepts c, the characteristics of the relation-set that are identical to the characteristics of the c centermarker are determined. The relation-set is a countably infinite, disjoint, regular set that does not contain the empty word (see Theorem 6.02). From Definition 3.21 of Section III, this relation-set must be accepted by some finite automaton. Hence, both the relation-set and the c centermarker are accepted by finite automata.

Another characteristic that the relation-set and the c centermarker share is that neither one contains the empty word. Hence, a relation-word must always exist in the words of SN just as c must always exist in the words of CM.

The third and final identical characteristic between the relation-set and c centermarker is that the relation-set is constructed from an alphabet that is disjoint from the node-label alphabet. Therefore, the relation-words are always easily identified from the node-label words. That is, the accepting states and paths of the relation-set are independent of the accepting states and paths

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for the node-label words. The c centermarker
also has this characteristic.

Based on these common characteristics and
the proof of Theorem 6.05, it follows that by
replacing the finite set of states and inter-
connecting paths accepting c with the finite
set of states and paths accepting the
relation-set, M then accepts words that
contain relation-words as the centermarkers.
Therefore, let M' be the machine M modified by
replacing the previously identified states and
paths used to accept c with a finite automaton
that accepts Y^+.

It is important to notice that this
replacement action did not modify either the
incoming paths to the initial state nor the
outgoing paths from the final states of the c
acceptor. This means that the previously
mentioned dual functions that some initial/
final states of the c acceptor may perform
remain unchanged. Additionally, the replace-
ment action did not change any other of the
states and interconnecting paths involving the
Z^+ words. It follows then that the $x \neq y$
constraint on the original set of words
remains unchanged. Hence, M' actually accepts
the words of SN.

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Finally, as long as the number of states remains finite, the power of any type of machine is not affected by changing the number of states (93). Therefore, M' still remains in the class of nondeterministic, single pushdown-store, machines. From reference 8, page 43, it follows that SN is at least a type-2 language. Applying Theorem 6.05, SN is found to be exactly a type-2 language. Q.E.D.

So, SN has been proven to be a type-2 language. By considering both the node-label and relation sets as languages themselves, this semantic-network language has been shown to be dependent on both the network's structure and the knowledge-language (see Definition 4.04 of Section IV) it contains. More is discussed about the characteristics of SN later. But first, consider the case where the node labels and the relations are defined to be symbols in an alphabet.

Case II: Symbol Approach. In order to "hide" the language characteristics of the node labels and relations in the semantic-network strings, the node labels and relations are treated as arbitrary entities. To achieve this, each node label and relation is considered to be a single alphabet-symbol of unit length. However, the disjoint nature of the node-label and relation sets is still maintained. Also, because only the individual characteristics of the node-label and relation words are hidden, each

alphabet of node labels and relations remains countably

infinite is size. Otherwise, the overall semantic-network

set does not contain all the possible node-label words in Z^+

and all the possible relation-words in Y^+. Using these

changes, the definition of a semantic-network is modified as

follows:

Definition 6.01: For any two arbitrary, disjoint, countably
infinite sets, LB and R, a semantic network
that has only category-1 characteristics
(see Tables IV, V and VI of Section IV) is
defined as a collection of 3-tuples. Each
3-tuple is of the form "arb" where "a" and
"b" represent individual node labels, "r"
represents the relation between the nodes,
$a, b \in LB$, $r \in R$, $|a|=|b|=|r|=1$ and $a \neq b$. The
form arb reads "a is related to b by r."
That is, the link arrow goes from a to b.

With this definition in hand, the first step is to

determine if arb is a formal word.

Theorem 6.07: Every semantic network constructed under the
constraints of Definition 6.01 consists of
only strings of the form arb that are not
finite words.

Proof: This follows directly from the definition of a
word. While the length of each string is
three and hence finite, it follows from
Theorem 3.05 of Section III that the

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overall alphabet, LB∪R, is countably infi-
nite. From Definitions 3.01 and 3.02 of
Section III, words are constructed from only
finite alphabets. Therefore, the strings are
not finite words. Q.E.D.

Similar to the production-rule development, the arbi-
trary node-label and relation conditions applied to the
semantic network force the strings not to be formal words.
Since a language has to have words, this countably infinite
alphabet leads to the following language theorem.

Theorem 6.08: The semantic network, SA, consisting of all
possible strings meeting the Definition 6.01,
is not a formal language.

Proof: Because languages require finite words as
members, SA can be proven not to be a formal
language immediately by applying Theorem 6.07.
However, to emphasize the critical nature of
the size of the alphabet, an alternate proof
is given.

Recall from Definition 3.07 of Section III
that a language is the set of all words that
can be generated from a grammar. From the
definition of a grammar (Definition 1.02 of
Section I), a grammar has to have a finite set
T of terminal symbols. The overall alphabet,
LB∪R, is this terminal-set T for the SA
grammar. But, this alphabet is countably

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infinite. Therefore, a grammar does not exist
that generates all the finite strings (words)
that are members of SA; thus SA cannot be a
type-0 formal language. Q.E.D.

As was the case for production rules, this theorem also
emphasizes that the finite length constraint on the symbol
strings is only a necessary but not sufficient condition to
make the strings formal words. This necessary condition is
emphasized not only for the case where both of the sets LB
and R are finite, but is also emphasized for the case where
either the node labels or relations, but not both, are
considered to be words in a language.

Theorem 6.09: Let either the node-label set or the relation-
set consist of all the words (except e) over a
nonempty, finite alphabet V and let the
remaining set be comprised of a countably
infinite set of symbols LB or R as needed.
Then, the semantic network, SK, formed from
all the possible strings meeting Definition
6.01, except $a, b \in V^+$ (or LB) and $r \in R$ (or V^+),
does not contain finite words.

Proof: This follows directly from the definition of a
word. While the length of a string is three
and hence finite, the overall alphabet, either
$LB \cup V$ or $V \cup R$, that the strings are con-
structed from is countably infinite. From
Definitions 3.01 and 3.02 of Section III,

words are constructed from only finite

alphabets. Therefore, the strings are not

finite words. Q.E.D.

Hence, the SK semantic network cannot contain finite

words. This lack of formal words leads to the next theorem

regarding the language-type of SK.

Theorem 6.10: Let either the node-label set or the relation-
set consist of all the words (except e) over a
nonempty, finite alphabet V and let the
remaining set be comprised of a countably
infinite set of symbols LB or R as needed.
Then, the semantic network, SK, formed from
all the possible strings meeting Definition
6.01, except a,b $\in V^+$ (or LB) and r $\in$ R (or V^+),
is not a formal language.

Proof: Recall from Definition 3.07 of Section III
that a language is the set of all words that
can be generated from a grammar. From the
definition of a grammar (Definition 1.02 of
Section I), a grammar has to have a finite set
T of terminal symbols. The overall alphabet,
LB $\cup$ V or V $\cup$ R, is this terminal-set for the SK
grammar. But, this alphabet is countably
infinite. Therefore, a grammar does not exist
that generates all the finite strings (words)
that are members of SK; thus SK cannot be a
type-0 formal language. Q.E.D.

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Theorems 6.08 and 6.10 reveal that when at least one of the disjoint sets of node labels and relations is constructed from an arbitrary, countably infinite alphabet, the semantic network cannot be a formal language. This is but one of the characteristics that have to be taken into account when attempting to map knowledge representations into formal languages. There are other characteristics that affect the SN, SA and SK semantic networks as well.

Semantic-Network Characteristics

Because of the abstract nature of the SA semantic-network definition (see Definition 6.01 and Theorem 6.08), the characteristics of SA are covered first. Since the SK semantic network (see Theorem 6.09) is only a variation on the SA network, it is not considered any further in this evaluation. Should the characteristics of SK be needed, they can be found by modifying the SA findings with the either/or case approach as was done in Theorems 6.09 and 6.10. However, the characteristics of the SN semantic-network language (see Theorem 6.06) are presented herein.

SA Characteristics. To investigate the SA semantic network further, the size of SA is determined.

Theorem 6.11: The SA semantic network, consisting of all possible 3-tuples of the form arb meeting Definition 6.01, is countably infinite.

Proof: Because the alphabets LB and R are each countably infinite, the proof of Theorem 6.02

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can be applied directly to this theorem. That

is, let the C0,C1,... of Figure 13 be members

of LB instead of Z^+. Then, let R1 range over

R instead of Y^+. Therefore, it follows that

SA is courtably infinite. Also the subset of

words where a=b is countably infinite for the

SA case as well. Q.E.D.

For reasons similar to those given for the PA

production-rule set, Theorem 3.17 of Section III cannot be

used to prove Theorem 6.11. However, the strings contained

in SA can be forced to be words by restricting both LB and R

to be finite sets.

Theorem 6.12: For an arbitrary, nonempty, finite subset of

LB, LBF, and an arbitrary, nonempty, finite

subset of R, RF, all of the strings that meet

Definition 6.01, except that the strings are

constructed from LBF and RF, are finite words.

Proof: Because LBF and RF are nonempty and finite,

the overall alphabet-set of the semantic-

network strings, LBF∪RF, is nonempty and

finite. Therefore, these semantic-network

strings meet the first of the two constraints

for formal words (see Definition 3.01 of

Section III).

The second constraint, finite length (see

Definition 3.02 of Section III), is met by the

constraint that $|a|=|b|=|r|=1$. Hence, each

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string is of length three, a finite number.
Therefore, each string is a finite word over
LBF ∪ RF.   Q.E.D.

Since the semantic-network words now exist, the search
for a language-type can begin.   But, this search is very
short in comparison to the previous search for the SN
language-type.

Theorem 6.13: For an arbitrary, nonempty, finite subset of
LB, LBF, and an arbitrary, nonempty, finite
subset of R, RF, the semantic network, SF,
consisting of all the semantic-network words
meeting Definition 6.01, except that the words
are over LBF and RF, is a finite set and hence
a type-3 language.

Proof: Let the size of LBF be a nonzero, finite
number, J.   Also let the size of RF be a
nonzero, finite number, K.   Following the same
technique of matrix construction used in
Theorem 5.02 of Section V and Theorem 6.02,
construct the SF set as a three-dimensional
matrix.   That is, for each of the K relations,
construct a two-dimensional matrix similar to
Figure 14 as follows: For each relation,
replace m in Figure 14 by the individual
relation and let C0,C1,...CM represent the
node labels in LBF.   Let the M value in Figure

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14 be equated to J. Finally, let the XX
symbol still represent the a=b cases.

For this three-dimensional matrix, each of
the two-dimensional matrices contain a total
of J(J-1) entries. Since there are K two-
dimensional matrices, the overall matrix
consists of J(J-1)K entries. But, J and K are
finite numbers. Therefore, J(J-1)K is a
finite number and so SF is a finite set.

Using this finite-size characteristic,
Theorem 6.12, and applying Definitions 3.19,
3.21 and Theorem 3.12 of Section III, SF is a
found to be a type-3 language. Q.E.D.

By constraining the node-label and relation sets to be
finite, a formal language can be obtained for the case where
node labels and relations are symbols. However, Theorem
6.13 only deals with a single arbitrary case of converting a
subset of strings in SA into some formal language. The next
theorem expands this finding to cover a class of languages.

Theorem 6.14: There exists a countably infinite number of
semantic-network languages where each language
is finite in size and consists of all the
words meeting Definition 6.01, except that the
node labels and relations are selected from
arbitrary, nonempty, disjoint, finite sets of
symbols.

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Proof: Theorem 6.13 was based on selecting a single,

finite subset of node labels from LB and a

single, finite subset of relations from R to

generate a semantic-network language that is

finite in size. Applying Theorem 3.10 of

Section III, there are a countably infinite

number of finite subsets that can be selected

from both LB and R. Now, from set theory, the

empty set ϕ is a finite subset of any set.

Hence, ϕ is a member of each of these count-

ably infinite sets of node labels and

relations.

Because of the nonempty-constraint, these

empty sets must be removed from the sets of

node labels and relations. By applying the

$f(x)=x-1$ mapping on the indexes of the remain-

ing finite sets of both node labels and

relations, there still exists a countably

infinite number of finite subsets of node

labels and relations.

Now, construct the matrix given in Figure

18, where the rows represent the relation-set

used to generate a given semantic-network

language and the columns represent the associ-

ated node-label set. That is, each entry

represents a node-label and relation set that

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	LBF0	LBF1	LBF2	..
RF0	RF0,LBF0	RF0,LBF1	RF0,LBF2	..
RF1	RF1,LBF0	RF1,LBF1	RF1,LBF2	..
RF2	RF2,LBF0	RF2,LBF1	RF2,LBF2	..
..	..	..	..	..

Figure 18. Node-Label and Relation Sets

can be used to generate a finite semantic-
network language.

Since there is a countably infinite
number of finite node-label sets, each row in
this matrix has a countably infinite number of
entries. By performing the union operation on
the countably infinite number of rows and
applying Theorem 3.05 of Section III, there is
a countably infinite number of unique entries
in the matrix. Therefore, there exists a
countably infinite number of unique semantic-
network languages that are finite in size.
Q.E.D.

Because finite languages have been studied extensively
by Maurer et al. (99; 100), further investigation of the
characteristics of these finite semantic-network languages
is not provided. However, it is important to notice that
when the node labels and relations are selected from arbi-

trary, countably infinite, disjoint symbols, then no single semantic-network language exists that can contain all the possible semantic-network words. See Section IX for additional affects of the node-label and relation languages on the semantic-network languages.

Category 1 Class. Since the SN version of the semantic network does contain all possible semantic-network words for given Z and Y alphabets, the characteristics of the SN language merit further investigation. Due to the fact that the general characteristics of context-free languages have been studied extensively, the common characteristics of type-2 languages (e.g. normal grammar forms, word membership algorithm, parsing algorithm) that apply to SN are not investigated further. The reader is referred to references 6, 92, 93, 94, 95, 96 and to the references contained in Appendix A for information on how to determine these individual type-2 characteristics.

However, there are characteristics of a class of semantic-network languages that contains the SN language that directly affect later findings of this investigation. The characteristics of this class are covered in depth.

Theorem 6.15: Any semantic network consisting of all the words meeting Definition 4.02 of Section IV, except that the node-label set and the relation-set are any nonempty, regular sets over Z and Y, respectively, is at least a type-2 language.

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Proof: This proof follows directly from Haines (98)

and the proofs of Theorems 6.06 and 6.14.

Haines proved that for any centermarker-

language where the x and y strings of the

centermarker-word xcy are selected from any

regular set, the resulting language is type 2.

By applying the constraint of a nonempty,

regular set on the node labels, Haines'

necessary condition for the type-2 language

finding is met. The nonempty-constraint comes

from the network's definition and does not

affect Haines' theorem in any way.

However, the constraint that the center-

marker is only a single symbol is not met.

Theorem 6.06 resolved this constraint for one

regular relation-set by showing that the same

type of machine (not identical machines) that

accepts Haines' centermarker-languages also

accepts the SN language. The key in that

proof was the replacement of the c accepting

mechanism with the finite automaton that

accepts the Y^+ relation-words.

Since Definition 3.21 of Section III

establishes that all regular sets are accepted

by some finite automaton, the proof of Theorem

6.06 can be expanded to include any nonempty

regular set of relation-words. That is,
replace the c accepting mechanism with the
specific finite automaton that accepts the
nonempty, regular relation-set. The nonempty-
constraint maintains the condition that a
centermarker must exist for these words.
Since the power of a machine does not change
by adding (subtracting) a finite set of states
to (from) a machine (93), the type of machine
does not change for any nonempty, regular
relation-set. Hence, these semantic-network
languages are upper bounded at type 2.

Now, to show the "at least" constraint,
Theorems 6.06 and 6.14 are needed. Theorem
6.06 established that SN is exactly a type-2
language. Since SN uses nonempty, regular,
node-label and relation sets, SN must be
contained in the class of category-1 languages
covered by this theorem.

Next, Theorem 6.14 established the exist-
ence of a countably infinite set of type-3
semantic-network languages where the node
labels and relations are selected from dis-
joint, nonempty, finite regular sets. If Z^+
and Y^+ are used as the countably infinite sets
of symbols in Theorem 6.14, then these finite
languages are also contained in the class of

category-1 languages covered by this theorem.

Therefore, since both type-2 and type-3

semantic-network languages are contained in

this class of category-1 languages covered by

this theorem, it follows from Chomsky's

language-hierarchy (8) and the upper type-2

language bound that these semantic-network

languages are at least type-2. Q.E.D.

As seen from Theorem 6.15, SN is only one of a number of

possible semantic-network languages each of which has only

category-1 characteristics (see Tables IV, V and VI in

Section IV). The actual size of this class of languages

provides another important characteristic.

Theorem 6.16: The SN semantic-network language, consisting

of all the words meeting Definition 4.02 of

Section IV, is a member of class of languages

that consists of a countably infinite number

of type-2 semantic-network languages.

Proof: This proof follows from Theorem 3.18 of

Section III and Theorems 6.02, 6.06, 6.14 and

6.15. Theorem 6.15 established that type-2

semantic-network languages can be constructed

provided the node labels and relations are

selected from nonempty, disjoint, regular

sets. Theorems 6.02 and 6.06 revealed the

existence of at least one language that is

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countably infinite in size, SN, that meets the

constraints of Theorem 6.15. By using Z^+ and

Y^+ as the arbitrary, countably infinite sets,

Theorem 6.14 shows the existence of a count-

ably infinite set of semantic-network

languages each of which is finite in size and

also meets the regular-set constraints of

Theorem 6.15. Hence, since SN is countably

infinite in size, SN cannot be contained in

this countably infinite set of finite lan-

guages. From set theory, the union of a

finite set and a countably infinite set is

countably infinite. So, SN is a member of a

set of languages that is at least countably

infinite in size.

To prove the upper bound, the size of

language space is needed. From Theorem 3.18

of Section III, there exists a countably

infinite number of languages over a given

alphabet. Therefore, the upper bound for this

class of category-1 languages is countably

infinite. Since both the upper and lower

bounds agree, this class of semantic-network

languages is countably infinite in size.

Q.E.D.

So, at the category-1 level of the definition-hierarchy

(see Figure 12 in Section IV) there exist countably infinite

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numbers of semantic-network languages of which SN is a member. The fact that this class consists of all possible languages over the regular node-label and relation sets yields a further characteristic about this class of category-1 languages.

Theorem 6.17: The class of category-1 languages consisting of semantic-network languages where each language consists of all the words meeting Definition 4.02 of Section IV, except that the node-label and relation sets for each language are any nonempty, regular sets over Z and Y, respectively, is not closed under the union operation.

Proof: This proof follows from construction of a counter-example. For this proof, arbitrarily select the Z and Y alphabets as follows: Z={c, d, g, h, k} and Y={p, s, t, x, y}. For the Z alphabet, arbitrarily select two finite, regular sets as follows: S1={c, d} and S2={g, h}. For the Y alphabet, arbitrarily select two finite, regular sets as follows: T1={p, t} and T2={x, y}. Now, construct two semantic-network languages using S1-T1 and S2-T2 as the node-label and relation sets: L1={cpd, dpc, ctd, dtc} and L2={gxh, hxg, gyh, hyg}. Finally, using these two languages, form a third language by

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the union operation: L3={cpd, dpc, ctd, dtc,

gxh, hxg, gyh, hyg}.

By this construction, L1 and L2 meet the

constraints needed to be members of this class

of semantic-network languages. That is, each

of these two languages consists of all the

words meeting Definition 4.02 of Section IV

except that the node labels and relations are

selected from some nonempty, regular sets over

Z and Y, respectively. However, the language

formed from their union, L3, does not meet

these constraints.

The L3 language contains semantic-network

words formed from regular sets of four indi-

vidual node labels, S3={c, d, g, h} and four

individual relations, T3={p, t, x, y}. But, L3

does not contain all possible semantic-network

words over the S3 node-label set and the T3

relation-set. For example, the legal

semantic-network word "cxg" is not contained

in L3. Yet, by definition of the semantic-

network languages contained in this class of

category-1 languages, this specific word (and

others) must be contained in a semantic-

network language over S3 and T3. Therefore,

L3 is a finite language but is not a semantic-

network language over these regular sets.

Since the union closure property requires that

L3 be in the class, it follows that this class

of category-1 languages is not closed under

the union operation. Q.E.D.

As was the case for the class of category-1 production-

rule languages (see Theorem 5.16 of Section V), this union

closure property is not the only regular operation that this

class of semantic-network languages does not meet. The

class also does not meet the product closure property. (The

reader is referred to the paragraph preceding Theorem 5.16

of Section V for the definition of product closure).

Theorem 6.18: The class of category-1 languages consisting

of semantic-network languages where each

language consists of all the words meeting

Definition 4.02 of Section IV, except that the

node-label and relation sets for each language

are any nonempty regular sets over Z and Y,

respectively, is not closed under the product

operation.

Proof: This proof follows from the construction of a

counter-example. For any two semantic-network

languages in this class of category-1 lan-

guages, this product operation will generate

strings of the form "A1R1B1A2R2B2." Because a

semantic-network word has only one relation-

word, the product operation generates illegal

network-words. Hence, the strings generated

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by the product operation cannot be contained in any semantic-network language. So, this class of category-1 semantic-network languages is not closed under product. Q.E.D.

These nonclosure properties of this class of semantic-network languages lead to the last characteristic of this class of languages that is presented in this section. This characteristic is that this class of semantic-network languages does not form an Abstract Family of Languages.

Theorem 6.19: The class of category-1 languages consisting of semantic-network languages where each language consists of all of the words meeting Definition 4.02 of Section IV, except that the node-label and relation sets for each language are any nonempty regular sets over Z and Y, respectively, is not an AFL.

Proof: From reference 24, an AFL contains languages that are closed under six operations: union, product, Kleene closure, e-free homomorphism, inverse homomorphism and intersection with a regular set. From Theorems 6.17 and 6.18, this class of category-1 semantic-network languages is not closed under either union or product. Therefore, this class of category-1 semantic-network languages cannot be an AFL. Q.E.D.

The result of Theorem 6.19 presents a major stumbling

block to the further study of this class of category-1

semantic-network languages. Because this class is not an

AFL, the determination of additional characteristics of this

class has to involve the analysis of the entire set of

network-languages in the class. Thus, the multitude of the

characteristics proven about AFLs by formal-language

theorists cannot be used to help expand the characteristic

set of this class of languages.

The characteristics of AFLs are not the only character-

istics that do not apply to this class of languages. The

characteristics of the general class of type-2 languages

also do not apply. For example, the entire set of Chomsky's

type-2 languages forms an AFL but this class of category-1

semantic-network languages does not. Another example is

that the entire set Chomsky's type-2 languages is closed

under the regular operations of union and product (6:12),

yet this class of languages is not.

So, while this class of category-1 semantic-network

languages is a set of type-2 languages, the characteristics

of the general type-2 languages cannot be used, without

proof, when referring to this class of languages. Even

though other characteristics of this class of languages as

well as the characteristics of other classes of category-1

semantic-network languages could be investigated, sufficient

information is now known such that the comparison of the

production-rule and semantic-network languages can begin.

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VII. Comparison of Rules and Networks

In Sections V and VI, the characteristics of the
production-rule and semantic-network languages were found to
be similar. At the category-1 level of the definition
hierarchies (see Section IV), there exist special classes
consisting of countably infinite numbers of production-rule
and semantic-network languages. Each language in those
classes is at most a type-2 language. However, each of the
classes itself is not an Abstract Family of Languages (24).
Because of these similarities, the question of equivalence
(one-for-one and onto) of these representation languages
comes to the forefront of this investigation. Therefore,
this section begins by investigating the production-rule and
semantic-network language equivalence, then, transforma-
tions between these languages are analyzed.

Equivalences

The question of equivalence between these two represen-
tation languages can be answered for two cases. The first
case is the trivial one where the implies relation does not
exist as a semantic-network relation and the bijective
mapping R1=m/m=R1 between one word in the relation-set and
the symbol m is not allowed. Because the fact-set and the
node-label set are arbitrary, these two sets can be mapped
into one another by using alphabets of the same size.

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However, if the m and relation centermarkers have no common mapping, then these two languages cannot be equivalent.

The second case is where either the implies relation does exist as a semantic-network relation or the bijective mapping R1=m/m=R1 between one word in the set of relations and the symbol m is allowed. Under either one of these conditions, equivalence of special sets of languages are shown to exist. For clarity in stating theorems that depend on these mapping conditions, the conditions are restated in the following definition of "condition-A." The theorem statements will then refer to these mapping conditions by stating that the languages meet condition-A.

Definition 7.01: Production-rule and semantic-network languages are said to meet condition-A if either the implies relation does exist as a semantic-network relation or the bijective mapping R1=m/m=R1 between one word in the relation-set and the symbol m is allowed.

Using this definition, the first of several equivalence theorems is given as follows:

Theorem 7.01: For the special classes of category-1 production-rule and semantic-network languages (see Theorem 5.13 of Section V and Theorem 6.15 of Section VI for class definitions), there exists a countably infinite set of equivalent pairs of finite production-rule and

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finite semantic-network languages. The
languages in this set meet condition-A.

Proof: This proof relies on construction. First,
consider the fact and node-label sets.
Because the production-rule's set of facts and
the semantic-network's set of node labels are
constructed from arbitrary, nonempty, finite
alphabets, a simple bijective mapping between
the alphabets can be used as the basis for
mapping between these sets. This mapping
consists of making the size of the alphabet
symbols of these two sets the same and
equating the alphabet symbols one-to-one.
Then, by applying the regular set constraint
on these isomorphic alphabets, isomorphic
fact and node-label word-sets results.

Next, for each of these isomorphic
alphabets, perform the e-free Kleene closure
(i.e. Z^+) and select all possible finite
subsets. From Theorem 3.10 of Section III and
the fact that these alphabets are isomorphic,
this action results in the formation of a
countably infinite number of pairs of isomor-
phic finite subsets. Because the empty set ϕ
is a finite subset of every set, one pair of
these isomorphic sets involves the empty set.
Since the fact and node-label sets cannot be

empty, this isomorphic pair must be removed
from this group of isomorphic pairs. By
applying the $f(x)=x-1$ mapping to the indexes
of the remaining pairs of isomorphic subsets,
there is still a countably infinite number of
pairs of isomorphic finite subsets.

Now that the finite fact and node-label
sets have been isomorphically mapped, con-
struct the finite set of relation-words needed
for the centermarker mapping as follows. For
the relation-alphabet Y, perform the e-free
Kleene closure Y^+. From this countably
infinite set, apply Theorem 3.10 of Section
III to obtain the countably infinite number of
finite subsets of relation-words. As before,
remove the empty set ϕ and apply the $f(x)=x-1$
mapping to the indexes of the remaining
subsets to obtain a countably infinite number
of nonempty, finite relation-sets. Then, from
these finite relation-sets, select the single-
element set that either contains the implies
relation or contains the relation where the
bijective mapping of R1=m/m=R1 is allowed
(only one subset exists). This relation-set
becomes the isomorphic centermarker for the
two language versions.

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With the fact, node-label and relation
sets established, consider first the mapping
of semantic networks to production rules.
Construct the semantic-network languages as
follows: Pair up each of the sets of node-
labels previously constructed with the
relation-set consisting of the isomorphic
centermarker. Then, using each of these
pairs, construct a finite semantic-network
language (see Theorem 6.13 of Section VI for
proof of the finite cardinality). The lan-
guage is constructed to consist of all the
words meeting the constraints of Definition
4.02 of Section IV, except the node-label and
relation sets are finite sets of words.
Because the node-label and relations sets are
finite, each set is also a regular set (see
Definition 3.19 of Section III). Therefore,
each of these finite semantic-network
languages is a member of the special class of
category-1 semantic-network languages (see
Theorem 6.15 for class definition). Also,
since there is a countably infinite number of
these finite node-label sets, there is a
countably infinite number of finite
semantic-network languages that are
constructed.

Now, to each of these finite
semantic-network languages, apply the bijec-
tive mapping m=Rl and exchange each node-label
word with its previously constructed isomor-
phic fact-word. For each network-language,
this action results in the generation of an
equivalent, finite, production-rule language.
Because each of the equivalent production-rule
languages has an associated finite, and hence
regular, set of facts, each rule-language is a
member of the special class of category-1
production-rule languages. Since there is a
countably infinite number of these finite
semantic-network languages, there is a
countably infinite number of production-rule
languages generated.

Next, consider the mapping of production
rules to semantic networks. Use each of the
finite fact-sets constructed previously and
construct the countably infinite set of finite
production-rule languages (see Theorem 5.11 of
Section V for proof of the finite cardinal-
ity). Each language is constructed to consist
of all the words meeting the constraints of
Definition 4.01 of Section IV, except the
fact-set is a finite set of words. Since each
set of facts is finite in size and hence

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regular, each language is a member of the
special class of category-1 production-rule
languages.

Now, to each of these production-rule
languages, apply the bijective mapping Rl=m
and exchange each fact-word with its pre-
viously constructed isomorphic node-label
word. For each rule-language, this action
results in the generation of an equivalent,
finite, semantic-network language. Because
each of the equivalent semantic-network
languages has finite, and hence regular, sets
of node labels and relations, each network-
language is a member of the special class of
category-1 semantic-network languages. Since
there is a countably infinite number of these
finite production-rule languages, there is a
countably infinite number of semantic-network
languages generated.

Finally, because the rule-to-network
mapping uses exactly the same isomorphic fact,
node-label and relation sets as the network-
to-rule mapping, the network (rule) language
that is produced as a result of the rule-
to-network (network-to-rule) mapping is
identical to the network (rule) language used
to generate the original rule (network)

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language. Therefore, the rule-to-network and
network-to-rule mappings produce pairs of
equivalent, finite, production-rule and
semantic-network languages. Hence, there
exists a countably infinite number of pairs of
equivalent, finite production-rule and finite
semantic-network languages. Q.E.D.

Even though there is a countably infinite number of
pairs of equivalent finite languages, there still exists a
countably infinite number of finite semantic-network
languages that are not equivalent to any of the finite
production-rule languages.

Theorem 7.02: For the special classes of category-1
production-rule and semantic-network languages
(see Theorem 5.13 of Section V and Theorem
6.15 of Section VI for class definitions),
there exists a countably infinite number of
finite semantic-network languages that are not
equivalent to any finite production-rule
language.

Proof: This follows directly from the proof of
Theorem 7.01. In that proof, the isomorphic
mapping between pairs of production-rule and
semantic-network languages uses only one of
the countably infinite, finite relation-sets
for the centermarker mapping. For a given
alphabet Z and Y, there still exist the other

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semantic-network languages that can be con-
structed out of the remaining finite relation-
sets. These languages are not equivalent to
any finite production-rule language. This is
shown in Figure 18.

In Figure 18, let the RFØ relation-set be
the single-element relation-set of Theorem
7.Ø1. Next, let each LBF(i) represent one of
the finite node-label sets of Theorem 7.Ø1.
Then, the row marked RFØ represents the
isomorphic set of semantic-network languages
of Theorem 7.Ø1. The remaining rows represent
the other finite semantic-network languages
that are not equivalent to any finite
production-rule language. They cannot be
equivalent because the relation-sets used to
construct them either contain more than one
relation-word or do not contain the necessary
centermarker relation-word.

Continuing to refer to Figure 18, remove
the RFØ row from the matrix. Using the
additional mapping of $f(x)=x-1$ on the indexes
of these remaining finite relation-sets, there
still exists a countably infinite number of
rows in this matrix. Since each row repre-
sents the pairing of a finite relation-set
with each of the countably infinite number of

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finite, node-label sets of Theorem 7.01, there is a countably infinite number of semantic-network languages possible per row. Applying Theorem 3.05 of Section III to the union of these remaining rows, there is a countably infinite number of finite, semantic-network languages that are not equivalent to any finite production-rule language. Q.E.D.

Now that the equivalence and nonequivalence cases for finite production-rule and semantic-network languages have been determined, the same cases for languages having countably infinite cardinality need investigating. First, the equivalence of the production-rule language, PR, and the semantic-network language, SN, is determined.

Theorem 7.03: The category-1 production-rule language, PR, that consists of all the words meeting Definition 4.01 of Section IV, is not equivalent to the semantic-network language, SN, that consists of all the words meeting Definition 4.02 of Section IV. These languages meet condition-A.

Proof: As was the case for the previous two theorems, this proof also relies on construction. First, let the fact and node-label alphabets used in PR and SN be bijectively mapped by equating their symbols as was done in Theorem 7.01. Then, the required closure, Z^+, yields

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isomorphic fact and node-label word-sets
between the rule and network languages.

Next, perform the Y^+ closure on the
relation-alphabet. In this set, identify the
relation Rl where the bijective mapping to the
m symbol is allowed. Using this Rl word,
group together all the words in SN that
contain Rl as their relation-word. Because of
the isomorphic mapping of the fact and node-
label sets and the Rl=m/m=Rl mapping, this
group of SN words is equivalent to the PR
language.

However, there exist additional words in
SN that are not contained in this isomorphic
group of words. This follows directly from
the fact that Rl is a single word and Y^+
contains countably infinite words. Therefore,
there exist words in SN where the relation in
the word is not bijectively mapped to m.
Hence, all the words in SN cannot be bijec-
tively mapped into all of the words of PR and
so PR and SN cannot be equivalent. Q.E.D.

Even though PR and SN are not equivalent, there exists
one category-1 semantic-network language that is equivalent
to PR.

Theorem 7.04: There exists only one category-1 semantic-
network language that is equivalent to the

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production-rule language PR. These languages
meet condition-A.

Proof: This proof is by construction. Construct a
subset of the special category-1 semantic-
network languages (see Theorem 6.15 of Section
VI for class definition) as follows. For each
semantic-network language in this subset, use
the Z^+ regular set as the node-label set and
one of all the possible unique regular sets
over Y for the relation-set.

Now, use the techniques of Theorem 7.01 to
bijectively map the node-label alphabet to the
fact-alphabet of PR. Then, the Z^+ closure
yields isomorphic fact and node-label word-
sets. Because PR is constructed from only the
Z^+ regular set, only those network-languages
in this specially constructed subset of
network-languages can possibly be equivalent
to PR.

Next, apply the bijective mapping of
R1=m/m=R1 to one and only one of the semantic-
network's relations. Because each of the
relation-sets is a unique regular set, there
exists one and only one semantic-network
language in this subset of network-languages
that has the single R1 relation as its
relation-set. Since this semantic-network

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language is constructed over the required Z^+ node-label set and the R1=m/m=R1 mapping applies to the only relation-word in this network-language, it is the only category-1 semantic-network language that can be mapped to PR.

Finally, using the techniques of Theorem 7.01 and reversing the steps of this proof, PR can be shown to map to this identical semantic-network language. Hence, there exists only one category-1 semantic-network language that is equivalent to PR. Q.E.D.

By using different, countably infinite, regular subsets of Z^+ for the node labels (e.g. $Z^+-\{F(i)\}$, $F(i) \in Z^+$), Theorem 7.04 can be expanded to show that there exists a countably infinite set of pairs of equivalent production-rule and semantic-network languages. Each language in one of these pairs has countably infinite cardinality. However, by using different regular subsets of Y^+, it is shown that there exists a countably infinite set of semantic-network languages that are not equivalent to any production-rule language. The semantic-network languages in this set have countably infinite cardinality.

Theorem 7.05: There exists a countably infinite number of countably infinite category-1 semantic-network languages that are not equivalent to any

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countably infinite category-1 production-rule language.

Proof: This proof is by construction. First, apply the bijective map between the fact-alphabet and the node-label alphabet and construct the isomorphic fact and node-label sets. However, there is an additional constraint on these sets. From the proofs of Theorem 5.02 of Section V and Theorem 6.02 of Section VII, any production-rule or semantic-network language that has countably infinite cardinality has a countably infinite fact-set or a countably infinite node-label (or relation) set, respectively. So, for the first part of this proof, select a countably infinite regular set for the isomorphic fact and node-label sets.

Next, using this countably infinite node-label set, construct a set of countably infinite semantic-network languages as follows. First, perform the Y^+ closure on the relation-alphabet to generate all the relation-words. Then, for each relation $R(j)$ in Y^+, construct the relation-set $Y^+-\{R(j)\}$. Since Y^+ and $\{R(j)\}$ are each regular sets, applying the difference closure property of regular sets yields that each of these new relation-sets are also regular sets (92:186).

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Because they are regular sets, they can be
used to construct semantic-network languages
that are contained in the special class of
category-1 languages (see Theorem 6.15 for
class definition). Each of these languages
has countably infinite cardinality. There-
fore, for each of these relation-sets and the
given node-label set, construct a set of
countably infinite category-1 semantic-network
languages.

Now that a set of countably infinite size
semantic-network languages has been con-
structed, the size of this set can be deter-
mined. Since Y^+ has of a countably infinite
number of individual relations $R(j)$, there is
a countably infinite number of $Y^+-\{R(j)\}$ regular
sets that can be constructed. Because each of
these semantic-network languages is con-
structed from one of these regular relation-
sets, it follows that this set of network-
languages is countably infinite in size.

With the size of this set established, all
that remains is to show that the semantic-
network languages in this set cannot be
equivalent to any production-rule language.
First, by applying the $f(x)=x-1$ mapping to the
remaining relation-words in each of the

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$Y^+ - \{R(j)\}$ relation-sets, each of these regular
relation-sets is found to be countably infi-
nite in size. Hence, no semantic-network
language exists in this set of network-
languages that has a relation-set of length of
one.

Because of this characteristic, it follows
from the proof of Theorem 7.03 that each
semantic-network language in this set of
network-languages contains words that cannot
be isomorphically mapped to any words con-
tained in any category-1 production-rule
language. Therefore, there exists a countably
infinite set of countably infinite category-1
semantic-network languages that are not
equivalent to any category-1 production-rule
language.

Finally, from Theorem 3.18 of Section III,
because there only exists a countably infinite
number of possible languages, there is at most
a countably infinite number of unique node-
label sets that can be used to construct other
sets of these semantic-network languages.
From Theorem 3.05 of Section III, the union of
all these sets of semantic-network languages
yields a countably infinite number of count-
ably infinite category-1 semantic-network

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languages that are not equivalent to any
countably infinite category-1 production-rule
language. Q.E.D.

With the proof of Theorem 7.05 complete, sufficient
information now exists to reach the general conclusion on
the equivalence of the special classes of category-1 rule
and network languages.

Theorem 7.06: The special class of category-1 production-
rule languages is not equivalent to the
special class of semantic-network languages
(see Theorem 5.13 of Section V and Theorem
6.15 of Section VI for class definitions).

Proof: Because finite languages cannot be equivalent
to countably infinite languages, it follows
from Theorems 7.02 and 7.05 that this special
class of category-1 semantic-network languages
contains finite and countably infinite lan-
guages that are not equivalent to any
production-rule language. Therefore, the
special class of category-1 semantic-network
languages is not equivalent to the special
class of category-1 production-rule languages.
Q.E.D.

So, even though special cases of equivalent production-
rule and semantic-network languages exist, these special
classes of category-1 production-rule and category-1
semantic-network languages are not equivalent. Further

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details of the impact of this finding are given in Sections VIII and IX. While these classes of languages are not equivalent, the question now arises about the ability to transform one type of language into another by any kind of mapping.

Transformations

Transforming one language into another depends on the ability to convert the constrained words of one language into the constrained words of the other. Or, in equivalent fashion, the ability to transform the grammar generating one language into one that generates the new language. From the proofs of Theorems 7.01 and 7.04, the transformation from a production-rule language to a semantic-network language is seen to be straightforward. Therefore, the rule-to-network transformation is considered first.

Theorem 7.07: Any production-rule language contained in the special class of category-1 rule-languages can be transformed into an equivalent category-1 semantic-network language that is contained in the special class of category-1 network-languages (see Theorem 5.13 of Section V and Theorem 6.15 of Section VI for class definition) by the following transformation:

1. Equate the fact and node-label alphabets and word-sets.

2. Equate the single implies symbol m to a single relation-word that is over an

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alphabet disjoint from the node-label
alphabet and use this word as the
entire relation-set.

3. Replace the terminal sets as described
    in steps 1 and 2 in the production-
    rule grammar and use the resulting
    grammar to obtain the semantic-network
    language.

Proof: Step 1. From Theorem 5.13 of Section V,
any production-rule language in the special
class of category-1 rule-languages has a
regular set over Z for the facts. From
Theorem 7.01, by assigning the fact-
alphabet to be the same alphabet for the
node labels, the regular set of facts
becomes the node-label set. This causes
the node-label set to become a regular set.
Hence, the first requirement of a category-
1 semantic-network language, a regular
node-label set, is met.

Step 2. By assigning the m symbol to a
single relation-word over an alphabet
disjoint from the node-label alphabet and
making this relation-word the entire
relation-set for the network-language,
another condition for the category-1
semantic-network language is satisfied.

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This condition is that the relation-set be a regular set disjoint from the node-label alphabet.

Step 3. Word-for-word transformations can be applied to generate the category-1 semantic-network language with the constraint, "consists of all the words over the node-label and relation sets where a≠b," upheld. That is, by replacing the fact-words with the node-label words and the m symbol with the single relation-word, this constraint that is already existing in the production-rule language is automatically passed on to the semantic-network language. However, when the production-rule language has countably infinite cardinality, this word-for-word transformation never terminates. This causes, in turn, difficulty in proving that the transformation generates an equivalent semantic-network language. To overcome this problem, a grammar-to-grammar transformation is used.

Because the only difference between the category-1 production-rule and semantic-network words is the terminal set of symbols, a grammar-to-grammar transformation can be accomplished by simply changing the terminal

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set in the production-rule grammar. That is,
in each of the grammar's generative rules,
replace m with the single relation-word R1 and
use the identical fact and node-label alphabet
for the remaining terminal symbols. Since the
form of the grammar's generative rules is not
changed by this grammar-to-grammar transforma-
tion, the a≠b constraint on the production-
rule words is passed on to the semantic-
network word. Also, by maintaining the same
form of grammar-rules, the modified grammar
still generates exactly the same number of
words as was contained in the original
rule-language. Therefore, the set of words
generated by this new grammar meet the last
constraint, "consists of all the words over
the node-label and relation sets where a≠b,"
of a category-1 semantic-network language.

Having proven that by following the steps
of this transformation a semantic-network
language can be obtained, all that remains is
to point out specifically that the network-
language is equivalent to the production-rule
language. This follows from several condi-
tions. One condition is that since the fact
and node-label alphabets are identical, the
regular word sets formed from these alphabets

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are one-for-one and onto mappings. Another
condition is that the Rl and m symbols are
identity relations and therefore bijective.
The final condition is that the modified
grammar generates exactly the same number of
words as was originally contained in the
production-rule language. That is, finite
languages transform one-to-one into finite
languages and countably infinite languages
transform one-to-one into countably infinite
languages. This convergence is guaranteed
because the original rule-language converged
using the same form and number of generative
rules.

From this proof of equivalence and the
fact that each transformation begins with a
given production-rule grammar (one is
guaranteed to exist), it follows that every
production-rule language contained in the
special class of category-1 rule-languages can
be transformed into an equivalent semantic-
network language that is contained in the
special class of category-1 network-languages.
Q.E.D.

While this rule-to-network language transformation is
quite simple, the transformation of a semantic-network
language into a production-rule language is not. The

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problem that has to be overcome is the transformation of the relation-words that are not identical to the symbol m. In a network-to-rule transformation, a one-for-one transformation to the m symbol is not possible when several relations exist. If a many-to-one transformation is used, then important relationship information is lost.

To keep from losing this relationship information, a fact-word in the production-rule word must exist that contains this relation information as well as the node-label information. That is, when a semantic-network relation-word is not equivalent to m, the a or the b fact-words in the amb rule-word must contain both the relation and the node-label word. In effect, the fact-alphabet has to become $Z \cup Y$. As an example, let "CR3D" represent a semantic-network word where "C" and "D" are specific node-label words and "R3" is a single relation-word that is not equivalent to m (i.e. C is related to D by R3). Then, one possible transformation of this network-word yields a rule-word of the form "Cm(R3D)." This rule-word reads "C implies is related to D by R3." While somewhat awkward, the same information that is contained in the semantic-network word is also contained in the resulting production-rule word. However, there is a problem with the resulting production-rule language when it is used in a production-rule system.

This problem is that the production-rule language only allows production-rule systems to be constructed in which each of the "(R3D)" fact-words is a terminal condition

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(answer). This can be seen from the description of production rules given in Section I. A production rule "fires" when the antecedent (C) is matched from the known information that is contained in the situation data (see Figure 4). The known information is either entered by a user or by the firing of a rule. Because the C position never contains a relation-word, the rule Cm(R3D) never activates any other rule once it is fired. That is, the "(R3D)" fact-word never occurs in the antecedent position (a) of the amb production-rule word. If another semantic-network word transforms into the production-rule word "Dm(R4F)" (D implies is related to F by R4), then firing rule Cm(R3D) does not activate the Dm(R4F) rule as it should. However, there is a way to correct this problem.

To solve this problem, the definition of category-1 semantic-network languages needs to be reviewed (see Theorem 6.15 of Section VI). Each of these network-languages consists of all the words of the form arb where a and b are members of a regular set. That is, words of the form "CR(i)D" and "DR(i)C" exist in each network-language. Each node D can be reached from node C by a relation R(i) and each node C can be reached from D by the same set of relations. This cycle exists because the language has to contain all possible words so that users can construct their particular implementations of a semantic-network any way they desire.

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Because this cycle results in all node labels being preceded by a relation, using the "[R(i)D]" form as the fact-words preserves the needed relation-information and corrects the "dead-end" problem. That is, every semantic-network word is transformed into a production-rule word of the form "[R(i)C]m[R(j)D]" where "i" and "j" may or may not be equal. If the relation-set contains the implies relation Rl, the CRlD word-forms can translate directly into CmD word-forms. Therefore, the new production-rule language has to consist of words of the following form: CmD, Cm[R(j)D], [R(i)C]mD and [R(i)C]m[R(j)D] in order to account for all possible semantic-network words. Of course, the awkwardness in reading the rule remains and is somewhat worse. But, all information is preserved and the production-rule systems using this language are able to operate as expected.

While these word transforms solve the dead-end problem by using a particular partition of the semantic-network word, they do not represent a legal transformation. As a matter of fact, no legal transformation exists for an arbitrary semantic-network language contained in the special class of category-1 network-languages.
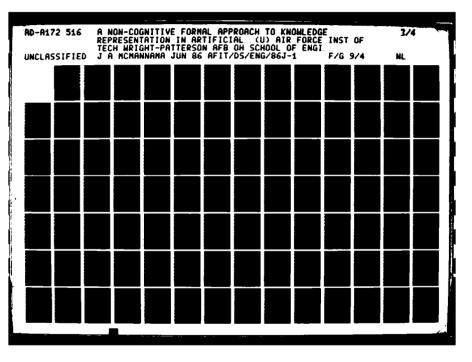
Theorem 7.08: There does not exist a single information-lossless transformation that will convert an arbitrary semantic-network language contained in the special class of category-1 network-languages into a production-rule language contained in the special class of category-1

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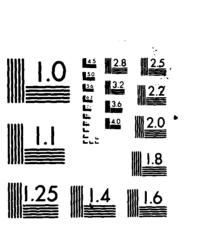
rule-languages (see Theorem 5.13 of Section V
and Theorem 6.15 of Section VI for class
definitions).

Proof: This proof follows from the definitions of
semantic-network and production-rule lan-
guages. While all four word-forms discussed
in the paragraphs preceding this theorem need
to be available in order to transform any
network-word into a rule-word, they have
brought out the specific condition that can be
used to prove this theorem. For an
information-lossless network-to-rule trans-
formation, the resulting fact-set must consist
of words where the individual relation/node-
label associations (e.g. R3D, R2C) are identi-
fiable. The term "identifiable" is used to
mean a one-to-one mapping of the relation/
node-label associations to unique words in the
fact-set, not necessarily a symbol-by-symbol
mapping of the relation/node-label strings to
the fact-strings. That is, every fact-word
must represent one of the unique relation/
node-label associations so that information is
not lost in the transformation.

However, the fact-set consisting of these
equivalent relation/node-label words is
directly affected by the previously identified

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semantic-network cycles CR(i)D/DR(i)C.
Because of these cycles, every relation has to
be associated with every node label. Hence,
this transformed set of facts must contain
individual words for every relation/node-label
association. For example, let the node-label
set contain only two labels, C and D, and the
relation-set contain only two relations, R2
and R3. Then, to handle all the associations,
the fact-set must contain four words to
represent the R2C, R2D, R3C and R3D relation/
node-label associations.

This requirement that the fact-set must
contain words for every relation/node-label
association creates a problem with any
network-to-rule transformation. By defini-
tion, a production-rule language that is a
member of this special category-1 class of
rule-languages has to consist of all possible
words of the form amb where a≠b. This
inequality constraint results in production-
rule words existing in the language where the
a and b fact-words can differ only by the
individual symbol placement in the fact-word.
That is, if the fact-set contains unique words
for every one of the relation/node-label
associations, the production-rule language

must then contain rule-words in which the node-label portion of the relation/node-label association is identical in both the a and b fact-words but the relation-portion is different. For example, if the fact-set contains two words representing two relation/node-label associations, R2C and R3C, then, the production-rule language must contain the rule-words representing the equivalent of "R2CmR3C" and "R3CmR2C."

However, by the definition of a semantic-network language, the a≠b node-label constraint prevents equivalent types of network-words from occurring. That is, no semantic-network word exists where identical node labels occur in the a and b positions of the arb word-form. Therefore, by applying any general transformation on these network-words, the resulting production-rule words must maintain the unequal node-label constraint. For example, let a semantic network consist of two network-cycles, CR2D/DR2C and CR3D/DR3C, where neither relation is the implies relation. Any information-lossless transformation that maintains the node-label inequality has to generate a set of rule-words that consists of the equivalent rule-words: R2CmR2D,

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R2CmR3D, R3CmR2D, R3CmR3D, R2DmR2C, R2DmR3C, R3DmR2C and R3DmR3C. Yet, by the definition of a production-rule language, equivalent rule-words of the form R2CmR3C, R2DmR3D, R3CmR2C and R3DmR2D must also exist in a rule-language over the four equivalent fact-words of R2C, R3C, R2D and R3D.

So, no matter how the relation/node-label associations are partitioned, there must always exist a unique fact-word representing each unique association. Therefore, any general information-lossless transformation used to transform an arbitrary category-1 semantic-network language into a production-rule language actually transforms the network-language into a subset of a production-rule language. This subset of rule-words itself does not meet the formal definition of a category-1 rule-language. By combining this finding with the existence of the special-case transformations of Theorems 7.01 and 7.04, it follows that no single information-lossless transformation exists that will transform an arbitrary semantic-network language contained in the special class of category-1 network-languages into a production-rule language

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contained in the special class of category-1
rule-languages. Q.E.D.

This theorem makes a very powerful statement. Even
though special cases exist where category-1 semantic-network
languages can be transformed into equivalent category-1
production-rule languages, a general transform does not
exist for all semantic-network languages contained in this
special class of category-1 network-languages. Therefore,
anyone performing any category-1 network-to-rule transforma-
tion has to prove that their transformation is correct for
their special class of languages. Because part of the proof
of Theorem 7.08 showed that general network-to-rule trans-
formations do not necessarily generate a true production-
rule language, the proof of correctness of special-case
transformations may be very involved if not impossible.

Additional affects of this theorem, as well as other
theorems contained in this section, upon rule and network
languages are discussed in Section IX. Section X contains
suggestions regarding the techniques to use in proving the
correctness of special-case transformations. However, the
specific affects that all the previous theorems have upon
the remaining production-rule and semantic-network languages
in the definition hierarchy (see Section IV) are given in
the next section.

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VIII. Hierarchical Language Results

So far this dissertation has dealt with only a special class of category-1 production-rule and semantic-network languages (see Theorem 5.13 of Section V and Theorem 6.15 of Section VI for class definitions). While detailed analysis of all possible classes of category-1 languages are not performed herein, the results of the analysis of these special classes of rule and network languages are used to determine characteristics of higher category-level representation-languages (see Section IV). From a review of the proofs of these category-1 theorems in Section V and VI, it can be seen that the proofs for semantic-network languages only differ slightly from those of production-rule languages. Therefore, instead of giving separate hierarchical theorems and propositions for each of these representations, each theorem and proposition in this section covers both rule and network representations. To begin developing these hierarchical theorems, a review of the tables in Section IV is required.

Hierarchical Language Expansion

After detailed evaluation of the tables in Section IV, it is noticed that the differences among categories of knowledge-words contained in these representations involve only the form used to represent the knowledge. For example, category-1 knowledge-words represent knowledge as simple

strings of symbols while a higher category level uses
functions with free variables to represent some of the
knowledge. From the investigations of the special category-
1 classes of languages, the language-type of the sets of
knowledge-words (i.e. the language-types of the fact,
node-label and relation sets) was found to affect the
overall language-type of the representation.

The most critical impact was identified by the category-
1 theorems that ignore the language-type of the fact,
node-label and relation sets altogether (see Theorem 5.08 of
Section V and Theorem 6.08 of Section VI). These theorems
revealed that the resulting overall knowledge representa-
tions did not have formal language equivalents at all.
Hence, if the complexities of the knowledge-languages are
ignored at all the category levels, the same results would
be expected to occur. That is, if the language-type of the
knowledge-words contained in a representation's structure is
ignored, then no formal language equivalents exist for the
overall knowledge representation. This leads to the first
hierarchical theorem for these two knowledge
representations.

Theorem 8.01: Given any set consisting of all possible
production-rule or semantic-network strings
where the strings have the characteristics
listed for one of the category levels of the
definition-hierarchy (see Section IV). If the
antecedent/consequent (fact), node-label

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and relation sets are treated as only symbols in alphabets, then, in general, the resulting overall knowledge representations formed by using these sets of strings are not formal languages.

Proof: This proof follows directly from the category-1 findings. Because the category-1 characteristics are included in all higher numbered categories of characteristics, each of the higher numbered categories of fact, node-label and relation sets has to contain special subsets for the strings that meet the category-1 characteristics. From Definition 5.01 of Section V and Definition 6.01 of Section VI, one of these special category-1 subsets of strings for each of the fact, node-label and relation sets are countably infinite in size. Therefore, by using the higher numbered categories of fact, node-label and relation sets that contain these particular category-1 subsets in the overall languages' alphabets, the size of these alphabets has to be at least countably infinite.

Now, from the grammar definition (Definition 1.02 of Section I), a language-generating grammar has to have a finite alphabet of terminal symbols. Since the alphabets for

these higher numbered categories of representations are at least countably infinite, no grammar exists that will generate formal language versions for these higher numbered categories of representations.

However, if each of the category-1 subsets is finite as well as the number of remaining symbols in the higher category-level alphabets (the knowledge-language could still be ignored even though these finite sets are type-3 languages over a different alphabet), then the grammar exists and a language version also exists. Therefore, depending on whether or not the set of knowledge-words is countably infinite, these production-rule and semantic-network representations cannot be formal languages. Q.E.D.

While Theorem 8.01 proved that cases exist where the production-rule and semantic-network representations cannot be formal languages, it remains an open question as to the exact language-types, if any, of the representations that contain knowledge-words which have all the characteristics listed for the top category of the definition-hierarchy (see Section IV). The problem comes from developing all the detailed constraints needed to generate an all-inclusive description of such a complex set of knowledge-words. Questions continue to come up that have no absolute answers.

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For example, how deep can Boolean combinations be nested? Are value assignments (like those used in MYCIN) additive so that the $a \neq b$ constraint has to be modified? Are free variables used in conjunction with procedure calls for variable passing? Can procedure calls be nested? These are but a sample of the problems that have to be overcome to reach a reasonable definition of the top-category characteristics.

Even though these problems are difficult and have not been resolved sufficiently in this dissertation, the conjecture used herein is that the set of knowledge-words at each category level is a formal language and the overall representation that uses these knowledge-words is also a formal language. This conjecture is supported by the existence of various programming languages like OPS5 and ROSIE (101) that operate with representations containing knowledge-words which have some of these complex characteristics. However, because of the possible countably infinite variations, reaching any final conclusion about the hierarchy of rule and network languages based on so small a sample would be foolish if not ridiculous.

In order to provide as much insight into these knowledge representations as possible, this conjecture is assumed to be true for both the production-rule and semantic-network representations. As a result, the findings on the special category-1 classes of rule and network languages can then be used to reach conclusions about these hierarchical sets of

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knowledge representations. Since these hierarchical findings will be based on this conjecture, these findings will be presented as propositions, not theorems. Section IX and X contains further discussion on resolving this conjecture so that these propositions may be converted into theorems.

However, before any propositions can be presented, the conjecture must be formally defined. For clarification, separate conjectures will be given for each representation.

Conjecture 8.01: The allowable sets of all possible knowledge-words formed at each category level of Tables II and III of Section IV produce formal language equivalents. When each of these knowledge-languages is combined with the production-rule's structure, a formal language equivalent exists for the overall representation.

Conjecture 8.02: The allowable sets of all possible knowledge-words formed at each category level of Tables IV, V and VI of Section IV produce formal language equivalents. When each of these knowledge-languages is combined with the semantic-network's structure, a formal language equivalent exists for the overall representation.

Using these conjectures, the following propositions can be proven.

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Proposition 8.01: Given that Conjectures 8.01 and 8.02 are
true, then, in general, the top-category
language equivalents of the production-
rule and semantic-network representations
cannot be context-free (type-2) languages.

Proof: This proof follows by construction and
from the formal language evaluations of
computer programming languages. By the
inclusion hierarchy property of Section
IV, the top-category knowledge-languages
contained in the production-rule and
semantic-network representations have
words that allow arbitrary procedure calls
to be made. Because these procedures
themselves can be implemented in any
computer programming language, they may be
considered, without loss of generality, as
being formal language "sentences" over an
alphabet that is disjoint from the rest of
the alphabet-symbols in the knowledge-
language's alphabet. That is, the
procedure-sentence is made up of words
that have no common alphabet-symbols with
the other knowledge-words.

Now, by construction, remove the
procedure-call words from the top-category
knowledge-language (a knowledge-language

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exists per Conjectures 8.01 and 8.02) and replace them with their equivalent, disjoint sentences. Recall that this dissertation is removing the semantics from the words and evaluating the resulting syntax. Therefore, this replacement action removes the semantics (meaning) of a procedure call by replacing it with the syntax strings that it represented.

Because the procedures are arbitrary, this replacement process will result in incorporating all possible procedure-sentences in order to handle all possible procedures that a user may require. By applying a set's property that duplicate words are not allowed, the union of all the sentences yields all of the words of the original computer programming language that incorporated the procedures. That is, the knowledge-language resulting from this construction contains all the words of the implementing computer programming language as members. Since these words consist of alphabet-symbols that are not used in any other knowledge-word, the words of the computer programming language can be easily identified in the knowledge-

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language. Because of this separation of
the words of the programming language and
the remaining knowledge-words, any machine
accepting the knowledge-language will have
to accept this implementing computer
programming language as a separate unique
subset. That is, when words of this
subset programmirg language are encoun-
tered, the machine has to use a special
set of states and paths that is only used
to accept these unique words. In effect,
the machine contains a separate acceptor
for the computer programming language.
Since Harrison has proven several computer
programming languages not to be context-
free (96:219-221), then, in general, this
separate acceptor must be more powerful
than a nondeterministic, finite machine
with a single pushdown-store, in order to
accept the words of the programming
language (9:43). Hence, the overall
machine accepting the entire knowledge-
language must be more powerful than this
machine-type as well.

Finally, since this knowledge-language
has to be accepted as part of the overall
representation language, the disjoint

property of the subset computer program-
ming language also forces the machine
accepting the overall representation to be
more powerful than a type-2 acceptor.
Hence, in general, these top-category
production-rule and semantic-network
representation languages cannot be type 2.
Q.E.D.

The finding of Proposition 8.01 has to be general
because only several but not all computer programming
languages have been evaluated. However, there is another
case that can support the general nature of the finding. It
may be the case that only certain types of procedures are
allowed. Then, the entire computer programming language may
not be a subset language. For these cases, the trace
language techniques would have to be used to make the
determination (88). But, knowing that the top-category
languages have a good chance of being type 1 or type 0
indicates that the detailed formal language analysis of the
top-category representations can become very complex.

Even the general finding of Proposition 8.01 still
points out once again that a representation's structure
alone does not control the final language-type. The form
that the knowledge-language itself takes (procedural vs.
declarative), greatly affects the final language equivalent
of the specific representation. With this lower bound of
type-1 languages established for the general case, the

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investigation now shifts from the individual languages to

the classes of languages formed at higher category levels.

Proposition 8.02: Given that Conjectures 8.01 and 8.02 are

true, then the entire class of production-

rule languages and the entire class of

semantic-network languages formed at any

of their respective category levels (see

Section IV) is not closed under the union

operation.

Proof: This proof follows by construction of a

counter-example. For the production-rule

representation, select the same two finite

languages that were used in the proof of

Theorem 5.15 of Section V. For the

semantic-network representation select the

same two finite languages that were used

in the proof of Theorem 6.17 of Section

VI.

Now, consider the entire category-1

set of rule (network) languages first.

Since each of the special classes of

category-1 languages consists of all the

possible category-1 finite languages for a

given representation, it follows from

Theorem 5.15 (Theorem 6.17) that the third

finite language resulting from the union

of two previously selected finite rule

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(network) languages cannot be contained in any of the remaining classes of category-1 rule (network) languages. Because this third finite language is not a finite rule (network) language, it follows that the the entire set of all category-1 production-rule (semantic-network) languages is not closed under union.

Next, consider the remaining category-levels of classes of rule and network languages. The inclusion hierarchy property (see Section IV) requires that every rule (network) language contain a subset of words which have category-1 characteristics. Conjectures 8.01 (8.02) requires that this subset be a formal language. Because of these requirements, there exist in every class of higher category-level rule (network) languages at least two separate languages that contain, as a subset, one of the two specific finite category-1 rule (network) languages used in Theorem 5.15 (Theorem 6.17). That is, there exist two production-rule (semantic-network) languages in each category-level class of rule (network)

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languages that contains these finite
subsets as their only category-1 language.

Now, perform the union of these two
higher category-level production-rule
(semantic-network) languages. This union
produces a third set of rule (network)
words that contains the third finite rule
(network) language as the category-1
word-set. However, from the proof of
Theorem 5.15 (Theorem 6.17), the third
finite language is not a production-rule
(semantic-network) language. From the
inclusion hierarchy property and Con-
jectures 8.01 and 8.02, this third higher
category-level rule (network) language
cannot be contained in the higher
category-level class of rule (network)
languages, since it does not contain a
category-1 rule (network) language as a
subset. Hence, the entire class of
production-rule (semantic-network)
languages at any category level is not
closed under the union operation. Q.E.D.

The union closure property is not the only property that
these classes of languages do not meet. These languages do
not meet the product closure property.

Proposition 8.03: Given that Conjectures 8.01 and 8.02 are
true, the entire class of production-rule
languages and the entire class of
semantic-network languages formed at any
of their respective category levels (see
Section IV) are not closed under the
product operation.

Proof: This proof is by construction. The
inclusion hierarchy property (see Section
IV) requires that every representation-
language contain a subset of words which
have category-1 characteristics. Con-
jectures 8.01 and 8.02 require that this
subset of words be a formal language.
Because of these requirements, every
higher category-level representation-
language must contain all the words of
some category-1 representation-language as
a subset. From Definitions 4.01 and 4.02
of Section IV, the form of the words in
the category-1 language subsets are amb
and arb, respectively.

Now, perform the product operation on
any two production-rule (semantic-network)
languages in the same category-level
class. The resulting set of rule
(network) strings contains category-1

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level strings of the form "A1mB1A2mB2"
(A1R2B1A1R3B2). That is, the category-1
rule (network) strings contain multiple m
(relation) symbols (words). There no
longer exist any of the required category-
1 words of the form amb (arb) in the
language. Therefore, from the inclusion
hierarchy property and Conjectures 8.01
and 8.02, the rule (network) language
formed after the product operation cannot
be contained in the entire class of
production-rule (semantic-network)
languages at that category level. Hence,
the entire class of production-rule
(semantic-network) languages at any
category level is not closed under the
product operation.

Q.E.D.

The fact that no entire class of production-rule or
semantic-network languages is closed under either the union
or product operations at any category level leads to the
last proposition on the individual characteristics of these
classes of languages.

Proposition 8.04: Given that Conjectures 8.01 and 8.02 are
true, then the entire class of
production-rule languages and the entire
class of semantic-network languages formed

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at any of their respective category levels
(see Section IV) are not Abstract Families
of Languages (AFL) (24).

Proof: From reference 24, an Abstract Family of
Languages (AFL) contains languages closed
under six operations: union, product,
Kleene closure, e-free homomorphisms and
intersection with a regular set. From
Propositions 8.02 and 8.03, the entire
class of production-rule (semantic-
network) languages is not closed under
either union or product at any category
level. Therefore, the entire class of
production-rule (semantic-network)
languages at any category level is not an
AFL. Q.E.D.

As was the case for similar findings on the special
classes of category-1 rule and network languages, the
results of Proposition 8.04 present a major stumbling block
to the study of these entire classes of production-rule and
semantic-network languages. Since these classes are not
AFLs, the determination of additional characteristics of
these classes has to involve analysis of the entire set of
languages contained in each class. With all the various
combinations of possible languages, each category level can
contain countably infinite classes each of which contains
countably infinite languages. With the loss of the

multitude of characteristics proved about AFLs by formal language theorists, developing a small subset of additional characteristics for these classes of representations can be very time consuming. From Godel's theorem (89), it may be the case that all the language characteristics of these two representations can never be determined.

Even if this is the case, there are still additional characteristics about these hierarchical classes of languages that deserve further attention. One of these characteristics is the equivalence between a top-category production-rule language and a top-category semantic-network language.

Hierarchical Equivalences

A detailed review of the equivalence theorems of Section VII, shows that the reason that equivalence exists between certain production-rule and semantic-network languages is that isomorphic fact and node-label sets could be constructed and the bijective Rl=m/m=Rl mapping could be used. These isomorphic mappings are possible because the needed detailed descriptions of the facts, node-label and relation sets are provided in the category-1 definitions of Section IV (see Definitions 4.01 and 4.02). For the higher level cases, these detailed definitions have not been provided.

Because these detailed definitions have not been and may never be (see Section IX for discussion) sufficiently developed, an additional conjecture is needed to be able to

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determine the equivalence between higher category-level rule and network languages. From the detailed literature review performed to develop the tables in Section IV, the descriptions of the antecedents/consequents (facts), node-labels and relations appear to agree, in general, at various levels. For example, both the rule's antecedents/ consequents and the network's node labels can contain procedure calls, free variables, etc. However, these equivalent descriptions do not necessarily occur at the same category level number in both representations.

But, if all the characteristics are considered (i.e. the top-category definition), then all the production-rule's characteristics appear to have general agreement with some of the semantic-network's characteristics. The word "some" is used because it appears that a few of the network's characteristics do not have a direct rule equivalent. For example, the network's exception-links do not directly match any of the rule's characteristics.

Because this equivalence of characteristics appears to be complete for the rules, the conjecture used in this dissertation is that all of the top-category rule-characteristics are indeed equivalent to some of the top-category network-characteristics. A formal definition of this conjecture follows. Section IX contains further discussion on resolving this conjecture so that the following propositions involving it may be converted into

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theorems. Section X contains suggestions on how to develop
special cases that support this conjecture.

Conjecture 8.03: All of the general descriptions for the
production-rule characteristics given in
Tables II and III of Section IV are
identical to some of the general descrip-
tions for the semantic-network character-
istics given in Tables IV, V and VI of
Section IV.

With this third conjecture, the equivalence of the
production-rule and semantic-network language can now be
determined. The equivalence investigation begins by
determining the equivalence of the single top-category rule
and network language that consists of all possible words.

Proposition 8.05: Given that Conjectures 8.01, 8.02 and 8.03
are true, then the single top-category
production-rule language consisting of all
the possible rule-words is not equivalent
to the single top-category semantic-
network language consisting of all the
possible network-words.

Proof: This proof follows from a category-1
equivalence theorem, the inclusion
hierarchy property of Section IV and
Conjectures 8.01, 8.02 and 8.03. Because
this theorem requires the top-category
languages to consist of all words, it

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follows from the inclusion hierarchy
property and Conjectures 8.01 and 8.02,
that each of these top-category languages
must contain the entire set of their
respective category-1 representation-words
as a subset category-1 language. These
special all-inclusive category-1 word-sets
were evaluated in Sections V, VI and VII
as the PR production-rule language and the
SN semantic-network language. From these
evaluations of PR and Sn, Theorem 7.03 of
Section VII established that PR is not
equivalent to SN because SN contains more
words than PR.

Excluding the PR and SN subsets for
the moment, by Conjecture 8.03, the
remaining words in the top-category
production-rule language are equivalent to
some of the remaining words in the top-
category semantic-network language. That
is, because the characteristics in the
tables of Section IV are incorporated as
words in these representation languages,
some of the remaining semantic-network
words must be equivalent to those in the
remaining set of production-rule words.

However, there are more remaining network-words than rule-words.

Since both the SN subset and the remaining semantic-network words outnumber the PR subset and remaining rule-words, the top-category all-inclusive rule-language cannot be equivalent to the top-category all-inclusive semantic-network language. Q.E.D.

Even though the single top-category languages are not equivalent, various subsets of top-category level rule and network languages can be shown to exist that are and are not equivalent to each other. Because of the fact that the characteristics at a specific lower category-level of rule-languages do not match the semantic-network character-istics at the same category-level number, these subsets of languages can only be proven to exist at the top category. While proving that these subsets exist provides additional information about the top-category languages, all of these subsets are not needed to prove the final equivalence proposition. If needed, the reader can prove that these subsets exist by using the proof technique used in the following proposition and substituting the specific category-1 theorem from Section VII for Theorem 7.06. For example, by substituting Theorem 7.05 for Theorem 7.06, a set of countably infinite top-category network-languages can

be proven to exist that are not equivalent to any

production-rule language.

Proposition 8.06: Given that Conjectures 8.01, 8.02 and 8.03
are true, then the entire class of top-
category production-rule languages is not
equivalent to the entire class of top-
category semantic-network languages.

Proof: This theorem follows from Theorem 7.06 of
Section VII, the inclusion hierarchy
property of Section IV and the three given
conjectures. Theorem 7.06 of Section VII
established that the special classes of
category-1 production-rule and semantic-
network languages are not equivalent (see
Theorem 5.13 of Section V and Theorem 6.15
of Section VI for class definitions). This
theorem was proved by showing that there
exist both finite and countably infinite
semantic-network languages that contain
more words than any finite or countably
infinite production-rule language. This
proposition can be proven using this same
unequal-size characteristic.

First, the inclusion hierarchy
property requires that every
representation-language contains a subset
of words which have category-1 character-

istics. Conjectures 8.01 and 8.02 require that this subset of words be a formal language. Because of these requirements, there exist top-category rule and network languages that contain all the words of one of their respective category-1 languages as a subset. That is, each one of the top-category languages must contain a category-1 language as a subset. Since the languages contained in these special classes of category-1 languages qualify as one of these subset languages, there must exist at least one top-category language for every one of these special category-1 languages. Because of the large number of word-sets that can have higher category-level characteristics, more than one top-category language can exist that contains the same special category-1 language as a subset. However, the maximum number of such languages is bounded at countably infinite by the language-space bound and Theorem 3.05 of Section III.

For the moment, exclude these special category-1 subsets from the the top-category languages. By Conjecture 8.03

and the fact that each of these top-
category rule and network languages have
to contain all possible representation-
words given a particular knowledge-
language, there must exist network-
languages whose number of remaining words
exceeds the number of words remaining for
any rule-language. That is, because the
characteristics in the tables of Section
IV are incorporated as knowledge-words in
a representation-language, the "some"
stipulation of Conjecture 8.03 means that
more knowledge-words exist for the
semantic-network languages. Therefore,
some semantic-network languages will
contain more higher category-level words
than any rule-language.

Finally, recombine these remaining
subsets of higher category-level words
with the special category-1 language
subsets. Then, it follows from the
unequal sizes of the special category-1
languages and the unequal sizes of these
higher category-level word-subsets that
there must exist certain top-category
network-languages that contain more words
than any production-rule language. Hence,

the entire class of top-category
production-rule languages cannot be
equivalent to the entire class of top-
category semantic-network languages.

Q.E.D.

Proposition 8.06 could have been proven directly from
Proposition 8.05 by showing the inclusion of the single
all-inclusive languages in the top-category classes.
However, by using this proof technique, it is revealed that
more than one case exists where languages are not equiva-
lent. This existence was shown without having to develop
equivalent propositions for all of the special-case theorems
of Section VII (e.g. Theorem 7.05). Further impacts of this
finding are discussed in Section IX. Section X contains
suggestions for knowledge representation researchers to
follow when dealing with equivalence issues.

Even though these top-category classes of knowledge
representations are not equivalent, transformation from a
top-category production-rule language to a top-category
semantic-network language can be made.

Hierarchical Transformations

As was the case in Section VII, there are two types of
transformations that need to be considered: rule-to-network
and network-to-rule. The rule-to-network is investigated
first.

As previously indicated, the top-category
production-rule to top-category semantic-network language
transformation does exist. Because the characteristics of
the rules at the individual category levels do not match the
characteristics of the networks at the same category-level
number, the transformation can only be proven to exist for
the top category. Also, because the definitions of the
characteristics are not provided, detailed definition of the
transformation steps cannot be given. However, if Conjec-
ture 8.03 is true, then the transformation for the
characteristics does exist. By assuming Conjecture 8.03 is
true, the following proposition regarding this rule-to-
network transformation is proven.

Proposition 8.07: Given that Conjectures 8.01, 8.02 and 8.03
are true, then any top-category
production-rule language can be trans-
formed into an equivalent semantic-network
language.

Proof: This proof follows directly from
Theorem 7.07 of Section VII, the hierarchy
inclusion property of Section IV and the
three given conjectures. By the inclusion
hierarchy and Conjectures 8.01 and 8.02,
various category-1 languages exist as
subsets of the top-category
representation-languages. However,
the words in these subset languages all

come from the category-1 word-set.
Theorem 7.07 established that an equiva-
lent rule-to-network transformation was
possible for the special classes of
category-1 languages (see Theorem 5.13 of
Section V and Theorem 6.15 of Section VI
for class definitions). Since the set of
all category-1 words is included in these
special classes (PR and SN), the transfor-
mation of Theorem 7.07 of Section VII can
be used to transform all the category-1
words. Therefore, the transformation
given in Theorem 7.07 becomes a subset of
the overall top-category rule-to-network
transformation.

To handle the remaining words in the
top-category rule-languages, Conjecture
8.03 must be invoked to establish that
every top-category production-rule char-
acteristic has an equivalent form in the
set of semantic-network characteristics.
That is, a transformation exists for the
rule-words incorporating these charac-
teristics into equivalent semantic-network
words that incorporates these same char-
acteristics. Therefore, by combining the
category-1 transformation with the trans-

formation for these equivalent charac-

teristics, any top-category production-

rule language can be transformed into an

equivalent semantic-network language.

Q.E.D.

While this production-rule to semantic-network transfor-

mation relies almost entirely on the acceptance of a

conjecture, the nonexistence a single semantic-network to

production-rule transformation can be proven from the

category-1 results.

Proposition 8.08: Given that Conjectures 8.01, 8.02 and 8.03

are true, then there does not exist a

single information-lossless transformation

that converts an arbitrary top-category

semantic-network language into a top-

category production-rule language.

Proof: This proof follows directly from

Theorem 7.08 of Section VII, the inclusion

hierarchy property of Section IV and the

three given conjectures. Theorem 7.08

proved that no information-lossless

transformation exists for the special

classes of category-1 languages (see

Theorem 5.13 and Theorem 6.15 for class

definitions). The reason was that the

transformed rule-grammar would generate

category-1 rule-words that have no

relation to the original semantic network.
Hence, any special category-1 network-
to-rule transformation would result in a
set of rule-words that was not a proper
production-rule language.

While Theorem 7.07 only dealt with a
special class of category-1 languages,
the results actually hold for any
category-1 language. The problem with the
transform involved the internal words of
the category-1 representation-words.
Since all category-1 words have the same
form and meet the $a{\neq}b$ constraint, any
category-1 production-rule grammar will,
in general, still generate rule-words that
contain the same node label on both sides
of the m symbol. Hence, the violation of
the $a{\neq}b$ constraint on the network-words
still occurs.

Recognizing that this violation holds
for all category-1 languages, consider the
top-category languages. From the inclu-
sion hierarchy property and Conjectures
8.01 and 8.02, it follows that each of the
top-category languages is formed by adding
more words to some category-1 language.
That is, every top-category production-

rule language and every top-category
semantic-network language contains all the
words of a category-1 language as a
subset. Hence, any top-category network-
to-rule transformation has to transform
the category-1 network-language into a set
of rule-words.

Now, consider the only three forms
that this transformation of the category-1
subset language can take. The first form
involves transforming all the category-1
network-words into higher category-level
rule-words. That is, the resulting set of
rule-words does not contain any category-1
words. This transformation is illegal
because, from Conjectures 8.01 and 8.02,
the production-rule language has to
contain a nonempty subset of category-1
words.

The second form involves transforming
the category-1 network-language into a
category-1 rule-language. This is also
illegal, in general, from the previously
mentioned expansion of the results of
Theorem 7.07 to include the entire set of
category-1 languages.

The third form involves transforming part of the category-1 semantic-network words into higher category-level rule-words and the remaining category-1 network-words into category-1 rule-words. There are two conditions on the form of this transformation that have to be considered. The first condition is that the resulting set of category-1 rule-words is not a complete production-rule language. For this condition, the transformation is illegal since the rule-language must contain all the words of a complete category-1 rule-language as a subset.

The second condition is that the resulting set of category-1 rule-words does form a category-1 rule-language. This transformation is also illegal. This is because the transformation results in mapping some of the knowledge-words (see Definitions 4.03 and 4.04 of Section IV) contained in the overall category-1 network-language, into two knowledge-words contained in the knowledge-language for the overall rule-representation. These two knowledge-words are actually at different category levels of definition.

In effect, the resulting rule-language has added characteristics to the semantic-network knowledge-words that did not originally exist. That is, the rule-language has gained knowledge. For example, the category-1 relation/node-label association R2C transforms into a category-1 fact-word, R2C, and a predicate-word "R2C(x,x)."

To understand why this problem occurs, the semantic-network relation/node-label cycle needs to be reviewed. No matter how the category-1 network-language subset is partitioned, the network-cycle CR2D/DR2C forces some node-labels and/or relations to be duplicated in both partitions. For these duplicated knowledge-words, the information-lossless requirement forces this transformation to convert these words into an equivalent category-1 knowledge-word and some higher category-level knowledge-word. Hence, the original category-1 network-words are transformed into two different category-level words.

To better understand how this effectively adds a characteristic to the semantic-network language, consider the

previous example's knowledge-words R2C and R2C(x,x). Make use of the fact that a rule-to-network transformation exists and transform these equivalent knowledge-words back into their network word-forms. Because the node label and relation words are over disjoint alphabets, let the rule-to-network transformation use a relation/node-label separator to retrieve the node labels and relations. Using this rule-to-network transformation, it then follows from Proposition 8.07 that the category-1 word R2C transforms into node labels for the network. Applying the separator, the actual node label and relation words can be obtained. Hence, R2C transforms into R2 and C.

However, for the R2C(x,x) knowledge-word, it follows from Conjecture 8.03 and Section IV that network-words exist whose node labels can contain predicates. Depending on the definition of n-ary relations, the relation-set may also contain predicates. Therefore, applying the transformation steps for these predicate-words and the separator, a new predicate node-label "C(x,x)" and a new

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predicate relation "R2(x,x)" are added to the network that did not originally exist.

Now, it may be argued that these R2C(x,x) words are syntactically different from R2C words and could be identified and mapped so that no extra words are added to the network. While this depends on whether or not the R2C(x,x) words form a language by themselves (it takes a Turing acceptor to identify these words), the point is that the production system using this equivalent production-rule knowledge representation may reach conclusions that could never be reached by the original network-system. The added characteristics actually reside inside the production-rule representation.

Since all the possible transformation-forms have been shown to be illegal for the general case, it follows that no single information-lossless transformation exists that will transform an arbitrary top-category semantic-network language into a top-category production-rule language. Q.E.D.

The finding of Proposition 8.08 may be hard for some people to accept. In one case, there are those who may

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argue that embedded procedures can be used to handle the problems of the transformation. This type of statement can be seen to be incorrect by realizing that a transformation is nothing more than a procedure itself. Since a single one does not exist, the embedded procedure-calls can only work for a limited number of cases (if any).

In another case, there are those who may argue that the hierarchical approach is not the only way to define a representation's characteristics. Using other definition approaches, the inclusion constraint can be removed from the proof of Proposition 8.08 and a transform may be able to be found. This argument has merit in that special cases may be found where a transformation does exist (see Theorems 7.02 and 7.05). However, this transformation is good for only that special case or some special subset of cases. As soon as their languages contain all of the characteristics of Section IV (if this is assumed to be a complete list), then they always have other language versions where the transform does not work (e.g. the top-category languages of Proposition 8.08). Because of the countably infinite variations possible, every special-case transformation has to be proven to operate correctly on the specific class of languages before it can be used in a application.

While other arguments may exist, the findings of this section still remain sound under some of the more severe complaints. Because they are sound, no further analyses of these hierarchies of representation-languages are performed

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in this dissertation. Therefore, this concludes the formal analysis of production-rule and semantic-network languages. However, there are some important conclusions that can be reached regarding the affects that the findings of Sections V-VIII have on the field of Artificial Intelligence Knowledge Representation.

IX. Conclusions and Discussion

Conclusions

The analyses of production rules and semantic networks via formal language theory provide conclusions that affect the knowledge representations. The first conclusion is that both the knowledge-language (see Definitions 4.03 and 4.04 of Section IV) and the representation's structure must always be included during formal language analyses of knowledge representations. The rationale for this conclusion follows.

Theorems 5.01 through 5.06 and 6.01 through 6.06 of Sections V and VI, respectively, revealed that even though the knowledge-language is a regular set, the constraints of the representation's structure causes the final language not to be regular. On the other hand, if the knowledge-language type is ignored as in Theorems 5.07, 5.08 and Theorems 6.07, 6.08 of Section V and VI, respectively, the overall set of representation-words fails to include formal words. So, no formal language versions exist for these types of knowledge representations.

Even when these types of representations are forced to be languages (see Theorem 5.12 of Section V and Theorem 6.14 of Section VI), the resulting finite languages are unable to handle all the possible representation-words. Haines even conjectured that his type-2 language finding for his

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centermarker-languages depends on the regular set constraint of the language used for the x's and y's in his "xcy" words (98). Therefore, the representation's structure and knowledge-language must be considered together when evaluating knowledge representations.

Another conclusion is that for either a production-rule or semantic-network representation, no single support-tool can be designed to handle all possible knowledge-languages. This conclusion has considerable impacts on the selection of knowledge-base support-tools, especially in regards to present manufacturers' claims of having developed generic representation support-tools (101). This conclusion is justified in a straightforward manner.

Because knowledge representation researchers cannot agree on any single definition of knowledge (84), the number of the possible knowledge-languages cannot be purposely restricted. This is also true for the number of the result- ing overall knowledge representation languages. For exam- ple, recalling from Section IV that predicates are allowable knowledge-words (see Definitions 4.03 and 4.04 of Section IV), the set of knowledge-languages could be selected to be the finite set of predicate calculus languages given by Manna (9:Chapter 2). It follows from the language-space bound and set theory that there still exists a countably infinite set of potential knowledge-languages that are not contained within this predicate calculus language set.

Even recognizing this need to account for all possible knowledge-languages, the manufacturer constructing a support tool for representations is only able to select a finite number of knowledge-languages for the tool to handle. From set theory, this still leaves a countably infinite number of possible knowledge languages that cannot be accommodated. The finite set criterion comes from the fact that no known physical machine can store and search for a countably infinite set of language acceptance/generation rules. Hence, no single tool exists that can support acceptance/generation of a production-rule or semantic-network knowledge representation for all possible knowledge-languages.

While the evidence developed in this dissertation supports the nonexistence of this general support tool, it appears to be countered by the existence of support tools that are proposed to handle any knowledge-language (101). It is important to notice that these types of tools only aid in the construction of a syntax representation from user supplied knowledge-words. The manufacturers of these tools have left it up to the user to ensure that the knowledge-words input are members of the particular knowledge-language of interest. Because of the possibility that a particular knowledge-language contains a countably infinite number of words, a machine that accepts this knowledge-language is needed to perform the missing acceptance test for the user. So, while these representation support-tools can handle any knowledge-language, the manufacturers are really misleading

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the users into thinking that only one tool is required to support a given representation. However, a countably infinite set of additional language-acceptors are actually needed to accept all knowledge-languages.

Support tools for construction of knowledge representations are not the only type of tools affected by the findings of this investigation. Based on these findings, an additional conclusion is that by using either the production-rule or semantic-network representation as the main data structure, no single automatic-programming tool can be designed that handles all the possible knowledge-languages. In order to understand the justification for this conclusion, a partial description of automatic-programming tools that use knowledge representations is presented first.

Automatic-programming tools make use of a (natural) language parser to extract the necessary data and algorithm information from a specified text (102). For the data information case, the automatic-programming tool also selects data structures to store the data information that was parsed. If these structures are knowledge representations, then the data extracted by the parser are the knowledge-words. Since a parser can only handle the "sentences" of one language, the knowledge-words extracted must come from a single knowledge-language contained within the parent text-language. Because a physical machine can only store and execute a finite number of parsers, it then

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follows that a given automatic-programming tool can only parse a finite number of parent text-languages.

With this understanding of the tool, the justification for the conclusion now can be presented. From Section III, there exists a countably infinite number of possible languages. Contained in this set are the parent text-languages that automatic-programming tools can handle. From the category-1 findings alone, there are at least a countably infinite number of unique knowledge-languages (the regular finite sets). So, there is at least a countably infinite number of possible parent text-languages. Since an automatic-programming tool can only parse a finite number of the countably infinite text-languages, it then follows that no automatic-programming tool can be designed to handle all the possible knowledge-languages.

The previous conclusions concerning support-tools and automatic-programming tools seems to indicate limitations on the applicability of such tools. However, this is not necessarily the case. Any physical machine requires that the implementable version of a knowledge representation contain a finite number of words. For the cases where the knowledge-language contains countably infinite words, there exists a countably infinite number of unique, finite subsets of words (see Theorem 3.10 of Section III). Hence, any support/automatic-programming tool that uses a knowledge-language of countably infinite cardinality can generate a countably infinite number of implementable knowledge repre-

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sentations. For the case in which the knowledge-language is some natural language, these implementation versions alone may be sufficient.

Since each implementable knowledge representation contains a finite number of words, a conclusion regarding a finite centralized database of knowledge can be stated. The conclusion is that for a finite centralized database, the semantic-network structure is a viable candidate for the storage-form. As will be shown later, the finite restriction comes from the search required to transform a portion of the semantic network into production rules. The term "viable" is used in the conclusion because the semantic network is a specialized case of the frame representation system (see Sections I and II). Without analysis of frames, no final selection of a structure should be made. Before presenting the justification for this conclusion, a short description of the concept of a centralized database is presented.

The concept of a centralized database of knowledge is to store and maintain all knowledge-words of a given knowledge-language in a single representation. Then, when needed, the knowledge representation in the database is transformed into the knowledge representation required for a given application. Since implementable knowledge representations contain a finite number of words, the finite database is capable of storing implementable versions.

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With this conceptual understanding of a centralized
database of knowledge, the justification for this conclusion
can now be presented. This conclusion is justified from
Theorem 7.07 of Section VII and Propositions 8.05 and 8.07
of Section VIII. From Theorem 7.07, every production-rule
language in the special class of category-1 languages (see
Theorem 5.15 for class definition) can be transformed into
an equivalent semantic-network language. It is important to
notice that the transformation algorithm only uses one
semantic-network relation. Thus, the semantic-network
language that is produced by transforming any of these
production-rule languages is a proper subset of a semantic-
network language that contains more than one relation.

Using this subset property, the hierarchy inclusion
property of Section IV and Propositions 8.05 and 8.07, it
follows that any production-rule language can be transformed
into an equivalent semantic-network language. This language
is a subset of the all-inclusive top-category semantic-
network language. So, any production-rule language can be
explicitly stored within this top-category semantic-network
language. The reverse transformation (i.e. generating the
production rules) is where the finite size constraint
becomes important.

To obtain a production-rule language from this top-
category semantic-network language, the algorithm of Prop-
osition 8.07 is applied in reverse to a special subset of
semantic-network words. This subset of words is found by

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locating all of the semantic-network words where the implies

relation exists or where the bijective mapping Rl=m/m=Rl is

allowed. Because this is a search process, the semantic

network has to be finite otherwise the search may never

terminate. Since the subset of words obtained by this

search is also finite, the production-rule language result-

ing from the reverse transformation of Proposition 8.07 is

also finite.

Even though this reverse transformation can be used to

obtain some finite production-rule languages from a finite

semantic-network oriented database, it can be argued that

the finite constraint limits the usefulness of the central-

ized database. That is, no single, finite, representation-

language can contain all the knowledge-words for countably

infinite knowledge-languages. While the argument is valid,

the physical constraints of finite memory require a finite-

size constraint on any database. The key is to recognize

that the transformation algorithm does not depend specif-

ically on the knowledge-language. It only depends on being

able to use equivalent knowledge-languages for both repre-

sentations. Therefore, as the finite number of words in the

knowledge-language increases, the same algorithm can still

be applied to obtain the rule-languages. This results in

fewer modifications being made to the database-handling

routines as the knowledge increases.

However, the concept of the centralized database is to

store knowledge in a single form so that only one form has

to be maintained. The application versions used in

knowledge-bases (see Figure 4) are generated from that form.

The centralized database itself does not have to be an

application version. But, it has to be able to be trans-

formable into application versions. The key is that while

in the semantic-network form, maintenance actions on the

database can be performed and validated by using a limited

set of proven algorithms. Hence, a set of maintenance

algorithms for every representation-form does not have to be

verified. The verification of algorithms can be very

difficult (9).

While a semantic-network form is a viable candidate for

a centralized database, it is concluded that a production-

rule form is not an acceptable candidate. This conclusion

follows from the fact that, in general, production rules do

not contain sufficient numbers of words to store a semantic

network.

To understand why production rules cannot store a

semantic network, the equivalence and transformation char-

acteristics of the category-1 languages need to be reviewed

(see Section VII). The PR and SN languages are not equiva-

lent because SN contains more words than PR. In order to

store these remaining semantic-network words in a

production-rule form, the fact-words in the rule-set would

have to involve some form of relation-word mappings.

However, the proof of the nonexistence of a single

network-to-rule transformation (Theorem 7.08 of Section VII)

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revealed that problems exist when using relation-words in the fact-set. In this transformation proof, by using fact-words containing relation-words, the resulting production-rule language was shown actually to contain rule-words that have no semantic-network word counterparts. That is, when applying the transformation of Theorem 7.07 of Section VII on a production-rule language modified to contain relations, illegal semantic-network words are produced. Since Proposition 8.08 of Section VIII indicated the same transformation problem exists for any category-level of languages, it follows that the production-rule structure cannot be used as the only storage-structure in a centralized database.

Discussion

The formal language findings contained herein may affect human modeling. As pointed out in Section VIII, the exact language-type of the top-category production-rule and semantic-network languages remains open. This open problem was observed to stem from the inability of the knowledge representation researchers to agree on the characteristics of a human knowledge-model (84). It may be the case that these disagreements can never be resolved.

This conjecture comes from the proposition that humans can only be proven to be a formal system from a meta-level that humans cannot directly observe (see the syntax/semantic level discussion in Section I and the meta-level discussions

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of Hofstadter (89)). That is, humans would have to leave
their present level of awareness in order to be able to
describe the form of knowledge that they use. Recognizing
the impossibility of this task, the meta-level theory leads
to the conjecture that there can never be a formal descrip-
tion of knowledge that can be used to finish the hierarchi-
cal language-development. Therefore, the language-typing
problem as well as the human storage-model issue could
remain unsolved for all time.

This meta-level conjecture is not the only reason that
the language-typing problem could remain open. Godel
established that it is not possible to prove all truths
about any formal system equivalent to or more complicated
than arithmetic (89). Because languages are members of a
formal system and it takes a Turing machine to generate the
type-$\emptyset$ languages as well as solutions to arithmetic prob-
lems, Godel's theorem yields the possibility that no formal
language versions can ever be proven to exist for the
remaining languages in the hierarchy. Hence, the language-
typing problem would remain open.

This language-typing problem not only exists for the two
knowledge representations analyzed herein, but also exists
for all forms of knowledge representations. That is, those
proponents of natural knowledge representations (103),
hierarchical cortical plane knowledge representations (104),
combined knowledge representations (see Section I), etc.,
all have to face a similar open language-typing problem

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associated with their representation-forms. This is due to the fact that no matter how complex their representations are, each of their representations has to have a formal language equivalent.

The reason all these knowledge representations must have a formal language equivalent comes from the work of Chomsky, Turing, and others (8; 89; Section III references; Appendix D references). They proved that computers can only accept, generate, or accept and generate formal languages. Since all of these knowledge representations are eventually implemented on a computer system and used as input data (the language being accepted) for a computer algorithm, it follows that they must be formal languages.

However, because the proponents of all of these knowledge representations do not have a widely accepted definition of their representations, any formal language analysis of these representations would eventually reach the same language-definition plateau as was reached in this dissertation. Once again, Godel's theorem and/or the meta-level conjecture would force the open language-typing problem to show up for each of the knowledge representations.

Not only does the potential exist for this language-typing problem to remain open for all knowledge representations, the potential also exists that a complete human computer-model will never be found. As was the case for the knowledge representations, any human model will be implemented on a computer. Since computers only accept/generate

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formal languages, they are a form of a formal system.
Godel's theorem can then be applied to the model's output
language to reach the conclusion that it is possible that no
human computer-model can ever be proven to represent the
true human being. In the worst case, the meta-level con-
jecture can be applied to reach the conclusion that no true
human computer-model will ever be found.

Even though all of these conclusions appear to complete
the formal language analysis on knowledge representation,
there are still recommendations that can be made for
additional work.

X. Recommendations and Closing

Recommendations

With the success that was achieved by applying formal language techniques to the production-rule and semantic-network knowledge representations, there are several recommendations that can be made. One recommendation is to continue to apply formal language theory techniques to the special classes of category-1 production-rule and semantic-network languages (see Theorem 5.13 of Section V and Theorem 6.15 of Section VI for class definitions), to determine if other special characteristics exist for these languages over and above those known for type-2 languages. By recognizing the existence of these special characteristics, other general conclusions about the top-category knowledge representations may be found. For example, while type-2 languages are closed under union and product, proofs were provided in Sections V and VI that these special classes of category-1 languages are not closed under either union or product operations. As a result, these special classes of category-1 languages as well as the classes of top-category languages were proven not to be an Abstract Family of Languages (AFL) (24). This finding prevented the application of the well published characteristics of AFLs to these knowledge representations.

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Another recommendation is to investigate the characteristics of each of the special classes of category-1 production-rule and semantic-network languages formed when the knowledge-language (see Definitions 4.03 and 4.04 of Section IV) is one of three other language-types: type 0, type 1 and type 2 (8). This dissertation only covered the category-1 languages formed from a type-3 knowledge-language. Since Haines conjectured that his type 2 finding for his centermarker-languages depended on the regular set membership of his equivalent knowledge-language (98), a different language classification may be found for these representations when using these other types of knowledge-languages. By remaining at the category-1 level, the complexities of the higher category-level knowledge-words (see Definition 4.03 and 4.04 of Section IV) can be avoided. This should make the task of determining the language-type of the related representation-languages somewhat easier.

A more general recommendation is to apply the formal language techniques of this dissertation to the other forms of knowledge representations. By using the inclusion-hierarchy definition-approach, basic formal knowledge can be gained about the other representations even though the language-typing problem for the top-category languages remains open for them. This new information combined with that of this dissertation can be used to establish foundations from which new knowledge-representation forms can be developed for specific applications. While this

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recommendation is to study all knowledge representations, a specific knowledge representation should be evaluated first.

The specific representation is the frame. In Section IX, it is concluded that a semantic-network form could be used as the storage-structure for a centralized database. However, because the network is a special case of a frame representation (the network-hierarchy is contained as a subset of the frame-hierarchy, see Sections I and II), it may be the case that a frame is the best storage-structure for a centralized database. Of course, there are still a lot of other knowledge representation forms that need to be evaluated before a final selection of the storage-structure can be made. But, by resolving the storage-structure issue for the frame first, a large majority of knowledge represen-tations used in existing expert systems may be able to be consolidated into one standard database.

While this recommendation involved other representation-forms, another recommendation that can be made involves the rule and network language-hierarchies (see Section IV). The recommendation is to provide a special-case definition for all of the characteristics of rules and networks given in Section IV. Then, using the same tech-niques given in Sections V-VIII, complete the formal analysis for these special language-hierarchies. If these special-case definitions could be made so that differences could be traced (e.g. the number of nested statements is "N"), then more than one special-case definition will

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actually have been accounted for by this approach. However, these special-case definitions must be developed so that the language-type of the specially defined knowledge-language does not exceed the expected type of a knowledge-language generated from a more general definition. Otherwise, the results will not be typical of the more complex knowledge representations.

Additionally, it is important to notice that the open language-typing problem applies to both the knowledge-languages as well as the overall representation-languages. The specialized definition can only eliminate the existence portion of the problem. Finding the true language description still remains a risk due to Godel's theorem. However, if a language version could be found for this special case, then the conjectures of Section VIII would have additional concrete basis. This would add credibility to the overall representation findings of this dissertation without waiting for the knowledge representation researchers to reach a consensus on the form of knowledge.

Mentioning knowledge representation researchers brings to mind several recommendations for them specifically. One recommendation for these researchers is to provide detailed supporting proofs when they state that their knowledge representation is equivalent to others. While the findings of this dissertation showed that special equivalence cases exist (see Section VII), the findings also showed that complete equivalence of rules and networks does not exist

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(see Proposition 8.06 of Section VIII). By showing that a
production-rule language maps into a semantic-network
language does not prove equivalence of the entire set of
languages. The fact that a reverse map can be used to
retrieve the original rules is not sufficient either. These
researchers need to expand their representation-definitions
in the manner used in this dissertation (see Section IV) to
generate the general class definition for each
representation-form. Then, they can use formal proof
techniques similar to those of this dissertation (see
Section VII) on these general classes to truly verify that
class equivalence exists.

Another recommendation for these knowledge representa-
tion researchers is that they prove the correctness of the
transformations they use when transforming from one repre-
sentation to another. The finding of this dissertation that
no single transformation exists for networks-to-rules
supports the need for this added task (see Proposition 8.08
of Section VIII). The methods used in this dissertation
(see Section VII) can be applied to help prove the correct-
ness of specific transformations. However, these special
transformations must not be used to transform a more general
version of a knowledge representation without a similar
generalization being applied in the correctness proofs of
these special transformations. That is, one transformation
may be proven correct for a representation containing a
specific subset of knowledge-words, yet all of the

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underlying characteristics of the overall knowledge-language may not have been taken directly into account in the original proof of correctness. Without expanding the proof of the special transformation to include all the words in the knowledge-language, representation-words that contain other knowledge-words could transform incorrectly when using this same transformation.

For example, let the general knowledge-language constitute a particular finite regular set. Now, let the specific word-set used to prove the correctness of a given network-to-rule transformation be a special regular subset of this general knowledge-language. Since both are regular sets over the same alphabet, a common mistake is to assume the same transformation would apply. However, as was shown in Section VII, some finite semantic-network languages exist that can never be transformed into a production-rule representation. Although, a semantic network formed from a subset of the knowledge-language can be transformed correctly. So, using the special transformation on the larger semantic-network representation would result in an incorrect production-rule representation being generated.

A further recommendation is that knowledge representation researchers get with the manufacturers of support tools and provide users the formal language description of the representation(s) that the tool will handle. As indicated in Section I, expert systems have to be validated for operational use. Since the knowledge representation used in

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the knowledge-base (see Figure 4) has to be validated during

the expert system's validation, users are faced with

developing validation tests for their particular implementa-

tion of the representation. By using the formal language

description along with their own implementation details,

existing formal language algorithms (e.g. word membership)

can be modified and used to perform validation tests. This

can reduce the time needed to develop these tests.

Closing

While the previous recommendations dealt with ways to

apply, expand upon and improve upon the results of this

dissertation, there is one final suggestion for future

investigations in applying formal language theory to knowl-

edge representations. This suggestion is to expand the

analysis techniques to include computational time and space

complexities. Formal language theory provides some of the

guidelines that can be followed (see the references in

Appendix A). Reference 105 provides other guidance for any

special circumstances that might surface as a result of the

detailed knowledge-word definitions.

This complexity information would be useful for those

who develop support tools for these representations.

Recalling that while this dissertation showed that no single

support or automatic programming tool existed that could

handle all knowledge-languages, there are tools that exist

that support a countably infinite number of specific

implementation-versions for a given knowledge-language.
Therefore, establishing complexity guidelines for these
manufacturers to follow would result in a standard form of
comparison among these different systems. That is, there
may be several existing tools that could suffice for a
particular application. However, one tool may be more
efficient in both time and space than any of the others.
This type of information would be invaluable in helping a
user make a final tool selection.

With this last suggestion, the efforts of this disserta-
tion draw to a close. The original goal of providing
formality to the field of knowledge representation has been
met. Even though open problems exist, it is important not
to falsely conclude that formal language theory should not
have been used to study knowledge representations. Godel's
theorem does not say that every truth is unprovable. By
using formal language theory, this dissertation has enhanced
the knowledge about the various representation-forms. The
formality provided by language theory allows objectivity to
be used when reaching conclusions about knowledge represen-
tations. This is needed in light of the many subjective
opinions of knowledge representation researchers (84).

While this dissertation has shown how to add formality
to the knowledge representation field, it also has provided
the foundation for an approach to study general computer
data structures. Knowledge representations are just forms
of abstract data types (3). By applying the same formal

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language theory techniques to general abstract data types, it should be possible to gain formal knowledge about a wider variety of computer storage approaches than just representation-structures. Even though the dissertation does not provide absolute proof of the applicability of the approach to all cases, the positive results of this dissertation provide support for this conjecture.

While this dissertation has contributed to the formality of both the knowledge representation and the abstract data type areas of computer science, it has also contributed to the field of formal language theory itself. The dissertation provided the proof of the size of the formal language (and grammar, see Appendix D) set. Because of the insight gained from this proof, the complexity of the proofs of new formal language theorems can be reduced. Additionally, the dissertation expanded the centermarker-languages of Haines (98) to include any regular set as the centermarker. Finally, the dissertation provided examples of formal languages that actually exist outside of the theoretical environment. As a result, this dissertation provides support to the position that research on formal languages is more that just a theoretical curiosity.

QUOD ERAT DEMONSTRANDUM

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Appendix A: References on Formal Language Theory

Languages and Grammmars

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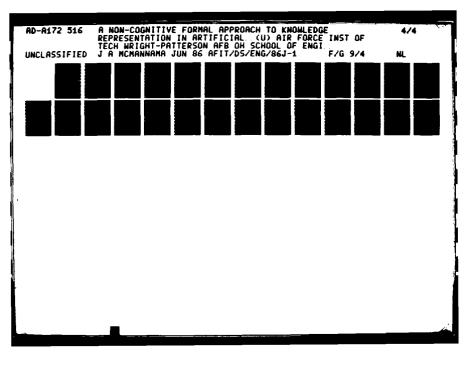
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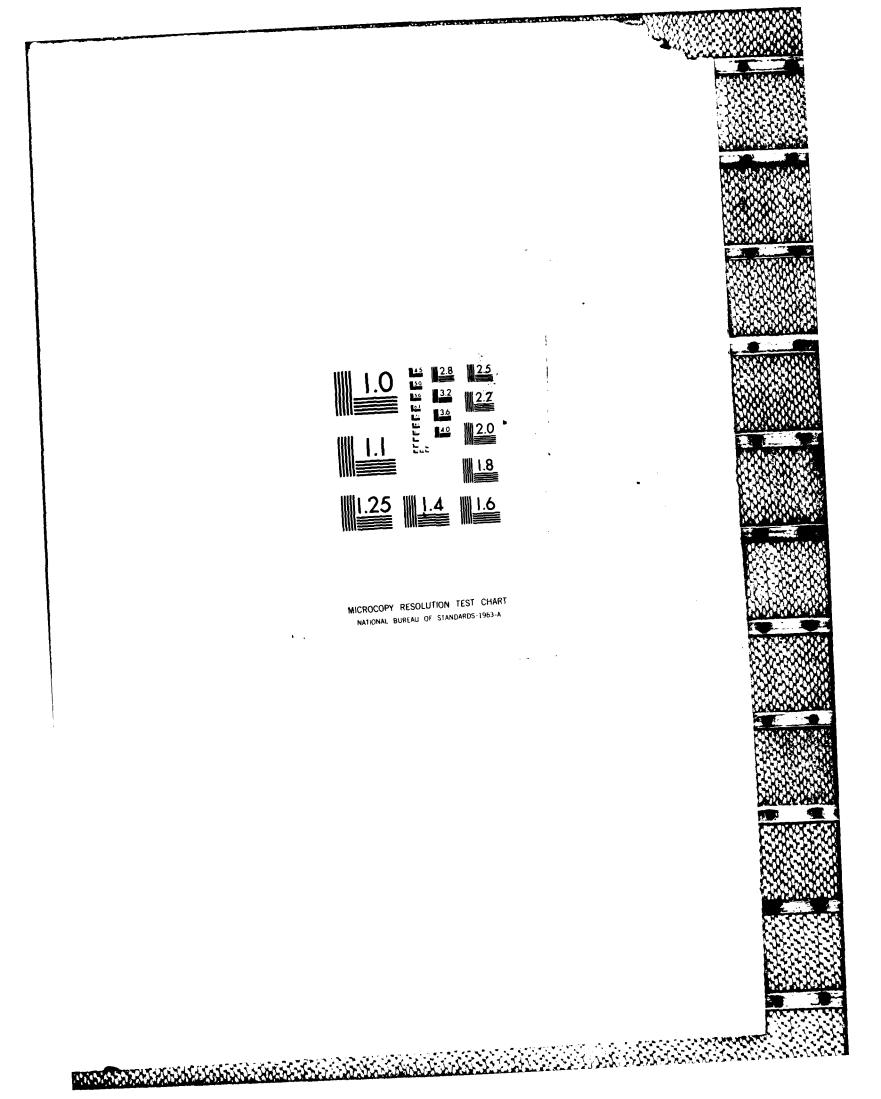
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Appendix C: <u>Invalid</u> <u>Nonenumerable</u> <u>Set</u>

As part of the work in formal language theory, theorists search for examples of sets of words that are not recursively enumerable. These examples provide evidence that Chomsky's hierarchy is a subset of yet a higher set (8:152). However, theorists sometimes propose such sets only to be disproven later. One invalid case was found during work on this dissertation. The case was Manna's construction of a nonrecursively enumerable set (9:39).

For his construction, Manna chose a two letter alphabet, $Z=\{a,b\}$. By placing the words of Z^* in lexicographic order, he could choose the jth word, xj. From a problem in his text, he stated that every Turing machine could be encoded as a word in Z^*. Therefore, he could choose the jth Turing machine, Tj.

With this notation established, he constructed a set $L1=\{xj|xj$ is not accepted by Tj$\}$. He then stated that L1 could not be accepted by any Turing machine because the set always contained a word which a given machine would not accept. Therefore, L1 could not be a recursively enumerable set.

However, he cannot construct L1 as stated for the set containing every Turing machine. That is, by selecting xj from Z^*, there always exists one machine which accepts every word in Z^*. Therefore, no xj exists for this machine.

This conclusion follows from several definitions given in Section III of this dissertation. From Definition 3.19, Z^* is a regular set since Z is a finite, regular set. From Definition 3.21, the Z^* regular set is accepted by some finite automaton (Turing machine). From Definition 3.18 and the fact that a regular set is a recursive set, this finite automaton accepts every word in the language and rejects all others. But, $Z^*-Z^*=\phi$ and so all words are accepted.

There are several different arguments that could be used in an attempt to counter this disagreement with Manna. It could be argued that L1 could contain the empty set and then the previously described machine would reject L1. However, this would violate the definition of the set L1. L1 contains words, not sets of words. The empty set is a set, not a single word. Language theorists added the empty word to handle this problem. But, Z^* already contains the empty word by definition.

Another argument possible is that L1 could be the empty set ϕ. Then, the previously described machine would not accept L1. This argument fails because ϕ is a regular set. By Definition 3.21 of Section III, there exists another machine in the set of all Turing machines that accepts ϕ.

Therefore, the set L1 as constructed by Manna is not a nonrecursively enumerable set.

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Appendix D: <u>Grammar</u> <u>Space</u>

When a set of characteristics for languages are found,
the grammars for those languages are usually studied to
determine if a related set of characteristics exists for
them. As was the case for this dissertation, both the
language-space size and grammar-space size are studied.
Since the findings of the dissertation were not based on
grammar-space size, the main body of the dissertation did
not contain the grammar-space size development. Therefore,
the results of this related effort are presented in this
appendix. In order to remain consistent with the body of
the dissertation, the format that was used to present the
language-space size effort is also used to present the
grammar-space size.

<u>Supporting</u> <u>Definitions</u> <u>and</u> <u>Theorems</u>

In addition to definitions and theorems already provided
in Sections I and III of the main body of this dissertation,
an additional set that relate to recursive function theory
is needed to be able to handle the generative nature of
grammars. In order to provide sufficient information to
understand some of these definitions and theorems, related
ones are also given. However, only the main definitions and
theorems are referred to in the actual proofs.

Also, to remain as consistent as possible with Sections
I and III, the same symbolic notation is used where

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possible. Therefore, Z represents a finite alphabet of symbols and Z^* represents the set of all finite words.

Definition D.01: A partial function, $f(x1,x2,..,xn)$, $n \geq 1$, mapping n-tuples of words over $Z=\{a,b\}$ into words over Z, is said to be Turing computable if there is a Turing machine, M, over $\{a,b,*\}$ which behaves as follows. For every n-tuple $(w1,..,wn)$ of words over Z, M takes the string $(w1*...*wn)$ as input and

1. If $f(w1,...,wn)$ is undefined, then M will loop forever.

2. If $f(w1,...,wn)$ is defined, then M will eventually halt (either accepting or rejecting the input) with a tape containing the value of $f(w1,..,wn)$ followed only by blank tape symbols (9:44).

Theorem D.01: A n-ary partial function mapping n-tuples of words over Z into words over Z is partial recursive if and only if it is Turing computable (9:52).

Definition D.02: A partial recursive function that is defined for all arguments is called a total recursive function (9:52).

Definition D.03: The class of all primitive recursive functions over an alphabet $Z=\{a,b\}$ is defined as follows (9:45):

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1. Base functions:

    nil(x)= e (empty word)

    consa(x)= ax

    consb(x)= bx

2. Composition:

    If h, g1,.., gm are primitive
    recursive then so is the n-ary
    function f(x1,..,xn)=
    h[g1(x1,..xn),..,gm(x1,..xn)].

3. Primitive recursion:

    If g, h1 and h2 are primitive
    recursive (some arguments of h1 and
    h2 may be missing) then so is the
    n-ary function (e represents the
    empty word):

    a. For n=1:

        $f(e)= w, \ w \in Z^*$

        f(ax)= h1[x,f(x)]

        f(bx)= h2[x,f(x)]

    b. For $n \geq 2$:

        f(e,x2,..,xn)= g(x2,..,xn).

        f(ax1,x2,..,xn)=
        h1[x1,..,xn,f(x1,..xn)].

        f(bx1,x2,..,xn)=
        h2[x1,..xn,f(x1,..,xn)].

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Theorem D.02: The following hierarchy exist for functions (9:52; 92:Chapter 13):

All Functions
$\cup$
Partial Recursive Functions
$\cup$
Total Recursive Functions
$\cup$
Primitive Recursive Functions

Now that the recursive functions have been identified, the tie between languages and these functions needs to be specified.

Definition D.04: A language L is Turing recognizable if it is the domain of a Turing realizable function (92:460).

Theorem D.03: A set is Turing recognizable if and only if it is Turing enumerable (92:489).

A final theorem is needed which forms the starting seed for the theorems that follow.

Theorem D.04: The set of base functions of the primitive recursive functions is countably infinite (92:525).

Grammar-Space Size

To determine the size of grammar space, the size of the recursive function space needs to be determined first.

Theorem D.05: The cardinality of the set of partial recursive functions is countably infinite.

Proof: First, from Theorem D.04, a subset of the primitive recursive functions has countably

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infinite cardinality. From Theorem D.02, this subset is contained within the partial recursive functions. Therefore, the set of partial recursive functions must be at least countably infinite.

Next, Definitions 3.22 and 3.23 of Section III and Theorem D.01 establishes that Turing machines can only compute partial recursive functions. Theorem 3.13 of Section III established that the cardinality of the set of all Turing machines is countably infinite. Therefore, the set of partial recursive functions can be at most countably infinite.

Finally, given that both the upper and lower cardinality-bounds are equal, the set of partial recursive functions is countably infinite. Q.E.D.

Having established the size of computable functions, the relationship between grammars and partial recursive functions is needed. Even though this relationship is well known (92:Chapter 13), the statement of the theorem and the proof technique used herein provides a clear view of this relationship.

Theorem D.06: For every set of type-0 grammars generating the same type-0 language over a given alphabet, there must exist a set of partial recur-

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sive functions that generate an equivalent recursively enumerable set (type-0 language).

Proof: The case for one grammar and one partial recursive function will be handled first. From Definitions 3.17 and 3.20 and Theorem 3.12 of Section III, every type-0 language is generated by some type-0 grammar and the language is a recursively enumerable set. Next, from Definition 3.17 and Theorem D.03, every one of the unique type-0 languages is Turing enumerable. Now, by Definition 3.24 of Section III, there must exist a Turing computable function that generates an equivalent, unique, recursively enumerable set of the natural numbers. Finally, by Theorem D.01, the Turing computable function performing the enumeration must be a partial recursive function. Therefore, for some type-0 grammar there must exist some partial recursive function that generates an equivalent recursively enumerable set.

Now, expand this finding to the set of grammars and functions. Because of the existence of normal-forms for the type-0 grammars (6:Chapter 5), more than one type-0 grammar can exist that generates the same type-0 language. Similarly, more than one

partial recursive function exists that gener-
ates the same equivalent recursively enumer-
able set (e.g. (4X+4)/2 and 2X+2). Therefore,
from the previous proof of the single language
case, it follows that for every set of type-∅
grammars generating the same type-∅ language,
there must exist a set of partial recursive
functions that generate an equivalent
recursively enumerable set. Q.E.D.

Theorem D.∅6 only establishes that some set of partial
recursive functions exists for a given set of type-∅ gram-
mars. The theorem does not indicate a one-to-one corre-
spondence of the members of these sets. However, a one-to-
one correspondence has to be assumed to exist in order to
bound the size of grammar space.

Theorem D.∅7: The cardinality of the set of all type-∅
grammars over a given alphabet is countably
infinite.

Proof: Because of the existence of normal-forms for
the type-∅ grammars (6:Chapter 5), more than
one type-∅ grammar can exist that generates
the same type-∅ language. However, formal
language theorists have not proven the exact
number of equivalent type-∅ grammars existing
per type-∅ language. Therefore, the size of
grammar space will have to be determined by

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establishing upper and lower size-bounds for the set of all type-∅ grammars.

The lower size-bound can be established from Definitions 3.∅7 and 3.2∅ and Theorem 3.11 of Section III. These definitions and theorem establish that there exists a countably infinite number of unique type-∅ languages each generated by a different type-∅ grammar. Since a countably infinite number of type-∅ languages exist, there must be at least a countably infinite number of unique type-∅ grammars. Hence, the lower size-bound on type-∅ grammars is countably infinite.

The upper size-bound follows directly form Theorems D.∅5 and D.∅6. Theorem D.∅6 established the existence of a set of type-∅ grammars and a set of partial recursive functions that generate an equivalent recursively enumerable set (type-∅ language). Because a single type-∅ grammar (partial recursive function) only generates a single type-∅ language (recursively enumerable set), all existing sets of type-∅ grammars (partial recursive functions) meeting Theorem D.∅6 have to be disjoint. That is, individual type-∅ grammar G1 (partial recursive function F1) can only be a member of one set of type-∅ grammars

(partial recursive functions). From this
disjoint property, set theory reveals that the
largest possible number of sets of type-∅
grammars (partial recursive functions) that
can meet Theorem D.∅6 are sets that contain
only one member. That is, type-∅ grammar G1
and partial recursive F1 are the only grammar
and function generating the same equivalent
recursively enumerable set (type-∅ language).

Therefore, to establish the upper size-
bound on the set of type-∅ grammars, assume
that this one-to-one correspondence exists.
Then, from Theorem D.∅5, the upper size-bound
on the type-∅ grammars is countably infinite.

Finally, since both the upper and lower
size-bounds are countably infinite, the
cardinality of the set of type-∅ grammars is
countably infinite. Q.E.D.

Now that the size of the set of type-∅ grammars for a
given alphabet has been established, the cardinality of the
set of all type-∅ grammars over all finite alphabets can be
found using set theory.

Theorem D.∅9: The set of type-∅ grammars over all finite
alphabets has countably infinite cardinality.

Proof: From AFL theory, all the finite alphabets are
obtained from a countably infinite alphabet
(97:33). From Theorem 3.1∅ of Section III,

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the set of all possible finite alphabets over this countably infinite alphabet has countably infinite cardinality. Since every set has the empty set ϕ as a finite subset, this countably infinite group of finite sets must contain ϕ. However, by Definition 3.01 of Section III, an alphabet cannot be the empty set. Therefore, remove the empty set from this group of alphabets. By applying the $f(x)=x-1$ mapping on the indexes of the remaining finite sets, there is still a countably infinite number of finite sets remaining.

Now, for each finite alphabet, form the countably infinite set of all type-0 grammars (see Theorem D.07). Then, perform the set union operation over these countably infinite sets of grammars. By Theorem 3.05 of Section III, the resulting set has countably infinite cardinality. Q.E.D.

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With the entry of Artificial Intelligence (AI) into real-time applications, a rigorous analysis of AI expert systems is required in order to validate them for operational use. To satisfy this requirement for analysis of the associated knowledge representations, the techniques of formal language theory are used. A combination of theorems, proofs and problem-solving techniques from formal language theory are employed to analyze language equivalents of the more commonly used AI knowledge representations of production rules (excluding working memory or situation data) and semantic networks.

Using formal language characteristics, it is shown no single support-tool or automatic-programming tool can ever be constructed that can handle all possible production-rule or semantic-network variations. Also, it is shown that the entire set of finite production-rule languages is able to be stored in and retrieved from finite semantic-network languages. In effect, the semantic-network structure is shown to be a viable candidate for a centralized database of knowledge.

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