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MYCIN: a knowledge-based consultation program for infectious disease diagnosis†

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MYCIN is a computer-based consultation system designed to assist physicians in the diagnosis of and therapy selection for patients with bacterial infections. In addition to the consultation system itself, MYCIN contains an explanation system which can answer simple English questions in order to justify its advice or educate the user. The system's knowledge is encoded in the form of some 350 production rules which embody the clinical decision criteria of infectious disease experts. Much of MYCIN's power derives from the modular, highly stylized nature of these decision rules, enabling the system to dissect its own reasoning and allowing easy modification of the knowledge base.

Introduction

The MYCIN system (Shortliffe, 1976) was developed to provide consultative advice to physicians regarding the diagnosis and treatment of patients with bacterial infections. Such patients must often be treated in the absence of complete information as to the source of the infection. A blood culture may show some initial bacterial growth, but definitive identification usually requires another 48 hours. Meanwhile, the physician must decide whether treatment is needed, and if so, what drugs are appropriate. Often the physician is not an expert in infectious diseases, and so requires the advice of a consultant. Recent studies (Roberts & Visconti, 1972; Kunin, 1973) have documented widespread inappropriate prescription of antibiotics, suggesting the need for more (or more accessible) infectious disease consultants. This is the principal role for which MYCIN is intended.

A number of constraints influenced the design of the MYCIN system. In order to be useful, the system has to be easy to use, and provide consistently reliable advice. It must be able to accommodate the large body of task-specific knowledge required for high performance, a knowledge base which is subject to change over time. The system must be able to utilize inexact or incomplete information. This applies not only to the absence of definitive laboratory data noted above, but to the medical domain itself, which is characterized by much knowledge which is highly judgmental in nature. Finally, to be a useful interactive system, MYCIN must be capable of supplying explanations for its decisions and responding to physician questions, rather than simply printing orders.

Structure of MYCIN

The MYCIN system comprises three major subprograms, as depicted in Fig. 1. The *Consultation Program* is the core of the system which interacts with the physician to

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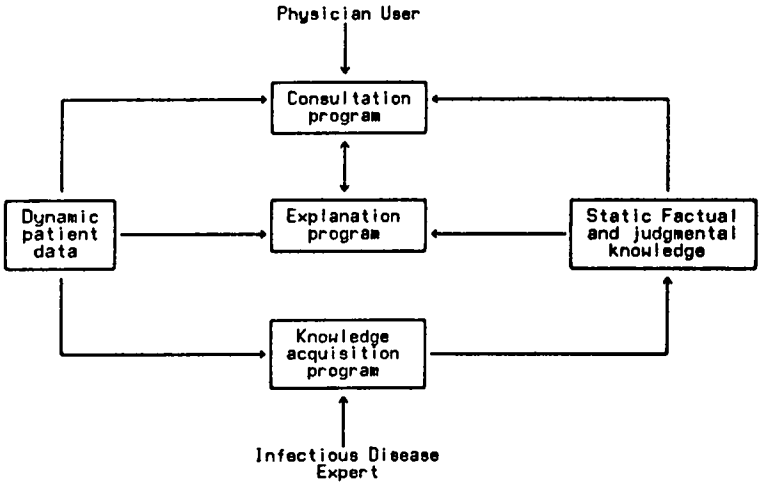

FIG. 1. Organization of the MYCIN system. Arrows denote information flow between modules, knowledge base and users.

obtain information about the patient, producing diagnosis and therapy recommendations. The *Explanation Program* provides explanations and justifications for the program's actions. The *Knowledge-Acquisition Program* is used by experts to update the systems knowledge base.

MYCIN is written entirely in INTERLISP, a dialect of the LISP language, and runs on a DEC PDP-10.

The consultation program

Excerpts from a sample consultation are shown in Fig. 2. The doctor's responses are all in upper case following the double asterisk prompt. A great deal of effort has gone into the human engineering aspects of the system, to make the interaction as smooth as possible. If the user finds a question unclear, he can request a rephrasing, with a list of sample responses. A large dictionary of synonyms allows the user much latitude in choice of responses, and simple typing or spelling errors are automatically corrected.

KNOWLEDGE ORGANIZATION

Information about the patient and conclusions drawn during the consultation are represented as associative (object-attribute-value) triples. The objects are such things as individual cultures taken from the patient, organisms that grew out of them, and drugs the patient is currently receiving. Various attributes, termed *clinical parameters*, characterize these objects. Questions asked during the consultation attempt to fill in the values for relevant attributes of these objects. To represent the uncertainty of data or competing hypotheses, attached to each triple is a *certainty factor* (cf), a number between -1 and 1 indicating the strength of the belief in that fact. A cf of 1 represents total certainty, while a cf of -1 represents certainty in the negation of the fact. While certainty factors are *not* conditional probabilities, they are informally based in probability theory (Shortliffe & Buchanan, 1975). Some triples from a typical consultation might be

(IDENTITY ORGANISM-1 PSEUDOMONAS (0·8))
(IDENTITY ORGANISM-1 E. COLI (0·15))

1) Patient's name: (first-last)
** *FRED BRAUN*
2) Sex:
** *M* *{background patient data}*
3) Age:
** *55*
4) Are there any cultures for Fred Braun which may be related to the present illness, and from which organisms have been grown successfully in the microbiology laboratory?
** *y*

--------CULTURE-1--------
5) From what site was the specimen for CULTURE-1 taken?
** *BLOD*
=BLOOD
6) Please give the date and time when CULTURE-1 was obtained. (mo/da/yr time)
** *JUN 20, 1977*
The first organism isolated from the blood culture of 20-JUN-77 (CULTURE-1) will be referred to as:

--------ORGANISM-1--------
7) Enter the laboratory-reported identity of ORGANISM-1:
** *UNKNOWN* *{typically identity is not yet known}*
8) The stain (Gram or Ziehl-Neelsen acid-fast) of ORGANISM-1:
** *NEG* *{preliminary lab results give some clues}*
9) Is ORGANISM-1 a rod or coccus (etc.):
** *ROD*
10) What is the form of the individual organisms (e.g. Lancet-shaped for cocci, fusiform for rods, etc.)?
** *FUSIFORM*

{...more questions follow in order to gather sufficient information to infer the identity and significance of the infecting organisms...}

23) What is the suspected portal of entry of the gramneg rod from the blood culture of 20-JUN-77 (ORGANISM-1) into this sterile site?
** *GI (.6)* *{user can indicate uncertainty}*
24) Is Fred Braun a burn patient?
** *N*
25) Is Fred Braun a compromised host (e.g. alcoholic, sickle-cell-disease, immunosuppressed)?
** *N*
26) Is Fred Braun febrile?
** *y*

{...etc...}

My therapy recommendations will be designed to treat for organisms that are either very likely or, although less likely, would have a significant effect on therapy selection if they were present. It is important to cover for the following probable infection(s) and associated organism(s):

INFECTION-1 is BACTEREMIA

<ITEM-1> E.COLI [ORGANISM-1]
<ITEM-2> KLEBSIELLA [ORGANISM-1]
<ITEM-3> ENTEROBACTER [ORGANISM-1]
<ITEM-4> KLEBSIELLA-PNEUMONIAE [ORGANISM-1]

{...questions follow to evaluate possible therapy choices...}

[REC-1] My preferred therapy recommendation is as follows:
In order to cover for items <1 2 3 4>: *{one drug covers 4 possible identities}*
Give: GENTAMICIN
Dose: 119 mg (6.0 ml) q8h IV for 10 days [calculated on basis of 1.7 mg/kg]
Comments: Modify dose in renal failure.

FIG. 2. Excerpts from a MYCIN consultation. Italicized comments in braces are not part of the actual interaction.

(SITE CULTURE-2 THROAT (1·0))
(BURNED PATIENT-298 YES (−1·0)).

i.e. organism 1 is probably *Pseudomonas*, but there is some evidence to believe it is *E. coli*, the site of culture 2 is the throat, and patient 298 is not a burn patient.

PRODUCTION RULES

MYCIN reasons about its domain using judgmental knowledge encoded as production rules (Davis & King, 1977; Davis, Buchanan & Shortliffe, 1977). Each rule has a *premise*, which is a conjunction of predicates over triples in the knowledge base. If the premise is true, the conclusion in the *action* part of the rule is drawn. If the premise is known with less than certainty, the strength of the conclusion is modified accordingly. A typical rule is shown in Fig. 3.

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RULE035

PREMISE: ($AND (SAME CNTXT GRAM GRAMNEG)
               (SAME CNTXT MORPH ROD)
               (SAME CNTXT AIR ANAEROBIC))
ACTION:  (CONCLUDE CNTXT IDENTITY BACTEROIDES TALLY .6)

If:   1) The gram stain of the organism is gramneg, and
      2) The morphology of the organism is rod, and
      3) The aerobicity of the organism is anaerobic
Then: There is suggestive evidence (.6) that the identity of the
      organism is bacteroides
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FIG. 3. A MYCIN rule, in its internal (LISP) form, and English translation.

The predicates are simple LISP functions operating on associative triples. $AND, the multivalued analogue of the Boolean AND function, performs a minimization operation on cf's. The body of the rule is actually an executable piece of LISP code, and "evaluating" a rule entails little more than the LISP function EVAL. However, the highly stylized nature of the rules permits the system to examine and manipulate them, enabling many of the system's capabilities discussed below. One of these is the ability to produce an English translation of the LISP rule, as shown above. This is possible because each of the predicate functions has associated with it a translation pattern indicating the logical roles of the function's arguments.

It is intended that each rule be a single, modular chunk of medical knowledge. There are currently some 350 rules in the MYCIN system.

APPLICATION OF RULES—THE RULE INTERPRETER

The control structure is a goal-directed backward-chaining of rules. At any given time, MYCIN is working toward establishing the value of some clinical parameter. To this end, the system retrieves the (precomputed) list of rules whose conclusions bear on this goal. The rule in Fig. 3, for example, would be retrieved in the attempt to establish the identity of an organism. If, in the course of evaluating the premise of one of these rules, some other piece of information is needed which is not yet known, MYCIN sets up a subgoal to find out that information; this in turn causes other rules to be tried. Questions are asked during the consultation when rules fail to deduce the necessary information. If the user cannot supply the requested information, the rule is simply ignored. This control structure results in a highly focused search through the rule base.

ADVANTAGES OF THE RULE METHODOLOGY

The modularity of rules simplifies the task of updating the knowledge base. Individual rules can be added, deleted or modified without drastically affecting the overall performance of the system. And because each rule is a coherent chunk of knowledge, it is a convenient unit for explanation purposes. For example, to explain why the system is asking a question during the consultation, a first approximation is simply to display the rule currently under consideration which requires the information from the user.

The stylized nature of the rules is useful for many operations. While the syntax of rules permits the use of any LISP functions, there is a small set of standard predicates which make up the vast majority of the rules. The system contains information about the use of these predicates in the form of function *templates.* For example, the predicate SAME is described as follows:

function template:	(SAME CNTXT PARM VALUE)
sample function call:	(SAME CNTXT SITE BLOOD)

The system can use these templates to "read" its own rules. For example, the template shown here contains the standard tokens CNTXT, PARM and VALUE, indicating the components of the associative triple which SAME tests. If the clause above appears in the premise of a given rule, the system can determine that the rule needs to know the site of the culture, and that the rule can only succeed if that site is, in fact, blood. When asked to display rules which are relevant to blood cultures, MYCIN will be able to choose that rule.

An important function of the templates, previously alluded to, is to permit MYCIN to automatically precompute (at system generation time) the set of rules which conclude about a particular parameter; it is this set which the rule monitor retrieves when the system needs to deduce the value of that parameter.

The system can also read rules to eliminate obviously inappropriate rules. It is often the case that, of a large set of rules under consideration, several are provably false by information already known. That is, the information needed to evaluate one of the clauses in the premise has already been determined, and that clause is false, thereby making the entire premise false. By reading the rules before actually invoking them, many can be discarded, thereby avoiding the deductive work necessary in evaluating the premise clauses which precede the false one. In some cases this means the system avoids the useless search of one or more subgoal trees, when the information thereby deduced would simply be overridden by the demonstrably false premise.

Another more dramatic case occurs when it is possible, on the basis of information currently available, to deduce with certainty the value of some parameter which is needed by a rule. This is the case where there exists a chain of one or more rules whose premises are known (or provable, as above) with certainty and which ultimately conclude the desired value with certainty. Since each rule in this chain must have a certainty factor of 1·0, we term such a chain a *unity path;* and since a value known with certainty excludes all other potential values, no other rules need be tried. MYCIN always seeks a unity path before trying a set of rules, or asking a question; typically this means "common sense" deductions are made directly, without asking the user "silly" questions, or blindly invoking all the rules pertaining to the goal. Since there are usually few rules on any potential unity path, the search tends to be small.

The ability to read rules opens the way to the writing of rules which manipulate other

rules. We term such rules *metarules*; they are used to make deductions not about the medical entities of the domain, but about strategies to be used by the system. Whenever the rule interpreter is about to invoke a list of rules to establish some goal, it first applies any metarules associated with that goal. These rules can reorder or prune the rule list, to make the search more suitable for the given case.

Explanation capability

A major subprogram of MYCIN is a general *Question Answering* (QA) program, which answers simple English-language questions concerning the system's decisions in a particular consultation or the system's knowledge in general. A small set of commonly desired explanations is also provided in a command style during the consultation by the *Reasoning Status Checker*. This special module explains the system's current line of reasoning and motivation for the questions asked. A more detailed study of explanation in MYCIN may be found elsewhere (Scott, 1977).

The QA module is entered automatically at the end of each consultation, and additionally is available to the user during the consultation if the need arises. The user is encouraged to ask questions about any aspect of MYCIN's performance.

Because of the relatively unambiguous vocabulary used in the medical domain, and because of our desire to minimize the delay in answering questions, we have forgone any complicated parsing techniques in the QA module. Rather, we use a simple pattern-matching approach, relying on the strong implications of certain keywords in the user's questions. The words in the translation of a clinical parameter, and values of that parameter are tagged in the system dictionary as implying that parameter. By suitably weighing the implications of each word in the sentence, the system comes up with one or more parameter/value pairs being asked about. Pattern matching is used to determine the general type of the question, which indicates what is being asked about those parameter/value pairs. Typical questions (see Fig. 4) seek the value of a certain parameter, how this value was concluded, or how this parameter was used.

Questions about the value of a given parameter of an object are answered by simply displaying the current hypothesis regarding it. To explain how the value of a parameter was concluded, MYCIN retrieves the list of rules which were successfully applied, and prints them, along with the conclusions drawn; or if the user supplied the value by answering a previous question, this is noted. More general questions about how certain information is used or concluded are answered by retrieving the relevant rules from the rule base.

As shown in Fig. 5, the Reasoning Status Checker is invoked by the HOW and WHY commands. At any time during the consultation when the user is asked a question, he can delay answering it, and instead ask WHY the question was asked. Since questions are asked in order to establish the truth of the premise of some rule, a simple answer to WHY is "because I'm trying to apply the following rule". Successive WHY questions unwind the chain of subgoals, citing the rules which led to the current rule being tried.

Besides examining the current line of reasoning, the user can also ask about previous decisions, or how future decisions might be made, by the HOW command. Explaining HOW the truth of a certain clause was established is accomplished as described above for the general QA module. To explain HOW a presently unknown clause might be established, MYCIN retrieves the set of rules which the rule interpreter would select to

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** IS ORGANISM-1 A STREPTOCOCCUS?

No. The identity of ORGANISM-1 is e.coli (.74) bacteroides (.7)
   klebsiella-pneumoniae (.4) pseudomonas-aeruginosa (.22) enterobacter (.21)
   proteus-non-mirabilis (.19) serratia (.03) salmonella (.02)

** WHY DID YOU RULE OUT STREPTOCOCCUS AS A POSSIBILITY FOR ORGANISM-1?

RULE033 could have been used to determine that the identity of ORGANISM-1 is
   streptococcus. However, clause 2 of rule033 ["the morphology of the
   organism is coccus"] was already known to be false for ORGANISM-1, so the
   rule was never tried.

** HOW DO YOU KNOW THAT CULTURE-1 WAS FROM A STERILE SOURCE?

I used rule189 to conclude that this blood culture was taken from a sterile
   source. This gave a cumulative c.f. of (1.0). The last question asked before
   the conclusion was made was 7.

** WHAT DOES GU MANIPULATION TELL YOU ABOUT THE IDENTITY OF AN ORGANISM?

The rules listed below use:
    whether the patient has had a genito-urinary manipulative procedure
to conclude about:
    the identity of the organism

156, 163, 190
Which do you wish to see?
   ** 156

RULE156
 If:  1) The site of the culture is blood, and
      2) The gram stain of the organism is gramneg, and
      3) The morphology of the organism is rod, and
      4) The portal of entry of the organism is urine, and
      5) The patient has not had a genito-urinary manipulative procedure, and
      6) Cystitis is not a problem for which the patient has been treated
 Then: There is suggestive evidence (.6) that the identity of the organism is e.coli

** IS BLOOD A STERILE SITE?

Yes. Blood is one of those sites that are normally sterile.

** WHAT ARE THE NONSTERILE SITES?

Those sites that are normally nonsterile are: CERVIX, CUTANEOUS-ULCER,
   LOCHIA, NOSE, SKIN, STOOL, THROAT, URETHRA, VAGINA.

** IS BACTEROIDES AEROBIC?

No, the aerobicity of bacteroides is anaerobic.
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FIG. 4. Interaction with the QA module. User questions follow the ** prompt.

establish that clause, and selects the relevant rules from them by "reading" the premises for applicability, and reading the conclusions for relevance to the goal.

Knowledge acquisition

The knowledge base is expanded and improved by acquiring new rules, or modifications to old rules, from experts. Ordinarily, this process involves having the medical expert supply a piece of medical knowledge in English, which a system programmer converts into the intended LISP rules. This mode of operation is suitable when the expert and the

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34) Was penicillinase added to this blood culture (CULTURE-1)?
** WHY

[i.e. WHY is it important to determine whether penicillinase was added to CULTURE-1?]

[3.0] This will aid in determining whether ORGANISM-1 is a contaminant.
   It has already been established that
     [3.1] the site of CULTURE-1 is blood, and
     [3.2] the gram stain of ORGANISM-1 is grampos
   Therefore, if
     [3.3] penicillinase was added to this blood culture
   then
     there is weakly suggestive evidence (.4) that ORGANISM-1 is a contaminant
   [RULE039]

      ** WHY

[i.e. WHY is it important to determine whether ORGANISM-1 is a contaminant?]

[4.0] ... in order to determine whether there is significant disease associated
   with this occurrence of ORGANISM-1.
   It has already been established that
     [4.1] this blood culture was taken from a sterile source
   Therefore, if
     [4.2] ORGANISM-1 is not a contaminant
   then
     there is strongly suggestive evidence (.9) that there is significant
       disease associated with this occurrence of ORGANISM-1
   [RULE032]

      ** WHY

[i.e. WHY is it important to determine whether there is significant disease
   associated with this occurrence of ORGANISM-1?]

[5.0] ... in order to determine the organisms which require therapy.
   It has already been established that
     [5.1] the infection is known, and
     [5.2] the identity of ORGANISM-1 is known
   Therefore, if
     [5.3] there is significant disease associated with this occurrence of ORGANISM-1
   then
     it is definite (1.0) that ORGANISM-1 is one of the organisms which require therapy
   [RULE090]

      ** HOW 5.2

[i.e. HOW was it established that the identity of ORGANISM-1 is known?]

Question 9 was asked, but you weren't sure; so the following was used:

   [5.5] RULE084 was used to conclude that the identity of ORGANISM-1 is
   streptococcus-group-a (.29).
```

FIG. 5. Use of the Reasoning Status Checker during the consultation.

skilled programmer can work interactively. Ideally, however, the expert should be able to convey his knowledge directly to the system.

A fair amount of work has been done (Davis, 1976) to allow experts to directly update the rule base. A rule-acquisition routine parses an English-language rule by methods similar to those used in parsing questions in the QA module. Each clause is broken down into one or more object-attribute-value triples, which are fit into the slots of the appropriate predicate function. This process is further guided by *rule models*, which

supply expectations about the structure of rules and the interrelationships of the clinical parameters.

One mode of acquisition has received special attention: that of acquiring new rules in the context of a program error. In this case, the user is trying to correct a deficiency in the rule base which is quite localized: if a new rule is to correct the program's faulty behavior, it must at the very least apply to the consultation at hand. In particular, each of the premises must evaluate true for the given case. These expectations greatly simplify the task of the acquisition program, and also aid the expert in formulating the new rules.

One aspect of rule acquisition which is difficult to automate is the actual formulation of medical knowledge into decision rules. Our desire to keep the rule format simple is occasionally at odds with the need to encode the many aspects of medical decision-making. The backward-chaining of rules by the deductive system is also often a stumbling block for experts who are new to the system; however, they soon learn to structure their knowledge appropriately. In fact, some experts have felt that encoding their knowledge into rules has helped them formalize their own view of the domain, leading to greater consistency in their decisions.

Recent developments and future plans

SYSTEM COMPETENCE

A formal evaluation of MYCIN's competence in the domain of bacteremia (bacterial infections in the blood) was recently undertaken. A group of infectious disease specialists evaluated various aspects of MYCIN's performance when presented with the cases of fifteen patients with bacteremia. Results indicate that MYCIN's performance in this area has begun to approach that of the subspecialist (Yu, 1978). The system will not be put into actual hospital use until we are satisfied with its competence and reliability.

EXPANDING THE KNOWLEDGE BASE

The scope of MYCIN's competence has recently been expanded to cover the diagnosis and treatment of meningitis. This entailed roughly doubling the number of rules and clinical parameters in the system. These additions are now nearing completion, and plans are underway for an evaluation of the system's performance on meningitis cases.

As the system's knowledge base expands to cover other infections, the number of rules which must be considered when drawing conclusions grows potentially larger. For example, the meningitis knowledge base is of little use in diagnosing a bacteremic patient; the presence of a large number of rules applicable only to meningitis should not degrade the system's performance in other areas. We are seeking methods of keeping this expansion under control.

One approach currently under development makes extensive use of the system's ability to manipulate its own rules. The set of rules which conclude about a particular parameter implicitly constitutes a "program" to deduce that parameter. This program can be made explicit and compiled as a single function. In the process, the conditional premises of related rules can be further restructured into an optimal decision tree that eliminates redundant computation of identical premise clauses. In effect, several rules are tried in parallel; a single test (e.g. "what is the infection?") can cause a whole block of rules to fail at once. Thus, with this "rule compiler" we retain the convenience of rules for explanation and debugging, while the consultation program uses the much more efficient compiled code to actually perform its reasoning.

OTHER APPLICATIONS

MYCIN's potential as an educational tool is also being explored. It appears that Computer-aided Instruction (CAI) techniques can be used to teach the content's of MYCIN's knowledge-base.

The usefulness of a rule-based approach has been demonstrated by a number of other projects following MYCIN. Completely separate rule bases for psychotherapy and pulmonary disease diagnosis have been developed to run under the MYCIN control structure. Other investigators have adapted the MYCIN methodology in designing a geological consultant (Duda, 1977) and an intelligent terminal system (Anderson & Gillogly, 1977).

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References

ANDERSON, R. H. & GILLOGLY, J. J. (1977). RAND artificial terminals agent: design philosophy. *Technical Note RAND R-1809-ARPA*. Santa Monica, California: The RAND Corporation, January.

DAVIS, R. (1976). Use of meta-level knowledge in the construction and maintenance of large knowledge bases. *Ph.D. thesis* (*University Microfilms* #76-25,988). Stanford University, California, U.S.A.

DAVIS, R., BUCHANAN, B. & SHORTLIFFE, E. (1977). Production rules as a representation for a knowledge-based consultation program. *Artificial Intelligence*, **8** (1), February, 15–45.

DAVIS, R. & KING, J. (1977). An over-view of production systems. In ELCOCK, E. W. & MICHIE, D., Eds, *Machine Intelligence*, **8**. Chichester: Ellis Horwood, pp. 300–332.

DUDA, R. O. (1977). Semantic network representations in rule-based inference systems. *Technical Note 136*. SRI Project 5821, May, Stanford Research Institute, Menlo Park, California, U.S.A.

KUNIN, C. M. (1973). Use of antibiotics: a brief exposition of the problem and some tentative solutions. *Annals of Internal Medicine*, **79** (4), 555–560.

ROBERTS, A. W. & VISCONTI, J. A. (1972). The rational and irrational use of systemic microbial drugs. *American Journal of Hospital Pharmacy*, **29**, 828–834.

SCOTT, A. C. (1977). Explanation capabilities of knowledge-based production systems. *American Journal of Computational Linguistics*, Microfiche 62.

SHORTLIFFE, E. H. (1976). *Computer-Based Medical Consultations: MYCIN*. New York: American Elsevier.

SHORTLIFFE, E. H. & BUCHANAN, B. G. (1975). A model of inexact reasoning in medicine. *Mathematical Biosciences*, **23**, 351–379.

YU, V. L. (1978). Evaluating the performance of a computer-based consultant. *Computer Programs in Biomedicine*, to appear.