MODELS FOR AUTOMATED MEDICAL CONSULTATION

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Abstract. This paper distinguishes *consultation* systems from more general intelligent *tutoring* systems and describes an approach to the problem of converting an existing medical expert system, INTERNIST-I/CADUCEUS, into an automated consultant. Transcripts of rounds discourse were used to identify expert *strategies* and *tactics* in instructing interns; and also were used to develop a model of medical-novice knowledge organization. One finding is that experts respond to evidence of incomplete or ill-structured information with a small number of knowledge-based actions such as *restatement*, *characterization*, and *generalization*, which afford straightforward computational interpretations.

1. Rationale in Automating Consultation.

Within the past ten years, with the development of increasing numbers of expert systems, we have produced computer-based information resources of unprecedented complexity and power. In a field such as internal medicine, for example, there is no textbook or collection of papers on medical diagnosis as extensive or accurate as the INTERNIST knowledge base ([Miller *et al.* 1982]). Nevertheless, almost all such resources remain inaccessible for any purpose other than their original design. In the case of the INTERNIST knowledge base, this means that information about diagnostically relevant procedures or disease relations is brought to the attention of a user only in the course of semi-automaticaUy solving a specific diagnostic problem.

Our broad goal is to identify computational techniques and models of man-machine interaction that can assist us in making expert-system resources more widely assessible. Our specific objective is to augment the CADUCEUS expert system ([Pople 1982]) with a facility to allow non-experts—students, for example—to practice the description and diagnosis of a case in internal medicine. The system's role would be to aid the novice in organizing the relevant information in a case and, in particular, to identify misconceptions.

We regard our problem, gencrically, as that of making expert systems into *consultants.* Consultant systems should be capable of identifying faulty knowledge in a user and responding with a display of correct knowledge. This contrasts with the more ambitious goal of *intelligent tutoring* as there is no global program of instruction and no preconception of a preferred end-state for a user. Tutoring systems often include a syllabus-like component, which are represented as fixed networks that relate skills in terms of their complexities and dependencies *(e.g.,* WUMPUS [Goldstein 1982]) and as program-generated plans relevant to a specific case and student *(e.g.,* GUIDON [Clancey 1982]). A good consultant must be able to correct a defect in understanding when he encounters it; a good tutor must be able to guide us in the acquisition of whole bodies of knowledge. In the special case of medical consultation, the good consultant can assume that there is a great deal of shared knowledge and can concentrate on discovering and correcting incomplete knowledge. Often this takes the form of a give-and-take discussion of the specific findings in a case, with the consultant offering alternative views of the situation.

In approaching the problem of designing a CADUCEUS consultant system we have focused first on an analysis of expert medical instruction in the context of "rounds" discussions. In particular, we have attempted to identify *strategies* and *tactics* used by experts to correct defective knowledge in students that are amenable to computational implementation in CADUCEUS. As a result, we have also developed partial models of medical-novice and expert problem solving, especially the aspects of medical problem solving that depend on the organization of medical knowledge.

We have made several assumptions to justify our approach. First, we would argue that the development of consultation facilities is computationally feasible in expert systems where relational knowledge is represented explicitly. Thus, a system like CADUCEUS is a better candidate for being made into a consultant as we have defined it than a system like MYCIN ([Shortliffe 1974]), where the knowledge exploited by the system is encoded in production rules. Second, we believe that many of the problems associated with intelligent tutoring can be avoided in the domain of medical consultation, since it is possible to assume a great deal of shared knowledge and motivation. Finally, we consider the sort of interaction we see in rounds discourse to be an excellent source of information about the organization and use of medical knowledge in diagnostic problem solving and about the style of instruction that is most appropriate for medical novices. We return to the first point in the concluding section of this paper; and we consider the last two points in somewhat greater detail, below.

2. A Scale of "Difficulty* in Tutoring.

In thinking about the potential difficulties in building tutoring and consultation systems, we can isolate several features of an instructional situation that contribute to the difficulty (or ease) of a task: (1) the degree of shared general knowledge that can be assumed; (2) the degree of shared, specific domain knowledge that can be assumed; (3) the ability the 'student' has to reason in the domain; and (4) the motivation the 'student' has to emulate the style of reasoning in the 'tutor'. Roughly speaking, the first two features affect our representation of the *passive* knowledge of the student and the second two affect our representation of the *active* processing of that knowledge.

For example, the worst possible tutoring situation would involve individuals with no common language, culture, or education. Nothing could be assumed about shared general or specific knowledge or ways of reasoning. Another difficult situation is exemplified by the "air-compressor" dialogues described in [Grosz 1977]: the novice has no domain knowledge (about air-compressors), little shared knowledge of general use (such as the names of tools, like 'ratchet-wrench'), and no motivation or interest in the task (assembling an air-compressor from parts) except to finish. An example of an extremely good situation is a dialogue between to experts in the same field, who are working on similar problems. They can be expected to share a great deal of both general and domain-specific knowledge, possess similar reasoning strategies, and have a keen interest in improving their knowledge through goal-directed interaction with a colleague. In terms of computational modeling, we could rely on one knowledge base covering domain-specific information and could be confident that the kinds of reasoning and judgments would overlap.

With medical consultation, we are clearly on the 'good' end of the scale. Medical students and interns share a great deal of general and domain-specific knowledge with their instructors; they can be expected to reason in predictable patterns; and they are extremely motivated to emulate experts. Most current tutoring systems have characteristics that place them closer to the more difficult end of the scale. They have focused on tasks such as teaching simple arithmetic to children as in DEBUGGY ([Burton 1982]) and WEST ([Burton & Brown 1982]), and teaching electronic trouble-shooting as in SOPHIE ([Brown *et al.* 1982]); or they have been in contexts such as game-playing as in WEST ([Burton & Brown 1982]). In developing computational models for medical consultation, we can assume that the expert's organization and use of knowledge is optimal and that students are interested in bringing their knowledge into congruence with the expert's. This assumption allows us to concentrate on the problem of diagnosing defective knowledge in the student with reference to a canonical knowledge base; and to simulate expert behavior as a principal method of instruction.

3. Discourse as Protocol-like Data.

Protocol analysis is one of the best sources of information about cognitive processes in problem solving. (See [Ericsson & Simon 1984].) Time pressure, logistics, and ethics all argue against the taking of protocols during actual medical diagnosis. However, we believe that the data obtained during bedside rounds discussions are equally valid as evidence of the cognitive processing associated with student medical problem solving. First, the discussions are often explicitly reQcctive: the discussion leader (expert) requires participants (typirnlly, students) to explain their statements ond to revenl the thoughts Mint have led them to specific conclusions. Second, the interaction is unrehearsed and rapid-fire: students, especially, are working 'in the limit'. Finally, the formal procedure for presenting a case (almost script-like) ensures that the same points will be discussed at different times in a presentation from different points of view. Thus, if it were one of the reasons for hospital admission, a problem in the esophagous, for example, would be discussed at the beginning of the discourse, during the canonical review of systems, while performing the physical exam, and in the final summarization of findings, and possibly at other times as well. These observations convince us that rounds data are sufficiently protocol-like to justify their use in developing models of the cognitive activity in medical consultation and instruction.

4. Analysis of "Rounds" Discourse.

Over the past twelve months, we have transcribed and analyzed approximately eight hours of rounds sessions between Dr. Jack Myers and students at the University of Pittsburgh School of Medicine. The transcripts represent the complete discussion and evaluation of seven cases in internal medicine. For our purposes, it was especially useful to have Dr. Myers as a rounds leader, as he is the principal architect of the INTERNIST knowledge base.

Rounds presentations follow a standard operating procedure (SOP) that functions, in many respects, like a script. One person, typically, a student, is responsible for presenting a case to a group, including especially the rounds leader (expert physician) who is to evaluate the student. The case is discussed at the patient's bedside; and the patient is examined by the expert and other participants in the discussion. The SOP specifies that the case will be discussed in the following order:

1. Presenting Condition (including chief complaint and other relevant signs and recent history)
2. Previous Diagnoses
3. History
4. Review of Systems (where only case-relevant observations are made)
5. Physical Examination (including general appearance and significant positive and negative findings)
6. Neurological Examination .
7. Laboratory Data

One important consequence of the SOP is that any hypotheses about the diagnoses in an actual case must stand the test of coherence from different points of view, i.e., in the context of different types of evaluations. If a student suggests a specific conclusion on the basis of, say, a physical examination, there had better be evidence in previous diagnoses, history, systems review, the neuroinjicnl examination, or laboratory data that is consonant with it. In fact, when such evidence is lacking, the student's error is quite obvious, at least for an expert who understands the consequences of the conclusion for different contexts of the case. Another effect of the SOP is that the same phenomena will be discussed repeatedly in the presentation. This provides a thread of continuity to the discourse that is, to a large extent, predictable on the basis of detailed knowledge of a diagnosis.

In analyzing transcripts, we coded the flow of information by *apparent topic, perceived plans,* and *associated knowledge.* While the control of all three of these components is necessary in the management of coherent *discourse,* we focused on the role of associated knowledge in identifying student errors and in framing the expert's responses: these are the critical factors in the management of medical *consultation* as we have defined it. Indeed, the analysis of the transcripts supports our hypothesis that effective consultation need not involve extended discourse, but rather a sensitivity to the association of knowledge appropriate in a particular case. Furthermore, we discovered that the expert seems to use only a handful of tactics to intervene when the student is in error. Some examples from the transcripts are found in Section 7.

5. Expert vs. Novice in Consultation.

The models of expert and novice that emerge in the rounds situation are similar to those identified in other contexts. ([Larkin *et al.* 1980]) Taking information about medical-expert problem-solving from other studies as well ([Elstein *et al.* 1978], [Johnson *et al.* 1981], and [Lesgold et al. 1981]), we can axgue that the expert has a repository of rich patterns to aid him in identifying relevant details; he employs reasoning more to confirm hypotheses than to generate them; and he is extremely sensitive to contextual features as sources of clues in a case. His knowledge is, above all, *integrated* and detailed; and his reasoning is *prototype-driven.* The medical novice may also have detailed knowledge, but it is not as well intergrated as the expert's. In fact, we can characterize the novice as having *modularized* knowledge of three types: (l) static, associative knowledge; (2) knowledge of effective procedures for reasoning; and (3) knowledge of heuristics associated with contexts.

By *associative* knowledge we mean knowledge of anatomy, physiology, findings associated with diagnoses, the scripts of procedures, *etc.* In the INTERNIST knowledge base, this is the sort of information that one finds in disease profiles and in links between diseases. By *effective procedures,* we mean strategies for inference, including ways to 'simulate' processes mentally (such as imagining a physiological consequence of a disease), and knowledge of how to verify diagnostic hypotheses. Finally, by knowledge of *heuristics in contexts,* we mean the ability to identify salient features, to adjust granularity, and to recognize certain questions as potentially more fruitful than others when pursuing hypotheses or when engaged in different phases of the SOP.

The novice may have information under each of these classes of medical knowledge, but in the course of actual problem solving {*e.g.,* diagnosis), he appears to fail to use his know-lodge effoctivrly. and his reasoning appears to bo inappropriate. Even when the novire says nothing that is *irrelevant* in the discussion, he frequently cannot answer questions that require *global* understanding of a case or see direct consequences of what he has noted.

6. Expert Strategies.

The expert in our rounds cases seems to have two principal goals: to help the novice integrate his knowledge via actual problem solving; and to respond to perceived defects in the novice's understanding of a problem by (1) displaying the correct associations and (2) demonstrating, explicitly, the interworkings of the three types of modular knowledge. It is interesting to note that there is no other special tutoring strategy (such as 'drilling' or 'retesting') involved. We would characterize this as a *"knowledge* in the eye of the beholder" phenomenon; and would claim it is a hallmark of consultation discourse. The tacit understanding, here, is that it is the patterns of associations themselves that must be learned; and that good tutoring can be effected by pointing to the right part of the pattern at the propitious moment.

We model the expert's reaction as a *fit-deficit* trigger that recognizes a lack of mapping between his knowledge (assumed to be right) and that of his student and then activates conversational tactics that are designed to effect repairs in the defective knowledge of the student. We can identify several *fit-deficit* triggers according to the degree of overlap in knowledge. Examples include:

- no fit—implying a disjunctive knowledge base; one in which the missing pieces can be concepts or links between concepts; and
- loose or fuzzy fit—requiring reorganization or modifications to an existing knowledge structure.

Traditionally, the concept of "differential modeling" has been used to compare the student's knowledge with the knowledge encoded in the tutoring system. In particular, we find differential modeling used to identify issues to be focused upon ([Burton & Brown 1982], [Clancey 1982]), to select lines of reasoning to be taught (i.e., generalization or refinement of a concept [Goldstein 1982]), and to diagnose and correct specific misconceptions frequently observed in novices ([Brown *k* Burton 1978], [Stevens *et al.* 1982]). A critical factor in all of these systems is extensive user modeling. Our fit-deficit triggers, on the other hand, are less dependent on user modeling because they don't require **a** global view of the user but can be sensitive to local configurations of information in the discourse.

7. Expert Intervention Tactics.

With rare exceptions, the expert in our cases responds to student misconceptions or potential confusion with one of six "tactics"—corresponding to speech acts that **operate**

on the information in focus: ***characterization, restatement, summarization, generalization,*** *explanation* and *question.* We discuss each of these, witli examples from the transcripts, in ^renter Hefnil below. (The lino numbers refer to the nrtuni trnnsrript; the line-brenks were **modified for** this **paper.)**

Characterization. We use *characterization* **to mean any** statement **that** asserts associative relationships, **especially facts related to findings or diagnoses. Typically, the expert** uses characterization to add details or to provide new information under **what** might be considered "textbook" knowledge.

Case 4 [lines **1089-1101]**

> ***Expert:*** **in the pathologic process / you get severe / diffuse spasm / it can be quite distressing / and he doesn't stress this component you see**
>
> ***Student:*** **well he has pain**
>
> ***Expert:*** **yeah but**
>
> ***Student:*** **but it's not a real sharp one**

Restatement. ***Restatement*** **actually includes several types of operations, for example, restatement with reordering or restatement with deletion of information. The expert uses restatement to call the student's attention to a preferred ordering or use of terminology; or to a salient subset of the information that the student may (correctly) have volunteered.**

Case 4 [lines 271-276]

> ***Student:*** **oh / his uvula is benign**
>
> ***Expert:*** **so the upper swallowing mechanism / is intact / is what you're saying**

Summarization. ***Summarization*** **is used to collect a set of relevant facts or to change context. It seems to be used at points where the group has many possible details to consider or when the expert's questioning has led the group astray.**

Case 4 [lines 908-927]

> ***Expert:*** **the patient's cause for dysphagia is not clear / the chest x-ray shows surgical clips / quite close to the esophagal gastric junction / so he must have had a liberal gastrectomy / in view of the hisory of chronic peptic ulcer / preceeding the surgery / one first thinks of reflux esophagitis producing stricture / and perhaps metaplasia leading to neoplasm**

Generalization. We think of ***generalization*** **in the special sense of** ***prototype instantiation.*** **The expert's use of generalization does not correspond to induction—to a universal quantification over similar findings or diseases, for example. Rather, the expert's generalization is a statement about expected or normative conditions.**

Case 4 [lines 500–505]

> *Expert:* because of / with his long history of ulcers / he ah almost certainly / has considerable hyperacidity

Explanation. When the expert engages in *explanation*, he typically demonstrates effective procedures for verifying hypotheses. Often explanation involves discussions of physiology and anatomy, which offer different perspectives on the understanding of a diagnosis.

Case 4 [lines 479–493]

> *Expert:* yes so if he's been gradually developing / an esophageal stricture / and it's now severe / then you see the reflux proximal to the stricture / wouldn't amount to anything / you still get reflux distal to the stricture / and you could even say / well sometimes / there's enough force and some acid will get through / whereas most of the time it wouldn't

Question. The use of a *question* is, by default, "insincere" in rounds discourse. Questions have presuppositions and the expert uses questions to assert those presuppositions. Also, of course, questions are used to force students to be explicit about what they assume.

Case 4 [lines 160–170]

> *Student:* incidentally he's had a cough
>
> *Expert:* is it incidental?
>
> *Student:* I think so / it's incidental to the complaint for which he's here
>
> *Expert:* you ask that question very seriously / well let's hear more about it

With the exception of *question*, the order in which we present the tacits reflects increasing computational difficulty. We consider the implications of these difficulties in the following section.

8. Implications: CADUCEUS as Consultant.

The INTERNIST-I and CADUCEUS systems are built upon the INTERNIST knowledge base, which contains explicit details about the associations of findings to diseases; about the relative importance of findings; and about preferred orderings of information. In addition, both systems that use the knowledge base have heuristics and procedures for identifying diagnostic hypotheses and for making (limited) inferences from findings ([Masarie *et al.* 1985]). In short, a system such as CADUCEUS seems ideally suited for use in consulting applications other than those for which it was originally designed.

The following is an example of the kind of information that can be exploited in the INTERNIST knowledge base. Small numbers (in the range 0-5) can be regarded as measures of significance; larger numbers correspond to opcnenHed scores as a result of processing findings under a potential diagnosis. [Note that information is represented here as extracted by the "Quick Medical Reference" system under development by Drs. Randy Miller, Fred Masarie, and Jack Myers.]

Significant findings in a diagnosis: REFLUX ESOPHAGITIS (partial listing)

3 3 CHEST PAIN SUBSTERNAL RELIEVED BY ANTACID
3 3 STOMACH BARIUM MEAL ESOPHAGEAL REFLUX
3 2 CHEST PAIN SUBSTERNAL EXACERBATION WITH SWALLOWING
2 4 CHEST PAIN SUBSTERNAL BURNING
2 3 CHEST PAIN SUBSTERNAL AT REST
2 2 DYSPHAGIA SOLED
2 2 REGURGITATION SOUR

Significant relations among diseases: REFLUX ESOPHAGITIS (partial listing)

2 3 caused-by PROGRESSIVE SYSTEMIC SCLEROSIS INVOLVING ESOPHAGUS
2 2 co-occurring-with BRONCHIAL ASTHMA
2 1 caused-by PEPTIC ULCER
2 1 predisposed-to-by OBESITY
1 2 causing IRON DEFICIENCY ANEMIA
1 1 causing ASPIRATION PNEUMONIA
1 1 predisposing-to HYPERTROPHIC OSTEOARTHROPATHY

Potential overviews of cases: (For a given set of findings):

ACHALASIA 88
leading to any of the following:
CARCINOMA OF ESOPHAGUS 20
ESOPHAGEAL CANDIDIASIS 14
ESOPHAGEAL SPASM DIFFUSE 22

These examples are merely a sampling of the sort of information that the knowledge base provides. Many other types of structured information are available. In this form, it is possible to identify relevant details under any potential diagnosis, so one could simulate the expert's *characterization* with little difficnlty. The lists also encode preferred orderings under a diagnosis. Thus, one could simulate the expert's *restatement* directly.

It should be noted, however, that there are important gaps in the INTERNIST knowledge base that would have to be bridged before it could be used as the basis of a complete consultant. INTERNIST contains no information about anatomy or physiology; about effective procedures for accommodating subjective evaluations; about contexts other than those generated in the pursuit of disease hypotheses; or about prototypes. Thus, it would be difficult to simulate *generalizations* or *explanations* of the sort we observe in actual rounds discourse at this stage of knowledge-base development.

We should note that other medical expert systems may not be as suitable for the type of consultation we describe as is CADUCEUS. In particular, systems that encode their knowledge in production rules combine domain knowledge with the specifics of its use in problem solving, making it difficult to reveal the relationships between components of domain knowledge outside the context of the application of a specific rule. The INTERNIST knowledge base represents this type of knowledge explicitly in a network structure, therefore making it possible to access portions of it through the links that are appropriate to the context of interaction.

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