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ABSTRACT

Part of a sustained program that has involved the design of personally tailored information systems responsive to the needs of scientists performing common research and teaching tasks, this project focuses on the procedural and content requirements for accomplishing need diagnosis and presents these requirements as specifications for an interactive, computer-based, knowledge delivery system for scientific researchers. A discussion of selected concepts from cognitive science and artificial intelligence describes their use as models for characterizing the research process or to specify procedural requirements for the system. Applications of these concepts in two manual "simulations" of the diagnostic process are described, including the research project as a procedural script (illustrated with scripts in microbiology and industrial psychology), the researcher as a problem solver, the diagnostic system as a problem solver, and the researcher's knowledge needs as schemata/frames. A 7-step process is described which is designed to successively narrow and define the researcher's current problem and his knowledge surrounding that problem thus providing a basis for developing a search strategy, selecting relevant knowledge, and developing information products to fill knowledge gaps. Fifteen references are listed, and appendices provide examples of knowledge schemata. (RAA)

COGNITIVE MODELS OF SCIENTIFIC WORK AND THEIR IMPLICATIONS FOR THE DESIGN OF KNOWLEDGE DELIVERY SYSTEMS

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ABSTRACT

Recent research and theory in cognitive psychology and artificial intelligence were reviewed as sources of concepts applicable to the development of an interactive, computer-based, knowledge-delivery system for use by scientists. A system concept evolved from this review, and the need-diagnosis portion of a future system was tried out.

The process of doing a piece of research can be viewed as following a <u>procedural script</u>. Subfields of science can be characterized by a finite number of research paradigms or methods for approaching problems, and those paradigms can be specified as a series of phases, tasks, steps, etc. Once a researcher decides to implement a given script, the full set of procedural requirements can be specified. A computer system which can store generic scripts can interact with researchers using procedures as a common framework for communication.

A researcher's current conceptualization of his research can be viewed as a set of interrelated <u>schemata or frames</u>, and knowledge needs viewed as gaps in the knowledge structures which define the schemata/frames. To diagnose researcher information needs, a computer system would construct a representation of the researcher's schema in which the gap occurs. The system's schema does not need to be identical to the researcher's schema, but sufficent for the system to search a data base for knowledge which would fill the gap.

The process of formulating a research project or developing a testable hypothesis can be viewed as an example of <u>decomposing the problem space</u> into manageable units. A system can aid in the problem decomposition process by providing an <u>external memory</u>. A key element in the system-researcher interaction is the process by which the researcher manipulates the problem representations, and the system reproduces and stores them for review and continued modification by the researcher.

These concepts were 'tested' with a small sample of researchers in marine microbiology and in industrial psychology. A series of interactive, 'think-aloud-about-your-research' sessions were conducted with each researcher over several months. Results of these sessions were illustrations of the utility of the selected concepts for describing the research process. Scripts were developed, problem decompositions were represented as hierarchies, knowledge structures were represented as tables with specified information gaps, data bases were efficiently searched, and useful knowledge was delivered to each researcher.

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I. INTRODUCTION

A. Rationale

Automated information storage and retrieval systems represent a significant advance over manual systems. First, they provide the capability to systematically process large numbers of bibliographic references and to maintain, on-line, large bibliographic files. Secondly, they expand the ability of a searcher to quickly identify targeted references through the use of multiple search terms.

These systems, however, have not been designed around any systematic analysis of user needs. The controlled vocabularies used in indexing and search are classification schemes that do not necessarily match the classification schemes of the users. The output of the search is a list of citations only some of which may contain needed information. Users, and specifically researchers, are looking for answers, for particular knowledge and not for the names of articles that may contain that knowledge. Interaction with the on-line systems requires training which most end-users do not have. The searching is primarily conducted by librarians or information specialists who develop search strategies which attempt to link their idea of a user's information need with appropriate references from the bibliographic data base. In most cases, the searcher does not have a comprehensive understanding of what the user is doing and what he needs to know; thus, the search is not properly focused.

The ideal information service is one that is highly personalized, responding to the very specific needs of each user. The feasibility of designing such a system rests on the assumption that individuals in the intended user group share some common frameworks of both process and content. The work reported here is one part of a sustained program that has involved the design of several personally-tailored information systems that were responsive to the needs of scientists performing common research and teaching tasks. In each of these systems the user's task provided the context for defining the information need. Basically, the approach was to describe the scientist's tasks in teaching a course or in conducting a research project, to identify the task or subtask he was currently working on and to determine the information needed to accomplish that task. These analyses resulted in the description of some common procedural frameworks: preparation for teaching a course involved a series of tasks that were common among teachers; researchers in a subfield followed similar steps in executing a research project. These commonalities were used successfully in establishing the requirements for a curriculum support system at a small liberal arts college and in designing individually tailored information packages for research scientists (Mavor and Vaughan, 1974; Mavor, Vaughan and Kidd, 1977). All system functions from need diagnosis to product delivery were accomplished manually by researchers and librarians.

The directions for the future of information science point to the development of fully automated systems which will provide the user with the specific knowledge he is seeking (Weiss,1977). In the long term, the system will interact directly with the user; the system will have programs for need diagnosis as well as for matching the stored knowledge base with defined needs. Several areas of work are needed to further advance the development of such a system. Specifications of procedures, programs and file structures are required for the diagnosis of knowledge needs, for the organization and storage of scientific knowledge from the literature, for the matching of knowledge needs to stored knowledge, and for the assembly of knowledge packages to fill diagnosed needs.

B. Purpose and Approach

The purpose of the present project was to establish the procedural and content requirements for accomplishing need diagnosis and to present these requirements as specifications for an interactive, computer based, knowledge delivery system for scientific researchers.

One of the obvious gaps in prior work within the overall study program was the lack of a theoretical framework. Since both the process of conducting research, and the structure and organization of the researcher's knowledge in a given content area are related to human cognition and memory, it was decided to sift the recent work of cognitive scientists for concepts that would assist in specifying the need-diagnosis process. In recent years cognitive science has experienced a significant revival. Cognitive psychologists are again actively using schema theory as a model of human memory and thought; artificial intelligence researchers are developing computer programs that function in ways that generate outcomes which simulate a variety of characteristics of human memory and comprehension.

The focus on concepts from cognitive science resulted in the following questions:

- Do the concepts covering human cognition that come out of AI research adequately characterize the processes by which scientists do their work?
- Can one model the processes of scientific problem-solving in a way that would permit those processes to be represented (in part at least) by a computer program of reasonable simplicity?
- Could a (rough) model of a given individual scientist's knowledge structure be represented by a computer program?
- Does the whole configuration of computerized information systems need to be redone in order to capture the full advantage of these new concepts - or -
- Could the concepts be used to "tune" the search and retrieval functions of an information search and retrieval system so that the product of the system would be improved?

This report describes the use of concepts from the cognitive sciences in characterizing the research process and in representing the researcher's knowledge needs. Additionally, some ideas are presented on an interactive procedure for the diagnostic process.

Along with reviewing the cognitive science literature for key concepts, interviews were conducted with eight Ph. D. candicates in marine microbiology and industrial psychology. Interviews with four microbiologists were conducted over a three-month period in order to develop longitudinal descriptions of the research process and of the researcher's changing knowledge needs over time; an average of nine sessions was held with each of these students. In order to test the accuracy and usability of the need diagnosis process, literature searches were performed and information products prepared to fill the diagnosed knowledge gaps. Throughout the interview process, extensive use was made of concepts from artificial intelligence and cognitive psychology in characterizing the research process being observed and in describing/representing the knowledge needs occurring at various points in this process. A second set of interviews was then conducted with four graduate students and a professor in psychology. These interviews served to further elaborate the diagnostic models and procedures developed with the microbiologists.

II. SELECTED CONCEPTS FROM ARTIFICIAL INTELLIGENCE AND COGNITIVE SCIENCE

The literatures of cognitive psychology and artificial intelligence contain a number of concepts which apply to the diagnostic process. Some of these concepts provide models for characterizing the research and the research process, others are useful in specifying procedural requirements for the system. The major concepts are:

- Scripts
- Frames
- Schemata
- Problem-solving processes

A. Scripts

A script is a generalized event sequence or episode that has occurred many times in the past. Children begin to learn scripts as classes of situations repeat themselves in the child's experience. Eventually the adult accumulates thousands of scripts. These scripts are the organizing contexts by which he is able to understand what is happening and to set up expectations about events that are likely to happen in a given situation (Schank, 1975a, 1975b). Schank has successfully developed situational scripts for computer representation based on his theoretical formulations. The program knows the sequence of events, actions, reasons why, etc. associated with 'going to a restaurant' and can apply inferencing rules to the knowledge it has. Although Schank's main program design work has been with situational scripts, he has suggested additional classes, one of which is 'procedural'.

<u>We assume that a large part of a researcher's training and experience can be represented as the accumulation of procedural scripts of the research process characteristic of his subfield.</u>

The number of different procedural scripts that are required to characterize the methods of a given subfield of science is not known, but we suspect the number is manageably small and for an individual researcher, even smaller.

Procedural scripts in research are assumed to be useful to a scientist in thinking about the feasibility of a project under consideration, e.g., "if I do this project, I'll need to use this method, do I have the appropriate apparatus?" Since a script is a time sequence of phased activities it serves as a checklist of what needs to be thought about and resolved at a particular time, what sorts of things will need to be thought about later, and how selections establish constraints and requirements on future phases.

Assuming that the computer program of our future system 'knew' the major procedural scripts and their important variations characteristic of given subfields of science. the early user-system interactions would 'locate' the researcher in what might be thought of as 'procedure space'. The program could then interact with the researcher about methodological and content issues and alternatives at the current stage of the user's project, and about projected consequences of the choices made.

B. Schemata and Frames

A schema is a psychological concept introduced by Bartlett in 1932 to explain how human beings remember, think and learn. Essentially, a schema is a large knowledge structure; the basic unit of memory and thought. Schemata exist at all levels of abstraction and are hierarchically organized and interrelated; they are used to comprehend new or complex situations (assimilation) and are in turn modified by experience (accommodation). The metaphor of a mental mosaic is sometimes used to convey the attributes of the concept.

Recently, schema theory has been revived and psychologists are beginning to conduct experiments in comprehension and memory based on a schema paradigm. Two important influences in this trend stem from the interactions between psychologists and linguists and between psychologists and computer scientists. The first provided a means for quantifying the structural characteristics of prose material, the second provided a means of implementing for test in actual computer operation, hypotheses about the nature of schema-based processes. (For reviews of modern schema theory see Norman and Bobrow, 1975; Rumelhart, 1975; Rumelhart and Ortony, 1977; Spiro, 1977.)

In artificial intelligence research, the term 'frame' is used to describe what psychologists generally call schema. Minsky (1975) formulated the theory of frames as a way to break out of the conceptual narrowness characteristic of both psychological theory and artificial intelligence practice. The main points about frames as presented by Minsky and summarized by Kuipers (1975) are stated below:

- A frame is a large data structure that creates and maintains a description representing knowledge in a limited domain.
- A frame structures a small domain of expertise and contains the knowledge necessary to create descriptions of objects and actions within that domain.
- A frame contains both content and procedural knowledge. Much of what the frame knows, it knows in relation to a procedure; e.g., information about tools is contained in procedures about how and in what context the tool is used.
- A frame contains knowledge that enables it to infer some features of the description being created from having observed others.
- A frame has terminals which are all filled with assumed values (a default assignment based on prior experience). As real-world values are observed, the default values are replaced with actual values. Default values represent the inductive knowledge gained by previous experience with the domain represented by the frame.

- A frame has specialists/framekeepers/subroutines that contain elaborated knowledge in a special area. They are called upon to resolve ambiguities, fill-in gaps with appropriate inferences, etc., in their area of special competence.
- Frames are interconnected with other related frames and there are frame hierarchies/frame systems; e.g., we have frames for stories and subframes for animal stories and superframes for narratives.

The properties and special functions of frames such as 'frame terminals', 'default assignments' and 'specialists' have been taken up by the schema theory psychologists so that descriptions of modern schema and frame theories are increasingly indistinguishable.

We assume that the researcher's knowledge structures can be represented as schemata/frames. A scientist conducting a research project has both content and procedural knowledge which is specific to the performance of each task. Gaps in these knowledge structures form the basis for information requirements. Need diagnosis involves the development of a representation of the researcher's knowledge structure. Precise specification of the knowledge need is dependent on a close match between the researcher's knowledge structure and the representation of that structure by the system.

C. Problem-Solving Processes

Newell and Simon (1972) conducted in-depth studies of how adults process information in attempting to solve problems. They asked their adult subjects to think aloud as they worked towards solutions to problems in logic chess and crypt-arithmetic. The results were represented as 'problem behavior graphs' which were used as a basis for creating a problem-solving computer program, the General Problem Solver. Their work is a rich source of ideas about how an interactive, knowledge delivery system might function in support of a research scientist.

A detailed review of this work is presented in Newell and Simon (1972). We have selected three of their notions as being clearly applicable to understanding the researcher as a problem solver in specifying his knowledge-need problems at a level that allows for effective solution.

We assume that the researcher follows problem solving principles in designing a research project and that the need diagnosis system follows many of these same principles in defining/structuring the researcher's knowledge requirements. A brief description of the main principles is presented in the following sections.

1. Problem Space

Problem solving has often been represented as choosing one of several alternative solutions, however, the more challenging and critical problems faced in real-world settings is the creation of even one solution that is feasible and adequate. This condition is the main challenge in research; testing hypotheses is a technical problem, formulating the hypothesis in the first place is the crucial problem-solving behavior. Newell and Simon describe ~~the process~~ as 'working in the problem space', the problem is represented in the mind of the problem solver; he creates an internal representation of an external problem, modifies it, reformulates it and builds a new representation. The process continues until the problem is represented in a fashion that enables the problem solver to see a way to solve it. "Solving a problem means that the problem has been represented in such a way as to make its solution apparent." (Simon, 1969, p. 77)

2. External Memory

Related to the idea of solving problems as working in a problem space, is the idea of external memory. In their experimental sessions, Newell and Simon permitted some subjects to make notes, work out partial solutions on paper and generally keep track of where they were, what they had tried before, etc.

These notes and sketches of trial solutions were labelled 'External Memory' and without them subjects "forgot where they were, forgot what conditional assignments they had made, forgot what assumptions were implicit in their prior assignments." (Simon, 1969, p. 55) In a sense 'external memory' is a person's representation of a problem and both the concept and the procedure could be further developed as a means to describe how a researcher structures the problem space.

An interactive knowledge delivery system could serve as the researcher's external memory. In order to perform this function the system would need devices for representing the researcher's initial formulation of the problem, for modifying or decomposing the problem and for storing successive representations of the problem.

3. Decomposition of Large Problems into Smaller Sub-Problems

Real-world systems are too complex for the capacity of men's minds. Fortunately most (or at least some) complex systems are hierarchical and nearly decomposable, i.e., the interactions between subsystems are sufficiently weak (relative to interactions within subsystems) as to be safely ignored, particularly in the short-term behavior of the overall system. Because of these two properties, complex problems can be broken down into smaller and smaller components for solution and yet the problem is still meaningful and the solution to the smaller problems useful in the solution of the larger ones. A human solves a complex problem by systematically decomposing it until he finds a level he can handle, i.e., he has, from experience, some model or metaphor that applies to it (Simon, 1969).

A central feature of knowledge need diagnosis is the ability of the system to decompose the researcher's requirements into independent sets of questions which are specified at what the system recognizes as a manageable level; a level that allows the system to proceed towards a solution of the researcher's need.

III. APPLICATIONS OF COGNITIVE SCIENCE CONCEPTS TO THE DIAGNOSTIC PROCESS

This section presents the results of our work with both marine microbiologists and industrial psychologists which support the assumptions about the application of cognitive science concepts to the research process and to the diagnosis of researcher knowledge needs. These assumptions are as follows:

- A large part of the researcher's training and experience can be represented as the accumulation of procedural scripts of the research process characteristic of his subfield.
- The researcher follows problem-solving principles in designing a research project.
- The need diagnosis system follows problem-solving principles in defining/structuring the researcher's knowledge requirements.
- The researcher's knowledge structures can be represented as schemata/frames.

A. The Research Project As A Procedural Script

Through training and experience scientists learn a number of research paradigms which are used to study a variety of content problems in their sub-disciplines. These paradigms, like procedural scripts, are composed of a series of structured phases and tasks. Scientists using a particular paradigm will perform the same phases and tasks regardless of the content area being researched. In the present study two research process scripts were developed; one in microbiology and a second in industrial psychology.

1. A Script in Microbiology

Interviews with three Ph.D. candidates working in marine microbiology led to the development of a script/paradigm for marine microbial ecology research. The main phases and tasks of this script are presented in Table 1. The delineation of phases and tasks was based on detailed discussion with each

Table 1. A Procedural Script for Research in Marine Microbial Ecology

Phase 1. Problem Identification

Tasks

A. Identify a naturally occurring phenomenon in marine bacteria that has not been studied or described fully.

B. Establish the importance of studying the identified phenomenon in terms of its contribution of knowledge and/or its contribution to applied problems (e.g. transmission of disease in the water, breakdown of toxic substances which allow for marine growth on surfaces, etc.).

C. Determine feasibility of studying the selected phenomenon.

D. Select organism or class of organisms which have demonstrated the phenomenon of interest.

Phase 2. Sampling and Culture Requirements Determination

Tasks

A. Develop a plan for sampling selected organisms from the marine environment.

B. Identify/select/develop most appropriate methods for collecting samples.

C. Identify/select/develop procedures and media for isolating selected organisms.

1. Media should provide for growth of selected organisms.
2. Media should replicate as closely as possible the conditions in nature.

D. Sample, isolate and grow selected organism.

Phase 3. Design Preliminary Experiments

Tasks

A. Identify characteristics of phenomenon that will be measured.

- Morphological
- Physiolcgical
- Biochemical
- Genetic

B. Identify/select/develop methods for measuring characteristics.

C. Identify/select/develop appropriate apparatus.

D. Develop a plan for manipulating independent variables and/or measuring characteristics and collecting data.

Table 1. A Procedural Script for Research in Marine Microbial Ecology (Continued)

Phase 4a. Morphological Descriptions

Tasks

A. Describe organism through use of electron microscopy; determine sizes, shapes, presence of attachment structures, identify and characterize attachment structures.

B. Classify organisms with other organisms have the same morphological characteristics.

Phase 4b. Physiological Descriptions

Tasks

A. Select methods for measuring physiological activity. Some methods include:

- Biomass measures
- ATP assay

B. Apply experimental treatments or levels of environmental conditions to be tested and take physiological measures at each level.

Phase 4c. Biochemical Descriptions

Tasks

A. Select/develop procedures for isolating that part of the organism to be analyzed biochemically.

B. Select/develop procedures for producing a purified sample.

C. Select/develop procedures or tests for biochemical analysis.

D. Apply procedures and perform biochemical analysis.

Phase 4d. Genetic Descriptions

Tasks

A. Select/develop method for genetic characterization.

- DNA analysis
- Plasmid analyses
- DNA hybridization
- Plasmid hybridization

B. Select/develop appropriate apparatus and procedure.

C. Apply methods to the analysis of selected organisms.

Table 1. A Procedural Script for Research in Marine Microbial Ecology (Continued)

Phase 5. Impact Determination

Tasks

A. Measure and assess impact on environment (e.g., water quality).

B. Measure and assess impact on other marine organisms (e.g., commercially valuable seafood).

C. Measure and assess impact on human health (e.g., divers, recreational swimmers, etc.).

student regarding the tasks they were currently working on, the tasks they had already completed and the tasks that remained. The major phases of the script are as follows:

- Problem Identification: Decisions leading to the selection of phenomenon and organism to study.
- Sampling and Culture Requirements Determination: Decisions leading to procedures for sampling, isolating and growing selected organisms.
- Design of Preliminary Experiments: Decisions leading to the selection of the characteristics to measure and the procedure and apparatus required to perform measurements.
- Develop Morphological Descriptions: Decisions, characterizations leading to classification of organisms.
- Develop Physiological Descriptions: Decisions leading to the selection of physiological characteristics and methods of measurement.
- Develop Biochemical Descriptions: Decisions leading to selection and application of biochemical tests.
- Develop Genetic Descriptions: Decisions leading to the selection of methods to perform genetic characterizations and genetic comparisons.
- Impact Determination: Assessments of the organisms impact on environments, other organisms, human health, etc.

The script served an important function in the need diagnosis process; it provided the system with a tool for locating each researcher in a phase and task, and for identifying tasks that had been accomplished and tasks that needed to be done in the future. Locating the researcher in the process is the first step in the diagnostic process. Once the researcher's current task is known the diagnostic system can begin to characterize the researcher's knowledge surrounding the accomplishment of the task and the gaps in that knowledge that must be filled for the researcher to progress.

Each of the microbiologists was working in a different phase of the script. The first researcher was in Phase 1: Problem Identification and was primarily concerned with Task D: Determining the Feasibility of Studying the Selected Phenomenon. The general topic was characterizing deep sea bacteria and comparing them with bacteria living in other environments. The procedure involved proposing an approach to studying deep sea bacteria and then evaluating existing methods in terms of effectively carrying out that approach. The knowledge needs (gaps) were in the area of knowing what methods existed and in being able to assess the value of each method to the stated problem. The problem was reformulated several times as available methods proved inappropriate.

The second researcher was working in Phase 2: Sampling and Culture Requirements Determination, and was involved in two tasks.

- Task B: Identify/select/develop most appropriate methods for collecting samples.
- Task C: Identify/select/develop media for isolating selected organisms.

The research problem was to examine the impact of aquatic pathogens on the health of divers and the specific pathogens had been identified. Knowledge gaps involved specific sampling procedures for brackish water and identification of media for recovering the bacteria included in the study.

The third researcher was working on the biochemistry of attachment in a marine environment and progressed through a number of phases during the three months covered by the interviews. In the initial sessions he was working on Task D in Phase 3: Developing A Plan for Manipulating Independent Variables and Collecting Data; in later sessions his tasks were in isolating and purifying samples of attachment structures (Phase 4, Tasks A and B).

In each case the task was an important determiner of researcher knowledge needs and the location of the researcher in the process was important in providing a context for the diagnostic system to understand the need. For example, the system knew that the second researcher had selected the organisms for study and that the third researcher had already obtained an experimental sample. Based on this knowledge the system knew that in both cases it could ask for the names of organisms and in one case it could obtain a description of the procedures for sampling and isolating the selected organism(s).

In a second study, two additional research scripts in microbiology were developed. One script described taxonomy research, the other described research on vaccine development. A complete discussion of these scripts was reported by Vaughan and Mavor (1981).

2. A Script in Industrial Psychology

The three industrial psychologists participating in this study were part of a research team working on a program evaluation project for the Air Force. Each researcher was involved in studying a different set of variables as possible contributors to program effectiveness. A series of interviews was conducted with one of the researchers for the purpose of specifying the phases and tasks of the research process script used in studying the problem. This script is shown in Table 2; the main phases are as follows:

- Problem Identification: Decisions leading to the program to be evaluated.
- Variable Selection: Decisions leading to the identification of variables that have potential influence on program effectiveness.
- Experimental Design: Decisions leading to the selection of experimental conditions, the development of test instruments, the methods of measurement, etc.
- Experimentation: Application of treatments and test instruments to selected subject groups.
- Analysis, Interpretation and Summary: Decisions leading to the selection of variables and test instruments to be included in a program evaluation model.

This script was used to locate each of the researchers in the program evaluation process: two were working on Tasks A and B in Phase 2 (Identifying and Selecting Variables), the third researcher was working on Task C in Phase 2 (the feasibility of studying selected variables with existing methodology and instrumentation). Identifying the tasks of these researchers and locating those tasks in the research process was instrumental in providing a basis for characterizing their specific knowledge needs.

Effective knowledge need diagnosis requires that the needs be stated in narrowly defined areas; if the need statements are too broad the system is unable to respond. Identifying the researcher's task inside a sequence of tasks is an important first step in narrowing and specifically defining the area of need.

Table 2. A Procedural Script for Research in Program Evaluation

Phase 1. Problem Identification

Tasks

A. Identify problem: a program to be evaluated.

B. Establish importance of the research as a contributor to evaluation methodology, as a factor in effective program performance.

Phase 2. Variable Selection

Tasks

A. Identify classes of variables associated with the general problem area by characterizing existing program and program participants.

B. Select variables for manipulation and/or measurement which will contribute to an understanding of the problem.

- Variables that have been used successfully as predictors in similar situations.
- Variables that have not been studied previously.

C. Determine feasibility of studying selected variables in terms of existing methodology and instrumentation.

Phase 3. Experimental Design

Tasks

A. Determine which variables will be controlled and how they will be controlled.

B. Determine comparisons that will be made (e.g., comparisons between programs, comparisons between subject groups varying on a specific factor or combination of factors).

C. Select method of statistical analysis: correlational, factor analysis, analysis of variance.

D. Specify experimental conditions: test plan - what will be done in what order with what groups of subjects.

E. Design test instruments and pretest these instruments for ease of administration, clarity, validity, reliability, etc.

- May need to do some interviews to develop the range of alternatives that should be specified if a questionnaire is to be used.

F. Develop a sampling plan.

G. Outline procedures for conducting experiments, administering test, etc.

Table 2. A Procedural Script for Research in Program Evaluation (Continued)

Phase 4. Experimentation
Tasks A. Administer experimental treatments, or tests to selected samples. B. Conduct preliminary analysis of results. C. Modify experiment or tests or treatments based on preliminary results (e.g., throw out variables that do not discriminate, streamline instruments, etc.). D. Administer modified treatments, test, etc., to full experimental sample.
Phase 5. Analysis, Interpretation and Summary

B. The Researcher As A Problem Solver

In the Problem Identification phase of research, the researcher's behavior is that of a problem solver. He works within a problem space, successively reformulating and decomposing the problem into smaller, more manageable units. At each level of reformulation the researcher applies criteria of problem importance/contribution to the field and of feasibility of studying the problem.

Figure 1 shows an example of problem decomposition. The researcher started with the general problem of comparing deep sea bacteria with bacteria from fish gut and from the water's surface. Over a period of three months, the researcher successively decomposed the problem into essentially independent areas of concern. For example, at the first level of decomposition, each of the four questions represents an independent area of study and each contributes to an understanding of the general problem. The four areas are the major ways in which bacteria could be characterized: genetically, morphologically, physiologically, and biochemically. Further breakdown of the problem resulted from literature reviews and from conversations with

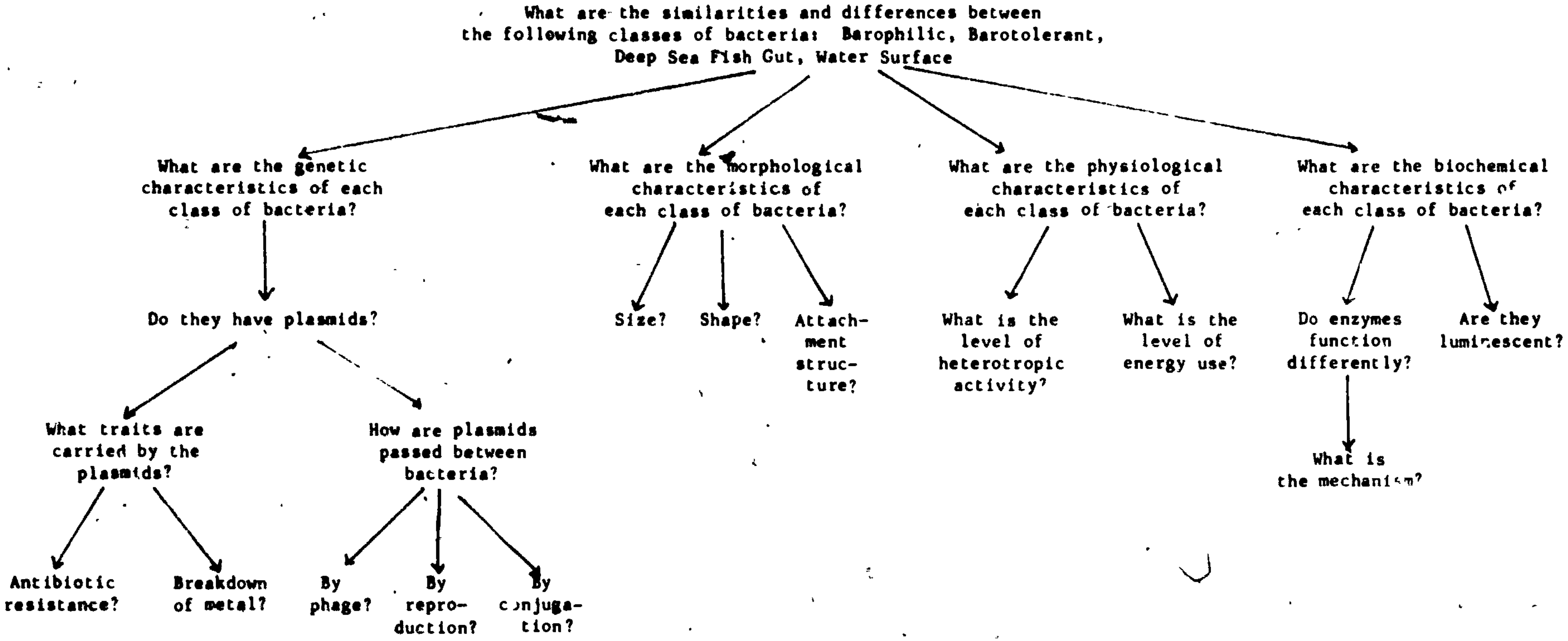

Figure 1. An Example of Problem Decomposition

other researchers. At each level of breakdown the feasibility criterion was applied: Is it within the state-of-the-art to study this problem? Based on these evaluations the researcher's final decision was to focus in the area of genetic characteristics and to address two questions:

- Do deep sea bacteria carry plasmids for antibiotic resistance?
- How are plasmids passed between bacteria?

The diagnostic system assisted the researcher in problem decomposition by providing successive representations of the problem. At each of the eight interviews the system presented the researcher with its current formulation of the problem and with a statement of the researcher's assessment of problem importance and feasibility. These descriptions served as one basis for further discussion and definition. Essentially, the diagnostic system was providing an external memory by documenting the decisions, evaluations, and problem statements of the researcher.

C. The Diagnostic System As A Problem Solver

The outcome of a successful need-diagnosis process is a statement of the researcher's knowledge needs at a level that can be effectively addressed by a knowledge search and delivery system. In order to fully develop a description of the researcher's knowledge need, the system decomposed the researcher's problem into hierarchical questions sets. An example of an hierarchical question set is shown in Figure 2. The questions are developed downward from general to specific; each level of question provided the search system with additional guidance as to what to look for in the literature. The greater the specificity of the question set, the more effective and focused the response.

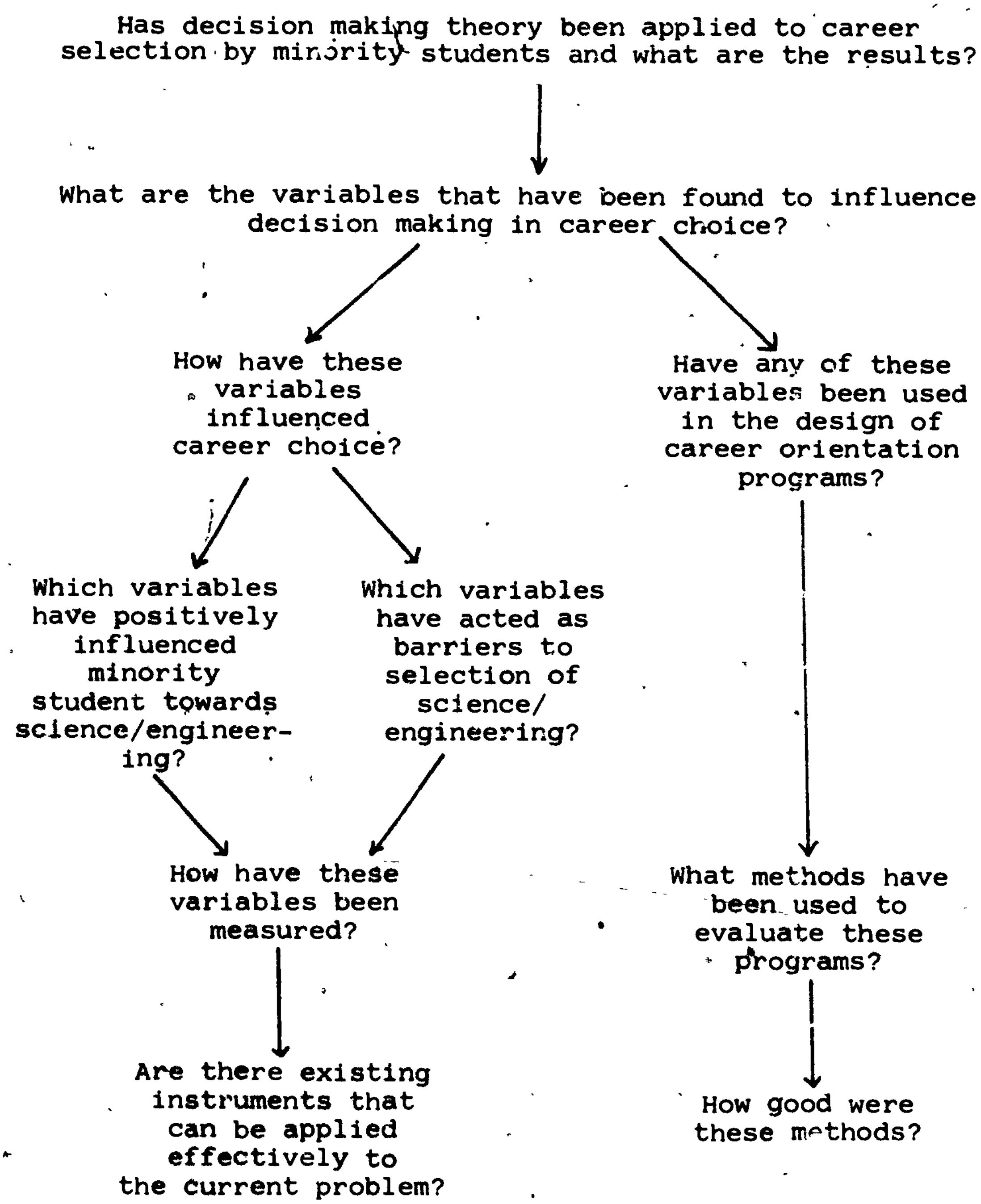

Figure 2. An Example of An Hierarchical Question Set

D. The Researcher's Knowledge Needs As Schemata/Frames

The researcher has a knowledge schema or frame which relates to the accomplishment of a given task or subtask in a specific research project. This schema contains two parts: What the researcher already knows and what the researcher knows he must learn in order to perform the task effectively. The accuracy of the system in providing the researcher with knowledge that corresponds to what he must learn is a function of the degree of match between the researcher's schema and the diagnostic system's representation of that schema. The system's representation guides the processes of search, selection and the preparation of knowledge packages.

The system, in constructing a schema, does not need to represent the researcher's full schema on the problem, but only those parts which focus on satisfying a specific need or gap. In our work with microbiologists and psychologists, schemata were developed by first identifying a gap and then describing the researcher's knowledge surrounding that gap.

What the researcher knows about a specific topic provides the system with an initial content model. The system uses this model in two ways: First as a basis for further defining what is relevant in the literature and, second, as a basis for eliminating certain topics from the search. As the literature is searched, the initial content model is modified and elaborated.

The first two columns of Table 3 illustrate the initial schema for a microbiology researcher working on the task of isolating pathogens. The first column presents the content model: What the system learned that the researcher knew about isolating pathogens. The second column shows the researcher's questions about isolation methods. In this case, the researcher needed to know the relative effectiveness of specific isolation methods and recovery media used by other investigators in both aquatic and clinical environments. The knowledge packages from the literature that responded to these questions are presented in the third column. These packages are summary statements which identify the relevant elements in each article. Knowledge contained in these packages and in the literature they summarize expands the initially constructed content model. Column 4 shows the researcher's responses to the knowledge in Column 3. Some of the methods and media were new and led the researcher to set up test experiments. In other cases the results merely confirmed work already accomplished by the researcher.

This example shows that the system's representation of a researcher's knowledge schema can provide clear guidance to the literature search and package-preparation process. Additional examples of knowledge schemata in both microbiology and psychology are shown in Appendix A.

Table 3. A Knowledge Schema About Isolating Pathogens

Content Model	Questions	Knowledge Package from the Literature	Researcher's Response to the Information
There are several methods for isolating a bacterial pathogen from a sample of water; these methods are usually called tests and include Membrane Filter Test and Most Probable Number. All isolation methods include the use of a recovery medium; a recovery medium is a combination of compounds designed to select for the organism; an effective medium recovers only the target organisms and rejects all others. Compounds composing the recovery media are in the form of broths or agars and are often labeled by letters which designate the ingredients of the compound (e.g., PSE media, PSE broth, PSE agar are synonymous). A range of media can be used with a given isolation methd; selection depends on organism to be captured.	What are the main methods for isolating pathogens from an aquatic environment? What recovery media have been used?	Cherry, W. B., et al, 1972. Confirmed her procedures: enrichment broth, incubation temperature, etc. Cherry says tetrathionate enrichment better than selinate.	She and Pollock have found selinate more useful.
		Thomason, B. M., 1971. Fluorescent antibody technique for detection of salmonella.	The laboratory of U. of M. is not set up for this approach.
		Pollack and Dahlgren, 1974. Confirmed the contamination by proteus of salmonella isolation procedure.	She found this in Anacostia River samples.
		Cherry, et al, 1972. Reinforced the fact that bacteria can adapt and survive in aquatic environments.	
		Litchfield, J. B., 1975. Discusses procedures for optimizing heterotrophic counts of bacteria from marine sediment. Includes methodological description of media (ASW) and handling procedures. Also provides a method (shaking) for removing bacteria from sediment.	She may compare ASW with the dilution medium she has been using.
		Koditschek, L. K., 1974. Describes a modification of the membrane filtration technique for counting total coliforms.	She may use this method; she has not used it at U. of M.

Table 3. A Knowledge Schema About Isolating Pathogens (Continued)

Content Model	Questions	Knowledge Package from the Literature	Researcher's Response to the Information
	What are the main methods for isolating pathogens from a clinical environment? What recovery media have been used?	Pollock, H. M., 1974. Enrichment broth should not be used for the isolation of shigella.	
		Pollock, H. M., 1974. XLD has provided a better rate of pathogen isolation.	This confirms her procedure.
		Bhat, P., et al, 1971. DCA is superior for isolation of pathogens.	This is new information. She may set up a small experiment to compare XLD and DCA.
		Taylor, W., and Schelhart (1968, 1968, 1971). The best combination for isolation of shigellae is GN broth and XLD plating media.	
		Yoshikawa, M., 1972. SS agar works better for isolating bacteria sensitive to antibiotics.	
		Waters, J. S., $^{14}CO_2$ is an effective method for detecting bacteria. However, this method kills the bacteria so there is no sample towork with.	
		Taylor, W., 1965-67. The best combination for shigella isolation is GN broth and XLD. The 1965 paper discusses biochemical reasons why XLD works.	

IV. SYSTEM DEVELOPMENT IMPLICATIONS

The process of diagnosing the knowledge needs of research scientists involves a series of steps which successively narrow and define the researcher's current problem and the researcher's knowledge surrounding that problem. A semi-structured procedure has been developed which includes the following steps.

Step 1. Identify researcher's field/subfield.

Step 2. Identify/describe the research topic.

Step 3. Identify appropriate procedural script.

Step 4. Locate the researcher in the procedural script at the phase/task/step level.

Step 5. Characterize the researcher's experience with the task (both procedure and content).

Step 6. Identify researcher's questions in each task.

Step 7. Identify the researcher's content knowledge relative to the specified questions.

As is apparent from the preceding discussion, these steps were conducted manually as a rough simulation of an automated system. In the discussion that follows, the phrase "diagnostic system" refers to operations and procedures that were performed manually but which can be envisaged as becoming procedures performed by a set of computer programs.

For each of the seven steps of the diagnostic process, the system has a specific series of questions that must be answered by the researcher. One approach is to step through the list of questions in a fixed order. This procedure would be the most easily translated into computer programs. Our experience with the diagnostic process shows, however, that this degree of structure is too restrictive to the researcher and does not work to elicit the most useful responses. What generally happens is that the researcher's response to the first question applies to that question as well as other questions in the list. In the manual operation, the system "knew" all the questions and was able to match the researcher's discussion with these questions. An automated diagnostic system of the future may have to build in mechanisms which accommodate this process.

Table 4 illustrates the need-diagnosis process with one of the students in microbiology. The information presented in this table represents a first step towards the specification of requirements for an interactive, need-diagnosis system. The first column, labeled aids, contains information/knowledge that the system should have as a frame for asking questions and interpreting responses. In the present study, aids were generated as the diagnosis proceeded; in the future it is expected that these aids would exist and could be read into the memory of the system. The aids are in the form of lists which present names of categories, names of process or content models, and names of specific sections within selected content or process models. The remaining three columns in the table show the questions that the system asks the researcher at each step in the process, the procedure for interacting with the researcher, and the output of the interaction.

A. Identify and Describe the Research Subfield and Topic

The first two steps in the diagnostic process (see Table 4) are to locate the researcher in a subfield of science and to describe his research topic. In the first step the diagnostic system asks the researcher to select from a list of fields/subfields, the one that represents his current research. If the specific subfield is not on the existing list the researcher is asked to indicate its name and its appropriate position on the list. In the second step, the researcher provides the system with a statement or description of the research problem. This description is guided by questions resulting from the tasks in the problem specification phase (Phase I) of the generic research script for the field or subfield. In the case of a microbiology research script, the tasks in this phase generally include:

- The name of the phenomenon, organism, problem being studied.
- The importance of studying the problem; how the problem contributes to science, etc.
- The feasibility of studying the problem within the existing state-of-the-art.

B. Locate the Researcher in the Research Process

The third and fourth steps involve identification of the appropriate research script and the location of the researcher at a task or subtask level in the selected script. In the third step the system presents the researcher with a list of the procedural scripts that have been used in the selected subfield and the researcher is asked to select the script he is following. The fourth step is to locate the researcher in the selected procedural script by having the researcher first identify the phase and then the task that is currently being worked on. The system is aided in this process by a list of phases and tasks within phases. If these lists appear incomplete to the researcher he is asked to make the appropriate additions.

C. Characterize the Researcher's Knowledge Needs

Once the researcher is located in the research process, the diagnostic system begins to structure the content of the researcher's knowledge needs. Step 5, characterizing the researcher's level of experience/sophistication, is the first step in defining the knowledge gaps and the system's response to these gaps. If the researcher is very familiar with the content, the system will be searching for different levels of knowledge than if the topic area is new to the researcher. Steps 6 and 7 create the system's representation of the researcher's knowledge schema. In Step 6, the system asks the researcher to state his specific questions/knowledge gaps for the current research task. In interpreting these questions the system uses as aids the researcher's current task, the subfield, the general statement of the research problem and the content models associated with the task and the research problem. Step 7 provides the system with a statement of what the researcher knows about the topic of the research. This is accomplished by asking the researcher to identify those parts of the appropriate content model that correspond to his knowledge. There is some evidence from our work that certain content models relate to certain procedural tasks. For example, the content models for sampling or isolating bacteria from an aquatic environment apply to any researcher involved in tasks of sampling or isolation. There are other content models that describe classes of organisms or specific processes associated with these classes. These content models would apply to any researcher working on that class or that process. The aids to the diagnostic process and their relationship to each other are diagrammed in Figure 3. The researcher's level of sophistication, his questions and his knowledge surrounding the questions serve as a basis for developing a search strategy, selecting relevant knowledge and developing information products which fill knowledge gaps.

Table 4. Example of the Need Diagnosis Process in Microbiology

Aids	Questions	Process	Products
Step 1. Identify Researcher's Field/Subfield			
Fields/subfields in microbiology • Aquatic and terrestrial • Clinical • Immunology • Genetics etc.	What is the field/subfield in which your current work is being conducted?	Ask researcher to select subfield from a list or to indicate field/subfield is not on the list.	Name of researcher's field/subfield • Aquatic and terrestrial microbiology - marine ecology
Step 2. Identify the Research Topic			
Problem specification tasks in marine microbial ecology		Ask researcher to respond to each question.	A statement of the research topic
• Identify phenomenon	What phenomenon is being studied?		• Aquatic pathogens as health hazards
• Establish its importance	Why is it important?		• Cause of disease in divers
• Determine feasibility	Is it feasible from a methodological standpoint?		• Methods exist to study problems
• Select organisms to study	What organisms are being studied?		• Organisms are: shagella, salmonella, aeromonas
Step 3. Identify Appropriate Procedural Script			
Procedural scripts in selected subfield • Marine microbial ecology • Taxonomy • Etc.	What research process/paradigm are you following in your current research?	Ask researcher to select the procedural script he is following.	Name of script • Marine microbial ecology.

Table 4. Example of the Need Diagnosis Proc in Microbiology (Continued)

Aids	Questions	Process	Products
Step 4. Locate Researcher in the Procedural Script			
Marine Microbial Ecology Script: Main Phases ● Problem identification ● Sampling and culture determination requirements ● Design preliminary experiments ● Morphological description ● Physiological description ● Biochemical description ● Genetic description ● Impact determination	Which phase are you currently working on?	Ask researcher to select phase he is working on	Name of phase ● Sampling and culture determination
Tasks in Sampling and Culture Determination Phase ● Develop sampling plan ● Identify/select/develop sampling method ● Identify/select/develop isolation method ● Sample/isolate/grow selected organisms	What tasks are you currently working on?	Ask researcher to select the task(s) he is working on. If the model is not elaborated enough ask the researcher to provide the specification.	Name of task(s) ● Identify/select/develop sampling method. ● Identify/select/develop isolation method.
Step 5. Characterize the Researcher's Experience with the Script and the Content Area			
Names of current task(s) ● Identify/select sampling methods. Field/subfield ● Marine ecology Statement of the research topic	Have you done this type of research before (followed this paradigm)? How would you characterize your knowledge of the topic: expert, some familiarity, etc.?		Yes Some familiarity

Table 4. Example of the Need Diagnosis Process in Microbiology (Continued)

Aids	Questions	Process	Products
Step 6. Identify Researcher's Questions in Each Task			
Names of current tasks ● Identify/select/develop sampling methods Field/subfield ● Marine ecology Statement of the research topic	What are your current questions?	Ask researcher to state questions (knowledge gaps for each task).	Researcher's questions ● What are the effects of temperature and salinity on survival and growth of salmonella, shagella, aeromonas? ● Where in the water column should samples be taken to maximize concentration of bacteria? ● How much water is needed to provide an adequate sample? ● What apparatus has been used successfully at different levels of the water column?
Step 7. Identify Content Knowledge of Researcher on the Selected Task			
The content model for sampling pathogens (Table A-2, Appendix A, page A-5)	Which parts of this model are you familiar with?	Ask researcher to identify the content in the model he knows about.	A description of what the researcher knows about the topic.
	Is there information on the content that is not included?	Ask researcher to add additional content to the model.	

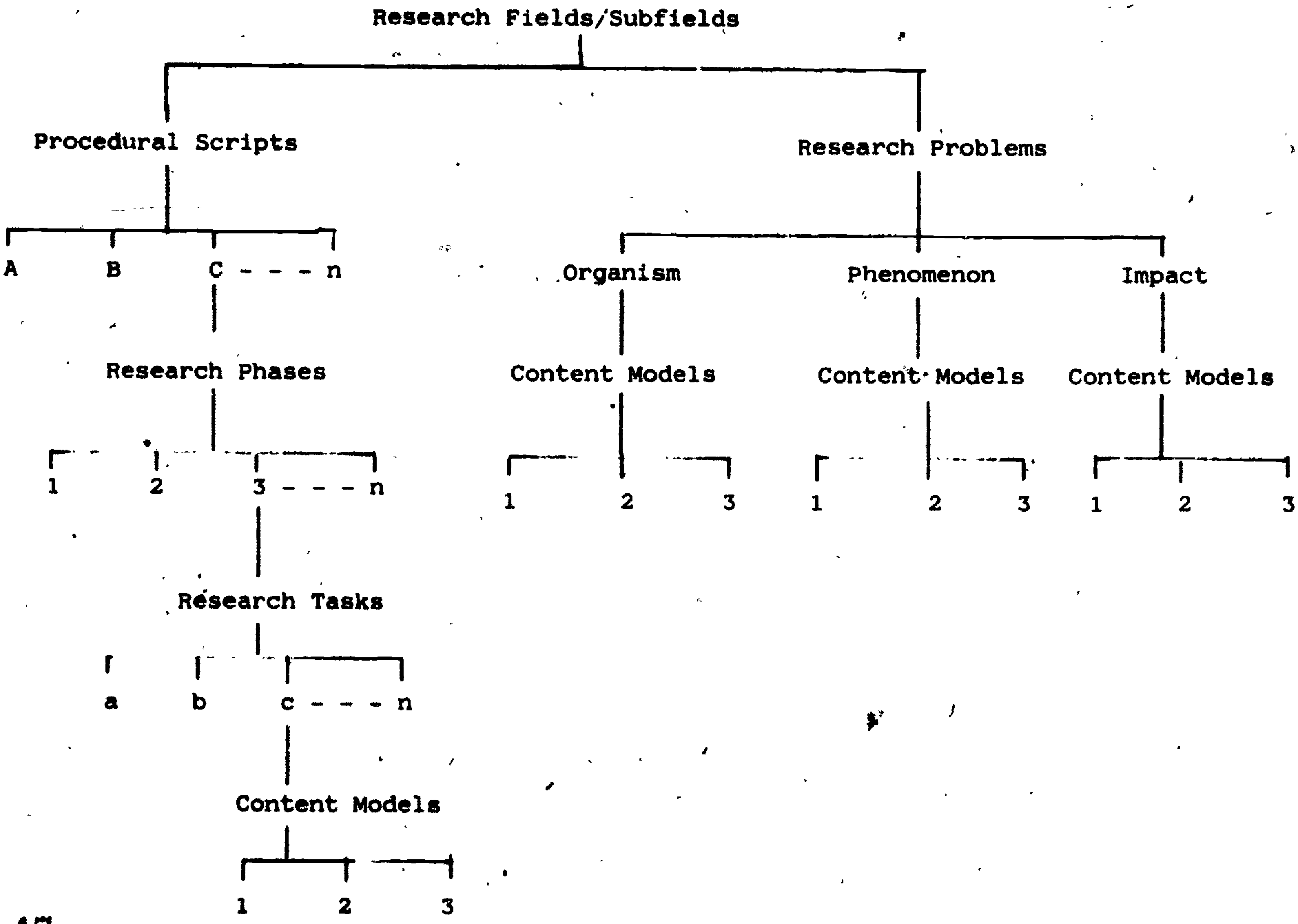

Figure 3. Aids to the Diagnostic Process

V. CONCLUSIONS

The observations described in this report suggest that the next generation of computer-based information systems should include an interactive, need-diagnosis component which develops a representation of the user's knowledge schemata. Interviews with both microbiologists and psychologists resulted in the identification of some common research process scripts and content models related to the scripts. These common scripts and models were used by the interviewers as aids in creating a representation of a given researcher's knowledge schema at a particular point in the research process. These representations provided effective frames for searching the literature and developing focused information products.

The next step is to develop a software prototype of the diagnostic process. Much work has been done in artificial intelligence research which applies directly to this effort. Of particular relevance is the work on knowledge representations and on the development of expert systems.

The possibility of being able to model the user on an individualized level is a most attractive challenge. The prospect of adapting the information retrieval process to the particular person by means of a model of that person's unique knowledge structure is an important area for further investigation.

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APPENDIX A

EXAMPLES OF KNOWLEDGE SCHEMATA

Table A-1. Biochemistry of Bacterial Attachment Structures

Content Model	Questions	Knowledge Package from the Literature
Bacteria have structures which they use to attach themselves to surfaces and other cells; these structures could be pili, fibrils, fibers.	What are the attachment structures of marine bacteria?	Pili have been described in the clinical literature; transmission electron microscope shows one marine bacteria to have pili.
Attachment structures are composed either of protein, lepid or polysaccharide. Pili of clinical strains of bacteria are composed of protein.	What are the attachment structures composed of?	No work has been done on pili in marine bacteria.
Two general steps are required to develop a sample for biochemical analyses; the structures must be isolated from the cell, t isolated structures must be purified.	What are the procedures for isolating attachment structures from the cell?	Weiss, R., 1972. E. coli pili are usually removed after 2 minutes of homogenization at room temperature. With P. aeruginosa, pili removal required 3.5 minutes of homogenization at top speed in an Omni mixer (Model OM-1150) with a chamber capacity of 100 ml. Novotny, C., et al, 1969. Pili were removed by homogenizing for 2 minutes at 37 C. in an Omni mixer 1150. F-pileated cells decreased as blending speed increased beyond 1,600 rev/min. Other effects of blending speed are also given (e.g., F-pili length). Kurosaka, R., 1974. Fimbrae of aeromonas were removed by blending in a Waring blender No. 4 for 5 minutes. Ellen, R. P., et al, 1978. Samples were blended for 60 seconds at 16,000 rpm (Vis Tis Model 23 homogenizer).
	What are procedures for purifying an isolated sample of attachment structures?	Kurosaka, R., 1974. This paper presents a method for purifying fimbrae of aeromonas. Figure 1, page 15: Fractionation procedure used to prepare fimbrial suspension, is specifically useful. This figure given a schemata for purification.

Table A-1. Biochemistry of Bacterial Attachment Structures (Continued)

Content Model	Questions	Knowledge Package from the Literature
Quantification of structures allows for examining conditions which produce growth of structures.	What are procedures for quantifying (counting attachment structures).	Buchanan, T., 1975. Describes antibody technique for assaying the number of fibrils. The antibodies are radio active labeled. Ellen, R. P., et al, 1978. Procedure for determining fiber growth (density) by measuring the solution turbidity. As more fibers grow the cells aggregate, become heavy, and settle out of solution.

Table A-2. Sampling Pathogens from A Marine Environment

Content Model	Questions	Knowledge Package from the Literature
Temperature and salinity affect the number of bacteria. Different species of bacteria require different temperatures and different levels of salinity for growth and survival Most bacteria reproduce more slowly at low temperatures.	What are the effects of temperature and salinity on the survival and growth rates of salmonella, shagella, vibrio cholera, aeromonas	Kaper, F., 1977. Vibrio species are restricted in their distribution bv salinity; vibrio cholera are found in brackish waters. Cherry, W. B., et al, 1972. Listed several environmental factors that could effect sample size of salmonella: rainfall, water temperature, pH.
A water column contains different temperatures and different salinity levels. Bacteria are distributed differently through the water column. The water column is represented by surface, sediment and levels of water in between.	Where in the water column should samples be taken to maximize on the numbers/concentration of bacteria? How much water is needed to provide an adequate sample?	Koditschek, C. K., 1976. Sediment samples may be a better source of pathogens than water. This work done in the New York Bight. Koditschek, C. K. Water Research 1974. This paper suggests that sediment samples may provide a better index of water quality than water samples. Generally more bacteria are found in sediment.
Different procedures are used for taking samples from different levels.	What apparatus has been used most successfully at different levels in the water column? What are the specific procedures at each level in the water column?	Colleague at NOAA, 1978. Some specific suggestions are using larger bottles for surface samples; using new collapsible bag which the diver takes to a depth, pulls open and fills with water. Litchfield, C.D. 1975. Collect bacteria sample from sediment using Smith-McIntyre grab - "Approximately 1 liter of the sandy sediment was removed from the grap to a wide-mouth plastic bottle and mixed with a sterile spatula to reduce subsequent sampling variations." It is better not to freeze samples.

Table A-2. Sampling Pathogens from A Marine Environment (Continued)

Content Model	Questions	Knowledge Package from the Literature
		Rittenberg, S. C., 1958. Describes a method for collecting surface sediment samples using divers and plastic tubes. The idea is to sample only surface layer and not the core. There are generally more bacteria on the surface. Koditschek, I. K., 1974. Sampled sediment using a Smith-McIntyre grab. Sampling procedures followed <u>Standard Methods</u> (1971).

Table A-3. Time Perspective As A Predictor of Career Choice

Content Model	Questions	Knowledge Packages from the Literature
Three classes of time perspective have been studied: past, present, future; present oriented people seek immediate reward/punishment; future oriented people are willing to work toward long-range goals. Career orientation programs are used to provide students with information on career options. The program of interest has been designed to inform students about careers in engineering. Career orientation programs are used to provide students with information on career options. The program of interest has been designed to inform students about careers in engineering.	How does time perspective relate to the effectiveness of present and future oriented career orientation programs?	
Lower class people tend to be present-oriented; middle class people are future oriented.	What factors have been found that correlate with an individual's time perspective?	Shannon, L. (1975). Disadvantaged subcultures have lower expectancies for the future because the future appears more uncertain. Kendall, M. B. (1970). Social class made little difference in time orientation. Teahan, J. E. (1958). High achievers are more optimistic and future oriented than low achievers.

Table A-3. Time Perspective As A Predictor of Career Choice (Continued)

Content Model	Questions	Knowledge Packages from the Literature
	Do individuals in minority groups differ in time perspective from middle and upper class whites?	
Tests have been developed to measure time perspectives; some involve story telling or goal selection.	What specific measurement instruments have been used to study time perspective?	Ruiz, R. A. (1967). Names and describes several tests of time perspective: ● Time Reference Inventory ● Incomplete Thought Test ● Story Root Test ● Write A Story Wallace, M. (1956). Names and describes three tests of time perspective: ● Story Completion ● Time Projection of Events ● Time Sequence of Events Teahan, J. E. (1958). Tests discussed include: TAT cards, story completions. Cottle, G. J. (1969). Describes the Lines Test for Measuring Time Perspective.
	How valid, reliable, etc., are these tests? What are the specific characteristics of each instrument? What are the administration procedures? Can any of the existing instruments be directly applied to the current problem?	

A-8