



1.0  
1.1  
1.25

1.4  
1.4

2.0  
2.2  
2.5

3.0  
3.6  
4.5



# Viewing Knowledge Bases as Qualitative Models

by

William J. Clancy

AD-A187 091

Department of Computer Science

Stanford University  
Stanford, CA 94305

**DTIC**  
**ELECTE**  
**DEC 14 1987**  
**S** **D**  
H



**DISTRIBUTION STATEMENT A**

Approved for public release  
Distribution unlimited

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>			1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED			
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE			4. PERFORMING ORGANIZATION REPORT NUMBER(S) STAN-CS-87-1170 or KSL-86-27			
6a. NAME OF PERFORMING ORGANIZATION STANFORD KNOWLEDGE SYSTEMS LABORATORY			6b. OFFICE SYMBOL (if applicable)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ONR TECHNICAL REPORT # 17		
6c. ADDRESS (City, State, and ZIP Code) COMPUTER SCIENCE DEPARTMENT 701 WELCH ROAD, BUILDING C PALO ALTO, CA 94304			7a. NAME OF MONITORING ORGANIZATION PERSONNEL AND TRAINING RESEARCH PROGRAMS			
8a. NAME OF FUNDING / SPONSORING ORGANIZATION			8b. OFFICE SYMBOL (if applicable)	7b. ADDRESS (City, State, and ZIP Code) OFFICE OF NAVAL RESEARCH (CODE 1142PT) 800 NORTH QUINCY STREET ARLINGTON, VA 22217-5000		
8c. ADDRESS (City, State, and ZIP Code)			9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-85K-0305			
			10. SOURCE OF FUNDING NUMBERS			
			PROGRAM ELEMENT NO. 61153N	PROJECT NO. RR04206	TASK NO. OC	WORK UNIT ACCESSION NO. NR702-003
11. TITLE (Include Security Classification) VIEWING KNOWLEDGE BASES AS QUALITATIVE MODELS						
12. PERSONAL AUTHOR(S) WILLIAM J. CLANCEY						
13a. TYPE OF REPORT TECHNICAL		13b. TIME COVERED FROM TO		14. DATE OF REPORT (Year, Month, Day) MAY 1986	15. PAGE COUNT 30	
16. SUPPLEMENTARY NOTATION KSL 86-27; INVITED TALK PRESENTED AT IEEE/APPLICATIONS CONF., ORLANDO, FEBRUARY 1987.						
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)			
FIELD 05	GROUP 09	SUB-GROUP	EXPERT SYSTEMS, PROCESS MODELING, KNOWLEDGE REPRESENTATION QUALITATIVE REASONING, INFERENCE STRUCTURE			
19. ABSTRACT (Continue on reverse if necessary and identify by block number)						
<p>→ The concept of a qualitative model provides a unifying perspective for understanding how expert systems differ from conventional programs. Knowledge bases contain qualitative models of systems in the world, that is primarily non-numeric descriptions that provide a basis for explaining and predicting behavior and formulating action plans. The prevalent view that a qualitative model must be a simulation, to the exclusion of prototypic and behavioral descriptions, has fragmented our field, so that we have failed to usefully synthesize what we have learned about modeling processes. For example, our ideas about "scoring functions" and "casual network traversal," developed apart from a modeling perspective, have obscured the inherent explanatory nature of diagnosis. While knowledge engineering has greatly benefited from the study of human experts as a means of informing model construction, overemphasis on modeling the expert's knowledge has detracted from the primary objective of modeling a system in the world. Placing AI squarely in the evolutionary line of teleologic and topologic modeling, this talk argues that the study of network representations has established a foundation for a science and engineering of qualitative models.</p>						
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED			
22a. NAME OF RESPONSIBLE INDIVIDUAL DR. SUSAN CHIPMAN			22b. TELEPHONE (Include Area Code) (202) 696-4318	22c. OFFICE SYMBOL ONR 1142PT		

# Viewing Knowledge Bases as Qualitative Models

by  
William J. Clancey

Stanford Knowledge Systems Laboratory  
Department of Computer Science  
701 Welch Road, Building C  
Palo Alto, CA 94304

The studies reported here were supported (in part) by:

The Office of Naval Research  
Personnel and Training Research Programs  
Psychological Sciences Division  
Contract No. N00014-85K-0305

The Josiah Macy, Jr. Foundation  
Grant No. B852005  
New York City

The views and conclusions contained in this document are the authors' and should not be interpreted as necessarily representing the official policies, either expressed or implied of the Office of Naval Research or the U.S. Government.

Approved for public release: distribution unlimited. Reproduction in whole or in part is permitted for any purpose of the United States Government.



Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

## 1. Introduction

With the growing interest in expert systems in academia and industry, one question recurs that never seems to receive a satisfying answer: How are expert systems different from conventional programs? Different perspectives suggest different answers. In terms of programming language, expert systems are programs written in "logic," "rules," or "frames" (Friedland, 1985). From the perspective of new computational capabilities, expert systems are programs that can explain their reasoning (Davis, 1986). Or considering how these programs are used, expert systems are consultants, monitors, designers, etc. (Hayes-Roth, et al., 1983). But these perspectives are not completely satisfying because they fail to explain how conventional programs are inherently different: Aren't Fortran conditional statements "rules"? Why is it difficult to write a Fortran program that can explain its reasoning? Why isn't a Bayesian diagnostic program an expert system?

An alternative point of view, which this paper develops, considers the nature of the knowledge encoded in these programs. Expert systems deal with heuristics, uncertain knowledge (Feigenbaum, 1977). Their reasoning is qualitative, not in terms of precise measures. But in the AI literature, the term "qualitative reasoning," characterizing an important and growing subarea of research, has been almost exclusively applied to programs with some kind of *simulation model* of a physical system, such as an electronic circuit (Bobrow, 1984, Chandrasekaran and Milne, 1985). This common definition of qualitative reasoning excludes the majority of expert systems, and, as this paper argues, it is largely responsible for the gap in our understanding.

What is an expert system? A simple answer can be given, one that is half-known and has been half-stated by many people: Expert systems contain qualitative models of the world, in contrast with quantitative models, which involve mathematical laws, such as in physics, electronics, and economics (Padulo and Arbib, 1974). The idea is half-stated in the common view that AI is concerned with *symbolic programming* (Harmon and King, 1985), but this is not a satisfying distinction because numbers are symbols, too. An alternative description, "non-numeric programming," avoids this ambiguity and is also widely used. However, the emphasis on "programming" has distracted us; the idea that these programs contain *non-numeric models* has been generally ignored. Describing AI as "non-numeric science and engineering" is more to the point: *Artificial Intelligence is the study of computational techniques for acquiring, representing, and using qualitative models of physical, perceptual, cognitive, and social systems.*

The purpose of this paper is to give this definition force by enriching our understanding of what qualitative models are. Briefly, a qualitative model describes some system in the world in terms of causal, compositional, or subtype relations among objects and events. One of the most important ideas of this paper is that there is a well-established repertoire of methods for representing qualitative models—networks based on the idea of prototype subsumption, state-

transition, and structural and procedural composition. By studying and using these network representations, AI has established a foundation for a science and engineering of qualitative models.

From early on, we have followed the approach of decomposing knowledge from how it is used, abstracting knowledge structures and reasoning procedures, and formulating an increasingly more general understanding of what knowledge engineering and knowledge bases are all about (Swartout, 1981, Clancey, 1983a, Clancey, 1983b, McDermott, 1983, Szolovits, 1985, Clancey, 1985, Smith, 1985). It is now apparent that knowledge bases contain *models of systems* in the world. Reasoning involves *sequences of tasks*, such as "monitoring" and "diagnosis," by which an understanding or model of specific situations is related to action plans (Section 3). Programs use a simple *repertoire of qualitative modeling techniques*, commonly called "knowledge representations" (Section 4). The idea of a *situation-specific model* makes concrete what programs know and how problem solving can be described in terms of model-manipulation operators (Section 5). Finally, an historical perspective shows how AI's concern with adaptiveness and rationality of the autonomous agent emphasizes the *role of a model* as what a problem solver knows (hence, "knowledge base") (Section 6). This has been to the detriment of understanding the primary characteristic of knowledge in terms of *models* that partition the world, viewing it selectively and making it coherent for some purpose.

## 2. The need for a synthesis

Given the generality of the term "model" and the all-encompassing nature of this paper, it is worthwhile addressing a few possible objections up front.

First, we tend to adopt an idealized view of what a model is. Observing how impoverished our programs are, we tend to say that they are not models or, at least, "not real models." This critical point of view is valuable for carrying our research forward, but it creates a distinction that only confuses what we are doing and have accomplished. This paper argues that knowledge base structures are models because they describe what is happening in the world and provide a basis for action, that is they *function* as models.

Second, when a number of pieces are brought together, it may look like the picture was always obvious. For example, recalling the idea of a "frame" (Minsky, 1975)—a prototypic description providing a basis for explaining what happens in the world, making predictions, and taking action—it may seem obvious that frames are a kind of qualitative model. *But why don't we teach it this way?* Our understanding of our field is fragmented and inconsistent. Consider:

- Classification and causal network descriptions are commonly used for modeling physical processes (Lehnert, 1978, Weiss, et al., 1978, Szolovits, 1985), but this work is not integrated in the collection, "Qualitative Reasoning about Physical Systems"

(Bobrow, 1984).

- When we refer to a knowledge base as an "expert model" or "consultation model" (Weiss, 1979), we tend to forget that it contains models of systems in the world. By separating out the system descriptions in a knowledge base, we can begin to identify particular kinds of network structures as *different ways of modeling processes* (Section 4).
- In most medical expert systems, a diagnosis is taken to be the *name* of a disease rather than a coherent description of what is happening in the world—a model—that causally relates states and processes. Perhaps because the programs do not structurally simulate pathophysiological processes, researchers have not thought about inference in terms of model construction (Section 5).
- Instructional research has emphasized that people generally have *some* model of how a system works or what procedure to follow for solving a problem, sometimes buggy and incomplete (Gentner and Stevens, 1983). From this, we might expect that expert system explanations would relate the program's model to the user's, perhaps focusing on violated expectations. Instead, we describe explanation in terms of articulating what the program knows and what it did (Davis, 1976, Swartout, 1981, Hasling, et al., 1984). By definition, the program has something the user does not have, "expertise." Thus, we think in terms of "transferring the expertise" (Davis, 1976, Clancey, 1979), rather than *relating alternative models*.

Similarly, the familiar line that AI is "constructing computer programs which exhibit behavior we call 'intelligent behavior' when we observe it in human beings" (Feigenbaum and Feldman, 1963) has provided a useful focus, but leaves out the modeling methodology upon which our work is based.

### 3. The inference structure of expert systems

Expert systems contain descriptions of system behavior and design, which are *models*, in the usual sense of selective abstractions that allow explanation and/or prediction of events in the world. The knowledge encoded in expert systems *functions* as a model, regardless of what representational form it takes. In this section we describe *what expert systems do* in terms of generic tasks for analyzing and synthesizing systems. The next section lays out a spectrum of representational methods.

All expert systems make assertions about what is true in the world or what actions might be taken: The patient has a fever, the infection might be meningitis, penicillin is a possible therapy, etc. If we lay out how assertions are related as chains of inference, we observe

regularities. A kind of secondary structure emerges. One such structure, termed "heuristic classification," involves systematic abstraction, association between class hierarchies, and refinement (Clancey, 1985). The inference process, that is, the order in which inferences are made, is of course important, but it is a different issue.

Heuristic classification is a problem-solving method by which solutions are selected from a set of pre-enumerated alternatives. The question naturally arises, for what kinds of problems is heuristic classification useful? One approach is to consider what kinds of things might be selected from a list of pre-enumerated alternatives. Examples include: user models, items in a catalog, diagnoses, skeletal plans, numeric models (Clancey, 1985).

Continuing our attempt to generalize, are there patterns in what data and solutions can be? What kinds of things are classified and heuristically related? We start by laying out common sequences:

Inference Structure	Example Program <sup>1</sup>
patient -> disease -> therapy	MYCIN
reader -> book	GRUNDY
customer -> wine	WINE ADVISOR
structure -> numeric model -> analysis program	SACON
circuit behavior -> fault	SOPHIE
causal reasoning bug -> misconception -> instruction	WHY
program bug -> misconception	MENO

Several generalizations can be made:

1. The "things" being related are *models*, that is, general, abstracted descriptions of specific things in the world. Different terminology—"disease prototype," "user stereotype," "numeric model," "structural abstraction"—has tended to obscure this basic pattern.

2. Models are related in a limited number of ways, by what are called *generic tasks*. We introduce the idea of a *system* and redescribe the things being related in terms of an operation performed to some system at each step (Clancey, 1985):

```
specify -> design -> assemble
monitor -> diagnose -> modify
identify -> predict
monitor -> control
```

For example, "patient -> disease" is replaced by "monitor (detect abnormal body system states and environmental influences) -> diagnose (describe and determine cause of the malfunctioning subsystem's structural and state abnormalities)."

3. We can extend the argument beyond heuristic classification to include all expert

<sup>1</sup>References: MYCIN: (Shortliffe, 1976); GRUNDY: (Rich, 1979); WINE ADVISOR: Teknowledge, Inc.; SACON: (Bennett, 1979); SOPHIE: (Brown, et al., 1982); WHY: (Stevens, et al., 1982); MENO: (Soloway, et al., 1981)

systems. The basis for this is simple: Patterns like "monitor -> diagnose -> repair" are very familiar; we know that they go beyond how diagnoses and repairs are reasoned about. For example, we can return to the pattern of the wine advisor ("specify -> design") and include R1 because it relates a customer's requirements to a VAX system configuration.

We aim for completeness, but of course establishing that these generalizations are true for every expert system is a daunting task. We can only consider them to be hypotheses, albeit based on considerable experience, and see if they hold up to further analysis.

In introducing the idea of a "system" as the focus of reasoning, we view tasks not in isolation (as described in (Hayes-Roth, et al., 1983)), but as the range of things that we can do to any given system. On this basis, we can begin to argue about the completeness of the list of tasks. For example, we can reformulate Davis's idea of fault models in these terms. Fault models make explicit "what might have been done to a system" to cause faulty behavior (Davis, 1984):

- Monitor the system and determine how it is different from the intended design: Structure intended to change, such as a gate, may be fixed; components may be functioning wrong or have the wrong structure (e.g., a short).
- The system may have been assembled wrong (e.g., chip flaw).
- The design may be wrong.
- The specification may be wrong.

Davis emphasizes the heuristic value of ordering these considerations. Our system-model orientation suggests that "fault models" can be generalized to all systems and generated from the set of generic tasks. Specifically, we could add "wrong prediction" (observer's expectations were incorrect) and "wrong control" (wrong input for desired output) to Davis's list.

We are now in a position to generalize once again, condensing the four sequences of generic tasks into one sequence (Figure 3-1). In simple terms, we relate desired or observed *system behavior* to a *system description* to some *plan* for taking action in the world or *expectation* about what will happen in the world. Common names for action plans are: "assembly plan," "instructional plan," "therapy plan," and "control plan." The intermediate design or identification might describe a *subsystem*, as in the relation between a patient and his infection. Also, in moving to the third stage, we often are describing a *containing system* that will carry out the assembly, modification, or control process, as in the relation between a client and his vacation plan or a design for a molecular structure and an experiment plan.

Again, this is a description of inference structure, not the order in which inferences are made. For example, specification and design are commonly iterative. In cognitive modeling for instruction, we work backwards from an artifact (say a student's computer program), to an implicit design (the model or plan for the program), to models of the environment in which

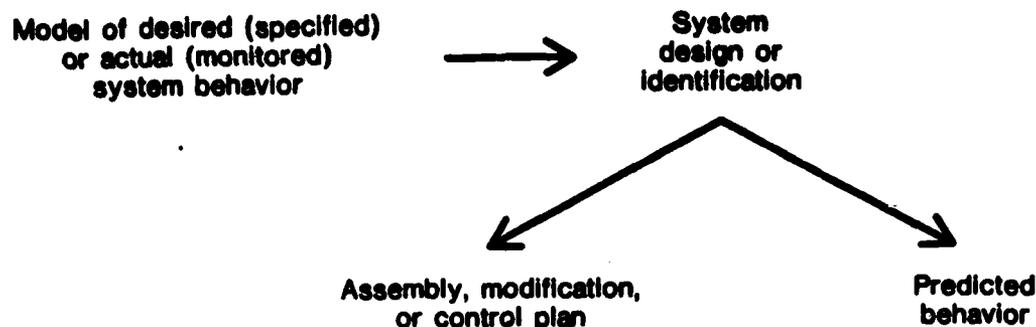


Figure 3-1: General inference structure for reasoning about systems

the artifact is to function (beliefs about what the program is supposed to do) and the components out of which it is made (beliefs about the programming language) (Johnson and Soloway, 1984). Note that for the special case of heuristic classification, system models and action plans are selected from pre-enumerated descriptions.

#### 4. Representation of qualitative models

By relating qualitative methods for modeling systems, we can see our enterprise as a whole. One possible taxonomy distinguishes between the explanatory power of classification and simulation models (Figure 4-1).

Classification models can be used to *recognize processes*, to "account for behavior" of a system, by naming or categorizing the observed pattern (Minsky, 1963). As a phenomenological description, this corresponds, in general terms, to the idea of *frames* (Minsky, 1975), with the temporal nature of processes made explicit in the idea of *scripts* (Schank, 1975, Stevens, et al., 1982) and described more carefully as an "encapsulated history" (Forbus, 1984). A process description identifies a sequence of events that happen over time, spread over several locations (Ackoff, 1974). For example, an infectious process involves intrusion of an organism into the body, movement to a favorable growth site, response by the body, and inflammation. Typically such descriptions are aggregated to reflect general properties and omit sequential details, thus treating the system as an "object" (e.g., descriptions of people as stereotypes (Rich, 1979)). Such descriptions are *models* because they provide an explanatory accounting of what happens in the world and a basis for action (Achinstein, 1983).

Simulation models, broadly construed, provide some description of how the system produces the observed behavior. The model is "runnable," allowing predictions to be made of how a system will change given a set of initial conditions. A *behavioral simulation* describes how a system *appears*, in terms of "hidden states," "observed manifestations," and causal relations among them. A *functional simulation* model places behavior in a larger context, indicating the *role* it plays in achieving the properties of a larger system. For example, a functional model of a radio would refer to amplification and locking on to a broadcast station, while a behavioral model would only describe current flow and changing voltages. Functional models

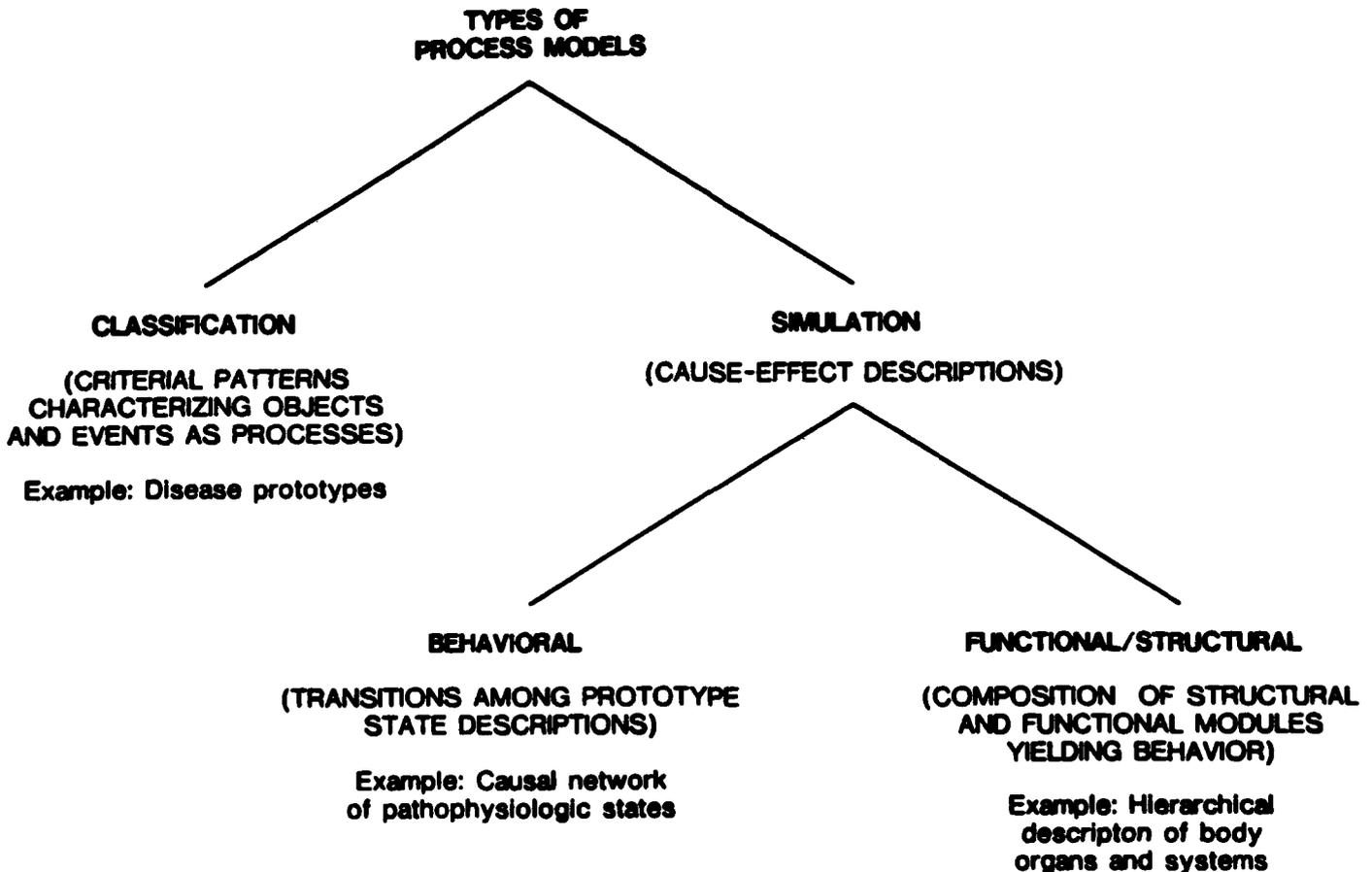


Figure 4-1: Types of qualitative models of processes

account for patterns in behavior and indicate what larger goals these patterns satisfy (Kosslyn, 1980). As an abstraction, a function is something the system can accomplish in multiple ways, depending on its state and the demands of its environment (Ackoff, 1974).

Regarding completeness, classification and behavioral models do not necessarily characterize the full state of the system being reasoned about on any level of analysis, and cannot necessarily predict what state will follow from arbitrary initial conditions (for example, allowing that parts of the system are functioning normally). "Hidden" internal states may be described, but the purpose of transitions and how transitions follow from the structure of the system (the physical components) are not completely described (Weiss, et al., 1978, Szolovits, 1985).

In contrast, a functional model makes a claim about *completeness* of the explanation or system description. The purpose of the system is captured procedurally on multiple levels of abstraction, so states can be related to functional goals. For example, a functional model of diagnosis describes reasoning in terms of general goals for supporting and refining alternative explanations (Patil, 1981, Clancey, 1984), rather than behaviorally, in terms of domain-specific inferences.

Finally, a structure/function model, to which the term "qualitative model" is usually applied in AI research, gives a full accounting for each component in the system in terms of its role in fulfilling the function of the system. Thus, a functional/structural simulation constitutes a strong theory of the design of a system and the mechanism that lies behind observed behavior (De Kleer and Brown, 1984). A model may be functional, without a structural component, as in models of human problem solving, which typically mention brain components in only very general terms (Kosslyn, 1980).

Figure 4-2 summarizes the different perspectives by which qualitative models describe systems: as *processes* (a prototype hierarchy of I/O or cause/effect patterns); *states* (a graph of states linked by cause and subtype); *functions* (procedural modules hierarchically composed by I/O relations); and *structures* (physical components composing functional modules). The next step in the analysis, beyond the scope of this paper, is to relate these alternative models for recognizing a system and understanding its behavior to the demands of generic tasks (Section 3). Notice in particular that the qualitative modeling repertoire is not specific to physical systems; for example, similar techniques are used for modeling the cognitive processes of discourse, diagnosis, and planning.

CONCEPT	RELATION	COMMON NAME	PROGRAM EXAMPLES
I. PROCESS	SUBSUMPTION	PROTOTYPE CLASSIFICATION	(Pauker, 1977) (Lehnert, 1978)
II. STATE	CONDITIONAL TRANSITION (CAUSE)	CAUSAL NETWORK	(Brown, et al., 1973) (Rieger & Grinberg, 1977) (Weiss, et al., 1978)
III. FUNCTION	COMPOSITION	PROCEDURAL NETWORK	(Sacerdoti, 1974) (Brown, et al., 1982) (Clancey, 1984)
IV. STRUCTURE	COMPOSITION	STRUCTURE-FUNCTION MODEL	(de Kleer, 1979) (Geneserath, 1982)

Figure 4-2: Conceptual structure of network representations for systems

This framework can be used as a starting point for understanding the value of multiple representations. For example, it is common for a causal-associational state network to be mapped to a disease process hierarchy (Weiss and Kulikowski, 1984, Szolovits, 1985, Clancey and Letsinger, 1984), thus relating a descriptive view of current system behavior to a developmental accounting. Process descriptions can be combined with a structural simulation for coping with complex or unusual situations (Bylander and Chandrasekaran, 1985, Koton, 1985, Fink, 1985). Qualitative models can be useful for controlling and interpreting quantitative simulations (Brown, 1975, Apte and Weiss, 1985). Finally, note that both

simulation and classification models can be quantitative (Nilsson, 1965), so the classification/simulation and qualitative/quantitative distinctions are orthogonal.

## 5. Example: Applying the model perspective to diagnosis

A diagnosis explains why observed system behavior is different from expected, generally in terms of a structural variation from the design. Corresponding to the types of qualitative models (Figure 4-1), the diagnostic process takes different forms:

- recognizing a disorder as a set of features;
- constructing an "historical" accounting for behavior (usually partial because only abnormal manifestations are explained, not normal functioning of the system); and
- constructing a "complete" description of the system being diagnosed (accounting for both abnormal and normal system behavior in terms of structural components).

As a model, a medical diagnosis is not just the name of a disease, but a *causal story* that relates the manifestations that need to be explained (because they are abnormal) to the processes that brought them about. Such an argument, shown as an inference network in Figure 5-1, is called a *patient-specific model* (Patil, 1981). In simple terms, it copies over from models of system processes, states, function, and structure the concepts and relations that are believed to hold in this particular problem.

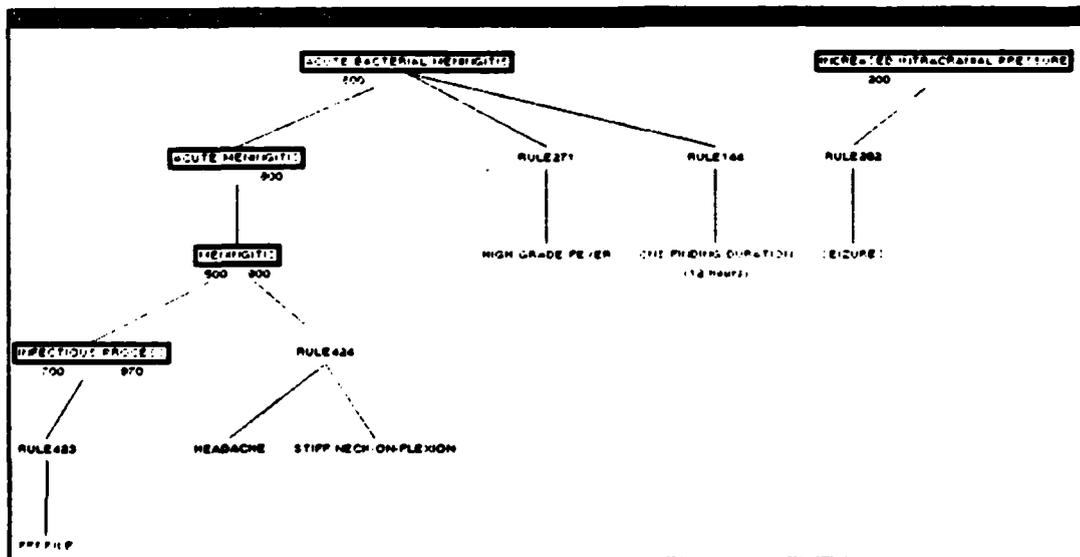


Figure 5-1: Partial diagnostic model in NEOMYCIN

The process of diagnosis can be viewed as the construction of a "proof tree." Proceeding upwards, the explanation becomes more specific in terms of the cause or subtype of the process that is occurring. At some intermediate stage when solving the problem, the network is disconnected and partial (Figure 5-1). The state-transition model indicates that seizures might be caused by increased intracranial pressure; this link is placed in the patient-specific model.

There is evidence for acute meningitis, but the alternative hypotheses have not been related. Is there some underlying cause or process that could account for all of the manifestations? Could meningitis cause increased intracranial pressure? Thus, the problem solver returns to the general model to search for connections that will allow a coherent explanation to be constructed.

While this description of diagnosis has intuitive appeal, most expert systems and their developers never check to see whether all of the findings are covered by the final "diagnosis." cursory examination of the inference network (as shown for NEOMYCIN in Figure 5-1) reveals surprising gaps in the program's model: Abnormal findings needing to be explained are found to be unrelated to the most likely diagnosis. How can we account for the fact that these gaps go unnoticed?

In part, our language is too loose: The program prints out the *name* of a disorder, and we say, "The program has *made* a diagnosis." We don't think of a diagnosis as a description of a system and how it evolved. Instead, emphasis is on "inferring the right answer." We view inference in terms of adding up belief or finding a linear path of assertions that ends in the right diagnosis.

Accumulating evidence by some scoring function (Pople, 1982) or certainty factor scheme—the predominant approach in expert system diagnosis—disguises the *structural* aspects of diagnosis, that is, how the hypotheses explain the findings. It would be difficult to find a better example of the proverbial groping around the elephant, with each researcher proclaiming a different aspect of the nature of diagnosis:

- In INTERNIST, a scoring function reduces a hypothesis score by the "importance" of the observed findings it fails to explain (Pople, 1982).
- Viewing diagnosis in terms of traversing a network of processes and states, CASNET extracts the longest path from findings to a disease process (Weiss, et al., 1978).
- Reggia defines the best diagnosis as one that satisfies the principle of parsimony, covering the largest set of findings (Reggia, et al., 1984).
- In CADUCEUS, orthogonal relations and the possibility of multiple disorders make linear network traversal combinatorially intractable. Operators piece together state and process descriptions according to subtype and causal relations (Pople, 1982).
- In NEOMYCIN, diagnostic operators focus on, group, refine, and support the *differential*, the most-specific state and process descriptions that explain the findings (Clancey, 1984).
- Finally, in ABEL, these ideas are brought together, so that a diagnosis is a constructed graph that explains the findings on multiple levels of detail (Patil, 1981).

Thus, research has progressed from viewing diagnosis in terms of inferring the name of disease by chains of reasoning (MYCIN), or finding the best match (INTERNIST), to *reasoning about* a constructed inference network, the causal story. Inference is described not in terms of particular evidence rules and backchaining, but in terms of operators for manipulating the

### patient-specific model.

An interesting result is that the uncertainty of the diagnosis no longer resides in a numeric score, but in the structure of the model: Alternative hypotheses are ranked by how well they cover the findings (Patil, 1981). Furthermore, by taking into account the *purpose* of the model, the issue becomes not to derive a precise measure of belief, but to determine if the uncertainty needs to be resolved. Medical diagnoses, like all engineering models, are partial. They need only be good enough to discriminate among choices for action, perhaps allowing for monitoring successful completion of a plan and improving an inadequate choice (Petroski, 1985). However, today's programs make a diagnosis independently of how it will be used, or therapeutic distinctions are implicit in the disorder classification. For example, MYCIN does not distinguish among types of viral meningitis because they are treated equivalently. Further development of this point would contrast the engineering demands of diagnosis with *scientific* modeling of systems (as in Dendral (Buchanan, et al., 1969)), which seeks mechanistic detail, and naive device models (Kieras, 1984, Suchman, 1985).

Even if a knowledge base lacks the detailed causal relations that enable reasoning about interactions as in ABEL, the patient-specific model can be useful. First, it can be used as a global perspective for controlling inference. For example, NEOMYCIN's patient-specific model indicates that unnecessary assertions are being made. Several new metarules prevent this, for example (stated negatively for clarity), "If a new disease hypothesis does not explain all abnormal findings, but some existing hypothesis does, then do not add the new hypothesis to the patient-specific model"

Second, as a form of output, the model (Figure 5-1) is a powerful knowledge acquisition tool. It reveals:

- Gaps in the knowledge base, evident by a missing link between an abnormal finding and a hypothesis (a feature we are exploiting in our teaching program, GUIDON-DEBUG (Clancey, et al., 1986))
- Implicit inferences, evident by the program's inability to link terms such as "headache chronicity" and "cns finding duration" (something we must correct for the program to explain its reasoning).
- Missing qualitative abstractions, evident by a direct link between a numeric finding (e.g., "csf protein is 100") and a disease. We must make explicit what ranges are high or low and what is abnormal in order for the program to know what findings need to be explained.
- Undirected causal links, where no distinction is made between causes or correlated predispositions and effects (e.g., the patient's age is never an effect of a disease). Again, the program cannot know if its explanation is complete if it doesn't know what facts need to be explained.
- Side-effects, evident by links composing a causal relation with a model-manipulation strategy (e.g., if the csf is bloody, rule out bacterial-meningitis). The model perspective disciplines the rule writer to record the correct causal association (bloody csf is caused by a subarachnoid hemorrhage) and to write control rules that reason about alternative explanations (such as the metarule shown above)

These observations do not mean that the classification/behavioral approach should be abandoned in favor of structure-function models. First, diagnosis based on structure-function has generally been restricted to component failures, rather than interactions the system has with its environment. Given the open nature of the world, an "experiential" classification model appears to be practical, and perhaps necessary. Second, regardless of diagnostic value, classification and behavioral descriptions represent what people know in domains such as medicine and everyday reasoning (Roach, 1978, Feltoovich, et al., 1984, Kolodner, 1984). Third, belief maintenance descriptions of inference (e.g., (De Kleer and Brown, 1984)) emphasize model coherence, but do not capture the structural aspects of situation-specific model manipulation, evident in the description of diagnostic tasks as graph-construction operators (Patil, 1981, Pople, 1982, Clancey, 1984). In applying the model perspective to classification and behavioral descriptions, we are not dismissing them as inferior, but rather recognizing their status as models and gaining a measure of quality for diagnostic inference.

Finally, the model-based perspective of Figure 5-1 is compatible with the blackboard paradigm (Hayes-Roth, 1984), viewing reasoning in terms of: A shared database; flexible, opportunistic operators for posting and modifying solution elements; and a separate control structure for scheduling inference. However, the blackboard is not *just* a database. It is a situation-specific model of a system, made apparent by the use of different blackboards or "panels" to separate different systems and action plans. The study of alternative kinds of models (Section 4) and the view of inference as model-manipulation operators is a step towards formalizing principles for structuring a blackboard and describing what "knowledge sources" do. This analysis also suggests that heuristic classification is not adequate for diagnosis and other systems problems when pre-enumerated processes or action plans can occur together and interact.

## 6. Historical perspective

We can resolve some of the uncertainty about the nature of expert systems and AI in general by relating this work to other science and engineering perspectives, placing it in historical context, and defining it comparatively. This is the chapter that AI textbooks consistently omit. We need to tell students not just what our goals and methodology are, but how we got here and how what we're doing is different from traditional science and engineering.

Today we take for granted that the words "machine" and "intelligence" go together because the idea of a machine today allows for adaptivity (McCorduck, 1979). But this was not always so. For scientists and engineers of the past, a "mechanism" was the antithesis of change and flexibility. It was something fixed, composed of known parts, and fully predictable. The "scientific perspective" in part had its origin in this mechanistic or deterministic conception of nature. Thus, the mysterious concepts of "a superhuman final cause" and "purpose" were rejected, and all observed behavior reduced to separate, discrete parts studied in isolation

(Frank, et al., 1948, Bertalanffy, 1968).

However, in this century, this view was found to be inadequate for understanding complex systems. The concept of goal was re-introduced in cybernetics by models of self-regulation, based on the concept of feedback (Wiener, 1961). Several sciences, including particularly biology and economics, turned to the study of systems not as "constitutive characteristics," of elements in isolation, but as relations among elements (Bertalanffy, 1968). Thus, study turned from invariant properties (such as molecular weight) to properties of a *complex*, dependent on relations among interacting elements (such as *topological structure* of a molecule and the *function* of molecular units).

In modeling the *open* and *non-linear* character of systems, analytic techniques broadened to include concepts such as: "compartmentalization" (near decomposability (Simon, 1969)), topology, adaptiveness, information flow, state-transition, and rationality (Bertalanffy, 1968, Newell and Simon, 1972). In particular, these perspectives address the need to represent discontinuities (non-linearity) in system behavior: "Representation by differential equations is too restricted for a theory to include biological systems and calculating machines where discontinuities are ubiquitous" (Bertalanffy, 1968).

From this perspective, Artificial Intelligence merges the *teleological concepts* of choice, regulation, adaptiveness and rationality with the *modeling concepts* of set, graph, net, and automata theory and formal logic (Newell and Simon, 1972). Furthermore, emphasis has shifted from modeling systems in themselves, to modeling "self-directed personalities" (Frank, et al., 1948) that incorporate a model of the world, goals, and a reasoning process for solving particular problems. The idea of the *autonomous agent* crucially frames our research. To determine what could be the basis for rationality and adaptation, we have focused on the *individual* interacting with the world to solve some problem. In order to *generate* intelligent behavior in an autonomous agent, a program, we put inside a *representation* of the agent's knowledge of the world and his goals. Rather than proving theorems about structures in themselves (as in graph theory), we use them to *represent* concepts and relations. Thus have evolved the well-known representational structures of our field: the augmented-transition network, the procedural network, the causal-association network, the semantic network, and so on.

In this historical context, we see that AI combines a framework for modeling (the idea of the autonomous agent) with qualitative modeling techniques. In describing AI, we have tended to emphasize the idea of generating intelligent behavior, and not made clear how our modeling techniques are different. Rather than numeric *measures*, we have devised methods for *describing* physical and cognitive systems. Our programs describe a system's physical appearance (structure), behavior, goals, and role in a larger context (function). These relations are distinguished in our advanced representation languages (Bobrow, 1984, Brachman and

Levesque, 1985).

In the buzzword "knowledge," we emphasize that what the problem solver knows or believes is central, providing a crucial focus for our research. But the term "knowledge" emphasizes the *role* of a representation, obscuring its primary status as a model of a system in the world. The discussion in Sections 3 and 5 gives examples of how our understanding of inference, uncertainty, and knowledge base design can be improved by applying the systems model perspective.

In general, the idea that knowledge bases, like all models, are selective, based on assumptions, and prone to failure has been given almost no consideration in knowledge engineering research. Perhaps the most basic engineering problem in constructing a model is to determine the range of its applicability. How can we determine what cases—situations in the world—will not be successfully modeled? Just as the structural engineer must ensure that his model of a bridge or building will be adequate for every real world event that occurs (given some assumptions) (Petroski, 1985, Weinberg, 1982), the knowledge engineer must certify the validity of his model. Yet, outside of established domains with a strong theory, such as electronics, no strong statements can be made about the accuracy of expert systems, except perhaps that they will work on the cases they have been tested on. While expert systems may only be designed to work for "typical cases," we must find some way to describe the extremes and articulate procedures for detecting when they occur. Until we shift from continuously blessing our programs with the name of "expert," and realize that they are only models, it is unlikely that the required engineering methodology will develop.

## 7. Conclusions

Focusing on the function of knowledge bases as models of systems, I have described expert-system problem solving in terms of generic tasks, provided a unifying description of qualitative representations, and related AI to the concerns of traditional science and engineering. Using medical diagnosis as an example, I showed the benefits of this perspective for detecting gaps in a knowledge base and understanding inference in terms of a model-manipulation strategy.

All knowledge bases contain qualitative models. Describing expert systems has been difficult because a "knowledge base" could be almost anything. Now, confronted with a knowledge base, you might ask: What system is it a model of? Whose model is it? Why is it believed? Is it a classification, state-transition, functional, or structural model? Are these composed? What is the inference procedure? Are situation-specific models selected or constructed? What is the explanatory/predictive or system synthesis capability? For what world? For what task? Under what assumptions? How do you know when it isn't good enough?

Along these lines, problem solving, learning, and explanation can be reconceptualized in terms of model acquisition, representation, and use. Many researchers have already adopted

this perspective (for example, see (Weiss, et al., 1978, Gaschnig, 1980, Swartout, 1981, Kahn, et al., 1985, Soo, et al., 1985)). But our work has barely begun in developing this new science and engineering of qualitative models:

We have explored a range of systems of different types: physical, perceptual, cognitive, and social. But the modeling methods are not practically accessible to professionals in other fields.

We now can see that the *locus* of a model can be strikingly varied: mathematical equations, a physical replica, a computer program, and a mental model. But we are struggling to understand what a representation is and how it might be confused with "reality" (Smith, 1982, Smith, 1985, Sloman, 1985).

We have developed qualitative models in expert systems for scientific and engineering applications (Sriram and Rychener, 1986). But we have not developed a methodology for testing models that distinguishes between these goals.

We have qualitative models of systems in the world, second order models (e.g., student models), and discourse and instructional models for communication and modification of models. But we are uncertain about how to represent these explicitly and to what extent they can be separated.

We continue to study the evolution of models, their origin and development in the individual, with recent successes in failure-driven and explanation-based learning (e.g., (Kolodner, 1984, Mitchell, et al., 1985)). But this has underscored how models from different domains and different perspectives interact in learning, in sharp contrast with the sparseness of today's knowledge bases.

We have developed a repertoire of computational methods for representing qualitative models and inference methods. But the relation of these methods to numeric techniques and their psychological aspects remain to be understood (Gentner and Stevens, 1983, Kuipers, 1985, Patel and Groen, 1986, Rouse and Morris, 1985).

Knowledge engineering is not just a new kind of programming. It is a new methodology for constructing models of systems in the world so they can be automatically assembled, modified, and controlled. We are not so much programmers as engineers, scientists, and perhaps philosophers. If we view our work in this way, consistently attempting to unify it from a modeling perspective, our claims and successes will be better understood.

## References

- Achinstein, P. *The Nature of Explanation*. New York: Oxford University Press 1983.
- Ackoff, R.L. Towards a system of systems concepts. In J.D. Couger and R.W. Knapp (editors), *System Analysis Techniques*, pages 27-38. John Wiley & Sons, New York, 1974.
- Apte, C.V. and Weiss, S.M. An approach to expert control of interactive software systems. *Pattern Analysis and Machine Intelligence*, September 1985, 7(5), 586-591.
- Bennett, J. S. and Engelmores, R. S. *SACON: A Knowledge-based Consultant for Structural Analysis*, in *Proc. IJCAI-79*, pages 47-49, IJCAI, Tokyo, Japan, August, 1979. Originally published as a Techreport in 1978 and as an Article in 1979.
- von Bertalanffy, L. *General System Theory: Foundations, Development, Applications*. New York: George Braziller, Inc. 1968.
- Bobrow, D. G. Special issue on qualitative reasoning about physical systems. *Artificial Intelligence*, 1984, 24(1-3), 1-5.
- Brachman, R.J. and Levesque, H.J. (eds.). *Readings In Knowledge Representation*. Los Altos: Morgan Kaufmann Publishers Inc. 1985.
- Brown, J. S. and Burton, R. R. Multiple Representations of Knowledge for Tutorial Reasoning. In D. G. Bobrow and A. Collins (editor), *Representation and Understanding: Studies in Cognitive Science*, pages 311-350. Academic Press, New York, 1975.
- Brown, J. S., Burton, R. R., and Zydbel, F. A model-driven question-answering system for mixed-initiative computer-assisted instruction. *IEEE Transactions on Systems, Man, and Cybernetics*, 1973, SMC-3(3), 248-257.
- Brown, J. S., Burton, R. R., and de Kleer, J. Pedagogical, natural language, and knowledge engineering techniques in SOPHIE I, II, and III. In D. Sleeman and J. S. Brown (editors), *Intelligent Tutoring Systems*, pages 227-282. Academic Press, London, 1982.
- Buchanan, B. G., Sutherland, G., and Feigenbaum, E. A. Heuristic Dendral: A program for generating explanatory hypotheses in organic chemistry. In B. Meltzer and D. Michie (editors), *Machine Intelligence*, pages 209-254. Edinburgh University Press, Edinburgh, 1969.
- Bylander, T. and Chandrasekaran, B. *Understanding behavior using consolidation*, in *Proceedings of the Ninth Joint Conference on Artificial Intelligence*, pages 450-454, Los Angeles, August, 1985.
- Chandrasekaran, B. and Milne, R. (eds.). Special section on reasoning about structure, behavior and function. *SIGART Newsletter*, July 1985, 93, 4-7.
- Clancey, W. J. *Transfer of rule-based expertise through a tutorial dialogue*. PhD thesis, SU, August, 1979.
- Clancey, W. J. The epistemology of a rule-based expert system: A framework for explanation. *Artificial Intelligence*, 1983, 20(3), 215-251.
- Clancey, W. J. *The advantages of abstract control knowledge in expert system design*, in *Proceedings of the National Conference on AI*, pages 74-78, Washington, D.C., August, 1983.

- Clancey, W. J. *Acquiring, representing, and evaluating a competence model of diagnosis*. HPP Memo 84-2, Stanford University, February 1984. (To appear in M. Chi, R. Glaser, and M. Farr (Eds.), *Contributions to the Nature of Expertise*, in preparation.)
- Clancey, W. J. Heuristic Classification. *Artificial Intelligence*, December 1985, 27, 289-350.
- Clancey, W. J. and Letsinger, R. NEOMYCIN: Reconfiguring a rule-based expert system for application to teaching. In Clancey, W. J. and Shortliffe, E. H. (editors), *Readings in Medical Artificial Intelligence: The First Decade*, pages 361-381. Addison-Wesley, Reading, 1984.
- Clancey, W. J., Richer, M., Wilkins, D., Barnhouse, S., Kapsner, C., Leserman, D., Macias, J., Merchant, A., Rodolitz, N. *Guidon-Debug: The student as knowledge engineer*. KSL Report 86-34, Stanford University, 1986. (Submitted to special issue of *Journal of Artificial Intelligence* on instructional programs.)
- Davis R. *Applications of meta-level knowledge to the construction, maintenance, and use of large knowledge bases*. HPP Memo 76-7 and AI Memo 283, Stanford University, July 1976.
- Davis, R. Reasoning from first principles in electronic troubleshooting. In M.J. Coombs (editor), *Developments in Expert Systems*, pages 1-21. Academic Press, New York, 1984.
- Davis, R. Knowledge-based systems. *Science*, February 1986, 231, 957-963.
- de Kleer, J. *Casual and teleological reasoning in circuit recognition*. PhD thesis, Massachusetts Institute of Technology, January, 1979. Also Report No. AI-TR-529.
- De Kleer, J. and Brown, J.S. A qualitative physics based on confluences. *Artificial Intelligence*, December 1984, 24(1-3), 7-83.
- Feigenbaum, E. A. *The art of artificial intelligence: I. Themes and case studies of knowledge engineering*, in *Proceedings of the Fifth International Joint Conference on Artificial Intelligence*, pages 1014-1029, August, 1977.
- Feigenbaum, E.A. and Feldman, J. *Computers and Thought*. Malabar, Florida: Robert E. Krieger Publishing Company, Inc. 1963.
- Feltovich, P. J., Johnson, P. E., Moller, J. H., and Swanson, D. B. The role and development of medical knowledge in diagnostic expertise. In W. J. Clancey and E. H. Shortliffe (editors), *Readings in Medical Artificial Intelligence: The First Decade*, pages 275-319. Addison-Wesley Publishing Company, Reading, 1984.
- Fink, P.K. *Control and integration of diverse knowledge in a diagnostic expert system*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 427-431, 1985.
- Forbus, K.D. Qualitative Process Theory. *Artificial Intelligence*, December 1984, 24(1-3), 85-168.
- Frank, L.K., Hutchinson, G.E., Livingstone, McCulloch, W.S., Wiener, N. Teleological Mechanisms. *Ann. N.Y. Acad. Sci.*, 1948, 50, .
- P. Friedland (ed.). Special section on architectures for knowledge-based systems. *Communications of the ACM*, September 1985, 28(9), 902-941.

- Gaschnig, J. *Development of uranium exploration models for the prospector consultant system.* Technical Report Final Report, SRI International, March 1980.
- Genesereth, M. R. *Diagnosis using hierarchical design models*, in *Proceedings of the National Conference on AI*, pages 278-283, Pittsburgh, PA, August, 1982.
- Gentner, D. and Stevens, A. (editors). *Mental models.* Hillsdale, NJ: Erlbaum 1983.
- Harmon, P. and King D. *Expert Systems: Artificial Intelligence in Business.* New York: John Wiley & Sons 1985.
- Hasling, D. W., Clancey, W. J., Rennels, G. R. Strategic explanations in consultation. *The International Journal of Man-Machine Studies*, 1984, 20(1), 3-19. Also in *Development in Expert Systems*, ed. M.J. Coombs, Academic Press, London.
- Hayes-Roth, B. *BBI: An architecture for blackboard systems that control, explain, and learn about their own behavior.* HPP Memo 84-16, Stanford University, December 1984.
- Hayes-Roth, F., Waterman, D., and Lenat, D. (eds.). *Building Expert Systems.* New York: Addison-Wesley 1983.
- Johnson, W. Lewis, and Elliot Soloway. *Intention-Based Diagnosis of Programming Errors*, in *Proceedings of the National Conference on AI*, pages 162-168, Austin, TX, August, 1984.
- Kahn, G., Nowlan, S., and McDermott, J. *MORE: An intelligent knowledge acquisition tool*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 581-584, Los Angeles, August, 1985.
- Kieras, D. E. *A simulation model for procedure inference from a mental model for a simple device.* Technical Report UARZ/DP/TR-84/ONR-15, University of Arizona, May 1984.
- Kolodner, J.L. Towards an understanding of the role of experience in the evolution from novice to expert. In M.J. Coombs (editor), *Developments in Expert Systems*, pages 95-116. Academic Press, New York, 1984.
- Kosslyn, S. M. *Image and Mind.* Cambridge: Harvard University Press 1980.
- Koton, P.A. *Empirical and model-based reasoning in expert systems*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 297-299, 1985.
- Kuipers, B. *The limits of qualitative simulation*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 128-136, 1985.
- Lehnert, W.G. *Representing physical objects in memory.* Techreport 131, Computer Science Department, Yale University, 1978.
- McCorduck, P. *Machines Who think: A Personal Inquiry Into The History And Prospects Of Artificial Intelligence.* San Francisco: W.H. Freeman and Company 1979.
- McDermott, J. *Extracting knowledge from expert systems*, in *Proceedings of the Eighth International Joint Conference on Artificial Intelligence*, pages 100-107, Karlsruhe, West Germany, August, 1983.
- Minsky, M. Steps toward Artificial Intelligence. In E.A. Feigenbaum and J. Feldman (editors), *Computers and Thought*, pages 406-450. Robert E. Krieger Publishing Company, Inc., Malabar, Florida, 1963.

- Minsky, M. A framework for representing knowledge. In P. H. Winston (editor), *The Psychology of Computer Vision*, McGraw-Hill, New York, 1975.
- Mitchell, T.M., Mahadevan, S., Steinberg, L.I. *LEAP: A learning apprentice for VLSI design*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 573-580, Los Angeles, August, 1985.
- Newell, A. and Simon, H. A. *Human Problem Solving*. Englewood Cliffs: Prentice-Hall 1972.
- Nilsson, N.J. *Learning Machines: Foundation of Trainable Pattern-classifying Systems*. New York: McGraw Hill Book Company 1965.
- Padulo, L. and Arbib, M.A. *System Theory: A unified state-space approach to continuous and discrete systems*. Washington: Hemisphere Publishing Corporation 1974.
- Patel, V.L. and Groen, G.J. Knowledge based solution strategies in medical reasoning. *Cognitive Science*, January-March 1986, *10(1)*, 91-116.
- Patil, R. S., Szolovits, P., and Schwartz, W. B. *Causal understanding of patient illness in medical diagnosis*, in *Proceedings of the Seventh International Joint Conference on Artificial Intelligence*, pages 893-899, August, 1981.
- Pauker, S. G., Gorry, G. A., Kassirer, J. P., and Schwartz, W. B. Toward the simulation of clinical cognition: taking a present illness by computer. *AJM*, 1976, *60*, 981-995.
- Petroski, H. *To Engineer is Human: The role of failure in successful design*. New York: St. Martin's Press 1985.
- Pople, H. Heuristic methods for imposing structure on ill-structured problems: the structuring of medical diagnostics. In P. Szolovits (editor), *Artificial Intelligence in Medicine*, pages 119-190. Westview Press, 1982.
- Reggia, J.A., Nau, D.S. and Wang, P.Y. Diagnostic expert systems based on a set covering model. In *Developments in Expert Systems*, pages 35-58. Academic Press, New York, 1984.
- Rich, E. User modeling via stereotypes. *Cognitive Science*, 1979, *3*, 355-366.
- Rieger, C. and M. Grinberg. *The Declarative Representation and Procedural Simulation of Causality in Physical Mechanisms*, in *Proc. IJCAI-77*, pages 250-256, IJCAI, MIT, Cambridge, MA, August, 1977.
- Rosch, E. Principles of categorization. In E. Rosch and B. B. Lloyd (editors), *Cognition and Categorization*, pages 27-48. Lawrence Erlbaum Associates, Hillsdale, NJ, 1978.
- Rouse, W.B. and Morris, N.M. *On looking into the black box: prospects and limits in the search for mental models*. Technical report 85-2, School of Industrial and Systems Engineering, Georgia Institute of Technology, May 1985.
- Sacerdoti, E. D. Planning in a hierarchy of abstraction spaces. *Artificial Intelligence*, 1974, *5(2)*, 115-135.
- Schank, R. C., and Abelson, R. P. *Scripts, Plans, Goals, and Understanding*. Hillsdale, NJ: Lawrence Erlbaum Associates 1975.
- Shortliffe, E. H. *Computer-based medical consultations: MYCIN*. New York: Elsevier 1976.

- Simon, H. A. *The Sciences of the Artificial*. Cambridge: The MIT Press 1969.
- Sloman, A. *What enables a machine to understand*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 995-1001, 1985.
- Smith, B.C. The computational methaphor. .
- Smith, B. *Models in expert systems*, in *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 1308-1309, 1985.
- Soloway, E.M, Woolf, B., Rubin, E., Barth, P. *Meno-II: An intelligent tutoring system for novice programmers*, in *Proceedings of the Seventh International Joint Conference on Artificial Intelligence*, pages 975-977, Vancouver, August, 1981.
- Soo, V., Kulikowski, C.A., and Garfinkel, D. *Qualitative modeling and clinical justification for experimental design*, in *Proceedings of the International Conference on Artificial Intelligence in Medicine*, pages 21-36, Amsterdam, 1985. Participants edition.
- Sriram, D. and Rychener, M.D. (eds.). *Expert systems for engineering applications*. *IEEE Software*, March 1986, 3(2), 4-5.
- Stevens, A., Collins, A. and Goldin, S.E. *Misconceptions in students' understanding*. In D. Sleeman and J.S. Brown (editors), *Intelligent Tutoring Systems*, pages 13-24. Academic Press, New York, 1982.
- Suchman, L.A. *Plans and situated actions: the problem of human-machine communication*. Technical report ISL-6, Xerox Parc, February 1985.
- Swartout W. R. *Explaining and justifying in expert consulting programs*, in *Proceedings of the Seventh International Joint Conference on Artificial Intelligence*, pages 815-823, August, 1981.
- Szolovitz, P. *Types of knowledge as bases for reasoning in Medical AI Programs*, in *Proceedings of the International Conference on Artificial Medicine in Medicine*, pages 31-48, Pavia, September, 1985.
- Weinberg, G.M. *Rethinking Systems Analysis and Design*. Boston: Little, Brown and Company 1982.
- Weiss, S. M. and Kulikowski, C. A. *EXPERT: A system for developing consultation models*, in *Proceedings of the Sixth International Joint Conference on Artificial Intelligence*, pages 942-947, August, 1979.
- Weiss, S. M. and Kulikowski, C. A. *A Practical Guide to Designing Expert Systems*. Totowa, NJ: Rowman and Allanheld 1984.
- Weiss, S. M., Kulikowski, C. A., Amarel, S., and Safir, A. *A model-based method for computer-aided medical decision making*. *Artificial Intelligence*, 1978, 11, 145-172.
- Wiener, N. *Cybernetics*. Cambridge, MA: MIT Press 1961.

Personnel Analysis Division,  
AF/MPXA  
5C360, The Pentagon  
Washington, DC 20330

Air Force Human Resources Lab  
AFHRL/MPD  
Brooks AFB, TX 78235

AFOSR,  
Life Sciences Directorate  
Bolling Air Force Base  
Washington, DC 20332

Dr. Robert Ahlers  
Code N711  
Human Factors Laboratory  
Naval Training Systems Center  
Orlando, FL 32813

Dr. Ed Aiken  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. William E. Alley  
AFHRL/MOT  
Brooks AFB, TX 78235

Dr. Earl A. Alluisi  
HQ, AFHRL (AFSC)  
Brooks AFB, TX 78235

Dr. John R. Anderson  
Department of Psychology  
Carnegie-Mellon University  
Pittsburgh, PA 15213

Dr. Nancy S. Anderson  
Department of Psychology  
University of Maryland  
College Park, MD 20742

Dr. Steve Andriole  
George Mason University  
School of Information  
Technology & Engineering  
4400 University Drive  
Fairfax, VA 22030

Dr. John Annett  
University of Warwick  
Department of Psychology  
Coventry CV4 7AJ  
ENGLAND

Dr. Phipps Arabie  
University of Illinois  
Department of Psychology  
603 E. Daniel St.  
Champaign, IL 61820

Technical Director, ARI  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Special Assistant for Projec  
OASN(M&RA)  
5D800, The Pentagon  
Washington, DC 20350

Dr. Michael Atwood  
ITT - Programming  
1000 Oronoque Lane  
Stratford, CT 06497

Dr. Patricia Baggett  
University of Colorado  
Department of Psychology  
Box 345  
Boulder, CO 80309

Dr. Eva L. Baker  
UCLA Center for the Study  
of Evaluation  
145 Moore Hall  
University of California  
Los Angeles, CA 90024

Dr. James D. Baker  
Director of Automation  
Allen Corporation of America  
401 Wythe Street  
Alexandria, VA 22314

Dr. Meryl S. Baker  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Donald E. Bamber  
Code 71  
Navy Personnel R & D Center  
San Diego, CA 92152-6800

Mr. J. Barber  
HQ5, Department of the Army  
DAPE-ZBR  
Washington, DC 20310

Capt. J. Jean Belanger  
Training Development Division  
Canadian Forces Training System  
CFTSHQ, CFB Trenton  
Astra, Ontario, KOK  
CANADA

CDR Robert J. Biersner, USN  
Naval Biodynamics Laboratory  
P. O. Box 29407  
New Orleans, LA 70189

Dr. Menucha Birenbaum  
School of Education  
Tel Aviv University  
Tel Aviv, Ramat Aviv 69978  
ISRAEL

Dr. Werner P. Birke  
Personalstammamt der Bundeswehr  
Kolner Strasse 262  
D-5000 Koeln 90  
FEDERAL REPUBLIC OF GERMANY

Dr. Gautam Biswas  
Department of Computer Science  
University of South Carolina  
Columbia, SC 29208

Dr. John Black  
College, Columbia Univ.  
525 West 121st Street  
New York, NY 10027

Dr. Arthur S. Blaiwes  
Code N711  
Naval Training Systems Center  
Orlando, FL 32813

Dr. Robert Blanchard  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Jeff Bonar  
Learning R&D Center  
University of Pittsburgh  
Pittsburgh, PA 15260

Dr. J. C. Boudreaux  
Center for Manufacturing  
Engineering  
National Bureau of Standards  
Gaithersburg, MD 20899

Dr. Gordon H. Bower  
Department of Psychology  
Stanford University  
Stanford, CA 94306

Dr. Richard Braby  
NTSC Code 10  
Orlando, FL 32751

Dr. Robert Breaux  
Code N-095R  
Naval Training Systems Center  
Orlando, FL 32813

Dr. John S. Brown  
XEROX Palo Alto Research  
Center

3333 Coyote Road  
Palo Alto, CA 94304

Dr. Bruce Buchanan  
Computer Science Department  
Stanford University  
Stanford, CA 94305

Dr. Howard Burrows  
National Institute of Health  
Bldg. 10, Room 5C-106  
Bethesda, MD 20892

Dr. Patricia A. Butler  
OERI  
555 New Jersey Ave., NW  
Washington, DC 20208

Dr. Tom Cafferty  
Dept. of Psychology  
University of South Carolina  
Columbia, SC 29208

Dr. Robert Calfee  
School of Education  
Stanford University  
Stanford, CA 94305

Joanne Capper  
Center for Research into Practice  
1718 Connecticut Ave., N.W.  
Washington, DC 20009

Dr. Jaime Carbonell  
Carnegie-Mellon University  
Department of Psychology  
Pittsburgh, PA 15213

Mr. James W. Carey  
Commandant (G-PTE)  
U.S. Coast Guard  
2100 Second Street, S.W.  
Washington, DC 20593

Dr. Susan Carey  
Harvard Graduate School of  
Education  
337 Gutman Library  
Applan Way  
Cambridge, MA 02138

Dr. Pat Carpenter  
Carnegie-Mellon University  
Department of Psychology  
Pittsburgh, PA 15213

Prof. John W. Carr III  
Department of Computer Science  
Moore School of  
Electrical Engineering  
University of Pennsylvania  
Philadelphia, PA 19104

Dr. Robert Carroll  
OP 01B7  
Washington, DC 20370

LCDR Robert Carter  
Office of the Chief  
of Naval Operations  
OP-01B  
Pentagon  
Washington, DC 20350-2000

Dr. Fred Chang  
Navy Personnel R&D Center  
Code 51  
San Diego, CA 92152-6800

Dr. Alphonse Chapanis  
8415 Bellona Lane  
Suite 210  
Buxton Towers  
Baltimore, MD 21204

Dr. Davida Charney  
Department of Psychology  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

Dr. Eugene Charniak  
Brown University  
Computer Science Department  
Providence, RI 02912

Dr. Paul R. Chatelier  
OUSDRE  
Pentagon  
Washington, DC 20350-2000

Dr. Michelene Chi  
Learning R & D Center  
University of Pittsburgh  
3939 O'Hara Street  
Pittsburgh, PA 15213

Mr. Raymond E. Christal  
AFHRL/MOE  
Brooks AFB, TX 78235

Dr. Yee-Yeen Chu  
Perceptronics, Inc.  
21111 Erwin Street  
Woodland Hills, CA 91367-371

Dr. William Clancey  
Stanford University  
Knowledge Systems Laboratory  
701 Welch Road, Bldg. C  
Palo Alto, CA 94304

Chief of Naval Education  
and Training  
Liaison Office  
Air Force Human Resource Lab  
Operations Training Division  
Williams AFB, AZ 85224

Assistant Chief of Staff  
for Research, Development,  
Test, and Evaluation  
Naval Education and  
Training Command (N-5)  
NAS Pensacola, FL 32508

Dr. Allan M. Collins  
Bolt Beranek & Newman, Inc.  
50 Moulton Street  
Cambridge, MA 02138

Dr. John J. Collins  
Director, Field Research  
Office, Orlando  
NPRDC Liaison Officer  
WTEC Orlando, FL 32813

Dr. Stanley Collyer  
Office of Naval Technology  
Code 222  
800 N. Quincy Street  
Arlington, VA 22217-5000

Dr. Lynn A. Cooper  
Learning R&D Center  
University of Pittsburgh  
3939 O'Hara Street  
Pittsburgh, PA 15213

Dr. Meredith P. Crawford  
American Psychological Association  
Office of Educational Affairs  
1200 17th Street, N.W.  
Washington, DC 20036

Dr. Hans Crombag  
University of Leyden  
Education Research Center  
Boerhaavelaan 2  
2334 EN Leyden  
The NETHERLANDS

LT Judy Crookshanks  
Chief of Naval Operations  
OP-112G5  
Washington, DC 20370-2000

Dr. Kenneth B. Cross  
Anacapa Sciences, Inc.  
P.O. Drawer Q  
Santa Barbara, CA 93102

Dr. Mary Cross  
Department of Education  
Adult Literacy Initiative  
Room 4145  
400 Maryland Avenue, SW  
Washington, DC 20202

CTB/McGraw-Hill Library  
2500 Garden Road  
Monterey, CA 93940

CAPT P. Michael Curran  
Office of Naval Research  
800 N. Quincy St.  
Code 125  
Arlington, VA 22217-5000

Dr. Cary Czichon  
Intelligent Instructional Sy  
Texas Instruments AI Lab  
P.O. Box 660245  
Dallas, TX 75266

Bryan Dallman  
AFHRL/LRT  
Lowry AFB, CO 80230

LT John Deaton  
ONR Code 125  
800 N. Quincy Street  
Arlington, VA 22217-5000

Dr. Natalie Dehn  
Department of Computer and  
Information Science  
University of Oregon  
Eugene, OR 97403

Dr. Gerald F. DeJong  
Artificial Intelligence Grou  
Coordinated Science Laborato  
University of Illinois  
Urbana, IL 61801

Goery Delacote  
Directeur de L'informatique  
Scientifique et Technique  
CNRS  
15, Quai Anatole France  
75700 Paris FRANCE

Mr. Robert Denton  
AFMPC/MPCYPR  
Randolph AFB, TX 78150

Mr. Paul DiRenzo  
Commandant of the Marine Corps  
Code LBC-4  
Washington, DC 20380

Dr. R. K. Dismukes  
Associate Director for Life Sciences  
AFOSR  
Bolling AFB  
Washington, DC 20332

Defense Technical  
Information Center  
Cameron Station, Bldg 5  
Alexandria, VA 22314  
Attn: TC  
(12 Copies)

Dr. Thomas M. Duffy  
Communications Design Center  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

Barbara Eason  
Military Educator's  
Resource Network  
InterAmerica Research Associates  
1555 Wilson Blvd  
Arlington, VA 22209

Edward E. Eddowes  
CNATRA N301  
Naval Air Station  
Corpus Christi, TX 78419

Dr. John Ellis  
Navy Personnel R&D Center  
San Diego, CA 92252

Dr. Richard Elster  
Deputy Assistant Secretary  
of the Navy (Manpower)  
OASN (M&RA)  
Department of the Navy  
Washington, DC 20350-1000

Dr. Susan Embretson  
University of Kansas  
Psychology Department  
426 Fraser  
Lawrence, KS 66045

Dr. Randy Engle  
Department of Psychology  
University of South Carolina  
Columbia, SC 29208

Lt. Col Rich Entlich  
HQ, Department of the Army  
OCSA(DACS-DPM)  
Washington, DC 20310

Dr. Susan Epstein  
Hunter College  
144 S. Mountain Avenue  
Montclair, NJ 07042

Dr. William Epstein  
University of Wisconsin  
W. J. Brogden Psychology Bld  
1202 W. Johnson Street  
Madison, WI 53706

ERIC Facility-Acquisitions  
4833 Rugby Avenue  
Bethesda, MD 20014

Dr. K. Anders Ericsson  
University of Colorado  
Department of Psychology  
Boulder, CO 80309

Dr. Edward Esty  
Department of Education, OER  
Room 717D  
1200 19th St., NW  
Washington, DC 20208

Dr. Beatrice J. Farr  
Army Research Institute  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. Marshall J. Farr  
2520 North Vernon Street  
Arlington, VA 22207

Dr. Pat Federico  
Code 511  
NPRDC  
San Diego, CA 92152-6800

Dr. Jerome A. Feldman  
University of Rochester  
Computer Science Department  
Rochester, NY 14627

Dr. Paul Feltovich  
Southern Illinois University  
School of Medicine  
Medical Education Department  
P.O. Box 3926  
Springfield, IL 62708

Mr. Wallace Feurzeig  
Educational Technology  
Bolt Beranek & Newman  
10 Moulton St.  
Cambridge, MA 02238

Dr. Craig I. Fields  
ARPA  
1400 Wilson Blvd.  
Arlington, VA 22209

Dr. Gerhard Fischer  
University of Colorado  
Department of Computer Science  
Boulder, CO 80309

J. D. Fletcher  
9931 Corsica Street  
Vienna VA 22180

Dr. Linda Flower  
Carnegie-Mellon University  
Department of English  
Pittsburgh, PA 15213

Dr. Kenneth D. Forbus  
University of Illinois  
Department of Computer Science  
1304 West Springfield Avenue  
Urbana, IL 61801

Dr. Barbara A. Fox  
University of Colorado  
Department of Linguistics  
Boulder, CO 80309

Dr. Carl H. Frederiksen  
McGill University  
3700 McTavish Street  
Montreal, Quebec H3A 1Y2  
CANADA

Dr. John R. Frederiksen  
Bolt Beranek & Newman  
50 Moulton Street  
Cambridge, MA 02138

Dr. Norman Frederiksen  
Educational Testing Service  
Princeton, NJ 08541

Dr. Alfred R. Fregly  
AFOSR/NL  
Bolling AFB, DC 20332

Dr. Bob Frey  
Commandant (G-P-1/2)  
USCG HQ  
Washington, DC 20593

Dr. Alinda Friedman  
Department of Psychology  
University of Alberta  
Edmonton, Alberta  
CANADA T6G 2E9

Julie A. Gadsden  
Information Technology  
Applications Division  
Admiralty Research Establish  
Portsmouth, Portsmouth PO6 4A  
UNITED KINGDOM

Dr. R. Edward Geiselman  
Department of Psychology  
University of California  
Los Angeles, CA 90024

Dr. Michael Genesereth  
Stanford University  
Computer Science Department  
Stanford, CA 94305

Dr. Dedre Gentner  
University of Illinois  
Department of Psychology  
603 E. Daniel St.  
Champaign, IL 61820

Dr. Robert Glaser  
Learning Research  
& Development Center  
University of Pittsburgh  
3939 O'Hara Street  
Pittsburgh, PA 15260

Dr. Arthur M. Glenberg  
University of Wisconsin  
W. J. Brogden Psychology Bldg.  
1202 W. Johnson Street  
Madison, WI 53706

Dr. Marvin D. Glock  
13 Stone Hall  
Cornell University  
Ithaca, NY 14853

Dr. Gene L. Gloye  
Office of Naval Research  
Detachment  
1030 E. Green Street  
Pasadena, CA 91106-2485

Dr. Sam Glucksberg  
Department of Psychology  
Princeton University  
Princeton, NJ 08540

Dr. Joseph Goguen  
Computer Science Laboratory  
SRI International  
333 Ravenswood Avenue  
Menlo Park, CA 94025

Dr. Sherrie Gott  
AFHRL/MODJ  
Brooks AFB, TX 78235

Jordan Grafman, Ph.D.  
2021 Lyttonville Road  
Silver Spring, MD 20910

Dr. Richard H. Granger  
Department of Computer Science  
University of California, Irvine  
Irvine, CA 92717

Dr. Wayne Gray  
Army Research Institute  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. James G. Greeno  
University of California  
Berkeley, CA 94720

H. William Greenup  
Education Advisor (E031)  
Education Center, MCDEC  
Quantico, VA 22134

Dipl. Pad. Michael W. Habon  
Universität Dusseldorf  
Erziehungswissenschaftliches  
Universitätsstr. 1  
D-4000 Dusseldorf 1  
WEST GERMANY

Prof. Edward Haertel  
School of Education  
Stanford University  
Stanford, CA 94305

Dr. Henry M. Halff  
Halff Resources, Inc.  
4918 33rd Road, North  
Arlington, VA 22207

Dr. Ronald K. Hambleton  
Prof. of Education & Psychol  
University of Massachusetts  
at Amherst  
Hills House  
Amherst, MA 01003

Dr. Cheryl Hamel  
NTSC  
Orlando, FL 32813

Dr. Bruce W. Hamill  
Johns Hopkins University  
Applied Physics Laboratory  
Johns Hopkins Road  
Laurel, MD 20707

Dr. Ray Hannapel  
Scientific and Engineering  
Personnel and Education  
National Science Foundation  
Washington, DC 20550

Stevan Harnad  
Editor, The Behavioral and  
Brain Sciences  
20 Nassau Street, Suite 240  
Princeton, NJ 08540

Mr. William Hartung  
PEAM Product Manager  
Army Research Institute  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. Wayne Harvey  
SRI International  
333 Ravenswood Ave.  
Room B-S324  
Menlo Park, CA 94025

Dr. Reid Hastie  
Northwestern University  
Department of Psychology  
Evanston, IL 60201

Prof. John R. Hayes  
Carnegie-Mellon University  
Department of Psychology  
Schenley Park  
Pittsburgh, PA 15213

Dr. Barbara Hayes-Roth  
Department of Computer Science  
Stanford University  
Stanford, CA 95305

Dr. Frederick Hayes-Roth  
Teknowledge  
525 University Ave.  
Palo Alto, CA 94301

Dr. Joan I. Heller  
505 Haddon Road  
Oakland, CA 94606

Dr. James Hendler  
Dept. of Computer Science  
University of Maryland  
College Park, MD 20742

Dr. Jim Hollan  
Intelligent Systems Group  
Institute for  
Cognitive Science (C-015)  
UCSD  
La Jolla, CA 92093

Dr. Melissa Holland  
Army Research Institute for  
Behavioral and Social Sci  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. Robert W. Holt  
Department of Psychology  
George Mason University  
4400 University Drive  
Fairfax, VA 22030

Dr. Keith Holyoak  
University of Michigan  
Human Performance Center  
330 Packard Road  
Ann Arbor, MI 48109

Prof. Lutz F. Hornke  
Institut fur Psychologie  
RWTH Aachen  
Jaegerstrasse 17/19  
D-5100 Aachen  
WEST GERMANY

Mr. Dick Hoshaw  
OP-135  
Arlington Annex  
Room 2834  
Washington, DC 20350

Dr. James Howard  
Dept. of Psychology  
Human Performance Laboratory  
Catholic University of  
America  
Washington, DC 20064

Dr. Steven Hunka  
Department of Education  
University of Alberta  
Edmonton, Alberta  
CANADA

Dr. Earl Hunt  
Department of Psychology  
University of Washington  
Seattle, WA 98105

Dr. Ed Hutchins  
Intelligent Systems Group  
Institute for  
Cognitive Science (C-015)  
UCSD  
La Jolla, CA 92093

Dr. Dillon Inouye  
WICAT Education Institute  
Provo, UT 84057

Dr. Alice Isen  
Department of Psychology  
University of Maryland  
Catonsville, MD 21228

Dr. Zachary Jacobson  
Bureau of Management Consulting  
365 Laurier Avenue West  
Ottawa, Ontario K1A 0S5  
CANADA

Dr. Robert Jannarone  
Department of Psychology  
University of South Carolina  
Columbia, SC 29208

Dr. Claude Janvier  
Directeur, CIRADE  
Universite' du Quebec a Montreal  
Montreal, Quebec H3C 3P8  
CANADA

COL Dennis W. Jarvi  
Commander  
AFHRL  
Brooks AFB, TX 78235-5601

Dr. Robin Jeffries  
Hewlett-Packard Laboratories  
P.O. Box 10490  
Palo Alto, CA 94303-0971

Dr. Robert Jernigan  
Decision Resource Systems  
5595 Vantage Point Road  
Columbia, MD 21044

Margaret Jerome  
c/o Dr. Peter Chandler  
83, The Drive  
Hove  
Sussex  
UNITED KINGDOM

Dr. Joseph E. Johnson  
Assistant Dean for  
Graduate Studies  
College of Science and Mathe  
University of South Carolina  
Columbia, SC 29208

Dr. Richard Johnson  
Boise State University  
Simplot/Micron  
Technology Center  
Boise, ID 83725

CDR Tom Jones  
ONR Code 125  
800 N. Quincy Street  
Arlington, VA 22217-5000

Dr. Douglas A. Jones  
P.O. Box 6640  
Lawrenceville  
NJ 08648

Col. Dominique Jouslin de No  
Etat-Major de l'Armee de Ter  
Centre de Relations Humaines  
3 Avenue Octave Greard  
75007 Paris  
FRANCE

Dr. Marcel Just  
Carnegie-Mellon University  
Department of Psychology  
Schenley Park  
Pittsburgh, PA 15213

Dr. Milton S. Katz  
Army Research Institute  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. Scott Keiso  
Haskins Laboratories,  
270 Crown Street  
New Haven, CT 06510

Dr. Dennis Kibler  
University of California  
Department of Information  
and Computer Science  
Irvine, CA 92717

Dr. David Kieras  
University of Michigan  
Technical Communication  
College of Engineering  
1223 E. Engineering Building  
Ann Arbor, MI 48109

Dr. Peter Kincaid  
Training Analysis  
& Evaluation Group  
Department of the Navy  
Orlando, FL 32813

Dr. Walter Kintsch  
Department of Psychology  
University of Colorado  
Campus Box 345  
Boulder, CO 80302

Dr. Paula Kirk  
Oakridge Associated Universities  
University Programs Division  
P.O. Box 117  
Oakridge, TN 37831-0117

Dr. David Klahr  
Carnegie-Mellon University  
Department of Psychology  
Schenley Park  
Pittsburgh, PA 15213

Dr. Mazie Enerr  
Program Manager  
Training Research Division  
NAMESO  
1100 S. Washington  
Alexandria, VA 22314

Dr. Janet L. Kolesner  
Georgia Institute of Technology  
School of Information  
& Computer Science  
Atlanta, GA 30332

Dr. Stephen Kosslyn  
Harvard University  
1236 William James Hall  
33 Kirkland St.  
Cambridge, MA 02138

Dr. Kenneth Kotovsky  
Department of Psychology  
Community College of  
Allegheny County  
800 Allegheny Avenue  
Pittsburgh, PA 15233

Dr. David M. Krantz  
2 Washington Square Village  
Apt. # 15J  
New York, NY 10012

Dr. Benjamin Kuipers  
University of Texas at Austin  
Department of Computer Science  
T.S. Painter Hall 3.28  
Austin, Texas 78712

Dr. David R. Lambert  
Naval Ocean Systems Center  
Code 441T  
271 Catalina Boulevard  
San Diego, CA 92152-6800

Dr. Pat Langley  
University of California  
Department of Information  
and Computer Science  
Irvine, CA 92717

M. Diane Langston  
Communications Design Center  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

Dr. Jill Larkin  
Carnegie-Mellon University  
Department of Psychology  
Pittsburgh, PA 15213

Dr. Robert Lawler  
Information Sciences, FRL  
GTE Laboratories, Inc.  
40 Sylvan Road  
Waltham, MA 02254

Dr. Paul E. Lehner  
PAR Technology Corp.  
7926 Jones Branch Drive  
Suite 170  
McLean, VA 22102

Dr. Alan M. Leopold  
Learning R&D Center  
University of Pittsburgh  
Pittsburgh, PA 15260

Dr. Alan Lechner  
Deputy Division Director  
Behavioral and Neural Sciences  
National Science Foundation  
1800 G Street  
Washington, DC 20550

Dr. Jim Levin  
University of California  
Laboratory for Comparative  
Human Cognition  
D003A  
La Jolla, CA 92093

Dr. John Levine  
Learning R&D Center  
University of Pittsburgh  
Pittsburgh, PA 15260

Dr. Michael Levine  
Educational Psychology  
210 Education Bldg.  
University of Illinois  
Champaign, IL 61801

Dr. Charles Lewis  
Faculteit Sociale Wetenschappen  
Rijksuniversiteit Groningen  
Oude Boteringestraat 23  
9712GC Groningen  
The Netherlands

Dr. Clayton Lewis  
University of Colorado  
Department of Computer Science  
Campus Box 430  
Boulder, CO 80309

Library  
Naval War College  
Newport, RI 02940

Library  
Naval Training Systems Center  
Orlando, FL 32813

Dr. Charlotte Linds  
SRI International  
333 Ravenswood Avenue  
Menlo Park, CA 94025

Dr. Marcia C. Linn  
Lawrence Hall of Science  
University of California  
Berkeley, CA 94720

Dr. Robert Linn  
College of Education  
University of Illinois  
Urbana, IL 61801

Dr. Don Lyon  
P. O. Box 44  
Wigley, AZ 85234

Dr. Jane Malia  
Mail Code 8R 111  
NASA Johnson Space Center  
Houston, TX 77058

Dr. William L. Maloy  
Chief of Naval Education  
and Training  
Naval Air Station  
Pensacola, FL 32508

Dr. Sandra P. Marshall  
Dept. of Psychology  
San Diego State University  
San Diego, CA 92182

Dr. Newton M. Matthews  
Department of Computer Science  
University of South Carolina  
Columbia, SC 29208

Dr. Richard E. Mayer  
Department of Psychology  
University of California  
Santa Barbara, CA 93106

Dr. James McBride  
Psychological Corporation  
c/o Harcourt, Brace,  
Jovanovich Inc  
1250 West 6th Street  
San Diego, CA 92101

Dr. David J. McGuinness  
Gallaudet College  
800 Florida Avenue N.E.  
Washington, DC 20002

Dr. Kathleen McKeown  
Columbia University  
Department of Computer Science  
New York, NY 10027

Dr. Joe McLachlan  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. James McMichael  
Assistant for RPT Research,  
Development, and Studies  
OP 01B7  
Washington, DC 20370

Dr. Barbara Means  
Human Resources  
Research Organization  
1100 South Washington  
Alexandria, VA 22314

Dr. Douglas L. Medin  
Department of Psychology  
University of Illinois  
603 S. Daniel Street  
Champaign, IL 61820

Dr. Arthur Melmed  
U. S. Department of Education  
724 Brown  
Washington, DC 0208

Dr. Jose Mestre  
Department of Physics  
Woburn Laboratory  
University of Massachusetts  
Amherst, MA 01003

Dr. Al Mayrowitz  
Office of Naval Research  
Code 1133  
800 N. Quincy  
Arlington, VA 22211-5000

Dr. Ryszard S. Michalski  
University of Illinois  
Department of Computer Science  
1304 West Springfield Avenue  
Urbana, IL 61801

Prof. D. Michie  
The Turing Institute  
36 North Menover Street  
Glasgow G1 2AD, Scotland  
UNITED KINGDOM

Dr. George A. Miller  
Department of Psychology  
Green Hall  
Princeton University  
Princeton, NJ 08540

Dr. James R. Miller  
NCC  
9430 Research Blvd.  
Schelon Building #1, Suite 2  
Austin, TX 78759

Dr. Mark Miller  
Computer-Thought Corporation  
1721 West Plano Parkway  
Plano, TX 75075

Dr. Andrew R. Molnar  
Scientific and Engineering  
Personnel and Education  
National Science Foundation  
Washington, DC 20550

Dr. William Montague  
NPRC Code 13  
San Diego, CA 92152-6000

Dr. Tom Moran  
NPRC  
1333 Coyote Hill Road  
Palo Alto, CA 94304

Dr. Melvyn May  
Navy Personnel R & D Center  
San Diego, CA 92152-6000

Dr. Allen Munro  
Behavioral Technology  
Laboratories - USC  
1045 S. Elms Ave., 4th Floor  
Redondo Beach, CA 90277

Director,  
Decision Support  
Systems Division, NMFPC  
Naval Military Personnel Command  
M-164  
Washington, DC 20370

Director,  
Distribution Department, NMFPC  
M-4  
Washington, DC 20370

Director,  
Overseas Duty Support  
Program, NMFPC  
M-62  
Washington, DC 20370

Head, NFM Operations Branch,  
NMFPC  
M-62F  
Washington, DC 20370

Assistant for Evaluation,  
Analysis, and MIS, NMFPC  
M-6C  
Washington, DC 20370

Spec. Asst. for Research, Experi-  
mental & Academic Programs,  
NFTC (Code 016)  
NAB Memphis (75)  
Harrison, TN 38054

Director,  
Research & Analysis Div.,  
NAVCNUTCOM Code 22  
4015 Wilson Blvd.  
Arlington, VA 22203

Technical Director  
Navy Health Research Center  
P.O. Box 05122  
San Diego, CA 92138

Leadership Management Educat  
and Training Project Offi  
Naval Medical Command  
Code 05C  
Washington, DC 20372

Technical Director,  
Navy Health Research Ctr.  
P.O. Box 05122  
San Diego, CA 92138

Dr. T. Niblett  
The Turing Institute  
36 North Manover Street  
Glasgow G1 2AD, Scotland  
UNITED KINGDOM

Dr. Richard E. Nisbett  
University of Michigan  
Institute for Social Research  
Room 5261  
Ann Arbor, MI 48109

Dr. Mary Jo Nissen  
University of Minnesota  
#218 Elliott Hall  
Minneapolis, MN 55455

Dr. Donald A. Norman  
Institute for Cognitive Scie  
University of California  
La Jolla, CA 92093

Director, Training Laborator  
NPRC (Code 05)  
San Diego, CA 92152-6000

Director, Manpower and Perso  
Laboratory,  
NPRC (Code 06)  
San Diego, CA 92152-6000

Director, Human Factors  
& Organizational Systems  
NPRC (Code 07)  
San Diego, CA 92152-6000

Fleet Support Office,  
NPRC (Code 301)  
San Diego, CA 92152-6000

Library, NPRC  
Code P201L  
San Diego, CA 92152-6000

Commanding Officer,  
Naval Research Laboratory  
Code 2627  
Washington, DC 20390

Dr. Harold F. O'Neil, Jr.  
School of Education - NFM 801  
Department of Educational  
Psychology & Technology  
University of Southern California  
Los Angeles, CA 90089-0031

Dr. Stellan Ohlsson  
Learning R & D Center  
University of Pittsburgh  
3939 O'Hara Street  
Pittsburgh, PA 15213

Director, Research Programs,  
Office of Naval Research  
800 North Quincy Street  
Arlington, VA 22217-5000

Office of Naval Research,  
Code 1133  
800 N. Quincy Street  
Arlington, VA 22217-5000

Office of Naval Research,  
Code 1142  
800 N. Quincy St.  
Arlington, VA 22217-5000

Office of Naval Research,  
Code 1142EP  
800 N. Quincy Street  
Arlington, VA 22217-5000

Office of Naval Research,  
Code 1142PT  
800 N. Quincy Street  
Arlington, VA 22217-5000  
(6 Copies)

Director, Technology Programs,  
Office of Naval Research  
Code 12  
800 North Quincy Street  
Arlington, VA 22217-5000

Special Assistant for Marine  
Corps Matters,  
OMR Code 00MC  
800 N. Quincy St.  
Arlington, VA 22217-5000

Assistant for Long Range  
Requirements,  
CNO Executive Panel  
OP 00K  
2000 North Beauregard Street  
Alexandria, VA 22311

Assistant for MPT Research,  
Development and Studies  
OP 01B7  
Washington, DC 20370

Dr. Judith Orasanu  
Army Research Institute  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. Jesse Orlansky  
Institute for Defense Analys  
1801 N. Beauregard St.  
Alexandria, VA 22311

Prof. Seymour Papert  
20C-109  
Massachusetts Institute  
of Technology  
Cambridge, MA 02139

CDR R. T. Parlette  
Chief of Naval Operations  
OP-112G  
Washington, DC 20370-2000

Dr. James Paulson  
Department of Psychology  
Portland State University  
P.O. Box 751  
Portland, OR 97207

Dr. Douglas Pearce  
DCIEM  
Box 2000  
Downsview, Ontario  
CANADA

Dr. Virginia E. Pendergrass  
Code 711  
Naval Training Systems Center  
Orlando, FL 32813-7100

Dr. Robert Penn  
NPRDC  
San Diego, CA 92152-6800

Dr. Nancy Pennington  
University of Chicago  
Graduate School of Business  
1101 E. 58th St.  
Chicago, IL 60637

Military Assistant for Training and  
Personnel Technology,  
OUSD (R & E)  
Room 3D129, The Pentagon  
Washington, DC 20301-3080

Dr. Ray Perez  
ARI (PERI-II)  
5001 Eisenhower Avenue  
Alexandria, VA 2233

Dr. David N. Perkins  
Educational Technology Center  
337 Gutman Library  
Appian Way  
Cambridge, MA 02138

LCDR Frank C. Petho, MSC, USN  
CNATRA Code N36, Bldg. 1  
NAS  
Corpus Christi, TX 78419

Administrative Sciences Department,  
Naval Postgraduate School  
Monterey, CA 93940

Department of Computer Science,  
Naval Postgraduate School  
Monterey, CA 93940

Department of Operations Research,  
Naval Postgraduate School  
Monterey, CA 93940

Dr. Tjeerd Plomp  
Twente University of Technol  
Department of Education  
P.O. Box 217  
7500 AE ENSCHEDE

#### THE NETHERLANDS

Dr. Martha Polson  
Department of Psychology  
Campus Box 346  
University of Colorado  
Boulder, CO 80309

Dr. Peter Polson  
University of Colorado  
Department of Psychology  
Boulder, CO 80309

Dr. Steven E. Poltrock  
MCC  
9430 Research Blvd.  
Echelon Bldg #1  
Austin, TX 78759-6509

Dr. Harry E. Pople  
University of Pittsburgh  
Decision Systems Laboratory  
1360 Scaife Hall  
Pittsburgh, PA 15261

Dr. Mary C. Potter  
Department of Psychology  
MIT (E-10-032)  
Cambridge, MA 02139

Dr. Joseph Psotka  
ATTN: PERI-1C  
Army Research Institute  
5001 Eisenhower Ave.  
Alexandria, VA 22333

Dr. Roy Rada  
National Library of Medicine  
Bethesda, MD 20894

Dr. Lynne Reder  
Department of Psychology  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

Brian Reiser  
Department of Psychology  
Princeton University  
Princeton, NJ 08544

Dr. James A. Reggia  
University of Maryland  
School of Medicine  
Department of Neurology  
22 South Greene Street  
Baltimore, MD 21201

CDR Karen Reider  
Naval School of Health Sciences  
National Naval Medical Center  
Bldg. 141  
Washington, DC 20814

Dr. Fred Reif  
Physics Department  
University of California  
Berkeley, CA 94720

Dr. Lauren Resnick  
Learning R & D Center  
University of Pittsburgh  
3939 O'Hara Street  
Pittsburgh, PA 15213

Dr. Mary S. Riley  
Program in Cognitive Science  
Center for Human Information  
Processing  
University of California  
La Jolla, CA 92093

William Rizzo  
Code 712  
Naval Training Systems Center  
Orlando, FL 32813

Dr. Linda G. Roberts  
Science, Education, and  
Transportation Program  
Office of Technology Assessment  
Congress of the United States  
Washington, DC 20510

Dr. Andrew M. Rose  
American Institutes  
for Research  
1055 Thomas Jefferson St., NW  
Washington, DC 20007

Dr. William B. Rouse  
Search Technology, Inc.  
25-b Technology Park/Atlanta  
Norcross, GA 30092

Dr. Donald Rubin  
Statistics Department  
Science Center, Room 608  
1 Oxford Street  
Harvard University  
Cambridge, MA 02138

Dr. David Rumelhart  
Center for Human  
Information Processing  
Univ. of California  
La Jolla, CA 92093

Ms. Riitta Ruotsalainen  
General Headquarters  
Training Section  
Military Psychology Office  
PL 919  
SF-00101 Helsinki 10, FINLAN

Dr. Michael J. Samet  
Perceptronics, Inc  
6271 Variel Avenue  
Woodland Hills, CA 91364

Dr. Roger Schank  
Yale University  
Computer Science Department  
P.O. Box 2158  
New Haven, CT 06520

Dr. W. L. Scherlis  
Dept. of Computer Science  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

Mrs. Birgitte Schneideibach  
Forsvarets Center for Leders  
Christianshavns Voldgade 8  
1424 Kobenhavn K  
DENMARK

Dr. Walter Schneider  
Learning R&D Center  
University of Pittsburgh  
3939 O'Hara Street  
Pittsburgh, PA 15260

Dr. Alan H. Schoenfeld  
University of California  
Department of Education  
Berkeley, CA 94720

Dr. Janet Schofield  
Learning R&D Center  
University of Pittsburgh  
Pittsburgh, PA 15260

Dr. Marc Sebrechts  
Department of Psychology  
Wesleyan University  
Middletown, CT 06475

Dr. Judith Segal  
OERI  
555 New Jersey Ave., NW  
Washington, DC 20208

Dr. Robert J. Seidel  
US Army Research Institute  
5001 Eisenhower Ave.  
Alexandria, VA 22333

Dr. Ramsey W. Seiden  
Assessment Center  
CCSSO  
Suite 379  
400 N. Capitol, NW  
Washington, DC 20001

Dr. W. Steve Sellman  
OASD(MRA&L)  
2B269 The Pentagon  
Washington, DC 20301

Dr. Sylvia A. S. Shafto  
OERI  
555 New Jersey Ave., NW  
Washington, DC 20208

Dr. T. B. Sheridan  
Dept. of Mechanical Engineering  
MIT  
Cambridge, MA 02139

Dr. Ben Shneiderman  
Dept. of Computer Science  
University of Maryland  
College Park, MD 20742

Dr. Ted Shortliffe  
Computer Science Department  
Stanford University  
Stanford, CA 94305

Dr. Lee Shulman  
Stanford University  
1040 Cathcart Way  
Stanford, CA 94305

Dr. Randall Shumaker  
Naval Research Laboratory  
Code 7510  
4555 Overlook Avenue, S.W.  
Washington, DC 20375-5000

Dr. Robert S. Siegler  
Carnegie-Mellon University  
Department of Psychology  
Schenley Park  
Pittsburgh, PA 15213

Dr. Herbert A. Simon  
Department of Psychology  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

LTCOL Robert Simpson  
Defense Advanced Research  
Projects Administration  
1400 Wilson Blvd.  
Arlington, VA 22209

Dr. Zita M Simutis  
Instructional Technology  
Systems Area  
ARI  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. H. Wallace Sinaiko  
Manpower Research  
and Advisory Services  
Smithsonian Institution  
801 North Pitt Street  
Alexandria, VA 22314

Dr. Derek Sleeman  
Stanford University  
School of Education  
Stanford, CA 94305

Dr. Charles F. Smith  
North Carolina State University  
Department of Statistics  
Raleigh, NC 27695-8703

Dr. Edward E. Smith  
Bolt Beranek & Newman, Inc.  
50 Moulton Street  
Cambridge, MA 02138

Dr. Linda B. Smith  
Department of Psychology  
Indiana University  
Bloomington, IN 47405

Dr. Alfred F. Snode  
Senior Scientist  
Code 07A  
Naval Training Systems Center  
Orlando, FL 32813

Dr. Richard E. Snow  
Department of Psychology  
Stanford University  
Stanford, CA 94306

Dr. Elliot Soloway  
Yale University  
Computer Science Department  
P.O. Box 2158  
New Haven, CT 06520

Dr. Richard Sorensen  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Kathryn T. Spoehr  
Brown University  
Department of Psychology  
Providence, RI 02912

James J. Staszewski  
Research Associate  
Carnegie-Mellon University  
Department of Psychology  
Schenley Park  
Pittsburgh, PA 15213

Dr. Marian Stearns  
SRI International  
333 Ravenswood Ave.  
Room B-S324  
Menlo Park, CA 94025

Dr. Robert Sternberg  
Department of Psychology  
Yale University  
Box 11A, Yale Station  
New Haven, CT 06520

Dr. Albert Stevens  
Bolt Beranek & Newman, Inc.  
10 Moulton St.  
Cambridge, MA 02238

Dr. Paul J. Sticha  
Senior Staff Scientist  
Training Research Division  
HumRRO  
1100 S. Washington  
Alexandria, VA 22314

Dr. Thomas Sticht  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. David Stone  
KAJ Software, Inc.  
3420 East Shea Blvd.  
Suite 161  
Phoenix, AZ 85028

Cdr Michael Suman, PD 303  
Naval Training Systems Center  
Code N51, Comptroller  
Orlando, FL 32813

Dr. Hariharan Swaminathan  
Laboratory of Psychometric &  
Evaluation Research  
School of Education  
University of Massachusetts  
Amherst, MA 01003

Mr. Brad Sympson  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. John Tangney  
AFOSR/NL  
Bolling AFB, DC 20332

Dr. Kikumi Tatsuoka  
CERL  
252 Engineering Research  
Laboratory  
Urbana, IL 61801

Dr. Martin M. Taylor  
DCIEM  
Box 2000  
Downsview, Ontario  
CANADA

Dr. Perry W. Thorndyke  
FMC Corporation  
Central Engineering Labs  
1185 Coleman Avenue, Box 580  
Santa Clara, CA 95052

Major Jack Thorpe  
DARPA  
1400 Wilson Blvd.  
Arlington, VA 22209

Dr. Douglas Towne  
Behavioral Technology Labs  
1845 S. Elena Ave.  
Redondo Beach, CA 90277

Dr. Amos Tversky  
Stanford University  
Dept. of Psychology  
Stanford, CA 94305

Dr. James Tweeddale  
Technical Director  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Paul Twohig  
Army Research Institute  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Headquarters, U. S. Marine Corps  
Code MPI-20  
Washington, DC 20380

Dr. Kurt Van Lehn  
Department of Psychology  
Carnegie-Mellon University  
Schenley Park  
Pittsburgh, PA 15213

Dr. Beth Warren  
Bolt Beranek & Newman, Inc.  
50 Moulton Street  
Cambridge, MA 02138

Dr. David J. Weiss  
N660 Elliott Hall  
University of Minnesota  
75 E. River Road  
Minneapolis, MN 55455

Roger Weissinger-Baylon  
Department of Administrative  
Sciences  
Naval Postgraduate School  
Monterey, CA 93940

Dr. Donald Weitzman  
MITRE  
1820 Dolley Madison Blvd.  
MacLean, VA 22102

Dr. Keith T. Wescourt  
FMC Corporation  
Central Engineering Labs  
1185 Coleman Ave., Box 580  
Santa Clara, CA 95052

Dr. Joseph L. Young  
Memory & Cognitive  
Processes  
National Science Foundation  
Washington, DC 20550

Dr. Douglas Wetzel  
Code 12  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Steven Zornetzer  
Office of Naval Research  
Code 1140  
800 N. Quincy St.  
Arlington, VA 22217-5000

Dr. Barbara White  
Bolt Beranek & Newman, Inc.  
10 Moulton Street  
Cambridge, MA 02238

Dr. Michael J. Zyda  
Naval Postgraduate School  
Code 52CK  
Monterey, CA 93943-5100

LCDR Cory deGroot Whitehead  
Chief of Naval Operations  
OP-112G1  
Washington, DC 20370-2000

Dr. Michael Williams  
IntelliCorp  
1975 El Camino Real West  
Mountain View, CA 94040-2216

Dr. Hilda Wing  
Army Research Institute  
5001 Eisenhower Ave.  
Alexandria, VA 22333

A. E. Winterbauer  
Research Associate  
Electronics Division  
Denver Research Institute  
University Park  
Denver, CO 80208-0454

Dr. Robert A. Wisher  
U.S. Army Institute for the  
Behavioral and Social Sciences  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Dr. Martin F. Wiskoff  
Navy Personnel R & D Center  
San Diego, CA 92152-6800

Dr. Merlin C. Wittrock  
Graduate School of Education  
UCLA  
Los Angeles, CA 90024

Mr. John H. Wolfe  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Wallace Wulfeck, III  
Navy Personnel R&D Center  
San Diego, CA 92152-6800

Dr. Joe Yasatuke  
AFHRL/LRT  
Lowry AFB, CO 80230

Dr. Masoud Yazdani  
Dept. of Computer Science  
University of Exeter  
Exeter EX4 4QL  
Devon, ENGLAND

Major Frank Yohannan, USMC  
Headquarters, Marine Corps  
(Code MPI-20)  
Washington, DC 20380

Mr. Carl York  
System Development Foundation  
181 Lytton Avenue  
Suite 210  
Palo Alto, CA 94301

END

FEB.

1988

DTIC