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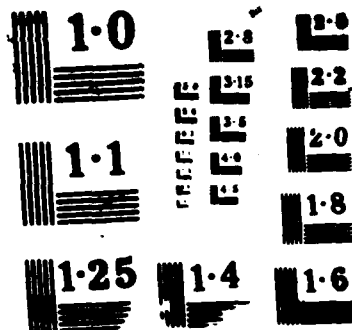
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Generative Processes in Representations of Problems

James G. Greeno

University of California, Berkeley

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Generative Processes in Representations of Problems

James G. Greeno

University of California, Berkeley

ABSTRACT

This project addressed the question: What knowledge and processes enable individuals to construct and modify representations of novel, nonroutine problems? The theoretical goal was to extend the information-processing theory of problem solving to include processes that have been characterized as restructuring of problems and productive thinking by Gestalt psychologists such as Duncker (1935/1945) and Wertheimer. (1945/1959).

Three lines of research were carried out. One investigated different kinds of knowledge that result in problems that are routine, semiroutine, or nonroutine, according to distinctions in a simulation model that was developed in the project. Experiments distinguished between functional knowledge, involving relations between components of a device, and component knowledge, involving information about behavior of components independent of their interconnections. A second line of work studied processes of generating representations of physics problems, and identified important interactions between everyday experience-based knowledge about motions of objects and knowledge of theoretical principles. The third line of research studied processes of understanding and solution of back-of-the-envelope problems, and identified use of general methods for reasoning about quantities that are combined with domain-specific information.

This project investigated knowledge that supports the generation of representations in problem situations. In an earlier period of research, Gestalt psychologists who studied problem solving emphasized processes of reformulating and restructuring problem representations. In tasks studied by Duncker (1935/1945), Wertheimer (1945/1959), and others, the main requirement of solving problems is achieving an adequate understanding of the problem, and when that is achieved, solution of the problem requires very little search or other further effort.

The research in this project extended current theories of problem solving to account for some generative aspects of the representation of problems. The theory of problem solving, developed by Newell and Simon (1972) and others, and reviewed by Greeno and Simon (in press), largely concerns knowledge for application of known operators and search for solutions in a problem space. Problem solvers also must construct the problem spaces in which they work, and processes of understanding routine problems have been studied and simulated by Hall, Kibler, Wenger, and Truxaw (1986), by Hayes and Simon (1974), by Kintsch and Greeno (1985), and by Novak (1975), among others. The present research concerned representation of problems when the initial representation is not adequate to support solution by application and search involving known operators.

The project was begun in March, 1984, at the University of Pittsburgh, in collaboration with Lauren Resnick. Two lines of research were included in the project: study of restructuring in insight problems of the kind investigated earlier by Gestalt psychologists, and restructuring of representations in intuitive physics. We began working on tasks involving the motion of a pendulum, a device that has been used both in insight problems (Maier, 1931) and in intuitive physics (Caramazza, McCloskey, & Green, 1981). Michael Ranney conducted preliminary protocol studies on the naive physics task of predicting what will happen if the bob of a pendulum is disengaged at different positions as it is swinging; Ranney has continued on this problem and has completed his dissertation at Pittsburgh based on the work that he continued subsequently.

In the fall of 1984 Greeno moved to Berkeley and continued working on the project with new staff and graduate students who joined the project. Research was conducted on three specific questions: (1) knowledge required for representing and solving different kinds of problems, with problems involving reformulation as one of the categories; (2) knowledge and processes of experienced physicists used in developing mental models to represent novel problems; and (3) knowledge and processes used in representing and reasoning in informal "back-of-the-envelope" problems that involve estimation of quantities.

1. Knowledge for different kinds of problems

Greeno and Daniel Berger have developed a characterization of knowledge needed for solution of different kinds of problems. The task they addressed initially was development of a model that would simulate knowledge involved in solving traditional "insight" problems, such as the candle problem (Duncker, 1935/1945) or the two-string problem (Maier, 1931). The model they developed is a generalization of a model of the candle problem that Weisberg and Suls (1973) developed earlier, and the extensive empirical tests that Weisberg and Suls conducted lend considerable plausibility to the general features of the model for the class of problems involving insightful reformulation.

While Weisberg and Suls developed a specific model for the candle problem, Greeno and Berger developed a general characterization of levels of knowledge used in different stages of solving problems that involve insightful restructuring. The levels of knowledge are examples of strong, medium, and weak methods, in Newell's (1980) sense. The most specific knowledge is knowledge of procedures. Procedures have conditions of applicability and actions that change the situation, leading to a solution. A second level of knowledge is functional knowledge, which includes knowledge of the consequences and requisite conditions for performing actions or using objects. Functional knowledge is the kind of knowledge used in systems for planning, including Sacerdoti's (1977) and other subsequent planners.

We say that a problem is routine or semiroutine for a problem solver if the problem solver's knowledge of procedures and functional knowledge are sufficient to solve the problem. These categories of problems include problems that are solved within a single problem space, as this was characterized by Newell and Simon (1972). By this criterion, routine problems include exercises in arithmetic, where instructions specify the operation to be performed. Exercises such as geometry proofs and other similar problems in school mathematics and science are semiroutine, requiring functional knowledge that is organized according to planning schemata (e.g., Greeno, Magone, & Chaiklin, 1979). Puzzles that are solved by means-ends analysis or other search heuristics are also semiroutine, involving selection of known operators to achieve definite goals.

Greeno and Berger characterized as nonroutine problems tasks in which the problem solver's knowledge of procedures and functional knowledge are insufficient to solve the problem. In many of the insight problems studied by Gestalt psychologists the required new material involves inferring a possible function for an object that is not stored as functional knowledge in the person's memory. The potential use of the object therefore has to be discovered through a deeper inference than is the case when functional knowledge is adequate. For example, in the candle problem, functions of support and fastening are probably associated with many of the objects in the situation, such as string and tacks, but not with the box. The potential function of the box as a support has to be inferred from its properties -- its flatness, stability, and so on.

In the terms of Greeno and Berger's analysis, new functional knowledge has to be generated by the problem solver in order to solve the problem. This terminology is consistent with Duncker's (1935/1945) discussion, which emphasized modifying the problem space by finding new functional relations. Another way to state the idea is that insight problems require the creation of new problem-solving operators that augment the problem space, which shows how this notion extends Newell and Simon's (1972) theory of problem solving.

Greeno and Berger have implemented programs that simulate solution of nonroutine problems, providing evidence for the sufficiency of their hypotheses. A more interesting question is whether the distinctions in their theory of knowledge requirements for different kinds of problems correspond to significant distinctions between the knowledge of different human problem solvers that influence their success in problem solving. This question has been pursued in two experiments. The first is completed, and the second is currently being conducted.

The experiments on knowledge for problem solving are related to studies by Kieras and Bovair (1984) who have investigated the influence of knowledge that they call a "device model" on capabilities of subjects to learn to operate a fictitious machine. Greeno and Berger invented a device that has components like those of a standard stereo system, but is disguised as a vehicle with alternative sources of energy. The use of a fictitious device enables us to give subjects specific kinds of background knowledge and examine the effect of that knowledge on their ability to solve problems or to learn procedures for operating the device. Components of the device are displayed on a computer screen, with displayed switches that can be set using the screen interface. Subjects solve problems by producing switch settings that cause components to be in different states and that produce internal connections among the components.

Our first experiment replicated and refined a result of Kieras and Bovair (1984), which showed that knowledge of a device model can facilitate learning and inference of procedures for operating the device. We refined Kieras and Bovair's concept of a device model, using a distinction introduced by deKleer and Brown (1981) between two kinds of knowledge about a device. One kind of knowledge involves information about the components of a device, including the states that each component can be in and the operations that control those states. The other kind of knowledge involves information about the interconnections and interactions among components. DeKleer and Brown called these structural and functional

knowledge, respectively. We retain the term "functional" for information about the relations among components, but use the term "component" to refer to information about the behavior of individual components, that can be stated independently of their interconnections in a device.

Greeno and Berger's analysis agrees with conclusions of Kieras and Bovair (1984), that functional information should play a more important role than information about individual components in allowing subjects to understand the operation of a device. Knowledge of functions provides a framework for planning the solutions of problems, requiring inferences about states of individual components. Knowledge about the states of components can also be helpful in understanding the operation of a device, but that knowledge does not provide the cause-effect connections that correspond to problem-solving operators. Those connections have to be inferred to expand the problem space needed to plan solutions of problems.

This conjecture was tested by giving different groups of subjects (a) information about behavior of components, (b) functional information, (c) neither component nor functional information, and (d) both component and functional information, respectively, as background for learning procedures for operating the fictitious device. Subjects with background knowledge were then given problems to solve, in which they were asked to set switches so that the device would operate using its different energy sources. Some of the switches determined states of individual components, and these switches were discussed in the component instruction. Other switches determined connections between components, and these switches were discussed in the functional instruction. All subjects received training showing the combinations of switch settings for operating the device in its various states, a transfer problem was given, and two of the trained problems were presented again for recall.

Knowledge for solving the problems could be in the form of schemata that associate requirements for components and for setting states of components with goals of operation of the device. For example, for the device to operate, power must be transmitted to the motor, requiring a connection to the motor from a component called the impulse purifier, and a

connection to the impulse purifier from the energy source that is specified in the problem. These requirements are achieved by setting switches that determine connections between the various components. There are other requirements involving the states of the motor, the impulse purifier, and the energy source that are achieved by setting different switches.

Information given in the functional instruction could be used to form schemata for forming subgoals involving flow of power and connections between components. Subjects given functional instruction but not component instruction would need to infer requirements involving states of components and infer or learn the switch settings that were needed to determine those states.

Information given in the component instruction could be used to form schemata for achieving goals involving states of the components. Subjects with component instruction but not functional instruction would need to infer the requirements involving connections between components and infer or learn the switch settings that determined the connections.

Kieras and Bovair (1984) concluded that the concept of power flow and knowledge about connections between components are the main requirements for understanding operating procedures of a device like the one used in these studies. Greeno and Berger agree, and the information in the functional instruction provides a version of that relevant knowledge. The schemata that subjects could form on the basis of the functional instruction relates directly to the general goals that are specified in problems, and requires inference of lower-level requirements. Using information in the component instruction, subjects are required to infer the functional interconnections among components of the device, which seems harder than inferences about the individual states.

The results confirmed Greeno and Berger's expectation. Knowledge about interactions among components was sufficient for subjects to infer significant portions of the procedures for operating the device, so that subjects with functional information were able to solve problems

on the basis of their background knowledge without specific training and were able to transfer to a new problem after they received training on another set of problems. In contrast, knowledge about the individual components was virtually ineffective, causing small and mainly insignificant differences either in combination with functional information (comparing the group with both functional and component information with functional information alone) or in isolation (comparing component information with no background).

The experiment that is now being conducted extends the investigation of effects of having a device model from tasks of learning operating procedures to tasks of diagnostic reasoning. Knowledge for diagnostic reasoning has been characterized in intelligent tutoring systems (Brown, Burton & deKleer, 1982). These characterizations include knowledge of the states that components can be in, including fault states.

We found in our first experiment that subjects who were given functional knowledge were able to infer structural information in tasks involving operation of a device. The question arises, then, whether component knowledge is an important factor in diagnostic tasks, or whether appropriate functional knowledge is a sufficient basis for inferring the more complex component information required for those tasks as well. Our current experiment investigates that question.

To investigate diagnostic reasoning, we have designed a more complicated version of the fictitious device that we used in our first study. The diagnostic problems that we designed using the initial version seemed easy to solve based on functional knowledge, but we want to apply a stronger test of the hypothesis that functional knowledge is sufficient. The initial version of the device had only one level of components, because knowledge of the internal structure of components is irrelevant for operating the device when it works properly. However, knowledge of the internal structures of components is relevant for diagnosis, if the task is to identify which part of a component needs to be replaced.

In redesigning the device for our next experiment, we were assisted by Douglas Towne and Allen Munroe, of the Behavioral Technology Laboratory. Towne and Munroe are developing a system, the Intelligent Maintenance Training System (IMTS), that enables a device to be designed using screen icons and specifications of component behaviors, including behaviors in fault states. Berger visited at BTL and consulted with their programmers in developing the current version of our display, and we are using programs supplied by BTL in our current experiment.

2. Generating mental models of physics problem situations

A second line of work begun when Greeno moved to Berkeley is a study of processes used by experienced physicists in generating representations of problem situations. Jeremy Roschelle and Greeno have conducted a study and analysis of performance in tasks designed to obtain information about generative processes. In one study, diagrams were shown to experienced physicists who were asked the open-ended question, "What's happening?" In another study, problems were presented in different forms, including a form with concrete objects, such as blocks and pulleys, and another form with abstract objects, such as masses and forces. The empirical work was conducted by Roschelle, and Roschelle and Greeno collaborated on a theoretical analysis of the findings.

Roschelle's findings present a quite different picture of expert reasoning than has been indicated by earlier studies such as Chi, Feltovich and Glaser's (1981), and Larkin's (1983). In some previous studies, performance on routine problems has led to a conclusion that novices represent problems mainly in terms of concrete objects and apply formulas whose variables correspond to abstract terms. In contrast, experts apparently apply schematic structures of abstract variables organized according to theoretical principles such as conservation of energy.

The experienced physicists in Roschelle's study generated representations using a more subtle combination of processes. The protocols for the question "What's happening?" described systems of objects and referred to images of moving objects as well as to theoretical concepts such as forces due to friction. In his experiment using different diagrams, Roschelle found that the representations of experienced subjects were strongly influenced by the concrete objects in the diagrams. This is contrary to expectations based on the idea that experts match abstract schemata to the components of a problem, because the abstract structures of problems were the same in cases that were represented differently because of the concrete objects.

An interpretation of the results of Roschelle's analysis has been developed by Roschelle and Greeno. The findings are the basis of a model of problem representation in which a mental model of the problem situation is generated by the problem solver. The process of forming the mental model includes parsing the components of the diagram into systems that function as units and creating an envisionment by applying qualitative causal knowledge to generate images of objects in motion. This part of the process is similar to the one described by deKleer (1979) in his model NEWTON. The process also uses knowledge of general principles that constrain the situation by known invariances or qualitative dependencies (e.g., "friction opposes relative motion," or "if velocity is constant the forces are balanced").

In Roschelle and Greeno's interpretation, the process of forming a mental model uses informal knowledge to parse the situation into functional systems and to create envisionments of objects in motion. The knowledge base for this process is assumed to be a set of "pieces" of knowledge, including small schemata that recognize configurations of objects (e.g., two blocks connected by a string that passes over a pulley) and generate simple motions of systems based on causes such as gravity. These informal knowledge pieces apply at the level of objects, and are similar to "phenomenological primitives" that diSessa (1983) has discussed. The model

includes theoretical concepts that are added to the representation, such as forces and accelerations, and knowledge about these concepts is used to overcome ambiguities and impasses (e.g., if forces are balanced, velocity is constant). An important constraint is that the theoretical components of the representation and the object-level components are kept consistent (e.g., if an object moves in one direction, there cannot be an unopposed force in the opposite direction).

The interaction of informal, piecemeal knowledge with knowledge of theoretical concepts has not been a salient feature of previous analyses. It clearly simplifies the situation to say that novices depend on surface features and experts use theoretical concepts. Roschelle and Greeno's hypothesis begins to show how knowledge at various levels of abstraction can interact in the development of an integrated representation. It also has the advantage of describing a system that could be acquired cumulatively, with knowledge of theoretical concepts added to knowledge that is related directly to objects that are experienced, rather than constituting a relatively disconnected structure of knowledge.

3. Reasoning based on general knowledge and methods

A third study conducted in this project investigated reasoning in tasks known as "back-of-the-envelope" problems. Joyce Moore asked question such as the following:

How many leaves fall in North America in a year?

Fueled only by a 2-ounce chocolate bar, how high could you climb, assuming that you convert energy with 40% efficiency?

At what distance would it be faster to send data by a bicycle rider carrying a reel of magnetic tape than to transmit it across a 1200-baud line?

Moore gave problems like these to graduate students in three fields: computer science, physics, and psychology.

The data provide useful information about two processes: informal estimation and the use of general methods of quantitative inference. The methods of quantitative inference are like those used by Larkin, Reif, Carbonnell, and Gugliotta (1985) in their model of expert physics problem-solving called FERMI. These methods provide ways of inferring quantities from other quantities using relations such as additive composition, decomposition into subsets specified by proportions of the whole, and multiplication of rates by quantities. Problem solving by Moore's subjects involve relating the unknown quantity to others, either smaller parts or a larger quantity that contains the unknown, or some other related quantity that can be compared to the unknown. A sequence of these relations was formed, using the general quantitative methods, until a quantity was reached that the problem solver either knew or could judge, at least roughly. These judgments were often very approximate -- for example, estimating the number of leaves on a typical tree by estimating the size of the pile of leaves that would fall from a typical tree (presumably from raking experience) and judging the number of leaves in that pile from the number of layers of leaves that would compose the pile and the number of leaves in a layer from the area of the pile and the size of a typical leaf.

One important conclusion from Moore's study is that the kind of reasoning methods in the FERMI model are not limited to use by problem solvers who are expert in a domain. Most of the problems were solved with similar methods by subjects whether they did or did not have advanced knowledge in the domain of the problem. Knowledge in the domain provided problem solvers with specific knowledge required for estimating quantities and provided some knowledge of specific relations among quantities. In a few cases, problem solvers used formulas that they knew in the domain, but this was rare. Primarily, problem solvers by experts as well as nonexperts in the domain used the same informal general methods for setting subgoals and making inferences about quantities.

4. Reports

Technical reports have been written that report each of the three projects that are summarized in this report. The reports are:

Greeno, J. G., & Berger, D. (1987). *A model of functional knowledge and insight*. Berkeley, CA: University of California, Berkeley, School of Education.

Moore, J. L. (1987). *Back-of-the-envelope problems*. Berkeley, CA: University of California, Berkeley, School of Education.

Roschelle, J. & Greeno, J. G. (1987). *Mental models in physics reasoning*. Berkeley, CA: University of California, Berkeley, School of Education.

A paper based on Greeno and Berger's report was presented at the meeting of the Psychonomic Society in New Orleans, LA, in November, 1986, and a paper based on Roschelle and Greeno's report was presented at the meeting of the Cognitive Science Society in Seattle, WA, in July, 1987.

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Dr. Phillip L. Ackerman
University of Minnesota
Department of Psychology
Minneapolis, MN 55455

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

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

Dr. Beth Adelson
Department of Computer Science
Tufts University
Medford, MA 02155

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

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

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

prof. dott. Bruno G. Bara
Unita di ricerca di intelligenza artificiale
Universita di Milano
20122 Milano - via F Sforza 23 ITALY

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

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

Dr. William M. Bart
Dept. of Ed. Psych., 330 Burton Hall
178 Pillsbury Dr., S.E.
Minneapolis, MN 55455

Dr. Shirley Brice Heath
School of Education
Stanford University
Stanford, CA 94305

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

Leo Beltracchi
U. S. Nuclear Regulatory Comm.
Washington, DC 20555

Dr. John S. Brown
XEROX Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, CA 94304

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

Dr. Mark H. Bickhard
University of Texas
EDB 504 Ed. Psych
Austin, TX 78712

Dr. Ann Brown
Ctr for the Study of Reading
51 Gerty Drive, Univ of Illinois
Champaign, IL 61820

Dr. James Anderson
Brown University
Center for Neural Science
Providence, RI 02912

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

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

Dr. Steve Andriole
George Mason U/Info Tech & Eng
4400 University Dr.
Fairfax, VA 22030

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

Maj. Hugh Burns
AFHRL/IDE
Lowry AFB, CO 80230-5000

Dr. Gary Aston-Jones
Dept. of Biology, N.Y.U.
1009 Main Bldg., Washington Sq.
New York, NY 10003

Dr. R. Darrell Bock
University of Chicago, NORC
6030 South Ellis
Chicago, IL 60637

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

Dr. Patricia Baggett
Dept. of Psych., Box 345
University of Colorado
Boulder, CO 80309

Dr. Sue Bogner
Army Research Institute, (PERI-SF)
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Joseph C. Campione
Ctr. for the Study of Reading
51 Gerty Dr., Univ. of Illinois
Champaign, IL 61820

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

Chair, Dept of Psych
Georgetown University
Washington, DC 20057

Dr. Charles Clifton
Dept of Psych, Tobin Hall
University of Massachusetts
Amherst, MA 01003

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

Chair, Dept of Psych
George Mason University
Fairfax, VA 22030

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

Dr. Susan Carey
Harvard Grad. School of Ed.
337 Gutman Library, Appian Way
Cambridge, MA 02138

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

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

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

Dr. Davida Charney
English Department
Penn State University
University Park, PA 16802

Dr. William Crano
Department of Psychology
Texas A&M University
College Station, TX 77843

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

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

Bryan Dallman
3400 TTW/TTGXS
Lowry AFB, CO 80230-5000

Chair
Dept of Computer Sciences
U.S. Naval Academy
Annapolis, MD 21402

Dr. Michelene Chi
University of Pittsburgh, L.R.D.C.
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. Laura Davis
NRL/NCARAI Code 7510
4555 Overlook Ave., S.W.
Washington, DC 20375-5000

Chair
Department of Psychology
Towson State University
Towson, MD 21204

Dr. L. J. Chmura
Comp. Sci. and Syst. Branch
Naval Research Lab.
Washington, DC 20375-5000

Defense Technical
Information Center (Attn. T. C.)
Cameron Station, Bldg. 5
Alexandria, VA 22314 (12 copies)

Chair, Department of
Computer Science
Towson State University
Towson, MD 21204

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

Dr. Natalie Dehn
Dept. of Comp. and Info. Science
University of Oregon
Eugene, OR 97403

Chair, Dept of Psych
The Johns Hopkins University
Baltimore, MD 21218

Dr. Yee-Yeen Chu
Perceptrics, Inc.
21111 Erwin Street
Woodland Hills, CA 91367-3713

Dr. Gerald F. DeJong
A.I. Grp., Coordinated Sci. Lab.
University of Illinois
Urbana, IL 61801

Chair, Dept of Psych
College of Arts and Sciences
Catholic University of America
Washington, DC 20064

Dr. William Clancey
Knowledge Syst. Lab., Stanford U.
701 Welch Rd., Bldg. C
Palo Alto, CA 94304

Geory Delacote
Dir. de L'info. Sci. et Tech., CNRS
15, Quai Anatole France
75700 Paris FRANCE

Department
of Computer Science
Naval Postgraduate School
Monterey, CA 93940

Dr. Richard Duran
School of Education
University of California
Santa Barbara, CA 93106

Dr. Paul Feltovich
So Illinois Univ, Sch of Med
Med Educ Dept, P.O. Box 3926
Springfield, IL 62708

Dr. Sharon Derry
Department of Psychology
Florida State University
Tallahassee, FL 32303

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

Mr. Wallace Faurzeig
Ed Tech Ctr, Bolt Beranek & Newman
10 Moulton Street
Cambridge, MA 02238

Director
Manpower and Personnel Lab
NPRDC (Code 06)
San Diego, CA 92152-6800

Dr. Susan Embretson
University of Kansas
Psych. Dept., 426 Fraser
Lawrence, KS 66045

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

Director
Training Laboratory
NPRDC (Code 05)
San Diego, CA 92152-6800

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

Fleet Support Office,
NPRDC (Code 301)
San Diego, CA 92152-6800

Director, Human Factors
& Organizational Systems Lab
NPRDC (Code 07)
San Diego, CA 92152-6800

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

J. D. Fletcher
9931 Corsica Street
Vienna, VA 22180

Dr. Andrea A. diSessa
School of Education, EMST
University of California
Berkeley, CA 94720

ERIC Facility
Acquisitions
4833 Rugby Avenue
Bethesda, MD 20014

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

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

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

Dr. Kenneth D. Forbus
Dept of Comp Sci, U of Illinois
1304 West Springfield Avenue
Urbana, IL 61801

Dr. Stephanie Doan
Code 6021
Naval Air Development Center
Warminster, PA 18974-5000

Dr. Jean Claude Falmagne
Department of Psychology
New York University
New York, NY 10003

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

Dr. Emanuel Donchin
University of Illinois
Department of Psychology
Champaign, IL 61820

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

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

Dr. Thomas M. Duffy
Communications Design Center
CMU, Schenley Park
Pittsburgh, PA 15213

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

Dr. Norman Frederiksen
Educational Testing Service
Princeton, NJ 08541

Dr. Michael Friendly
Psych Dept, York University
Toronto Ontario
CANADA M3J 1P3

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

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

Julie A. Gadsden
Info Tech and Applications Div
Admiralty Research Est
Portsmouth, Portsmouth PO6 4AA U.K.

Dr. James G. Greeno
School of Education
Stanford University
Stanford, CA 94305

Dr. Barbara Hayes-Roth
Dept of Computer Science
Stanford University
Stanford, CA 94305

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

Dr. Dik Gregory
Behavioral Sciences Division
Admiralty Research Est.
Teddington, Middlesex ENGLAND

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

Dr. Dedre Gentner
Dept of Psych, U of Illinois
603 E Daniel Street
Champaign, IL 61820

Dr. Gehard Grossing
Atominstut
Schuttelstrasse 115
Vienna, AUSTRIA a-1020

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

Dr. Robert Glaser
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15260

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

Dr. Jim Hollan
Intelligent Systems Group
Inst for Cog Sci (C-015), UCSD
La Jolla, CA 92093

Dr. Arthur M. Glenberg
WJ Brogden Psych Bldg
1202 W Johnson St, U of Wisconsin
Madison, WI 53706

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

Dr. Melissa Holland
ARI for the Behavioral and Soc Sci
5001 Eisenhower Ave.
Alexandria, VA 22333

Dr. Sam Glucksberg
Dept of Psych, Green Hall
Princeton University
Princeton, NJ 08540

Dr. Ronald K. Hambleton
Prof of Ed and Psych
U of Mass at Amherst, Hills House
Amherst, MA 01003

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

Dr. Susan Goldman
University of California
Santa Barbara, CA 93106

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

Ms. Julia S. Hough
Lawrence Erlbaum Associates
6012 Greene Street
Philadelphia, PA 19144

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

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

Dr. James Howard, Dept of Psych
Human Performance Lab.
Catholic University of America
Washington, DC 20064

Dr. T. Govindaraj
Georgia Institute of Technology
Sch of Industrial & Syst Eng
Atlanta, GA 30332

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

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

Dr. Ed Hutchins
Intelligent Systems Group
Inst for Cog Sci (C-015), UCSD
La Jolla, CA 92093

Dr. Douglas A. Jones
Thatcher Jones Assoc.
P.O. Box 6640, 10 Trafalgar Ct.
Lawrenceville, NJ 08648

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

Dr. Barbara Hutson
Virginia Tech Graduate Center
2990 Telestar Ct.
Falls Church, VA 22042

Dr. Marcel Just
Carnegie-Mellon University
Dept of Psych, Schenley Park
Pittsburgh, PA 15213

Dr. Walter Kintsch
Dept of Psych, Campus Box 345
University of Colorado
Boulder, CO 80309

Dr. Barbel Inhelder
University of Geneva
Geneva SWITZERLAND 12U-4

Dr. Daniel Kahneman
The U of BC, Dept of Psych
#154-2053 Main Mall
Vancouver, BC CANADA V6T 1Y7

Dr. David Klahr
Carnegie-Mellon University
Dept of Psych, Schenley Park
Pittsburgh, PA 15213

Dr. Dillon Inouye
WICAT Education Institute
Provo, UT 84057

Dr. Ruth Kanfer
Dept of Psych, Elliot Hall
75 E River Rd, U of Minnesota
Minneapolis, MN 55455

Dr. Mazie Knerr
Training Research Div, HumRRO
1100 S. Washington
Alexandria, VA 22314

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

Dr. Mary Grace Kantowski
University of Florida, Math Ed
359 Norman Hall
Gainesville, FL 32611

Dr. Janet L. Kolodner
Georgia Institute of Technology
School of Info & Comp Sci
Atlanta, GA 30332

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

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

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

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

Dr. Frank Keil
Department of Psychology
Cornell University
Ithaca, NY 14853

Dr. Kenneth Kotovsky, Dept of Psych
Comm Coll of Allegheny Co
800 Allegheny Avenue
Pittsburgh, PA 15233

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

Dr. Wendy Kellogg
IBM T. J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

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

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

Dr. Dennis Kibler
Dept of Info and Comp Sci
University of California
Irvine, CA 92717

Dr. Benjamin Kuipers
U of TX at Austin, Dept of Comp Sci
T.S. Painter Hall 3.28
Austin, TX 78712

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

Dr. David Kieras
Tech Comm, Coll of Engineering
1223 E. Engineering Bldg, U of MI
Ann Arbor, MI 48109

Dr. David R. Lambert
Naval Ocean Syst Ctr, Code 411T
271 Catalina Boulevard
San Diego, CA 92152-6800

Dr. Pat Langley
Dept of Info & Comp Sci
University of California
Irvine, CA 92717

Dr. Clayton Lewis
Dept of Comp Sci, Campus Box 430
University of Colorado
Boulder, CO 80309

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

Dr. Marcy Lansman
U of NC, Davie Hall 013A
The L.L. Thurstone Lab.
Chapel Hill, NC 27514

Library
Naval Training Systems Center
Orlando, FL 32813

Dr. Douglas L. Medin
Dept of Psych, U of Illinois
603 E. Daniel Street
Champaign, IL 61820

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

Library, NPRDC
Code P201L
San Diego, CA 92152-6800

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

Dr. Jean Lave
School of Social Sciences
University of California
Irvine, CA 92717

Dr. Jane Malin
Mail Code SR 111
NASA Johnson Space Center
Houston, TX 77058

Dr. George A. Miller
Dept of Psych, Green Hall
Princeton University
Princeton, NJ 08540

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

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

Dr. William Montague
NPRDC Code 13
San Diego, CA 92152

Dr. Alan M. Lesgold
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15260

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

Dr. Allen Munro
Behavioral Tech Labs - USC
1845 S. Elena Avenue, 4th Floor
Redondo Beach, CA 90277

Dr. Jim Levin
Dept of Ed Psych, 210 Ed Bldg
1310 So Sixth St
Champaign, IL 61810-6990

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

Dr. Allen Newell
Carnegie-Mellon University
Dept of Psych, Schenley Park
Pittsburgh, PA 15213

Dr. John Levine
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15260

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

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

Dr. Michael Levine
Ed Psych, 210 Education Bldg
University of Illinois
Champaign, IL 61820

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

Dr. Mary Jo Nissen
University of Minnesota
N218 Elliott Hall
Minneapolis, MN 55455

Matt Lewis
Department of Psychology
Carnegie-Mellon University
Pittsburgh, PA 15213

Dr. James McMichael
Assistant for MPT Research,
Dev, and Studies, OP-01B7
Washington, DC 20370

Dr. Harold F. O'Neil, Jr.
School of Ed, WPH 801
Dept of Ed Psych & Tech - USC
Los Angeles, CA 90089-0031

Dr. Michael Oberlin
Naval Training Systems Center
Code 711
Orlando, FL 32813-7100

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

Dr. Joseph Psotka
ATTN: PERI-1C
Army Research Institute
5001 Eisenhower Avenue

Office of Naval Research
Code 1142
800 North Quincy Street
Arlington, VA 22217-5000

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

Psychologist
Office of Naval Research
Branch Office, London, Box 39
FPO New York, NY 09510

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

Dr. Nancy Perry, Chief
Naval Ed. and Training, Code 00A2A
Naval Station Pensacola
Pensacola, FL 32508

Psychologist
Office of Naval Research
Liaison Office, Far East
APO San Francisco, CA 96503

Dr. Stellan Ohlsson
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. Steven Pinker
Department of Psychology
E10-018, MIT
Cambridge, MA 02139

Dr. Lynne Reder
Department of Psychology
Carnegie-Mellon University
Schenley Park

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

Dr. Tjeerd Plomp
Twente U of Tech, Dept of Ed
P.O. Box 217, 7500 AE ENSCHEDE
THE NETHERLANDS

Dr. James A. Reggia
Sch of Med, Dept of Neurology
22 So Greene St, U of Maryland
Baltimore, MD 21201

Professor Seymour Papert
20C-109
MIT
Cambridge, MA 02139

Dr. Martha Polson
Dept of Psych, Campus Box 346
University of Colorado
Boulder, CO 80309

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

Dr. James Paulson
Dept of Psych, Portland State U
P. O. Box 751
Portland, OR 97207

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

Dr. Lauren Resnick
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. Roy Pea
Bank Street College of Education
610 West 112th Street
New York, NY 10025

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

Dr. Gil Ricard
Mail Stop C04-14
Grumman Aerospace Corp.
Bethpage, NY 11714

Dr. Douglas Pearse
DCIEM
Box 2000
Downsview, Ontario CANADA

Dr. Harry E. Pople
U of Pittsburgh, Decision Syst Lab
1360 Scaife Hall
Pittsburgh, PA 15261

Mark Richer
1041 Lake Street
San Francisco, CA 94118

Dr. James W. Pellegrino
Department of Psychology
University of California
Santa Barbara, CA 93106

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

Dr. Mary S. Riley
Program in Cognitive Science
Ctr for Human Info Processing, UCSD
La Jolla, CA 92093

Dr. Linda G. Roberts, Sci, Ed,
& Trans Prog, Tech Assessment
Congress of the United States
Washington, DC 20510

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

Special Asst for Marine
Corps Matters, ONR Code 00MC
800 North Quincy Street
Arlington, VA 22217-5000

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

Dr. Sylvia A. S. Shafto
Department of Computer Science
Towson State University
Towson, MD 21204

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

Dr. David Rumelhart
Ctr. for Human Info. Processing
University of California
La Jolla, CA 92093

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

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

Dr. Roger Schank
Comp Sci Dept, Yale University
P.O. Box 2158
New Haven, CT 06520

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

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

Dr. Walter Schneider
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Robert Siegler
Carnegie-Mellon University
Dept of Psych, Schenley Park
Pittsburgh, PA 15213

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

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

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

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

Dr. Janet Schofield
University of Pittsburgh, LRDC
3939 O'Hara Street
Pittsburgh, PA 15260

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

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

Karen A. Schriver
Department of English
Carnegie-Mellon University
Pittsburgh, PA 15213

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

Technical Director, ARI
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Judah L. Schwartz
MIT
20C-120
Cambridge, MA 02139

Dr. Elliot Soloway
Comp Sci Dept, Yale University
P.O. Box 2158
New Haven, CT 06520

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

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

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

Professor Chu Tien-Chen
Mathematics Department
National Taiwan University
Taipei, TAIWAN

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

Dr. Robert A. Wisner
Army Inst. for the Beh. and Soc. Sci.
5001 Eisenhower Avenue
Alexandria, VA 22333

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

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

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

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

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

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

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

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

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

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

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

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

Dr. Christopher Wickens
Department of Psychology
University of Illinois
Champaign, IL 61820

Dr. Heather Wild
Naval Air Development Center
Code 6021
Warminster, PA 18974-5000

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

END

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DTIC