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ABSTRACT

Intended for use by managers and developers of Army training, this report provides an introduction to "smart technology," which represents the application of cognitive and computer science to Army training problems. Differences between "intelligent tutors"--a major component of smart technology--and conventional computer-assisted instruction (CAI) are discussed, with emphasis on the current status of intelligent CAI. Abstract concepts from cognitive and computer science are discussed in the context of specific projects that represent both the long-term promise and the current status of smart technology: (1) the exploratory development of a prototype smart tutor to train high-level diagnostic and troubleshooting skills for repair of a complex reprographics system; (2) development of a smart tutor to train technicians in maintenance of an Army radar system; and (3) the development and implementation of CAI courseware for the U.S. Army Engineer School that takes advantage of both current knowledge of human learning and more advanced computer technology than is employed in conventional CAI. Also discussed are efforts to replace some obstacles to learning that are embedded in conventional technical instruction with embedded facilitators, which include the creation of problem-solving contexts. It is anticipated that this application will produce a stream of smart facilitators that can be embedded in PLATO or any conventional CAI. An outline of projected efforts by the Army Research Institute (ARI) to make smart technology a standard tool of the Army training community concludes this report. Thirteen references are listed. (BBM)

Research Report 1412

Smart Technology for Training: Promise and Current Status

Wayne D. Gray, Daniel B. Pliske, and Joseph Psotka

Instructional Technology Systems Technical Area
Training Research Laboratory

U. S. Army
Research Institute for the Behavioral and Social Sciences

March 1985

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Smart Technology represents the application of cognitive and computer science to Army training. A major component of this technology is "intelligent tutors." The authors discuss differences between intelligent and conventional CAI and emphasize the "current status" of intelligent tutors. Also discussed is ARI's effort to produce Smart Technology for CAI developers. The authors contend that most conventional CAI is "undersophisticated" and that this problem can be corrected by producing Smart Technology aids for CAI (Continued)

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developers. A project for the Army Engineer School, which is applying research on problem-solving to engineer training, is discussed.

Research Report 1412

Smart Technology for Training: Promise and Current Status

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FOREWORD

One of ARI's roles as an Army research and development agency is to identify important new technologies and encourage their application to Army problems. Smart Technology fits into this category.

Smart Technology represents the application of cognitive and computer science to Army training. A major component of this technology is the creation of "intelligent" tutors (or intelligent computer-assisted instruction (CAI)). Intelligent tutors have long been heralded as the next wave of computer-assisted instruction. The authors discuss differences between intelligent and conventional CAI and emphasize the current status of intelligent tutors. Further, the authors conclude that intelligent tutoring systems are no longer just the "toys" of academia, but are beginning to play a vital role in technical training. Examples of systems being developed by ARI are provided.

Also discussed is ARI's effort to produce Smart Technology for CAI developers. The authors contend that most conventional CAI is "undersophisticated" and that this problem can be corrected by producing Smart Technology aids for CAI developers. By way of illustration, a project at the U.S. Army Engineer School is discussed. This project is an attempt to apply cognitive science findings on problem solving to PLATO CAI for technical courses for engineers.

Smart Technology may be the best way to meet the training challenge of the late 1980s and 1990s without a great and unrealistic increase in money and personnel. We at ARI expect that Smart Technology applications will be welcomed by training developers as these applications become available.

EDGAR M. JOHNSON
Technical Director

SMART TECHNOLOGY FOR TRAINING: PROMISE AND CURRENT STATUS

EXECUTIVE SUMMARY

Requirement:

The Army's training system is straining under greatly increased demands. Maintenance and repair of complex, high-technology weapons systems require an increasing flow of highly skilled and very specialized technicians. Mobilization requires better training for Reserve Components (training that must be delivered at the home station one weekend a month and be available in 2-week increments during summer duty). Force Readiness requires qualitatively better schoolhouse training in less time for the regular Army. Present methods of training development and delivery are unlikely to meet these demands without an unrealistic increase in resources.

Product:

This paper provides an introduction to a new technology. "Smart Technology" is defined as the application of cognitive and computer science to Army training problems. Abstract concepts from cognitive and computer science are discussed in the context of specific projects that represent both the long-term promise and the current status of Smart Technology. (Note that the projects discussed emphasize two types of Smart Technology: Intelligent Tutors (intelligent computer-assisted instruction (CAI)), and cognitive science approaches to teaching problem solving in technical domains.)

Use:

The report is intended for managers and developers of Army training. In recent years cognitive science has grown into a large and fruitful field and has reached the point where theories are ripe for training applications. Unfortunately, most of the training development community comes from an intellectual tradition and moves in professional circles that do not include cognitive science. It is our intent to bring cognitive science and the applications of Smart Technology to the attention of the training community. We expect that such approaches will shed new light on old training problems and that putting the ideas of cognitive science to the test of training applications will help define the nature and limits of those ideas.

SMART TECHNOLOGY FOR TRAINING: PROMISE AND CURRENT STATUS

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SMART TECHNOLOGY FOR TRAINING: PROMISE AND CURRENT STATUS

OVERVIEW

The Army's training system is straining under greatly increased demands.

- Maintenance and repair of complex, high-technology weapons systems require an increasing flow of highly skilled and very specialized technicians.

- Mobilization requires better training for Reserve Components (training that must be delivered at the home station one weekend a month and be available in 2-week increments during summer duty).

- Force Readiness requires qualitatively better schoolhouse training in less time for the regular Army.

To meet these demands, present methods of training development and delivery would require an unrealistic increase in resources. However, an alternative exists: Smart Technology.

In this paper we attempt to explain the jargon and to provide an introduction to this new technology. Abstract concepts are discussed in the context of specific projects that represent both the long-term promise and the current status of Smart Technology.

Definitions

Smart Technology represents the application of cognitive and computer science to Army training problems. Cognitive science takes an information processing approach to the study of human cognitive processes. Of particular importance to trainers is the recent focus on the nature of expertise including expert versus novice, "naive" theories, mental models, and problem solving in technical domains. (For a recent review of the importance of cognitive science to the national interest, see the National Academy of Sciences, 1983.)

Smart Technology uses three aspects of the new computer technology. The first aspect is the well-publicized availability of sophisticated technology at a low cost. The availability of special symbol-manipulating, or LISP, machines is the second aspect; these machines were developed specifically as tools for research in cognitive science and applications of artificial intelligence (AI). The third aspect is the AI technology of expert systems and intelligent tutors (or computer-assisted instruction--CAI).

In many cases, the cognitive science side of Smart Technology can be applied via "chalk and talk," paper-based, or standard CAI techniques. However, in other cases, the application of Smart Technology requires a delivery vehicle that can interactively model a soldier's current knowledge and problem-solving strategies, compare this with what an expert would do, and in real time, design and deliver instruction. The new computer technology provides a vehicle capable of meeting these needs. (For a "popular" discussion of this new computer

technology, see Feigenbaum & McCorduck's book Japan and the Fifth-Generation Challenge, 1983.)

Projects

For the past 2 years the Army Research Institute's (ARI) Smart Technology for Training team has monitored research in cognitive and computer science to determine its applicability to Army training. First, the team has identified areas that if nurtured will help meet the training needs of the Army in the 1990s. At present ARI is supporting long-term development efforts by some of the nation's best cognitive and computer scientists.

Second, there is a critical gap between the skills soldiers must have to maintain and repair high-tech systems and the capability of the Army school system to train these skills. (Currently, some 80% of these skills are taught on the job, not in the school.) Clearly, bold solutions are required to bridge this gap. Part of the solution lies in the development of "intelligent" or "smart" maintenance tutors capable of delivering high-quality technical training in less time and at less cost than current training. ARI is supporting an exploratory development effort to build a prototype and is working on a smart maintenance tutor for the HAWK Air Defense System.

Third, there are many findings from cognitive science research that can be applied now to improve training developments. Research to apply this knowledge to improve conventional CAI is currently underway.

LONG-TERM DEVELOPMENTS

Long-term development projects have been funded through joint ARI/ONR (Office of Naval Research) contracts. Several of these projects relate to the development and use of mental models of physical phenomena and devices.

People use mental models as a basis for predicting outcomes and for planning and reasoning. An example of a simple but erroneous mental model is the "stove model" of thermostat control. Anyone who has walked into a cold house at the end of the day and set the thermostat at 90° is using the stove model. This model treats the central heating system as analogous to a gas stove: the higher the setting, the higher the flame; the higher the flame, the greater the heat; the greater the heat, the faster the pot boils; hence, the higher the thermostat setting, the faster the house heats. In the correct model the thermostat is viewed merely as an on/off switch. Setting the thermostat at 90° will not cause the house temperature to reach 68° any faster than setting it at 68°. (See Gentner & Stevens, 1983, for in-depth discussions of mental models.)

One of the projects is examining how mental models of electric circuits influence the learning of troubleshooting strategies and, conversely, how training in troubleshooting influences the mental models that are developed. For example, people often view the flow of electric current as analogous to either "flowing water" or "teeming crowds" (Gentner & Gentner, 1983). These models produce different patterns of errors in reasoning about electric circuits. Does the effective use of different troubleshooting strategies require

the support of different models of current flow? Can one model of current flow be found that supports the application of different troubleshooting strategies to different problems? The goal is to find some combination of models and strategies that results in flexible and effective troubleshooting behavior and that can also be easily learned.

Forming mental models of physical phenomena is so pervasive that people will form models based upon incomplete and erroneous information. A wrong model may be just incomplete, that is, a preliminary stage in the development of more accurate and complete understanding. In contrast, however, misconceived models must be unlearned before the correct model can be acquired. For example, when given the coiled tube shown in Figure 1 and asked to predict the path of a ball after it exits the tube, about half of the college students tested said that the ball would continue to curve. A few students said that the ball would circle the coil (McClosky, 1984). Apparently, these individuals have a pre-Newtonian "impetus" model of this phenomenon. (Passing through the coil imparts a "circular impetus" to the ball, which is gradually lost after the ball exits.) McClosky found that even students who had taken a college physics course still held some form of impetus theory. Rather than supplanting "naive" models of physics, college instruction coexisted or was incorporated into the students' preexisting mental models.

There is a growing appreciation that much of what a good human tutor does is to discover students' misconceptions about a domain and provide examples or instructions that discredit these intuitive models and lead to the adoption of accurate ones. ARI is supporting two projects that examine these aspects of mental models and tutoring. The first project supports the development of an AI-based medical consultation and explanation system. By interacting with the student, the system constructs a dynamic model of the student's knowledge and diagnostic reasoning abilities. The system is able to tailor instruction to support the student's development of accurate mental models and to help discredit misconceived models. The second project supports an AI-based system that identifies a student-programmer's errors and relates these to the set of plans and subplans the student used to write the program. The goal is to use errors to diagnose the student's underlying misconceptions about programing and then target instruction to correct these misconceptions.

Another ARI-supported effort is investigating how experts in a domain go from a problem statement to making <u>inferences</u> about the problem. The goal is to implement these patterns of inference as a computer model and to compare the inferences experts make to those that students make.

The last ARI/ONR project described here is an attempt to develop AI text-generation techniques that can be used to teach reading skills to adults. In the current prototype, text generation is embedded in a gaming situation that requires the student to advance in a fictional organization (for example, an Armor Company). The system will generate appropriate written responses to the student's moves in the game, administer diagnostic tests for isolating problems in reading comprehension, and adaptively introduce novel materials based on the results of the diagnosis. Once the text-generation techniques are developed, the content of the gaming situation can be easily altered. The long-term application is to build a family of intelligent tutors in which soldiers can acquire job knowledge as they improve their reading skills.

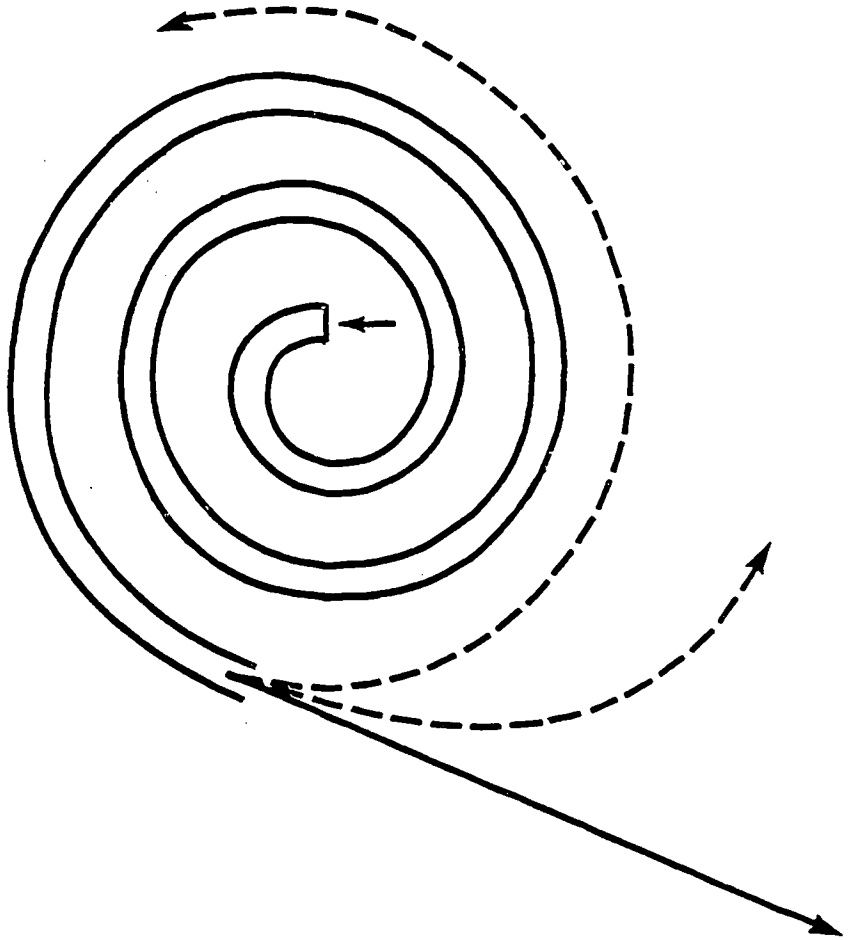


Figure 1. "Naive physics." In accord with medieval impetus theory, half of the college students tested predicted that a ball shot through a coiled tube would continue to curve after exiting.

EXPLORATORY DEVELOPMENT

ARI is supporting Xerox Palo Alto Research Center (PARC) in the exploratory development of a prototype smart tutor to train high-level diagnostic and troubleshooting skills for repair of a complex reprographics system. The chosen system represents a stable, high-technology testbed (with electronic, mechanical, chemical, and electro-optic components). These complex, interacting technologies require the sophisticated diagnostic and troubleshooting skills vital for Army systems in the late 1980s and 1990s. Also important is the fact that the system is not classified and has an existing training program with which to compare the smart tutor. Measures of on-the-job performance of smart-tutored versus conventionally trained technicians will be obtained. The ultimate proof of the tutor will be whether Xerox uses it for in-house training.

The main goal of this effort is not the prototype tutor per se, but the software tools, programing environments, and modeling techniques that such a tutor requires. Once these tools, environment, and techniques are developed

and tested, they will be used to develop a family of smart tutors for training maintenance and troubleshooting for Army weapons systems.

Those researchers who have watched the development of CAI systems such as PLATO and TICCIT will understand the importance of building specialized software tools and programing environments to expand the access to new technology. However, the role of mental models and the importance of developing techniques to construct such models may not be obvious.

As an example, a smart tutor for teaching radar maintenance requires four different models: first, a straightforward computer model of the radar system itself--such device models are becoming standard in many conventional computer-based training systems; second, a model of how experts think about the device while troubleshooting--an experts' mental model of the device; third, a theory-based model of an expert instructor--this model includes pedagogical strategies such as when to let a student pursue a wrong answer and when to provide feedback; fourth, the capability to interactively create a model of the student's knowledge--including their understanding and misconceptions. (For a discussion of smart tutors, see Sleeman & Brown, 1982, and Bregar, 1983.)

In a smart tutor, these models interact so that at all times the feedback provided and problems presented are appropriate to the student's current state of knowledge. This technology promises smart tutors that will generate feedback and problems to meet each student's unique needs. This generation is in contrast to the best conventional CAI in which students' responses result in their being branched down one of a limited number of predetermined paths.

The HAWK MACH-III

The Maintenance Computer for HAWK--Intelligent Institutional Instructor (MACH-III) represents the first attempt to build a smart tutor for Army training. The HAWK provides over 50% of the air defense for Army units. Current training costs run from $10,000 to $50,000 per radar maintenance trainee, yet a recent study identified training as a major problem area that has plagued HAWK from the outset. Even a small increase in training effectiveness should more than pay back the cost of developing and fielding the MACH-III.

Our approach at ARI is to pinpoint areas where the MACH-III has the most to contribute. We will determine what the major radar maintenance problems are and how these problems are addressed by the current training system. Generally, we will be interested in how Smart Technology can be used to improve existing training methods, and specifically, how a smart tutor can be used with greatest leverage.

The application of smart tutors to HAWK training is ideal. Training problems for the HAWK have been recognized as large and costly. Good conventional training strategies (that is, chalk and talk, CAI, and videodisk) have been tried, but still a large deficit remains. The proponents for the HAWK recognize this problem and are willing to try a new approach.

The MACH-III represents a target of opportunity. The high cost of development is more than justified by the potential to improve maintenance training. The experience gained in developing the MACH-III will be an important test of

newly developed software tools, programing environment, and modeling techniques. Experience gained in using the MACH-III will provide guidelines for the most effective use of smart tutors. Finally, the experience gained in building the MACH-III should cut down the time and costs involved in applying smart tutors to other training problems and help transfer smart tutor technology to the Army's training development community.

APPLICATIONS RESEARCH: SMART TECHNOLOGY FOR CAI DEVELOPERS

It is our contention that most conventional CAI is undersophisticated, that is, (a) does not take advantage of what we know about human learning, and (b) does not come close to exploiting the power of the computer. We believe that the best way for the Army to increase the return on its investment in CAI is to put Smart Technology in the hands of CAI developers.

Toward this end, we are working with the U.S. Army Engineer School (USAES) to develop and implement CAI in the Engineer Officer Advanced Course (EOAC). First, as advisors, we have helped organize and train a CAI courseware cell and are now assisting in the formative evaluation of courseware. Second, as researchers, we have taken a hard look at the nature of the technical courses being taught and the traditional ways (both chalk and talk and CAI) of teaching them. The Engineer School teaches its Captains a variety of technical courses in Civil Engineering (for example, bridge design, soil analysis, flexible pavements, and so on). The goal of these courses is to teach Engineer Captains how to solve problems in each of these subdomains.

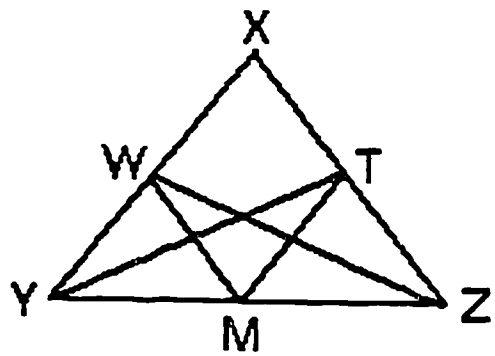
The simple observation that Engineer Captains are taught how to solve problems in various technical domains led us to compare the nature of EOAC instruction with findings of cognitive science on problem solving in other technical domains (such as physics, chemistry, geometry, and programing). As a result of these comparisons, we have begun research designed to apply cognitive science theories to the design of instruction delivered on a conventional PLATO CAI system.

Obstacles to Learning

One research goal is to eliminate obstacles to learning embedded in conventional technical instruction. These obstacles are not unique to the Engineer School, but are found in all such instruction.

Identifying the Goal Structure. The goal structure of a problem is the "path" taken from the problem statement to its solution. Instruction should teach students how to traverse this path but usually does not. In fact, most instruction on goal structures contains obstacles to learning. For example, Figure 2 presents a traditional two-column proof for a geometry problem. After learning a few postulates and theorems, the student is shown one or two of these proofs and then is asked to solve problems (Anderson, Boyle, Farrell, & Reiser, 1984).

This "linear" proof structure is very misleading. First, by definition, the proof provides no sense of hierarchical relationship among the steps.



GIVEN: $\overline{XY} \cong \overline{XZ}$,
$\angle WMY \cong \angle TMZ$,
M midpoint of $\overline{YZ}$

PROVE: $\overline{YT} \cong \overline{ZW}$

STATEMENT	REASON
M is midpoint of $\overline{YZ}$	Given
$\overline{YM} \cong \overline{MZ}$	Definition of midpoint
$\overline{XY} \cong \overline{XZ}$	Given
$\angle XYZ \cong \angle XZY$	base angles of isoceles triangle
$\angle WMY \cong \angle TMZ$	Given
$\triangle WMY \cong \triangle TMZ$	Angle-side-angle (ASA)
$\overline{WY} \cong \overline{TZ}$	Corresponding parts
$\triangle WYZ \cong \triangle TZY$	Side-Angle-side (SAS)
$\overline{YT} \cong \overline{ZW}$	Corresponding parts

Figure 2. Linear (traditional) two-column proof for geometry problems. (Adapted from Anderson, Boyle, Farrell, & Reiser, 1984.)

Second, it is not clear to the student whether the order of the steps is accidental or essential. These failings are easily overcome by teaching a hierarchical proof structure as shown in Figure 3.

Searching a Problem Space. The problem space includes an individual's representation of the objects in the problem situation, the goal of the problem, and the actions that can be performed and strategies that can be used in working on the problem. It also includes knowledge of constraints in the problem situation: restrictions on what can be done, as well as limits on the ways in which objects or features of objects can be combined (Greeno & Simon, 1984, p. 4). The search for a problem solution involves a search through some subset of this space. For example, Figure 4 shows the search through a subset of the geometry problem space that an expert made while solving the problem given in Figure 2. The numbers indicate the sequence of the search.

The linear proof given in Figure 2 provides no inkling of the false starts that the expert went through. The novice is led to believe that all such problems are solved in a strictly linear fashion--starting with the givens, and generating the next step, until with clock-like precision an answer is found. Experts do not solve problems by this process; unfortunately, however, experts do teach this way.

The consequence of these obstacles is that the problem-solving process is never explicitly taught but is left to the student to discover alone. This "discovery" learning often leads to frustration or failure and can actively retard the development of expertise.

Facilitating Learning

We plan to replace embedded obstacles with embedded facilitators. First, for selected engineering subdomains, we plan to discover the goal structure underlying successful problem-solving and to communicate that goal structure to the student.

Second, typical instruction separates information about the task (usually presented by lecture and text) from performance of the task. At best, performing the task is regarded as a chance to practice (not acquire) knowledge and skills. We plan to revise this procedure and to create problem-solving contexts in which students acquire knowledge and skills as they perform the task.

Creating problem-solving contexts should facilitate learning for several reasons (Anderson, et al., 1984). First, many studies have shown that human memory is partially context dependent. If performing a task requires a problem-solving activity, then instruction in the facts and theories of the task domain should take place in a problem-solving context. Additionally, many concepts are hard to understand when presented in the abstract. Teaching these concepts in a problem-solving context provides a concrete example of the concept and how it is used. Finally, there is the problem of the applicability of information. When facts are taught in the abstract, students may be perfectly capable of demonstrating that they know these facts (by tests of recall or recognition) but not recognize that the fact is relevant in a particular context. Students can access memory, but they do not know when to apply it. Teaching facts in a problem-solving context assists students in learning the "goal relevance" of knowledge.

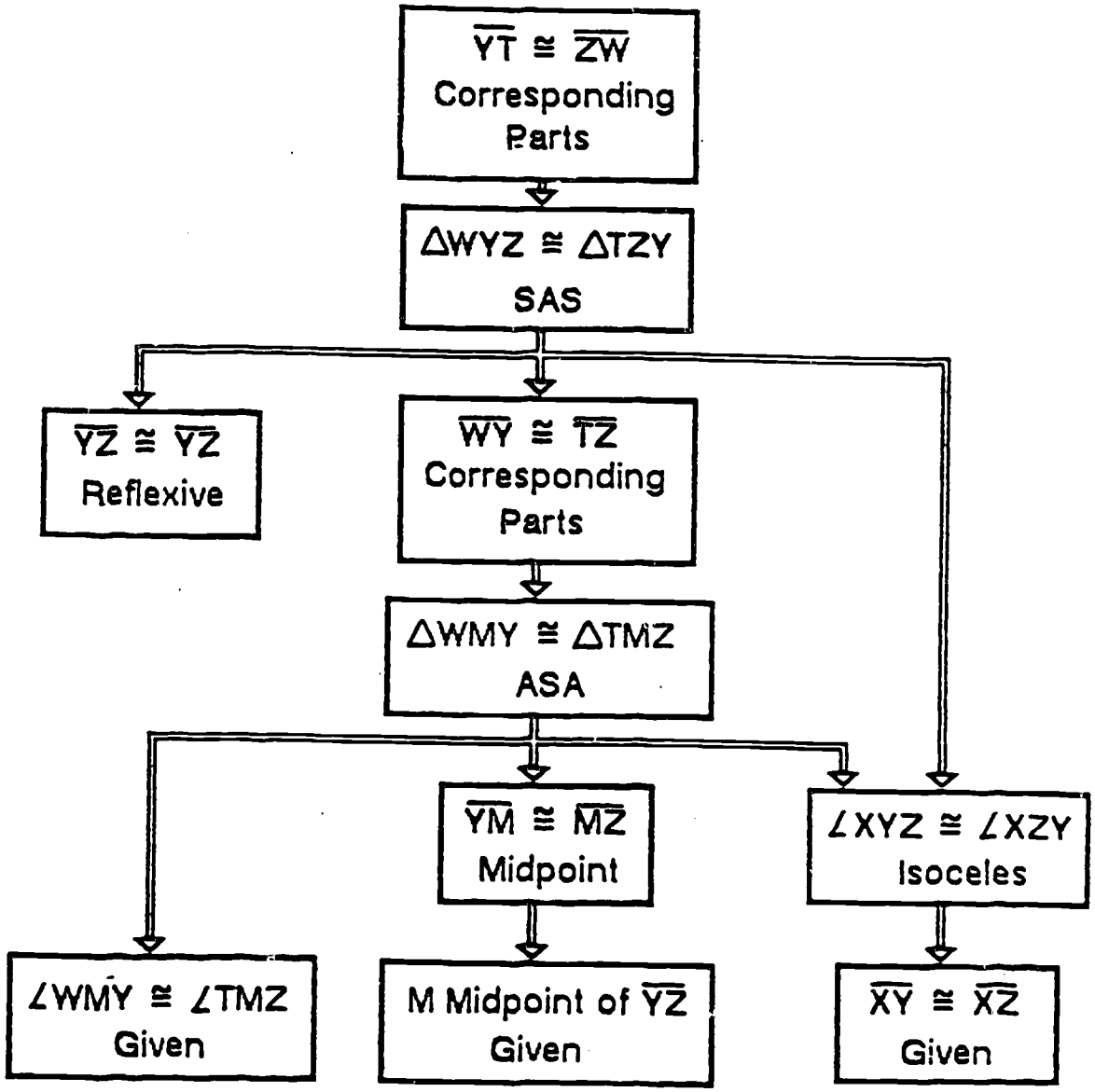


Figure 3. Hierarchical proof structure for geometry problems. (Adapted from Anderson, Boyle, Farrell, & Reiser, 1984.)

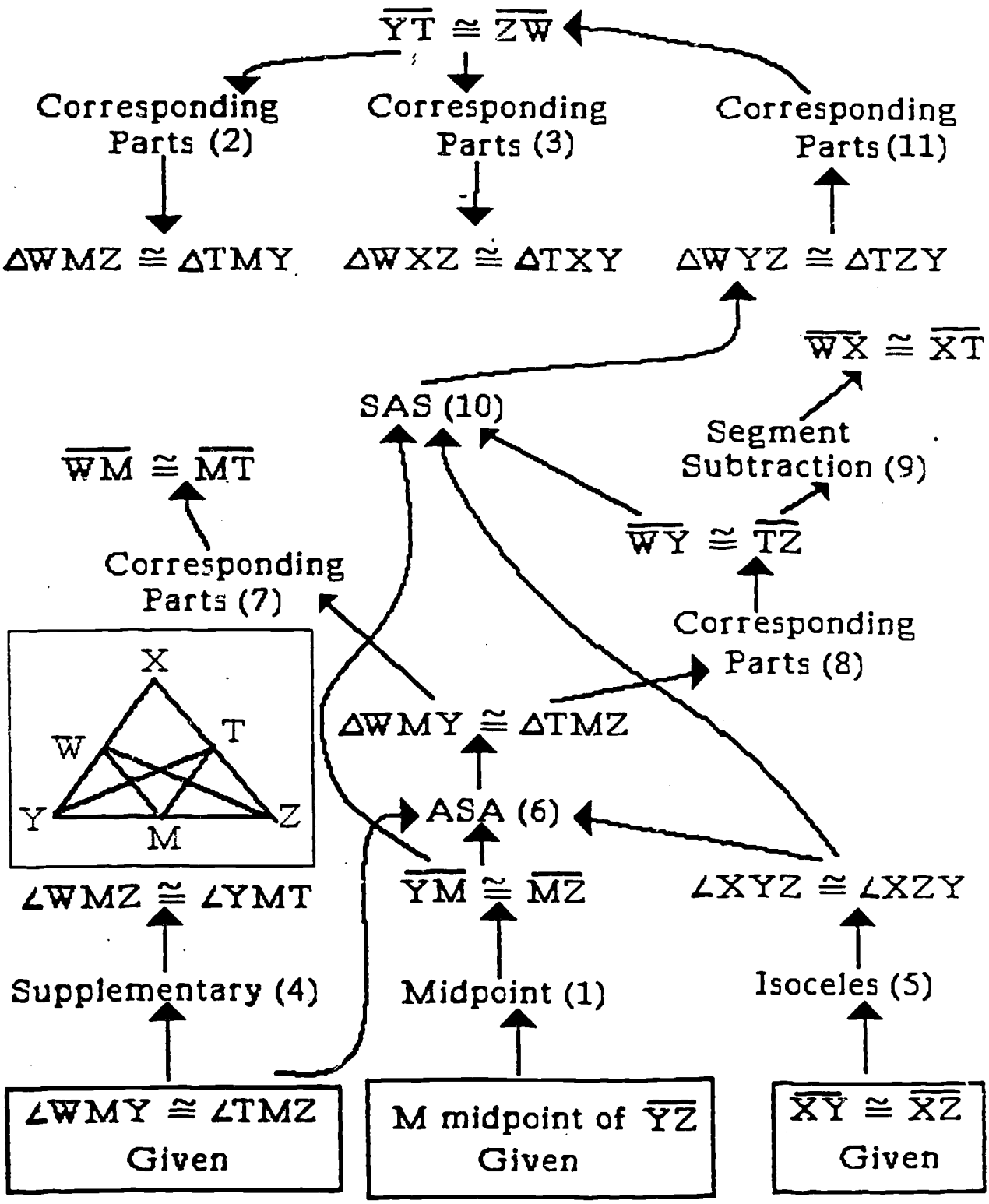


Figure 4. An expert's search through a subset of the geometry problem space. (Adapted from Anderson, Boyle, Farrell, & Reiser, 1984).

The third way we intend to facilitate learning is by reducing working memory failures. Anderson, et al. (1984) argue that working memory failures are (a) the major source of errors during learning, (b) an additional limitation on the learning rate, (c) a barrier to certain effective types of problem solving (such as backwards reasoning in geometry), and (d) a cause of incorrect retrieval from long-term memory. Since it is generally accepted that working memory expands with expertise, the problem is how to minimize the working memory load of novices while they acquire the long-term memory structures prerequisite to a larger working memory. (Working memory is viewed as domain dependent. An expert with a large working memory in a domain of expertise would not have a large working memory available in an unfamiliar domain.)

Rather than yielding one large product, our applications should produce a stream of smart facilitators that can be embedded in PLATO (or any conventional) CAI. Many ideas will be rapidly developed and tested using LISP machines. Then the most successful ideas will be translated into TUTOR (the language of PLATO) as prototype lessons and compared with existing instruction. The prototype lessons that prove effective will be immediately made available to the Engineer School. More important, those ideas that prove successful will be immediately transferred to the Engineer School's courseware developers to incorporate into their own lessons. In this way we will watch closely the process of technology transfer to assist the movement of Smart Technology aids from the laboratory to the user. Our ultimate goal is to make all validated Smart Technology aids accessible to the Army training community.

SUMMARY: CONTINUING EFFORTS

One of ARI's roles as an Army research and development agency is to identify important new technologies and encourage their application to Army problems. We plan a concerted effort to make Smart Technology a standard tool of the Army training community.

Spreading the word is the keystone of our effort. In recent years cognitive science has grown into a large and fruitful field and has reached the point where theories are ripe for training applications. Unfortunately, most of the training development community comes from an intellectual tradition and moves in professional circles that do not include cognitive science. Our intent is to bring cognitive science and its Smart Technology applications to the attention of the training community. We expect that Smart Technology will shed new light on old training problems and that putting cognitive science ideas to the test of training applications will help define the nature and limits of those ideas. (For a discussion of the application of artificial intelligence to training, see Psotka, 1983. For a discussion of how cognitive science is changing the nature of learning theory, see Gray & Hamza, 1983.)

There are an increasing number of successful training programs based on a Smart Technology approach. These programs include such long-standing conundrums as literacy training (Wisher, 1983; Wisher & O'Hara, 1981) and technical writing (Redish, Felker, & Rose, 1981). While these programs demonstrate the effectiveness of Smart Technology, their developers tend to come from and publish outside the traditional training development community.

Demonstrating the effectiveness of Smart Technology is also part of our continuing effort. The smart tutor for a complex reprographics system is intended as a demonstration. Arrangements have been made with Xerox to compare the effectiveness of the smart tutor with conventional instruction. Students will be Xerox field technicians. Measures of effectiveness will be based upon on-the-job performance.

Also, we expect that our work with the Engineer School and on HAWK MACH III will result in impressive demonstrations of Smart Technology's effectiveness.

Handbooks and guidelines for the application of Smart Technology to training do not exist. This lack severely limits the widespread application of Smart Technology to training. At present, our efforts at creating guidelines are focused on evaluating software tools for building smart tutors. As these tools are tested, guidelines will be developed and made available to the training community.

In summary, we see the current examples of Smart Technology as just the beginning. Other teams at ARI and at Air Force and Navy laboratories are moving quickly to exploit this emerging technology. Smart Technology is the only way to meet the training challenge of the late 1980s and 1990s without a great and and unrealistic increase in money and personnel.

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