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THE DAB MODEL OF DRAWING PROCESSES

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I. ABSTRACT

The problem of automatic drawing was investigated in two ways. First, a DAB model of drawing processes was introduced. DAB stands for three types of knowledge hypothesized to support drawing abilities, namely, Drawing Knowledge, Assimilated Knowledge, and Base Knowledge. Speculation concerning the content and character of each of these subsystems of the drawing process is introduced and the overall adequacy of the model is evaluated. Second, eight experts were each asked to understand six engineering drawings and to think aloud while doing so. It is anticipated that a "concurrent protocol analysis" of these interviews can be carried out in the future. Meanwhile, a general description of the videotape database is provided. In conclusion, the DAB model was praised as a worthwhile first step toward solution of a difficult problem, but was considered by and large inadequate to the challenge of automatic drawing. Suggestions for improvements on the model were made.

II. INTRODUCTION

What does a person have when she has the ability to draw? At the broadest level, the purpose of this paper is to describe drawing processes. More narrowly, however, focus is on how engineering drawings are created from a knowledge base which abstractly represents the object to be portrayed. Additional concern is with development of a conceptual model of the drawing process.

The model is designed to assist thinking about the cognitive and information processing operations involved in translating from a knowledge base to a drawing of the system represented. The model is also designed to help understand the requirements of creating an automatic drawing mechanism to accomplish that task.

The model is called DAB because its activities are supported by three general knowledge systems, Drawing Knowledge, Assimilated Knowledge, and Base Knowledge. The parts of the DAB model and their relationships are shown in Figure 1.

The DAB model was inspired by recent efforts to expand the capabilities of KATE, an artificial intelligence project developed in the laboratories of NASA, the National Aeronautics and Space Administration. KATE (Knowledge-based Autonomous Test Engineer) is a reasoning system which uses stored knowledge about the structure and function of a variety of systems. Its purpose is to apply captured abstract thinking processes of engineers in the form of algorithms to the tasks of monitoring, diagnosis, and control of launch systems.

KATE represents in its memory both the components of the modeled system (e.g., electronic relays, valves, pumps) and the connections of those components. Ideally, with added dynamic drawing capabilities, KATE could produce visual representations of the target system. The drawings should portray both functional and structural characteristics. Such visual displays would speed any human's understanding of the modeled system and its components.

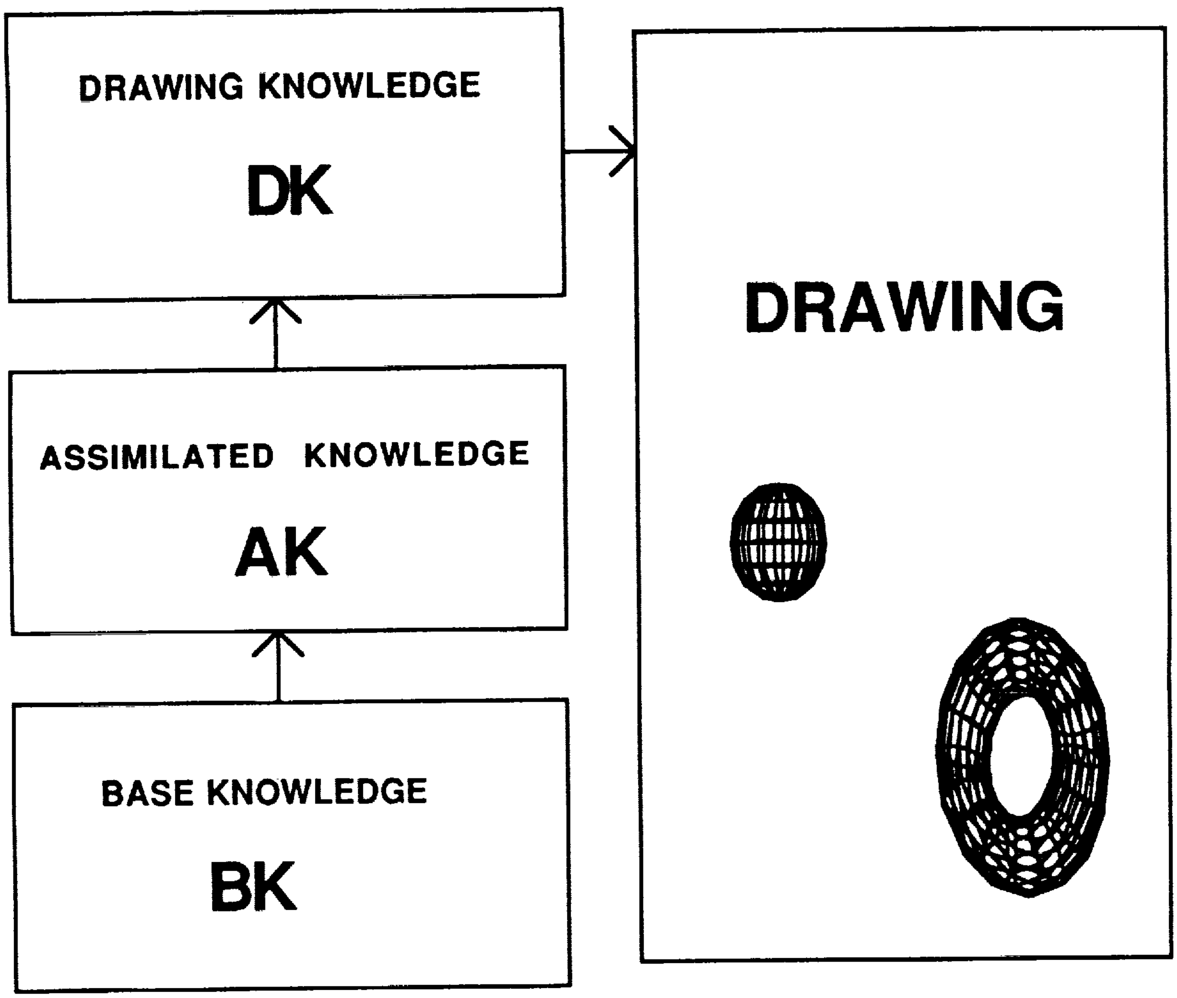

FIGURE 1 THE DAB MODEL

III. OVERVIEW OF KATE

As indicated, KATE is an artificial intelligence system designed to mimic the reasoning processes of an experienced engineer. At NASA, the initial applications of KATE were narrowly specific. Nevertheless, by continually readapting KATE to many systems and problems, the character of KATE has become continually more generic and pertinent to a wider variety of engineering systems.

The review by Scarl, Jamieson, and Delaune [1] provides a fuller description of KATE than will be offered here. Instead of another thoroughgoing review, the present summary will focus on KATE's drawing capabilities and on the descriptions of KATE which pertain to the creation of visual representations of the systems KATE is modeling. In doing so, it will help to keep in mind the distinction made by Simon [2] and others between declarative and procedural knowledge. Declarative knowledge pertains to facts and relationships between facts while procedural knowledge refers to knowledge about how to do things. As one might guess, KATE contains both types of knowledge.

KATE's declarative knowledge is primarily in the form of a knowledge base. This base knowledge represents the components of the system being modeled, the connections of these components to one another, mathematical values (such as pressure or temperature readings on a sensor in the system), and functional relationships between component values. The base knowledge of KATE is one of the three fundamental knowledge systems which support the DAB drawing model. More will be said about base knowledge characteristics in the next section of this report.

Procedural knowledge in KATE consists of how KATE uses its knowledge base. One example of this is KATE's diagnostic capacity in which an evaluation is made of possible causes of faulty sensor readings in the system being modeled. KATE attacks such problems by creating a suspect list. Next, through inference processes KATE attempts to logically rule out or determine the innocence of the various suspects. Under ideal circumstances, only the component actually at fault will remain on the suspect list. (KATE assumes only a single point of failure). When more than one suspect remains, further tests (e.g., application of commands to the system) may be needed to appropriately narrow the explanations of the erroneous reading or readings.

As mentioned in the introduction, it would be very helpful if KATE could automatically create visual representations of the system being modeled. Such visual representations would not augment KATE's declarative or procedural knowledge with respect to solving engineering problems, but the drawings could be very useful to any human user of KATE. Some of the uses which could be made of graphical representations of KATE's declarative knowledge are:

1. Creating alarms which alert humans to emergency situations.

2. Permitting humans to understand how KATE operates.

3. Teaching a novice about the modeled system.

4. Creating a user interface.

5. Aiding diagnosis of system faults.

These five functions, alarms, understanding KATE, teaching about a new system, creation of a human-machine interface, and fault diagnosis are the motivation for the present efforts to increase KATE's drawing ability.

At the time of this writing, KATE can do some drawings, but its visual representation ability is limited in two primary ways. These limitations correspond to KATE's two ways of visually portraying the modeled system, tree drawings and iconic drawings. Concerning the first of these, KATE by lines can create a visual tree-structure to show how the parts of the modeled system are connected to one another. To avoid line crossings, KATE, whenever a series of parts form a loop, will create a doubled representation of a component in the system and mark the duplicated node in the drawing with an asterisk to note its replication. Size limits to the drawings are accomplished by selecting a focal component and then moving upstream and downstream a criterion number of components.

In two ways, the tree diagram is not a faithful drawing of the modeled system. First, whenever they occur, duplicated representations of components in the system will guarantee the drawing will lack accuracy as a representation of a real world system. Second, the components of the tree drawings are not realistic representations of what they stand for. For example, pumps are not drawn to look like pumps, but are protrayed only as a labeled node in the network.

KATE additionally creates iconic drawings of the system being modeled but, in its current form, KATE sometimes generates these, but most often relies on human artists. The KATE programs (presently in LISP) contain "icons" or computer graphics images of the modeled parts. The layout, organization, and placement of these icons, however, is typically not automatically generated, but is given by the user in a template-type drawing system which simply places the selected icons at their predetermined locations on the screen.

At present, only a small portion of KATE's drawings are fully automatic. In most cases, KATE draws in iconic form only what has been predefined as a subsystem of the system being modeled. Hence, the visual drawings currently produced by KATE are more like memorized drawings than like sketches generated to suit the situation. Stated another way, the layout of iconic drawings is not currently created by procedural knowledge within KATE, but is a form of declarative knowledge based on what has been drawn by a human artist. Because

KATE's drawings are "canned" rather than synthesized, the creation of iconic drawings is an extremely time-consuming step in using KATE and is necessary for each new application. Were this drawing process more generic, considerable savings and generalizability could be realized for the KATE system.

IV. THE DAB MODEL

4.1 The Nature of Automatic Drawing

The scope of the problem of creating automatic drawings from a highly abstract engineering knowledge base is enormous. In magnitude, the task is akin to a request to simulate the creative talents of a design engineer and an engineering draftsman. One can reasonably ask, where does one begin? Where indeed? It is one purpose of the present paper to make such a beginning.

The present DAB model is partly the result of ideas stimulated by interviews of eight engineers and designers which are described in Section V of this paper. Primarily, however, DAB is simply a rationalistic effort to indicate what an automatic drawing system would have to know in order to produce reasonable drawings and schematics of systems such as those modeled within KATE. Put another way, what would an expert designer have to have to be able to create a good schematic representation of an electrical or mechanical system? DAB is thus a process model of the skill that results from such an ability.

It is an assumption of the present approach that knowledge of human drawing ability will ultimately aid development of automatic drawing abilities. Unfortunately, the lines of distinction between DAB as a process model of human abilities and DAB as a model of automatic drawing have not been kept clear throughout this paper. Primarily, DAB is a model of human skills and processes, yet it is hoped that by starting here the drawing process can be brought under fully automatic control.

The current DAB model of drawing is additionally a cataloging system by which to organize the varieties of declarative and procedural knowledge required to create effective functional representations of systems. Once again, DAB stands for Drawing Knowledge, Assimilated Knowledge, and Base Knowledge (see Figure 1). For the purpose of cataloging artistic abilities and processes, these three components are seen as mutually exclusive and exhaustive categories. Dynamics of information exchange between these subsystems, however, may at times blur their boundaries.

The Base Knowledge component has been reviewed somewhat already in describing KATE in the preceding section of this report. The Base Knowledge is the declarative knowledge of the KATE system and is a list of components, physical connections between components, and mathematical functions relating commands, components, and outputs. The mathematical expressions represent transfer functions. Such transfer functions are equations which relate changes in command values to changes in outputs.

Drawing Knowledge represents what is required to directly create the visual representation to be presented to humans. Such

Drawing Knowledge will include procedures for creating drawings which satisfy aesthetic constraints and will include other complex mechanical routines needed in the actual drawing process.

The Drawing Knowledge aspect of the DAB model will include additional knowledge in the form of a subsystem which knows how to create a general layout and knows where to begin in doing so. The source of this knowledge is considered one of the central keys in the drawing process. The possibility of including a Layout Knowledge processing component between Assimilated Knowledge and Drawing Knowledge was considered, but rejected due to a simplicity criterion. For now, knowledge of layout procedures are included as a part of the Drawing Knowledge component of DAB.

Expanded consideration of the Drawing Knowledge component is given in the next subsection, 4.2. It may help to keep in mind that all of the Drawing Knowledge is procedural knowledge. As such, the Drawing Knowledge stage merely tells the DAB model how to put pen to paper.

The third component of the DAB model, Assimilated Knowledge, represents the planning, organization, and preparation a designer must go through before actually beginning to draw. Interviews described in Section V of this report indicate such prior planning is a large measure of what is done when a designer puts a schematic together. The actual time spent in drawing (application of Drawing Knowledge) appears to be minor compared to the work that must be undertaken in getting ready to draw. Assimilated Knowledge is the link between the declarative knowledge of the Base Knowledge component and the procedural knowledge of the Drawing Knowledge stage of the DAB model.

At the start of this writing, it is not clear whether Assimilated Knowledge is declarative or procedural in character. Later, we will return to consideration of this issue. For now, I suspect it is a creative mixture of both. Perhaps the Assimilated Knowledge stage, via as yet unspecified procedures, creates a set of declarative knowledge structures out of the vast encyclopedic knowledge which it must possess and turns these synthesized chunks of knowledge over to the Drawing Knowledge component just prior to drawing.

The following quotation vividly conveys the mental processes involved between the time a designing problem is presented to introspective awareness and the moment a creative solution to that problem is discovered. It is not hard to imagine that similar mental steps would take place as an artist or a design engineer prepares to start the overt drawing process.

"I have this amplifier to design. It is supposed to operate at a center frequency of 100 megahertz. The output must be one volt and the input is one-tenth volt, which is a gain of 10. I better make the gain variable from 10 to 20 in case the other devices are off normal. The amplifier will have to be shielded. I can use a metal can for the shield with coaxial lines for all signals and high frequency reject for the power and control lines. Say, this amplifier sounds a lot like the amplifier I designed for the XYZ project - where did I put the design drawings for the XYZ project?" [3].

The designer in the quotation above has drawn on what numerous cognitive psychologists have called schemata (singular, schema). Schemata are broad generalizations based on past experience. Schemata, therefore, are distillations of the enormous quantities of knowledge accumulated through humans' memories of their encyclopedic repertoire of interactions with the world.

The concept of schemata is most often credited to Bartlett [4] who himself acknowledged inspiration in the writings of the neurophysiologist, Head. Head's thinking, however, was limited to the notion of procedural knowledge schemata, such as those an experienced player would employ in a game of tennis. Bartlett simply extended the concept of schemata to include declarative as well as procedural knowledge. For example, in recalling complex narratives, such as Bartlett's famous "War of the Ghosts" story, intrusions of words such as "canoe" for the word "boat" in the original story, led Bartlett to infer the operation of perceptual schemata which must have distorted the participant's original perception of the story.

Since Bartlett, numerous cognitive psychologists have extended the concept of schemata both theoretically and empirically. For example, at a theoretical level, Minsky [5] introduced the idea of "frames" and Schank [6] developed the notion of "scripts" which, among other things, made the concept of schemata both more precise and more functional. Empirical demonstrations of the operation of schemata have been frequent also. A common example along these lines was provided by Chase and Simon [7] who showed that an expert chess player surpassed a novice in the recall of sensible chess board configurations, but showed no differences in memory for senseless chess board patterns. The implication is that the expert's schemata for previous chess positions were responsible for the result.

To return to the main point, Assimilated Knowledge within the DAB model may represent a process of activation of the proper schemata from the individual's encyclopedic knowledge so that these schemata may be passed along to the Drawing Knowledge component in a usable form.

The expanded consideration of the nature of the Assimilated Knowledge component of the DAB (subsection 4.3) consists of further speculation about the varieties of schemata which must operate at various times in the drawing process as well as additional consideration of what those knowledge assimilation processes may be. Section 4.4 is an evaluation of the DAB model.

4.2 Drawing Knowledge

To appreciate the complexity of the drawing process, try this simple exercise: Write down a list of four components and name them for the letters A through D. Add to this list six connections between pairs of components (such as A-B, B-C, or B-D). Keep in mind that each letter should have at least one connection but that any letter could have multiple connections to other letters. From this list of parts and pathways between parts, create a two-dimensional drawing depicting the symbolic connections. The demonstration should convince anyone that with just a few more components and a few more pathways the drawing task could quickly turn into spaghetti chaos if it has not done so already.

In spite of this complexity, a number of papers have attempted to produce objective descriptions of such a drawing process [e.g., 8, 9, 10]. The brief but thoughtful paper by Batini et al. [8] covers several key contributions these efforts have produced and illustrates a number of essential features of the Drawing Knowledge process. Batini et al. describe four aesthetic criteria useful as guides to the drawing process: 1) minimization of the number of crossed lines, 2) minimization of bends along connections, 3) minimization of the global length of connections, and 4) minimization of diagram area.

By establishing a rigid priority between aesthetic criteria, Batini et al. were able to create a layout algorithm (called GIOTTO) consisting of a five-stage process. The stages are modeling, planarization, orthogonalization, compaction, and drawing. The last four stages of the GIOTTO model represent what may be called Drawing Knowledge in the terms employed in the present paper. The first stage, modeling, is the transition process between the conceptual schema of the depicted system and the earliest conceptual graph of the system. As such, modeling represents part of what is meant in the present report by Assimilated Knowledge.

Clearly, I would not want to suggest that all the problems of screen layout have been solved. Related papers [e.g., 11] on the topic of automatic circuit design further confirm the scope of such a challenge. Nevertheless, to allow more space to focus on the equally tough problems in specifying the nature of Assimilated Knowledge in the DAB model, further discussion of Drawing Knowledge will be herewith suspended. Because of its relevance to the problem of drawing by the KATE model, however, applause is issued for what researchers have done with Drawing Knowledge so far and encouragement is offered to keep up efforts along these lines.

4.3 Assimilated Knowledge

In one of the interviews described in Part V of this report, an experienced designer hinted at what has to be done before the drawing process is overtly initiated. When asked to elaborate on this planning process, he described taking field trips to carefully inspect and get to know the system to be drawn. If an electrical system was under consideration, lists of pin connections would be made, checked, and rechecked to ensure high accuracy. Overall, this preparatory stage was characterized as typically containing over 80% of the work involved in drawing.

Like a number of designers these days, the individual made extensive use of computer-aided design (CAD) programs to accelerate the actual drawing process. The almost trivial act of completing the remaining lines once the CAD templates had been put in place once again emphasized that establishment of the Base Knowledge and Assimilated Knowledge procedures constitute a major portion of the experienced designer's repertoire. Drawing Knowledge is important, but prior planning is essential.

Where then does the designer begin in creating or activating the Assimilated Knowledge needed prior to the overt expression of her drawing? The interview report of the designer in the paragraphs above suggests that, in humans, creation of a solid Base Knowledge is part of the planning process. If a thoroughgoing understanding of the Knowledge Base cannot be assumed, it is the designer's responsibility to create such a mental structure.

One way to create such a Base Knowledge is to physically interact with the system to be depicted. This might involve field visits to look at, possibly touch, and possibly dismantle the system to be understood. Conversations with other engineers or experts at the site of the system might also be exploited in order to rapidly establish the requisite understanding. In short, part of the contents of the Assimilated Knowledge component of the DAB model is an executive which can make high-level decisions about what to do to be sure all is known that needs to be known before starting the overt drawing process.

How can a system know it is missing key information without knowing exactly what it is that is missing? That is, how can a system know it should search for something if it doesn't know just what it is searching for? Such a "metasystem" process sounds altogether mysterious, yet need not be so. For example, an executive process such as the one described could merely ask if it was in the posession of a complete Base Knowledge for the system to be depicted. If not, the executive could initiate any or all of a list of activities (such as field trips or questions directed toward experts) which would heuristically lead toward completion of the missing Base Knowledge.

Creation of a Base Knowledge is not critical within KATE; presence of an intact Base Knowledge can be assumed. It should be noted that KATE does do some consistency checking. For example, KATE can determine if inputs and outputs are connected. This evaluation is in no way semantic, however. For example, KATE never asks if any configuration of parts makes reasonable sense. The problem of organizing the Base Knowledge component for drawing purposes, however, is an important area where the DAB model needs expansion. The question at issue is how can KATE achieve a meaningful parse of the system it is modeling in a way that it can capture functional as well as structural roles for the system's components. A related question is how KATE can subdivide the drawing problem into perceptual organization units or "chunks."

A good designer, like the one who reminded himself of the prior design of the XYZ project, should have an extensive repertoire of prior experience with drawings and a good system of retrieving more detailed memory of those drawings. The manner in which this access takes place is not immediately apparent, however.

This is not the place to launch a description of a novel analog memory retrieval scheme, but clearly something akin to continuous information access or image retrieval must be operating within Assimilated Knowledge processing. Consequently, a brief model will be sketched; elaboration and full development of this model of image recall will be deferred to others.

The problem is that when provided with discrete retrieval cues, how are continuous memory images accessed? Take Donald Norman's example... "As you approach from the outside the house you lived in three houses ago, did the door open on the left or the right?" How do discrete signals call forth continuous memory images?

Let's call the required memory process a Discrete to Analog Memory (DAM) retrieval system. DAM processing takes place by using the richly creative and generative imagery system [see 12] to build an analog image from the discrete question cues. Once established, the generated image could be matched to stored images hence triggering retrieval of the best matching continuous image in memory.

It is surprising no one has suggested anything like the presently proposed DAM system for recall of continuous experience, but I am not presently aware of such a system. Future research could be directed toward elaboration of tests of the implications of such a memory model.

In a nutshell then, the Assimilated Knowledge component of the DAB model requires a memory system which is capable of retrieval of continuous images stored in the designer's experience. For expository convenience, I have called this a DAM retrieval process.

A third possible aspect of the DAB model's Assimilated Knowledge processing is constraint of the proposed drawing on the basis of drawing standards in force within the professional community of the designer. Many engineers in the interviews summarized in Part V complained that the drawings shown to them during the interviews depicted the flow of fluids from right to left rather than the opposite way which they were used to seeing within the NASA community.

Because of my limited knowledge of engineering drawing and due to my short stay here at NASA, I have only a sketchy knowledge of such drawing standards. Nevertheless, some example constraints are as follows:

1. Put power supplies on the left.

2. Put electrical ground connections on the right.

3. Put sensor measurements and input commands on the top.

4. Put electro-mechanical components at the bottom.

5. Group similar devices on a horizontal line.

This third aspect of Assimilated Knowledge functioning will be called constraint processing. It could easily be argued that constraint processing should also be incorporated within the Drawing Knowledge stage of the DAB model, but it is realistic to believe these adjustments exert their influence as early as the Assimilated Knowledge stage. Constraint number five above, for example, suggests acknowledgement of repetition within the drawing is part of the planning that must take place before overt drawing is initiated. Therefore, it appears that both Drawing Knowledge and Assimilated Knowledge are subject to constraint processing.

The present elaboration of the Assimilated Knowledge component of the DAB model provides for three subprocesses or subsystems within it; namely, executive processes, DAM retrieval, and constraint processing. In future elaborations of the DAB model, additional processes surely must be incorporated into the Assimilated Knowledge component in order for it to function adequately. For now, however, it will consist of the present short list.

1. Executive Processes 2. DAM Retrieval 3. Constraint Processing

4.4 Evaluation of the DAB model

The greatest problem with the DAB model is its sketchiness and its incompletness. Given little prior work to go on in this area, however, the present modest start should perhaps not be discounted. Much more time needs to be devoted toward outlining the character of the critical stages of drawing, assimilated, and base knowledge. The Assimilated Knowledge component needs elaboration in particular. The three subprocesses suggested are at best a very rough first guess at what might belong in the Assimilated Knowledge stage. Executive processing seems essential, though in need of further development. Specification of behaviors and activities triggered by the executive processor in reaction to missing Base Knowledge information needs to be made. The operation of organizing components of the Base Knowledge on the basis of functional knowledge of those parts is a key shortcoming in the present early sketch of the Assimilated Knowledge component.

DAM retrieval, the process by which pertinent schemata are activated is clearly underdeveloped in its present form. Also, the locus of the constraint processing mechanism must be resolved. As noted earlier, the nature of the knowledge within the Assimilated Knowledge stage (declarative vs. procedural) should be specified in future extensions of the DAB model. Perhaps the lack of specificity with respect to the character of the Assimilated Knowledge component's information is a result of the preliminary character of the DAB model. Finally, the Base Knowledge and Drawing Knowledge processes are generally well understood. While knotty problems in the drawing processes supporting Drawing Knowledge must still be worked out, it is felt that the spotlight of attention should remain on the Assimilated Knowledge component for quickest progress.

At present, plans for a major overhaul of the DAB model are already underway. It appears that the general character of the Assimilated Knowledge component of the model is procedural. In the revision, Assimilated Knowledge will likely be replaced with a general functioning set of control processes which reorganize the declarative knowledge structures of the Base Knowledge to create and deliver layout procedures to the Drawing Knowledge component. In doing so, use would be made of semantic knowledge concerning real world functional properties of components.

Regardless of these shortcomings, the DAB model has provided the springboard to thinking about visual thinking that it was supposed to. Its lack of elaboration seems to point to a gap in our understanding about the productive processes which drive artistic expression. In many areas of psychology we know far more about comprehension processes than about the converse operations of production, such as in the area of language models [13]. The reasons for our difficulties in generating good models of production processes seems to stem from our inability to conduct rigorously controlled experiments to test hypotheses about production processes. The targets of comprehension, however, are far easier to manipulate and control, hence comprehension processes are better understood. Such a state of affairs, however, should not daunt our efforts to make reasoned guesses about production processes such as those involved in drawing operations.

The gap between our understanding of production and comprehension processes is even more exaggerated in the areas of perception and drawing than it is in theories of language. A visit to any reasonably stocked library will document this. Shelves and shelves of books can be found on the topic of perceptual processes, but while examples of drawings may exist, written works describing the information processing operations in drawing are scarce indeed. Two exceptions are the excellent texts by McKim [14, 15]. While these are not fully developed cognitive models of processing operations in drawing, they go beyond what is presented here to a fair degree. McKim's works on the topic of drawing models are highly recommended.

V. OTHER SUMMER RESEARCH ACTIVITIES

5.1 Background

Work on the current project began with orientation to the NASA community, preliminary efforts to define a summer project, and reading background literature. After two weeks, a research plan was established, a 10 page proposal was drafted and typed, and the project described in the remainder of this section was undertaken.

Another week was spent in locating and selecting schematics to be used and in securing tentative agreements with potential participants. Once the data were collected, the rough plan for this report (brief theory paper and summary of data collection procedures) was adopted. The remainder of Section V is a description of the data collection activities undertaken and is organized somewhat along the lines of a typical scientific report.

5.2 Introduction

To advance understanding of the manner in which electronic and mechanical drawings are produced, steps were taken to collect basic data concerning the processes by which experienced engineers comprehend such drawings. This approach tacitly asserts that knowledge of drawing comprehension processes is propaedeutic to theories of drawing production. As indicated in Section 4.4 of this report, scientific rigor in the investigation of comprehension can be expected to excede the control available for research on production processes. Later, as the efforts begun here are carried foreward, the assumption that production and comprehension processes are converse can be more carefully evaluated.

A common research method for discovering the mental processes behind intelligent behavior has been "concurrent protocol analysis" or the "think aloud method." Newell and Simon used this technique to evaluate a number of skills from problem solving and cryptarithmetic to chess ability. Their summary of these efforts [16] is considered classic reading in the area of artificial intelligence. See also [17].

Letovsky [18] provides a recent example of the use of concurrent protocol analysis in the study of comprehension processes. Letovsky gathered verbal protocols from professional computer programmers as they attempted to understand and modify a computer program. Efforts were made to catalog cognitive events as the programmers were engaged in the comprehension portion of their task. These event types were used to derive a computational model of the programmers' mental processes.

With the think aloud method, data collection is relatively rapid while the protocol analysis itself is painstakingly slow. Given the brief time available for the present fellowship activities, it was decided that a data base would be created which would consist of videotape recordings of eight experienced engineers each evaluating six schematic drawings.

Detailed analysis of the contents of those recordings will await further investigation resources of time and money.

The purposes of Section V of this report then are 1) to describe the visual materials and participants that were employed in creation of the videotape recordings and 2) to provide a record concerning details of method behind establishment of the tapes so as to help one understand their contents at a later time.

5.2 Method

5.2.1 Materials

The six drawings were selected from various sources suggested by engineers and staff in the Artificial Intelligence laboratory here at the Kennedy Space Center. In the order presented to each participant, the schematics employed were 1) Apollo - Skylab-I Launch Complex 39 Environmental Control System Mechanical System (79K00076; sheet 29), 2) ibid. (sheet 12), 3) Hypergol Fuel Deservicing System (79K09247; sheet 82), 4) Apollo - Skylab-I Condenser Water (79K00076; sheet 19), 5) Hypergol Fuel Deservicing System (79K09247; sheet 4), and 6) Red Wagon - Simulation of Liquid Hydrogen Loading System (unclassified).

Drawings 3 and 5 were electrical and the remainder were mechanical schematics. Most of the drawings were cropped to retain a portion of the drawing which was judged to be both somewhat coherent and at an intermediate level of complexity. If still in view, bottom titles to drawings were removed. In several mechanical drawings, a few labels (such as "water glycol tank") were obliterated to make the comprehension process more challenging. For managability, Drawing 4 was made smaller (.67 original size) with a reduction copy machine.

5.2.2 Participants

Eight experienced NASA and Boeing employees were used as participants. In the order they appear on the two videotapes, highest academic degrees and disciplines represented were as follows: 1) PhD-Mechanical Engineering, 2) BS-Chemical Engineering, 3) BS-Electrical Engineering, 4) BS-Electrical Engineering, 5) BS-Computer Science, 6) MS-Computer Science and Electrical Engineering, 7) PhD-Mechanical Engineering, and 8) BS-Mechanical Engineering. Mean age was 38.1 years and mean years of work experience was 10.6. There were seven males and one female represented.

5.2.3 Procedure

Participants were individually interviewed by the present author. When possible, attempts to build rapport were made with participants by informal chatting prior to videotaping.

Taping occurred in a large conference room (104 Engineering Design Laboratories). The tripod-mounted videotape camera (Panasonic model WV-CC60) was placed on a table adjacent to the six foot diameter round work table. The field of view captured about one-half of the table and included the drawings and the left arm and upper trunk of the interviewee.

Participants were read a set of general instructions describing the think-aloud method. Primarily, the instructions described the goals of the research project and encouraged participants to keep talking throughout the interview.

Following general instructions, a page of specific instructions used three sets of questions to orient participants to the task of understanding the schematics. Verbatum, these questions were:

1. **What does it do?** What does the item or parts of items in the schematic do? (What is the function of the components you see?)

2. **Talk about the drawing.** Why was the schematic drawn in this way? (Are there ways you could improve the drawing?)

3. **What goes with what?** Tell us specifically about any structural or functional relationships between components you see. (How do the parts of the drawings fit together?)

Participants were allowed to refer to the specific instructions sheet whenever they wished during the task.

At this point, the schematics were introduced one at a time. The interviewer prompted participants in a variety of ways as a means to keep them talking about the drawings. Interviews ranged from 20 to 45 minutes in duration.

5.3 Results

Without typed protocols or other means to assist evaluation of the interview results, analysis of the videotapes in presently quite limited. The ideas expressed were influential concerning creation of the DAB model described in Section IV of this report. In any event, the tapes provide a data base, which in addition to protocol analysis, could be used to evaluate specific hypotheses concerning processes during visual perception.

5.4 Discussion

Generally speaking, the interviews accomplished their purposes. Ideas concerning the drawing process were gathered and a database which could support a detailed protocol analysis was created.

Originally, a goal of the present procedures was to learn what "perceptual chunks" or visual organizing units were employed during the comprehension process. It is for this reason the third specific orienting question was framed to detect how parts of a drawing were grouped. Other types of task orientation were condidered and rejected. For example, Letovsky [18] asked his programmers to make a meaningful modification to the programs they were studying thereby indirectly forcing participants to comprehend the computer programs.

Limits of time, however, precluded this approach. Another orienting task, memorization in preparation for identification of the function of parts of the drawing in a test to follow, was dismissed because it was felt the direct methods used here would provide better access to perceptual organization units.

VI. CONCLUDING REMARKS

A problem clearly stated is a problem half solved. The present DAB model begins to show some of the problems that exist in the areas of automatic drawing and models of human drawing processes, yet it has really only scratched the surface of the problem in doing so. In spite of this, the DAB model is a beginning. If it serves as a challenge to others to go on to elaborate a more workable model, it will have served its purpose well.

It is unfortunate such a large-scale project was undertaken with severe time limitations. In the empirical phase of the present research also, greater planning could have structured the data collection procedures to good advantage. The analytical scheme of Letovsky [18], for example, is particularly admirable. Questions, conjectures, and searches were grouped together where possible into higher order structures called inquires. Further subdivisions within questions, conjectures, and searches created a highly useful taxonomy. Once classified, these cognitive events were used to make inferences about the types of knowledge structures that make up programming expertise. The types of knowledge include: programming language semantics, goals, plans, efficiency knowledge, domain knowledge, and discourse rules.

It was hoped that a similar classification scheme for verbal/cognitive events and hypothetical knowledge structures in engineers in the present task could be established but, because the protocol analysis of computer programmers and schematics readers differ widely, it was not possible to adapt Letovsky's scheme for the present purposes. It appears a system for the specific purpose of classifying statements about engineering drawings will need to be created.

In spite of these shortcomings, the positive contributions of the present work seem to be: 1) creation of a database consisting of verbal protocols of experienced engineers attempting to comprehend technical drawings, 2) stimulation of thinking about possible processes underlying the drawing process (i.e., the DAB model), and 3) definition of the problems of learning more about drawing processes. With respect the these criteria, the project has been a great success.

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