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Menlo Park, California 94025 · U.S.A.

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RESEARCH AND APPLICATIONS— ARTIFICIAL INTELLIGENCE

By B RAPHAEL L J CHAITIN R O DUDA
R E FIKES P E HART N J NILSSON

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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RESEARCH DIVISION
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Approved By

DAVID R BROWN, *Director,*
Information Science Laboratory

BONNAR COX, *Executive Director*
Information Science and Engineering Division

Copy No

ABSTRACT

This is a semiannual progress report about a program of research in the field of Artificial Intelligence. The research areas discussed include automatic theorem proving, representations of real-world environments, problem-solving methods, the design of a programming system for problem-solving research, techniques for general scene analysis based upon television data, and the problems of assembling an integrated robot system. Major accomplishments include the development of a new problem-solving system that uses both formal logical inference and informal heuristic methods, the development of a method of automatic learning by generalization, and the design of the overall structure of a new complete robot system. Eight appendices to the report contain extensive technical details of the work described.

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I INTRODUCTION

A. General

This is a report of progress during the past six months in a program of research into techniques and applications of the field of Artificial Intelligence. This field deals with the development of automatic systems, usually including general-purpose digital computers, that are able to carry out tasks normally considered to require human intelligence. Such systems would be capable of sensing the physical environment, solving problems, conceiving and executing plans, and improving their behavior with experience. Success in this research will lead to machines that could replace men in a variety of dangerous jobs or hostile environments, and therefore would have wide applicability for Government and industrial use.

This project began in October 1970 as a direct continuation of work performed and reported under previous contracts.[1]* Some of the work reported here has been partially supported by other, concurrent SRI projects whose goals are closely related to the general Artificial Intelligence problem. Such joint support is acknowledged below wherever relevant.

During the past six months we have written several Technical Notes, consolidating some of the results obtained both during the present project and toward the end of the previous project. The contents of these notes are summarized in the following sections of this report, and the complete notes are attached as appendices.

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*References are listed at the end of this report.

The balance of this section summarizes our general orientation, activities, and major results thus far in this project. Subsequent sections and appendices contain additional technical details.

B. Background

The basic goal of our work is to develop general techniques for achieving artificial intelligence. To this end, we are pursuing fundamental studies in several areas: problem solving, perception, automated mathematics, and learning. However, we find it productive to choose as a goal the creation of a single integrated system, and thus bring to a common focus the activities in these separate studies. Such a specific goal helps us define interesting research problems and measure progress towards their solutions.

Our research method has involved studies aimed at both short-term and long-term results. The short-term studies usually consist of first defining an "intelligent" task that is slightly beyond present capabilities for the system to perform, and then attempting to develop a specific solution for that task. Long-term studies are concerned with developing more general methods for achieving future intelligent systems. We believe that pursuing these two kinds of studies in parallel, and using short-term task domains as test beds for proposed long-term techniques, has been (and will continue to be) a fruitful research strategy.

C. The Problem

Our system consists of a mobile robot vehicle controlled by radio from a large digital computer. The principal goal is to develop software for the computer that, when used in conjunction with the hardware of the vehicle, will produce a system capable of intelligent behavior.

Before we changed computers (at the end of 1969), our robot system had achieved a primitive level of capabilities: It could analyze a simple scene in a restricted laboratory environment; plan solutions to certain problems, provided that exactly the correct data were appropriately encoded; and carry out its plans, provided nothing went wrong during execution. Therefore, when we began planning a new software system for controlling the robot from a new computer, we set more difficult short-term goals: The system is to be able to operate in a larger environment, consisting of several rooms, corridors, and doorways; its planning ability must be able to select relevant data from a large store of facts about the world and the robot's capabilities; and it must be able to recover gracefully from certain unexpected failures or accumulated errors.

We have not yet accomplished these goals. However, we have essentially completed the design and partial implementation of a system that we believe can exhibit such performance. This system differs from our previous robot system in several basic ways. We expect to demonstrate the new system before the end of the next six-month period.

D. Report Organization

The remainder of this progress report consists of four major sections and eight appendices, describing our current robot system and associated longer-term studies. We now present brief overviews of the contents of those sections.

Every integrated "artificially intelligent" system must contain several component elements. Some of these elements may define significant long-term research fields, as well as requiring short-term formulation as part of a current system. Section II describes our recent progress in several of these areas: logic, modeling, planning, and implementation language. Our logical inference research is still based upon the QA3.5

program for proving theorems in first-order predicate calculus. However, the basic inference rule (viz., resolution) has been considerably augmented by a variety of devices, e.g., predicate evaluation, heuristic equality substitution, and parametric terms, that enable close coupling between the general inference program and a particular problem domain.

How to model the real world is a basic problem in many AI systems. Our present approach is simpler than the dual geometric and symbolic models that we used in previous years, and is highly related to the logic system.

Part C of Section II describes our work on problem-solving systems. Our previous use of the logic system as the entire problem solver has been discarded in favor of a more efficient scheme that uses logical inference as a subroutine within a GPS-like[2] framework.

Finally, Section II-D reports on the status of a long-term effort to develop a new implementation language, QA4, that will simplify the programming of future problem-solving and logic systems.

Section III is devoted to the problems, and potential benefits, of assembling the components discussed above into a complete integrated system. First, we consider the nature of an executive program that can carry out plans generated by a problem solver like STRIPS. Second, we examine a proposed internal structure of the subroutines--the "Intermediate Level Actions"--that are called upon by the executive in order to accomplish things in the real world. This structure, based upon a Markov algorithm formalization, provides a conceptually easy way to specify methods for communication between subroutines and recovery from errors. Finally, the largest part of Section III describes a proposal for "bootstrap learning" by constructing and storing generalized plans. This promising technique for learning depends upon several of the previously discussed features of the overall robot system.

Section IV describes recent work in vision research. Short-term vision work has consisted of developing particular program packages, compatible with the rest of the system, for gathering visual data about an environment containing corridors and doorways. Longer-term studies of color and stereo vision have also been initiated.

Finally, Section V discusses the bottom-level software and hardware that make the rest of the research possible. This consists of the robot vehicle and its recent modifications, the PDP-10/PDP-15 computer systems, and the software that enables LISP and FORTRAN programs on the PDP-10 to control the vehicle by radio link from the PDP-15.

II INDEPENDENT RESEARCH STUDIES

A. Automatic Theorem Proving

QA3.5 is a question-answering system containing a resolution-based theorem-proving program for first-order predicate calculus, and various features for indexing axioms, extracting answers from proofs, and so on.[3] During the past few months, we have completed the implementation of an efficient version of QA3.5 on our PDP-10 computer, and added a variety of features that make QA3.5 usable as the logic component of a larger problem-solving system. In addition to a general clean-up of QA3 and its interface to other routines, we have made the following developments in the general area of theorem proving (all aimed at extending resolution to improve the effectiveness of automatic procedures):

Equality--A method was developed for using efficient tree-search heuristics for guiding the use of the "paramodulation" rule of inference for first-order logic with equality. This work is described in detail in Appendix A, and the method has been implemented and is available for experimentation.

Analogy--A study of reasoning by analogy has used QA3.5 proofs as a subject domain, and has concluded that automatic theorem proving can be aided by making appropriate use of analogies to similar proofs. This work is detailed in Appendix B.

Evaluation--For some time a "predicate evaluation" feature has been present in QA3.5, although this important innovation has not been adequately documented. The basic idea is that it is sometimes more efficient to use a special program to test the truth of a simple logical assertion than to deduce its truth from axioms. (For example, this technique

would permit the inclusion of arithmetic relations such as "3 > 2" in our axioms without axiomatizing arithmetic.) Such predicate-evaluation functions, if appropriately used, could eliminate the need for large (perhaps infinite) sets of axioms. QA3.5 contains provisions for inserting a broad class of predicate evaluation functions.

Parameters--Expressions of first-order logic in clause form, the standard form for all resolution-based theorem provers including QA3.5, contain two classes of individual symbols. constants, each of which has a unique identity (unless the equality relation between two of them can be proven), and variables, which are assumed to be universally quantified. We have discovered that a third class of individuals, parameters, would be extremely useful in problem-solving work and may have much wider significance in logic. The use of parameters in a mechanism for making an axiom set into a scheme of alternative possible axiom sets. A parameter is an unspecified constant. It may take on any--but only one--value during a proof (subject to certain limitations discussed below). For example, suppose we wish to use QA3.5 to determine a convenient initial placement for the robot before carrying out some task. We would like to assert that, in that initial configuration, the robot is someplace; and then let the particular place be chosen by the normal unification procedure of the theorem prover as it considers other relevant facts. However, if we encode, "The robot is someplace," by the existential assertion, (∃place)AT(Robot,place), i.e., "There exists a place where the robot is at," then the Skolemization process chooses a new constant to name the place and give us the clause AT(Robot,a), where a cannot be identified as any particular place that we know anything about (unless we introduce many more axioms and equality). On the other hand, if we try AT(Robot,v) where v is a universally quantified variable, v ranges over all the relevant constants, but we can also prove all kinds of silly false results (because we have asserted that the robot is everywhere at

at once). The solution is to use AT(Robot,p), where the parameter p is a new kind of individual that sometimes behaves like a constant and sometimes like a variable, giving just the appropriate results. We believe we have identified the appropriate behavior of parameters, and they are now available within QA3.5.

The basic property of any parameter is that it represents precisely a single element of a given domain. This property implies that parameter names (and, therefore, their interpretations) are global to the entire set of clauses involved in a QA3.5 proof (as opposed to variables, whose names are local to a single clause). This further requires that any parameter appearing in a proof tree have but one interpretation in that tree.

The allowed instantiations of a parameter are restricted in accordance with the above basic property. Bindings can be formed between a parameter and another parameter, or to a non-Skolemized (possibly parameterized) ground term only. It is illegal to bind a parameter to a variable, or a function of variables (i.e., a nonground term), as this allows a single parameter to represent a whole class of interpretations. Also, a parameter may not be instantiated by a term containing Skolem functions, since such terms represent new individuals, while parameters are intended to represent previously known (although perhaps not yet specified) individuals.

B. Models of the Environment

1. The Robot's World Model

As a result of our experience with the previous robot system and our desire to expand the robot's experimental environment to include several rooms with their connecting hallways, we have adopted new conventions for representing the robot's model of the world. In particular,

whereas the previous system had the burden of maintaining two separate world models (i.e., a map-like grid model and an axiom model), the new system uses a single model for all its operations (an axiom model); also, in the new system conventions have been established for representing doors, wall faces, rooms, objects, and the robot's status.

The model in the new system is a collection of predicate calculus statements stored as prenexed clauses in an indexed data structure. The storage format allows the model to be used without modification as the axiom set for STRIPS' planning operations (see Appendix C) and for QA3.5's theorem-proving activities.

Although the system allows any predicate calculus statement to be included in the model, most of the model will consist of unit clauses (i.e., consisting of a single literal) as shown in Table 1. Nonunit clauses typically occur in the model to represent disjunctions (e.g., box2 is either in room K2 or room K4) and to state general properties of the world (e.g., for all locations loc1 and loc2 and for all objects ob1, if ob1 is at location loc1 and loc1 is not the same location as loc2, then ob1 is not at location loc2).

We have defined for the model the following five classes of entities: doors, wall faces, rooms, objects, and the robot. For each of these classes we have defined a set of primitive predicates which are to be used to describe these entities in the model. Table 1 lists these primitive predicates and indicates how they will appear in the model. All distances and locations are given in feet and all angles are given in degrees. These quantities are measured with respect to a rectangular coordinate system oriented so that all wall faces are parallel to one of the X-Y axes. The NAME predicate associated with each entity allows a person to use names natural to him (e.g., halldoor, leftface, K2090, etc.) rather than the less-intuitive system-generated names (e.g., d1, f203, r4450, etc.).

Table 1

PRIMITIVE PREDICATES FOR THE ROBOT'S WORLD MODEL

Primitive Predicate	Literal Form	Example Literal
FACES		
type	type(face"face")	type(f1 face)
name	name(face name)	name(f1 leftface)
faceloc	faceloc(face number)	faceloc(f1 6.1)
grid	grid(face grid)	grid(f1 g1)
boundsroom	boundsroom(face room direction)	boundsroom(f1 r1 east)
DOORS		
type	type(door"door")	type(d1 door)
name	name(door name)	name(d1 halldoor)
doorlocs	doorlocs(door number number)	doorlocs(d1 3.1 6.2)
joinsfaces	joinsfaces(door face face)	joinsfaces(d1 f1 f2)
joinsrooms	joinsrooms(door room room)	joinsrooms(d1 r1 r2)
doorstatus	doorstatus(door status)	doorstatus(d1 "open")
ROOMS		
type	type(room"room")	type(r1 room)
name	name(room name)	name(r1 K29090)
grid	grid(room grid)	grid(r1 g1)
OBJECTS		
type	type(object"object")	type(o1 object)
name	name(object name)	name(o1 box1)
at	at(object number number	at(o1 3 1 5 2)
inroom	inroom(object room)	inroom(o1 r1)
shape	shape(object shape)	shape(o1 wedge)
radius	radius(object number)	radius(o1 3 1)
ROBOT		
type	type("robot""robot")	type(robot robot)
name	name("robot"name)	name(robot shakey)
at	at("robot" number number)	at(robot 4.1 7.2)
theta	theta("robot"number)	theta(robot 90.1)
tilt	tilt("robot"number)	tilt(robot 15.2)
pan	pan("robot"number)	pan(robot 45 3)
whiskers	whiskers("robot"integer)	whiskers(robot 5)
iris	iris("robot"integer)	iris(robot 1)
override	override("robot"integer)	override(robot 0)
range	range("robot"number)	range(robot 30.4)
tvmode	tvmode("robot"integer)	tvmode(robot 0)
focus	focus("robot"number)	focus(robot 30.7)

Figure 1 shows a sample environment and a portion of the corresponding world model. Rooms are defined as any rectangular area, and therefore the hallway on the left is modeled as a room. There is associated with each room a grid structure that indicates which portions of the room's floor area have not yet been explored by the robot. During route planning the grid is employed to help determine if a proposed path is known blocked, known clear, or unknown.

Four wall faces are modeled in Figure 1. The FACELOC model entry for each face indicates the face's location on either the X or Y coordinate depending on the face's orientation. There is associated with each face a grid structure to indicate which portions of the wall face have not yet been explored by the robot. This grid is used in searching wall faces for doors and signs.

Two doors are modeled in Figure 1. The DOORLOC model entry for each door indicates the locations of the door's boundaries on either the X or Y coordinate, depending on the orientation of the wall in which the door lies. Any opening between adjoining rooms is modeled as a door, so that the complete model of the environment diagrammed in Figure 1 would have a door connecting rooms R1 and R3. This door coincides with the south face of room R3 and will always have the status "open."

The RADIUS and AT model entries for the object modeled in Figure 1 define a circle circumscribing the object. These entries simplify the route-planning routines by allowing each object to be considered circular in shape. Our current set of primitive predicates for describing objects is purposely incomplete; we will add new predicates to the set as the need for them arises in our experiments.

We do not wish to restrict the model to only statements containing primitive predicates. The motivation for defining such a predicate class is to restrict the domain of model entries that the robot action

ROOMS

type(r1 room)
name(r1 mainroom)
grid(r1 g1)

type(r2 room)
name(r2 office)
grid(r2 g2)

type(r3 room)
name(r3 hall)
grid(r3 g3)

FACES

type(f1 face)
name(f1 nfrl)
faceloc(f1 15 0)
grid(f1 g4)
boundsroom(f1 r1 north)

type(f2 face)
name(f2 sfr2)
faceloc(f2 15 5)
grid(f2 g5)
boundsroom(f2 r2 south)

type(f3 face)
name(f3 wfr2)
faceloc(f3 5 0)
grid(f3 g6)
boundsroom(f3 r2 west)

type(f4 face)
name(f4 efr3)
faceloc(f4 4 5)
grid(f4 g7)
boundsroom(f4 r3 east)

DOORS

type(d1 door)
name(d1 officedoor)
doorlocs(d1 10.0 12 5)
joinsfaces(d1 f1 f2)
joinsrooms(d1 r1 r2)
doorstatus(d1 open)

type(d2 door)
name(d2 halldoor)
doorlocs(d2 22 5 25 0)
joinsfaces(d2 f4 f3)
joinsrooms(d1 r3 r2)
doorstatus(d2 closed)

OBJECTS

type(o1 object)
name(o1 box)
at(o1 14 1 20 3)
inroom(o1 r2)
shape(o1 rectangular)
radius(o1 1 5)

ROBOT

type(robot robot)
name(robot shakey)
at(robot 7 3 10 4)
theta(robot 90)

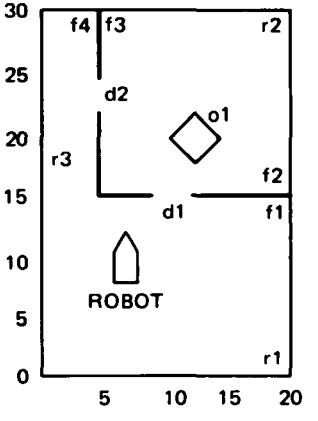

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FIGURE 1 EXAMPLE MODEL

routines have responsibility for updating. That is, it is clear that the action routine that moves the robot must update the robot's location in the model, but what else should it have to update? The model may contain many other entries whose validity depends on the robot's previous location (e.g., a statement indicating that the robot is next to some object), and the system must be able to determine that these statements may no longer be valid after the robot's location has changed.

We have responded to this problem by assigning to the action routines (discussed in Section IV-B) the responsibility for updating only those model statements which are unit clauses and contain a primitive predicate. All other statements in the model will have associated with them the primitive predicate unit clauses on which their validity depends. When such a nonprimitive statement is fetched from the model, a test will be made to determine whether each of the primitive statements on which it depends is still in the model; if not, then the nonprimitive statement is considered invalid and is deleted from the model. This scheme, which is also discussed in Section 2 of Appendix C, ensures that new predicates can be easily added to the system and that existing action routines produce valid models when they are executed.

2. Model-Manipulating Functions

We have designed and programmed a set of LISP functions for interacting with the world model. These functions are used both by the experimenter (as he defines and interrogates the model) and by other routines in the system to modify the model. To the experimenter at a teletype, these functions are accessible as a set of commands. A brief description of these commands follows.

ASSERT--This is the basic command for entering new axioms into the model. The user follows the word ASSERT by either CUR or ALL to

indicate whether the entries are to be for the current model or are to be considered part of all models. The system then prompts the user for predicate calculus statements to be typed in using the QA3.5 expression input language. After each statement is entered, the system responds with "OK" and requests the next statement. To exit the ASSERT mode the user types "↑."

FETCH--This is the basic command for model queries. The user follows the word FETCH by an atom form, and the system types out a list of all unit clauses in the model that match the form. Each term in an atom form is either a constant or a dollar sign. The dollar sign indicates an "I don't care" term and will match anything. The last term of an atom form can also be the characters "$*" to indicate an aribtrary number of "I don't care" terms. For example, the atom form "(AT ROBOT $*)" will fetch the location of the robot, and the atom form "(INROOM $ R1)" will fetch a list of model entries indicating each of the objects in room R1.

DELETE--This is the basic command for removing statements from the model. The user follows the word DELETE by an atom form, and the system deletes all unit clauses in the model that match the form. Atom forms have the same syntax and semantics for the DELETE command as described above for the FETCH command.

REPLACE--This is a hybrid command combining the operations of DELETE and ASSERT. The user follows the word REPLACE by an atom form and by a predicate calculus statement. The system first deletes all unit clauses in the model matching the atom form and then enters the statement into the model. This command is useful for operations such as changing the robot's position in the model, indicating in the model that a previously closed door is now open, and so forth.

3. Long-Term Modeling Studies

We have been investigating some different ways of representing the robot's model of the world, for possible use in future system implementations. In particular, we will need to represent a large store of knowledge of the world, hopefully including many objects, actions the robot can take, and general principles about the world in which it resides. Until now we have only used small domains for specific problems and have not entirely faced the problem of a lot of information in one model.

The main concentration so far has been on comparing semantic nets with the first-order predicate calculus representations now used. Preliminary study seems to indicate that either can be used to make a reasonable model for the robot. One major concern is that the system have the ability to make inferences from the model--so the robot can solve the problems posed to it. So far, we have not found any inference mechanism for semantic nets that has the formal completeness of the resolution-based theorem prover, QA3.5, that we now use. The net structure does, however, have the advantage of directing one's attention to pertinent information to be used in the deduction. This is of particular importance when the amount of information in the model is large in comparison with the amount needed to solve a specific problem.

A possible next step is to see if we can develop an inference scheme for semantic nets which has some of the formal completeness properties of logic. Another approach is to try to incorporate semantic information into QA3.5 to guide the resolution toward the axioms pertinent to the current problem. Because we already have a working theorem prover, and are getting some experience in resolution strategies, the latter approach seems the one to pursue.

Another method of representation that has been used recently entails encoding information in procedures rather than data structures. During the next six months we plan to explore this alternative, particularly with respect to using the QA4 language (see Section II-D).

C. Problem-Solving Studies

A problem-solving process generally consists of two parts: planning a solution, and executing the plan. Most previous work in heuristic problem solving has really been concerned with the planning aspects, since interesting problems of execution do not arise until a complete robot system has been created. We shall delay discussion of our work on the execution phase of problem solving until Section III of this report.

The need for a new planning program for our robot system followed from our decisions, discussed above, to enlarge the robot's environment (by adding rooms and hallways), and to model the world by predicate-calculus formulas. In the new experimental environment a world model will contain 100 or more formulas. The complexity of these models raised certain difficulties with previously developed problem-solving systems, and led to the design of a new problem-solving system.

The first difficulty was that our world models are too large for any problem solver to create a complete new world model at each step in its search. That is, when a problem solver considers some action taken in the world, it creates a new model to indicate the state of the world after the action. Typically, this new model is formed by copying the old model and then making the changes implied by the action in the copy. For our models this process would be extremely costly in both memory space and computing time. Our response to this problem was to establish conventions for representing a model as a set of changes from the initial model given to the problem solver. That is, each model created during

the problem-solving process is represented by two lists: one of formulas that exist in that model but do not exist in the initial model, and the other of formulas that exist in the initial model but do not exist in the new model. Since most formulas in a model are not changed by an action, the two lists representing each new model contain only a small number of formulas (usually less than about ten) and can be managed efficiently.

The second difficulty was that for large models, the use of axioms to represent the effects of action routines, our previous planning method, becomes extremely clumsy. That is, in our previous automaton system each model change produced by an action was described by an axiom. Unfortunately, it was also necessary to include axioms describing all those portions of the model that were <u>not</u> changed by an action. (This latter set of axioms allowed the system to produce those portions of the new model which were unchanged from the old model when an action was applied.) The problems with this scheme are basically twofold: First, a large number of axioms need to be written by a person in order to describe an action to the system; and secondly, when the problem solver applies an action to a model it must perform a deductive step using one of these axioms to produce each portion of the new model. Large world models amplify these problems to the extent that the problem solver becomes completely impotent. Reference 4 discusses these problems more fully.

We have responded to this second difficulty by removing the descriptions of actions from the predicate calculus. We provide a form for describing actions that requires only that the person indicate the changes produced by the action. The assumption is made that all portions of the model not mentioned in an action description are not changed by the action. This assumption enables concise action descriptions to be written with little effort. Our new problem-solving program, which we call STRIPS (STanford Research Institute Problem Solver), contains an action-application

routine, which takes as input a world model and an action description, and produces as output the model that would be produced by applying the action to the input model. This routine uses the "change list" world-model representation discussed above and is quite efficient, even with large models.

The third difficulty we have responded to in our new system is that of providing the problem solver with powerful heuristics for guiding its search for a plan. In our previous system, all the search was carried out by the theorem prover, QA3.5. Although the search heuristics in QA3.5 may be adequate for proving theorems, they are unacceptably weak when used to conduct the search for a plan in a space of world models. Again, this difficulty is accentuated by the large models we are now using. We have responded to this difficulty by designing STRIPS so that standard graph-searching techniques can be applied to its search for a solution. We may consider STRIPS to be searching in a space of world models for a path from the initial model to a model in which a given goal predicate is satisfied. During its search it uses the action-application routine discussed above to create new models, and it uses the theorem prover, QA3.5, to ask questions of any given model (e.g., Is the goal true in this model?). Hence, it can employ powerful heuristic-search techniques to determine which action application to consider next, and it can use QA3.5's powerful deductive techniques to determine properties of individual world models.

The primary search strategy employed by STRIPS is means-ends analysis. This strategy, borrowed from GPS,[2] uses the following basic technique: Given a world model and a goal, compare the two to determine a difference between them, select an action that is relevant to reducing the difference, establish a new subgoal of achieving a world model to which the relevant action can be applied, and repeat the process to achieve the new subgoal.

This strategy provides STRIPS with a strong sense of direction toward a goal and has produced very encouraging results with the problems we have given to the program. (STRIPS is described more fully in Appendix C.)

D. Language Development

During the past six months this project has participated in the support of the design and implementation of a new programming language, QA4. (QA4 development is primarily supported by SRI Project 8721 under Contract NASW-2086 with NASA.) QA4 contains a novel combination of features that promise to make it more useful for programming theorem-proving and problem-solving systems than any existing language. Appendix D contains a general description of QA4.

The QA4 programming language has reached a first major milestone in its development. Micro-QA4 is implemented. This restricted version of the full QA4 language lacks only the more advanced control statements and the complete pattern matcher. It includes the following debugged program packages:

- Input-Output--A parsing system that converts the mathematical style infix notation of the QA4 language to internal format.
- Expression Storage--A set of programs that:
  (1) Store QA4 expressions in a discrimination net and recognize equivalence of sets and expressions with bound variables.
  (2) Store and retrieve properties of expressions with respect to QA4 "contexts," automatically handling process-variable bindings and backtracking.
- QA4 Evaluator--A set of programs that:

(1) Evaluate all the QA4 primitive functions (e.g., PLUS and UNION).

(2) Execute QA4 statements (e.g., IF and GO).

(3) Work in small nonrecursive steps so that time can be shared between parallel processes.

Features such as backtracking, process-control structures, set operations, and tuple pattern matching make Micro-QA4 suitable for experimenting and testing designs for future heuristic programs.

The immediate plans are to finish the pattern matcher and complete the implementation of the control and strategy statements. The resulting initial version of the full QA4 language will then be used for the construction of theorem provers and automatic program writers. Throughout the implementation, however, we have consistently used general data structures and clear program design instead of the specific structures and tight code dictated by space and time considerations. Thus, as we use the language, we expect to enter an iterative cycle of modification and extension. As we gather statistics we can properly optimize, and as we discover language deficiencies we can extend the semantics.

III ASSEMBLING AN INTEGRATED ROBOT SYSTEM

A. The Executive

One of the difficulties in devising a robot system is that of providing feedback during the execution of plans. That is, since a plan produced by STRIPS must be executed in the real world by a mechanical device (as opposed to being carried out in a mathematical space or by a simulator), consideration must be given to the possibility that operations in the plan may not accomplish what they were intended to, that data obtained from sensory devices may be inaccurate, and that mechanical tolerances may introduce errors as the plan is executed. Hence, we wish STRIPS to provide information in a plan that will allow the executor to determine whether each of the plan's actions is achieving the desired result in the real world. The executor can then use this information to recognize failures as they occur during plan execution, and can take appropriate steps (e.g., initiate replanning) to put the system back on a course toward the goal.

Appendix D describes algorithms for including the needed information in STRIPS plans and for using that information during plan execution. These algorithms produce and use a plan containing steps of the following form:

```
Bi:BEGIN
      FAILTEST⟨predicate-calculus formula⟩FOR Bj1,Bj2,...,Bjn;
      FAILTEST⟨predicate-calculus formula⟩FOR Bk1,Bk2,...,Bkm;
      .
      .
      .
      IF⟨preconditions for action_1⟩THEN DO action_i
        ELSE GOAL⟨relevant results of action_1⟩
   END;
```

The predicate-calculus formulas in the FAILTEST statements indicate what STRIPS expects to be true in the world model at this point in the plan. If one of these formulas is not true, then the executor deletes those subsequent portions of the plan having the labels, Bxy, listed in the right side of the FAILTEST statement; that is, STRIPS determines that the portions of the plan being deleted cannot produce the desired results unless the formula in the FAILTEST statement is true, and therefore they should not be executed. The IF statement in the plan tests to see whether the next action in the plan ($action_1$) is applicable to the model. In the case where it is, then the action is executed; in the case where it is not, a replanning effort is initiated with the goal being the model changes that $action_1$ was expected to make. If a replanning effort succeeds, then the new plan takes the place of the IF statement in the old plan and execution proceeds as before. These plan formation and execution schemes are designed to provide continual checking on the progress of plan execution and to allow a productive interaction between the planning and execution sections of the system.

A comment is in order on the status of this work. The world-model maintenance routines and the STRIPS problem solver exist as running programs. The mechanisms for creating and executing the FAILTEST and IF statements in plans have been specified but have not yet been coded. We have successfully run STRIPS with several example problems and are engaged in experimenting with various search heuristics for it. We have not yet had the opportunity to put the entire system together and input a problem, have STRIPS produce a plan, and then have an executor carry out the plan. The primary missing link presently is a set of intermediate-level action routines (described below) for the robot. These should be completed shortly, and we expect to be able to exercise the entire system in the next few months.

B. Intermediate-Level Actions

1. Introduction

A planning program such as STRIPS assumes the existence of certain action routines that enable the robot to interact with the world. Thus far in this report we have assumed the availability of some such set of routines, with their preconditions and effects assumed to be formalized and known to the problem solver. Now we face the task of actually creating an appropriate set of routines.

As with most programming tasks, the problem of programming robot actions is simplified when it is done in terms of well-defined subroutines. At the lowest level it is natural to define routines that have a direct correspondence with low-level robot actions--routines for rolling, turning, panning, taking a range reading, taking a television picture, and so forth. However, these routines are too primitive for high-level problem solving. Here it is desirable to assume the existence of programs that can carry out tasks such as going to a specified place or pushing an object from one place to another. These intermediate-level actions (ILAs) may possess some limited problem-solving capacity, such as the ability to plan routes and recover from certain errors, but the ILAs are basically specialized subroutines. None of these routines has as yet been written. However, considerable thought has been devoted to their design, and this section describes our plans for a set of ILAs that are suitable for use with the STRIPS problem-solving system. (Low-level actions, the robot's elementary hardware capabilities, are described in Section V of this report.)

Perhaps the most difficult problem that confronts the designer of ILAs is the problem of detecting and recovering from errors. Sometimes errors are detected automatically, as when an interrupt from a touch sensor indicates the presence of an unexpected obstacle. Other

times it is necessary to make explicit checks, such as checking to be sure that a door is open before moving through it. When an error is detected, the problem of recovery arises. This problem can be very difficult, and is one aspect that distinguishes work in robotry from other work in artificial intelligence.

It is natural to think of an intermediate-level action as a composition of somewhat lower-level actions, which in turn are compositions of lower-level actions. While this hierarchical organization possesses many advantages (and is in fact the organization that we use), it is not ideally suited for error recovery. Errors are made most frequently at low levels by routines that are too primitive to cope with them. An error message may have to be passed up through several levels of routines before reaching one possessing sufficient knowledge of both the world and the goal to take corrective action. If any routine can fail in several ways, this presents the highest-level routine with a bewildering variety of error messages to analyze, and requires explicit coding for a large number of contingencies.

To circumvent this problem, we have chosen to have the subroutines communicate through the model. With a few special exceptions, neither answers nor error messages are explicitly returned by subroutines. Instead, each routine uses the information it gains to update the model. It is the responsibility of the calling routine to check the model to be sure that conditions are correct before taking the next step in a sequence of actions. Detection of an error causes returns through the sequence of calling programs until the routine that is prepared to handle that kind of error is reached. In the following sections we describe in more detail the formal mechanism by which this is done.

2. The Markov Algorithm Formalization

a. General Considerations

The formal structure of each ILA routine is basically that of a Markov algorithm.* Each routine is a sequence of statements. Each statement consists of a statement label, a predicate, an action, and a control label. When a routine is called, the predicates are evaluated in sequence until one is found that is satisfied by the current model. Then the corresponding action is executed. The control label indicates a transfer of control, either to another labeled statement or to the calling routine.

Table 2 gives a specific example of an ILA coded in this form. This routine, gotoadjroom (room1, door, room2), is intended to move the robot from room1 to room2 through the specified door. The first test made is a check to be sure that the robot is in room1. If it is not, an error has occurred somewhere. Since this routine is not prepared to handle that kind of error, no action is taken, and control is returned to the calling routine. The subroutine return is indicated by the "R" in the control field.

Under normal circumstances, the first two predicates will be false. The third predicate is always true, and the corresponding action sets the value of a local variable "s" to give the status of the door. The function "doorstatus" computes this from the model, and evaluates to either OPEN, CLOSED, or UNKNOWN. Rather than tracing through all of the possibilities, let us consider a normal case in which the door is open but the robot is neither in front of nor near it. In this

---

*It also bears a close resemblance to Floyd-Evans productions.

Table 2

SUBROUTINE GOTOADJROOM(ROOM1,DOOR,ROOM2)

Label	Predicate	Action	Control
1	~ in(room1)		R
2	in(room2)		R
3	T	setq(s,doorstatus(door))	4
4	infrontof(door)∧eq(s,OPEN)	bumblethru(room1,door,room2)	2
	near(door)∧eq(s,OPEN)	align(room1,door,room2)	4
	near(door)∧eq(s,UNKNOWN)	doorpic(door)	3
	eq(s,CLOSED)		R
	T	navto(nearpt(room1,door))	4

case, the action taken is the last one, navto(nearpoint(room1,door)). Here the function "nearpoint" computes a goal location near the door. The function "navto" is another ILA that plans a route to the goal point and eventually executes a series of turns and rolls to get the robot to that goal. Of course, unexpected problems may prevent the robot from reaching that goal. Nevertheless, whether navto succeeds or fails, when it returns to gotoadjroom the next predicate checked will be that of statement 4. If navto succeeds and the robot is actually in front of the door, the bumblethru routine will be called to get the robot into room2. If navto had failed and the robot is not even near the door, navto will be tried again. Clearly, this exposes the danger of being trapped in fruitless infinite loops. We shall describe some simple ways of circumventing this problem shortly.

b. Predicates and Actions

The predicates used in the ILAs have the responsibility of seeing that preconditions for an action are satisfied. In general,

the evaluation of predicates is based on information contained in the model. If this information is incorrect, the resulting action will usually be inappropriate. However, the act of taking such an action will frequently expose errors in the model. When the model is updated (which typically occurs after bumping into an object or analyzing a picture), the values of predicates can and do change. Thus, the values of the predicates will depend on the way the execution of the ILA proceeds, and will steer the routine into (hopefully) appropriate actions when errors are encountered.

The actions can be any executable program. The most common actions are to compute the values of local variables, update the model, call picture-taking routines that update the model, or call other ILAs. Only the first of these causes any answers to be returned directly to the calling program. This constraint of communicating through the model occasionally leads to computational inefficiencies. For example, the very computation used by one routine to determine that it has completed its job successfully may be repeated by the calling routine to be sure that the job has been done. While some of these inefficiencies could be eliminated with modest effort, they appear to be of minor importance compared to the value of having a straightforward solution to the problem of error recovery.

c. Loop Suppression

We mentioned earlier that the failure of a lower-level ILA might result in no changes in the model that are detected by the calling ILA. In this case, one can become trapped in an infinite loop. There are a number of ways to circumvent this problem. Perhaps the most satisfying way would be to have a monitor program that is aware of the complete state of the system, and that could determine whether or not the actions being taken are bringing the robot closer to the goal.

An alternative would be to have each ILA keep a record of whether or not its actions are leading toward the solution of its problem.

The simplest kind of record for an ILA to keep is a count of the number of times it has taken each action. In many cases, if an action has been taken once or twice before, and if the predicates are calling for it to be taken again, then the ILA can assume that no progress is being made and return control to the calling program. This strategy can be improved by computing a limit on the number of allowed repetitions, and making this limit depend on the task. For example, if the action is to take the next step in a plan, the limit should obviously be related to the number of steps in the original plan. Both of these strategies can be criticized on the grounds that they are indirect and possibly very poor measures of the progress being made. However, they constitute a frequently effective, simple heuristic, and will be used in our initial implementation of the ILAs.

d. Status and Implementation

As mentioned earlier, none of the ILAs has been implemented to date. However, some 15 have been sufficiently well defined to allow coding to begin. These are listed in Table 3, together with the ILAs that they call. The specification of the ILAs has also led to the specification of a number of specialized planning and information-gathering routines. The planning routines include programs for planning pushing sequences, tours from room to room, and trips within a single room. These will be developed along the lines of the navigation routines that were one of our earliest efforts on this project. The information-gathering routines are primarily special-purpose programs for processing television pictures. For example, PICLOC is a special-purpose routine that uses landmarks to update the location of the robot, and CLEARPATH

Table 3

INTERMEDIATE LEVEL ACTIONS. ROUTINES MARKED BY ASTERISKS ARE VIEWED AS PRIMITIVE ROUTINES.

ILA	Routines Called	Comments
PUSH3	PLANOBMOVE*, PUSH2	Can plan and execute a series of PUSH2's
PUSH2	PICLOC*, OBLOC*, NAVTO, ROLLBUMP, PUSH1	Check if object being pushed slips off
PUSH1	ROLL*	Basic push routine; assumes clear path
GETTO	GOTOROOM, NAVTO	Highest level go-to routine
GOTOROOM	PLANTOUR*, GOTOADJROOM	Can plan and execute a series of GOTOADJROOM's
GOTOADJROOM	DOORPIC*, ALIGN, NAVTO, BUMBLETHRU	Tailored for going through doorways
NAVTO	PLANJOURNEY*, GOTO1	Can plan and execute a trip within one room
GOTO1	CLEARPATH*, PICDETECTOB*, GOTO	Recovers from errors due to unknown objects
GOTO	PICLOC*, POINT, ROLL2	Executes single straight-line trip
POINT	PICTHETA*, TURN2	Orients robot toward goal
TURN2	TURNBACK*, TURN1	Responds to unexpected bumps
TURN 1	TURN*	Basic turn routine; expects no bumps
ROLL2	ROLLBACK*, ROLL1	Responds to unexpected bumps
ROLL1	ROLL*	Basic roll routine that expects no bumps
ROLLBUMP	ROLLBACK*, ROLL1	Basic roll routine that expects a terminal bump

analyzes a picture to see whether or not the path to the goal is clear. (The status of these routines is described in Section IV of this report.)

One aspect of implementing the ILAs that has not yet been resolved concerns whether the ILAs should be written as ordinary LISP programs, or should be kept in tabular form as data for an interpreter. It is quite easy to go from a representation such as that in Table 1 to a LISP program realization; the basic structure is merely a COND within a PROG. However, the use of an interpreter would simplify the implementation of the loop suppressor, and would also simplify monitoring and the incorporation of diagnostic messages. In addition, the same program that interprets the ILAs might be used to interpret the plans produced by STRIPS; that is, the Markov algorithm structure of ILAs is similar to the FAILTEST structure of STRIPS-produced plans so that, if we can make these structures identical, the same executive program will be usable for both. Uniformity in program structure is also important for the plan generalization ideas (to be discussed in the following section). Final decisions on ILA implementation will be made in the near future.

C. The Construction of Generalized Plans

1. Introduction

There are several senses in which a program or machine can be said to learn. A robot may "learn" about the physical objects in its environment; for example, it may discover the presence of a doorway at some particular location. In another sense, a program may "learn" the values of parameters through what is essentially an estimation process; for example, threshold levels may be set in a picture-processing program on the basis of average light levels. In a third sense, a program may "learn" (i.e., remember) solutions of earlier problems in order to solve later problems. This form of learning, which we term bootstrap learning,

has been the subject of much interest but few serious investigations in artificial intelligence.[5] This section presents some preliminary results in this area, based upon the robot system organization described in previous sections.

We consider bootstrap learning within the context of the STRIPS problem-solving program that composes sequences of ILA operators to manipulate objects in a domain. In this setting we envision a problem-solving program that can store a solution to a problem in some appropriate form and use this information to help solve a subsequent (and possibly more difficult) problem. The solution to the new problem can also be stored, and so on through a progression of increasingly difficult problems.

Perhaps the most important advantage of bootstrap learning in this context has to do with reducing the amount of search done by the problem-solving program. The solution to a problem involves searching for appropriate sequences of operators; composing longer sequences of operators requires more search. If bootstrap learning can be accomplished, then a "useful" or "powerful" sequence of primitive operators is available to the problem-solving program as a single operator and the combinatorics of the search thereby reduced.

2. Parameterization of a Sequence of Operators

a. The Need for Parameterization

Let us consider the following very simple problem. A room contains a box named BOX1 at Position 1 and another box named BOX2 at Position 2. Using a robot initially at Position 3, capable of moving through the room and pushing boxes, the problem is to create a state in which BOX1 and BOX2 are at the same place. (We ignore here for simplicity the refinement that two boxes cannot be literally at the same place, but only near each other.) Using the primitive operators

GO(initial position, final position)

and

PUSH(box, initial position, final position) ,

we would expect STRIPS (or any other competent problem-solving program) to compose a sequence of primitive operators such as the following:

GO(3,1)

PUSH(BOX1,1,2) .

While this sequence solves the stated problem, it is unlikely that we would want to save it for future use because the solution is in terms of constants. Unless there is some special reason to believe that we will again be in a state characterized by BOX1 being at Position 1, BOX2 at 2, and the robot at 3, this particular sequence of instantiated primitive operators will be useless. It would be far more useful if the entire situation were expressed in parametric form. Using the previous situation as an example, we would prefer to save for future use information of the following sort, where all symbols written in lower case letters are parameters and AT is a predicate with the obvious interpretation:

Starting from the state

AT(oba,a), AT(obb,b), AT(ROBOT,c) ,

the sequence of primitive operators

GO(c,a) ,

PUSH(oba,a,b)

produces a state in which oba and obb are at the same place--namely, b. In this section we shall present a means for producing a parameterized sequence of operators using STRIPS as the basic problem-solving program.

b. Solving Parameterized Problems with STRIPS

There appear to be two distinct approaches to the problem of producing a parameterized sequence of operators using the STRIPS problem solver: We can use STRIPS to solve a specific problem and seek ways to generalize the arguments of operators from constants to parameters, or we can generalize the problem statement so that it is in terms of parameters only and seek ways to modify STRIPS so that it can solve parameterized problems. Surprisingly, perhaps, the second of these two approaches has proven to be the fruitful one. Following this approach, the modification to STRIPS is as follows:

(1) Replace every constant in the description of the initial state by a distinct parameter symbol. (Multiple occurrences of the same constant lead to differently named parameters.) For each parameter symbol, create a "binding" that binds it to the constant it replaces.

(2) Similarly, replace each constant in the goal statement with a distinct parameter symbol. Bind each parameter to the constant it replaces.

(3) When performing resolutions within QA3, parameters obey the rules for parameter bindings as discussed in Section II-A. However, no parameter is ever actually replaced by its binding in a logical expression. Instead, separate lists are used to keep track of parameter bindings, and the logical unification operation must be aware of this special bookkeeping.

Upon completing the solution to a problem, STRIPS produces a sequence of primitive operators whose arguments are parameters. If all parameters bound to constants are in fact replaced by those constants, we will have precisely the sequence of instantiated operators produced by the existing, unparameterized problem solver.* Remarkably, the STRIPS search for a solution to the parameterized problem is isomorphic to the search for a solution to the unparameterized problem . Thus no more effort is expended in producing the general solution than would be expended in producing the specific solution.

3. Construction of a Plan Description

Once STRIPS has solved a problem and generated a parameterized plan, we can make it into a new complex operator to be added to the existing repertoire of ILAs available to STRIPS as operators. To do this, the complex operator must be characterized in the same fashion as any other operator; we must construct a precondition wff, an add-list, and a delete-list.

In order to extract the appropriate information from a plan to make these constructions, we need the notion of a kernel state. A kernel state is a collection of axioms constituting a subset of the axioms defining a given state.† We intend to include in each kernel

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*It is possible, even using the standard unparameterized STRIPS problem solver, to produce as a final solution a sequence of operators that are only partially instantiated.

†Note that if we extract from a set s of axioms a subset k, then the totality of worlds satisfying s is a subset of the totality of worlds satisfying k. In other words, fewer axioms specify a more general world.

state only those axioms relevant to fulfilling the goal. Figure 2 illustrates the situation we have in mind. STRIPS can produce both the sequence of (parameterized) operators $OP_1,\ldots,OP_{n-1}$ and the sequence of (parameterized) states $s_1,\ldots,s_n$. The kernel states $k_1,\ldots,k_n$ are to be computed. We first assume that the sequence of operator preconditions have been labeled $g_1,\ldots,g_{n-1}$, and g_n is the final goal. The following algorithm computes kernel states by beginning from the final state and working backwards to the initial state.

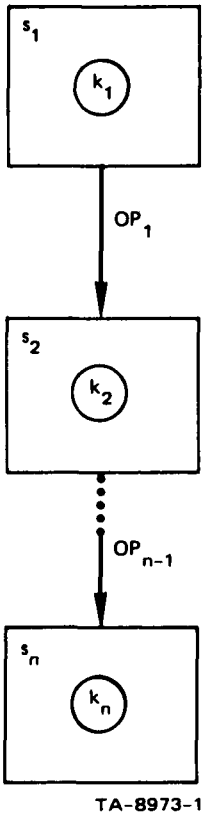

FIGURE 2 SEQUENCE OF STATES AND KERNEL STATES

Start:

Put in k_n exactly those axioms of s_n used in the proof of the overall goal g_n.

Recursion:

Put an axiom in kernel k_i only if

(1) It is in s_i and used in the proof of the precondition of OP_i, or

(2) It is a member of k_{i+1} but is not on the add-list of OP_i.

It is not difficult to prove that the following properties are consequences of this algorithm definition:

(1) Each set k_i of kernel axioms is in fact a subset of the corresponding set s_i of state axioms.

(2) If a set of kernel axioms k_i is satisfied by a configuration of the world, then application of OP_i will produce a configuration of the world in which kernel k_{i+1} is satisfied.

In other words, if we are in a situation in which k_i is satisfied for some i, then application of the remaining operators in the sequence will result in a state in which the overall goal g_n is satisfied. Thus, the sequence of kernel states $k_1,\ldots,k_n$ defined by our algorithm serves as a set of natural milestones for monitoring the execution of a sequence of operators.

We may now complete the description of a complex operator (from a plan generated by STRIPS), by using the following simple rules, where s_1 and s_n are respectively the initial and final parameterized states. (Note that the parameters in s_1 and s_n are those resulting after making whatever substitutions were necessary in constructing the plan.)

(1) The precondition wff is the conjunction of the axioms in the initial kernel.

(2) The add-list consists of all axioms in s_n and not in s_1.

(3) The delete-list consists of all axioms in s_1 and not in s_n.*

By the definition of the kernels, if any set of kernel axioms is satisfied, then application of the remaining sequence of operators must lead to a state in which the goal is satisfied; hence, Rule (1). Notice that the add- and delete-lists are formed by set differences on the initial and final states rather than set differences of kernels. This is because these lists reflect all the (planned) effects of an operator on the world, not just those effects that happen to be relevant to a particular problem.

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*This rule is still somewhat tentative, but works well in "typical situations.

IV VISION RESEARCH

A. Introduction

Three separate efforts are currently in progress in the area of vision research. The first concerns the development of special-purpose picture-processing routines needed for the intermediate-level actions. The second conerns an exploration of the use of color and stereoscopic information to obtain better-formed regions for general region analysis. The third is an investigation of ways in which visual information obtained during exploration can be used to build a world model; this work is described in Appendix F.

These activities represent a dichotomy between short-range and long-range plans for vision work. Our long-range plans continue to be based on a region-oriented approach to general scene analysis. However, we have encountered problems in getting the merging heuristics to function well in the corridor environment. In addition, the amount of computation required for a general scene analysis is often excessive for the limited amount of information required by the intermediate-level actions. Thus, the special-purpose routines are being written to provide users of the robot with certain specific kinds of visual information. Hopefully this information will be useful for more general scene analysis programs as well, and thus the short-range effort will also contribute to the long-range effort.

B. Vision Programs for Intermediate-Level Actions

The special-purpose vision programs basically perform only three functions: orienting and locating the robot, detecting the presence

of objects, and locating objects. We shall consider each of these functions in turn.

When the environment of the robot is represented accurately and completely in the model, the chief role of vision is to provide feedback to update the robot's position and orientation. Angular orientation information is often needed in advance of a relatively long trip down a corridor, where a small angular error might be significant. The simplest way to obtain orientation feedback is to find the floor/wall boundary in the picture, project it into the floor, and compare this result with the known wall location in the model; any observed angular discrepancy can be used to correct the stored value of the robot's orientation.

For manuevers such as going through a doorway, both the robot's position and orientation must be accurately known. This information can be obtained from a picture of a known point and line on the floor. Such distinguished points and lines are called landmarks, and include doorways, concave corners, and convex corners. The basic program for finding such landmarks has been described previously.[8] The program has undergone several refinements and improvements, and now works with the model described in Section II-B of this report. Execution time is essentially the time required to pan, tilt, and turn on the camera.* Concurrently, the accuracy is limited by mechanical factors to between 5 and 10 percent in range and 5 degrees in angle. Increased accuracy, if needed, can be obtained by improving the pan and tilt mechanism for the camera.

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*Since the camera, television control unit, and television transmitter draw a large amount of power from the batteries, they are normally off. Approximately ten seconds is required from the time these units are turned on to the time that a picture can be taken.

Before the robot starts a straight-line journey, it may be desirable to check that the path is indeed clear. A simple way to do this is to find the image of the path in the picture and examine that trapezoidal-shaped region for changes in brightness that might indicate the presence of an obstructing object. This is a simple visual task, and a program implementing it has been written. In its current form the program uses the Roberts-cross operator to detect brightness changes. When we first ran the program, we were surprised to discover that at steep camera angles the texture in the tile floor can be detected and give rise to false alarms. This is an instance of a major shortcoing of special-purpose vision routines, namely, the failure of simple criteria to cope with the variety of circumstances that can arise. This particular problem can be solved by requiring a certain minimum run-length of gradient. However, shadows and reflections can still cause false alarms, and the only solution to some of these problems is to do more thorough scene analysis.

If there is reason to believe that an object is in a given area, but its location is not known exactly, vision can be used to locate the object. We are currently working on an object location routine that will

- Use the model to compute the image of the floor area
- Delete all but the floor area from the picture
- Use the region-merging routines to partition the floor area into regions
- Inspect these regions to find the faces of the object that touch the floor
- Calculate the coordinates that locate the object.

This is the most complicated of the special-purpose vision programs. By making use of the model to exclude extraneous data and limiting attention to finding merely the points where the object meets the floor, we hope to obtain an efficient, reliable, and still useful special-purpose vision routine.

C. Techniques for General Scene Analysis

For the past 18 months, we have based our work in general scene analysis on the partitioning of the digitized picture into regions.[7,8] If this partitioning is substantially correct, there are several ways to identify the regions and complete the analysis of the scene.[6,8,9] Unfortunately, it has not been possible to obtain reliable partitioning in the corridor scenes. Regions that we wish to keep distinct--such as two walls meeting at a corner--are frequently merged, and fragments of meaningful regions that should be merged are too often kept distinct.

There are several ways in which this problem can be attacked. One is to try to improve the quality of the input data. Another is to seek improved merging heuristics. Another is to guide the merging by more a priori knowledge, such as the fact that real region boundaries are straight, and many edges are vertical. Another is to guide the merging by feedback from recognition of parts of the scene. One can even consider using the information in the model to compute an expected partitioning, and turn to confirming, augmenting, and/or rejecting the hypothesized partitioning.

Of these possibilities, we have concentrated on the first two. One of the more promising ways of obtaining better input data is through the use of color. When we explored color previously,[10] we encountered problems chiefly because of the low sensitivity of the vidicon sensor, the low saturation of most of the colors encountered in the real world,

and the sensitivity of color measurements to such factors as the type of ambient light, specular reflections, shadows, the dynamic range, and nonlinearities in the camera tube.

To attack these problems and gain the advantages of color information, the following program has been initiated and is now being carried out:

(1) The vidicon has been replaced by a plumbicon, resulting in an approximately ten-fold increase in sensitivity.

(2) A set of color filters has been selected and experimentally checked. The filters match both the spectral transfer characteristics of the plumbicon and the spectral characteristics of the fluorescent lights used in the laboratory and the corridors.

(3) An effort has been made to obtain adequate discrimination with unsaturated colors covering a wide range of objects in the laboratory. These colors range from pastels to unsaturated but deep reds, greens, etc. It appears that, with appropriate adjustment of the camera characteristics, such discrimination will be adequate under most operating conditions.

(4) A subsidiary investigation is planned to automatize the iris control of the camera, such that the dynamic range is automatically adjusted as a function of varying light level of a scene. A fairly simple program will be written to read one picture, analyze the distribution of light levels, adjust the iris setting, and repeat the process until a satisfactory distribution is obtained.

(5) The Fennema-Brice region analysis program has been modified to accept color data. In addition, an alternative approach to region analysis tailored to the characteristics of color data is being developed. Although several test pictures have been taken and analyzed, this work is still in a formative stage and requires further investigation.

Another area that is being investigated is the use of stereoscopic information to aid scene analysis. This study assumes that corresponding vertex points in stereo pairs can be identified, and that the range to these points can be computed. The basic question concerns the use of this information in detecting and correcting errors in partitioning the picture. One of the early observations was that this kind of information can detect errors and suggest corrections, but it can not detect all errors or yield unique corrections. For example, if Figure 3(a) is an imperfect representation of part of a box, they by knowing the range to the vertices of region A one will conclude that the region is not planar. However, as the other constructions in Figure 3 illustrate, no unique correction of the errors is possible. Nevertheless, if a list of possible corrections can be obtained, one can try to see which one best explains the original picture data. (This is essentially the line proposer and verifier technique suggested by Minsky and investigated by Griffith.[11]) Hopefully, the improvements provided by color or stereo information will allow us to attack the more interesting, higher-level problems in scene analysis.

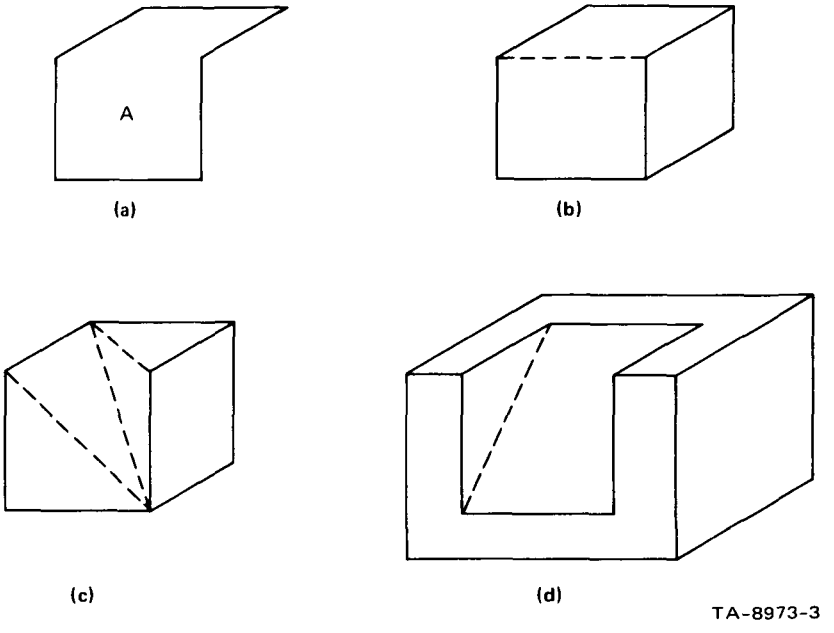

FIGURE 3 SOME POSSIBLE WAYS OF CORRECTING AN IMPERFECTLY PARTITIONED PICTURE

V HARDWARE AND SYSTEMS SOFTWARE

A. Introduction

The work of the systems group can be divided into three parts: hardware modification and addition, monitor and diagnostic programs, and user support programs. The first section deals with hardware, and includes discussion of problems as well as current additions and future modifications. The second section treats diagnostic programs and monitor modifications. The third section discusses user programs and their relation to existing hardware.

B. Hardware

The AI computer system is pictured in Figure 4. The dotted figures and connections are future additions; the solid lines indicate existing equipment. The left side shows the PDP-10 and its peripherals, the right side the PDP-15 complex.

Changes in the past six months include:

- Moving two DECtape units from the PDP-15 to the PDP-10. It is still possible to use these on the PDP-15 by switch control.
- Modifying the TV interface from manual control to program control.
- Modifying the robot.

The robot was adjusted to fix slippage in the wheels. A new gear is on order to fix the pan motor. A new sensor was added, which enables

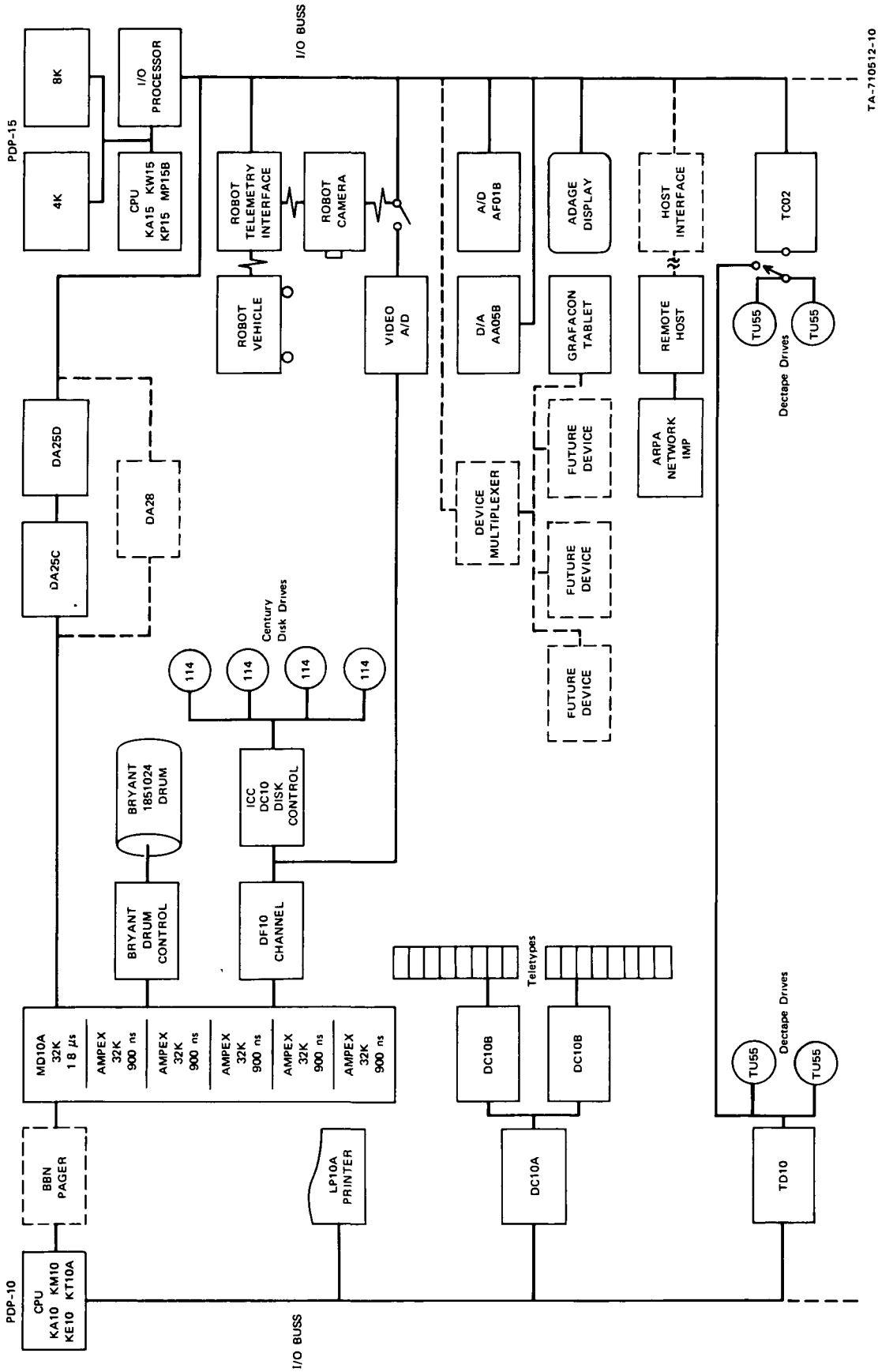

FIGURE 4 SRI ARTIFICIAL INTELLIGENCE GROUP COMPUTER SYSTEM

the robot to generate an interrupt (which is overridable) when it loses contact with an object that it was pushing. Built into this sensor is an interrupt capability which is triggered when the robot tries to push against something that is too heavy for it (e.g., a wall).

During the past period it was determined that the DA25 interface was unsatisfactory because the transfer rate was too slow. The maximum rate that could be hoped for is one 18-bit word every 8 μs. In fact, due to a design flaw, the best we have been able to obtain is a word every 12 μs, and this is maximum rate. Average rate is closer to 16 μs.

Since we shall eventually require speeds approaching a word per microsecond, we entered into negotiation with DEC. The resulting design of the DA28 was a result of our joint efforts, and meets our needs. It is to be delivered to SRI in August.

Another new development is the future receipt of the TENEX system. This is a system designed and implemented by BBN to convert the PDP-10 into a paged machine. This will greatly increase throughput. The system includes both hardware and software.

The hardware includes a paging box and certain modifications to the PDP-10 CPU. These modifications are being made now.

Design specifications have been developed by us for an interface between the IMP remote host and the PDP-15. This is to enable us to enter the ARPA network. This design has been let out for competitive bids and we are evaluating them prior to awarding a contract to build it.

The final hardware modification is another future development. This is our device multiplexer. It is possible, in the future, that devices as yet unspecified will be added to the system. Rather than designing an interface to the PDP-15 for each device, a universal

interface is being built to multiplex these future devices, one of which is a Grafacon, which we would like to use in conjunction with our display.

C. Diagnostic and Monitor Programs

The Systems Group completed checkout of the diagnostic programs for the drum and display during the past six months. The drum diagnostic exercises all tracks of the drum (reading and writing), both fixed and random patterns. It checks timing and parity. It also turns out to be a good memory diagnostic, when used in conjunction with other programs.

The display diagnostic enables the standard Adage diagnostic pattern to be displayed and refresh rate and interrupt levels to be checked.

The major monitor modification was a new swapper. This uses the drum as a swapping device (rather than the disk packs). Preliminary study seems to indicate an average enhancement of response time of from 150 to 200 percent. We plan to optimize the code in hopes of getting another 50 percent increase in user response time. We have decided not to implement any files on the drum, since the entire system will be changed with the advent of TENEX.

Some modifications to the LOGIN and LOGOUT routines were implemented. This gave a clearer picture of where most of the time was spent, and which users were spending it.

The monitor was modified to handle the PDP-15 as a sharable device. The PDP-15 peripherals (i.e., robot, display, A/D converter) are handled as single-user subdevices. Also the monitor was modified to handle TV input. When a picture is to be taken, the monitor ensures that no accesses to the disk pack will take place. It then allocates core to the user area and acknowledges that a picture may be acquired. The picture is read in through the TV A/D converter via the DF10 channel.

It is then written on a unique disk file in that user's area. The TV is then released by the monitor, and that core allocated for the picture acquisition is returned to the available area.

Currently, we are learning about TENEX and its monitor. The first job we hope to do on that monitor is to change its file-handling I/O. It currently treats all tertiary file space as one large disk. We want to have removable, separate disk pack software, thereby giving each subproject a disk pack for its own files and allocating one disk pack for systems and backup availability. We are also starting to consider rewrites for the various parts of the system which will change under TENEX--specifically TV interface, DA25 interface, and drum utilization.

D. User Support Programs

The most important user support programs that were written were the robot programs in the PDP-10 and PDP-15. They are described in Appendix G, "Robot Communications Between the PDP-15 and the PDP-10."

The PDP-15 programs have been written entirely by the Systems Group. This was necessary because existing DEC software was written for the customer who had a stand-alone PDP-15. Our monitor (if such it may be called) is efficient and compact. It appears that our present 12K will be sufficient core memory on the PDP-15 for the immediate future, but it is easy to visualize that amount as being too small. Currently we handle the PDP-10 interface, robot, display, and A/D converter programs.

The PDP-10 interface program always assumes that the PDP-10 is the master and the PDP-15 the servant. Therefore if any information has to go from the PDP-15 to the PDP-10, it must be asked for by the PDP-10. Similarlym if the PDP-15 is sending a message and the PDP-10 decides to initiate a transfer the other way, it takes priority, its message is sent, and the original message is retransmitted afterwards.

All assembling of programs for the PDP-15 is done by an SRI-written PDP-15 assembler on the PDP-10 and then transferred to the PDP-15 via the DA25. This is much faster and does not interfere with existing PDP-15 routines while the assembly is running.

The Adage display has been programmed so that a user on the PDP-10 writing in MACRO or FORTRAN can use it. This is described in Appendix H, "User Display Software Memo," Currently, a higher-order implementation for use by LISP programmers is being done.

Two other user routines currently being written are an A/D converter routine, and a magtape-to-DECtape program.

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Appendix A

A HEURISTICALLY GUIDED EQUALITY RULE IN A RESOLUTION THEOREM PROVER

by

Claude R. Brice and Jan A. Derksen

Appendix A

A HEURISTICALLY GUIDED EQUALITY RULE IN A RESOLUTION THEOREM PROVER

ABSTRACT

A new way of handling the equality relation within the framework of a resolution theorem prover is described. The system uses a modification of Morris' E-resolution, a rule of inference to handle equality, controlled by heuristic tree search techniques. The modification makes possible an implementation to which new rules of inference may be added easily.

I INTRODUCTION

The equality relation is widely used but difficult to axiomatize efficiently. We describe a new way of handling this relation within the framework of a resolution theorem prover. The system uses a modification of Morris' E-resolution, a rule of inference to handle equality, controlled by heuristic tree search techniques. The modification makes possible an implementation to which new rules of inference may be added easily.

Each time the resolution theorem prover makes an attempt to resolve two clauses, but cannot unify a pair of literals, the "equality tree" generator is called. A tree of clauses is built by substituting equal terms in one of the literals, until unification is possible. The growth of the equality tree is controlled by bounds on the processing time, the

breadth and depth of the tree, and a "reluctance" function. The reluctance function associates a cost with each node of the tree and selects nodes for expanding with minimal cost. The function is a linear combination of several "features." Some of the features are the probability that the literals will unify, the length of the literals, the number of constants the literals have in common, and the length of the clauses in which the literals occur.

Section II gives information on terminology, theoretical background and completeness results for E-resolution and variants. Section III describes the heuristic machinery of the system. It includes also descriptions of the "equality tree" and the search strategies used to find a path from the root to the goal node of the tree. Four sample proofs are given in Section IV.

II E-RESOLUTION

It is assumed that the reader is familiar with the standard notation and terminology used in literature on resolution.[1]* Among other methods for dealing with equality, paramodulation is relevant as E-resolution can be shown to be definable in terms of paramodulation with resolution.[1] Therefore, let us recall briefly the definition of paramodulation.

Paramodulation--This is a rule of inference that, given two clauses:

$$A$$

and

$$\alpha = \beta \vee B \qquad (\text{or } \beta = \alpha \vee B) \quad ,$$

---

*References are listed at the end of this appendix.

having no variables in common and such that A contains a term δ, with δ and α having a most-general unifier σ, forms A' by replacing in A_σ one single occurrence of δ_σ by β_σ and infers $A' \vee B_\sigma$.

Example: given the following three clauses

$$c = d \vee \overline{Q}c$$

$$f(c) \neq f(d)$$

$$x = x \quad ,$$

letting A correspond with $f(c) \neq f(d)$, B with $\overline{Q}c$, $\alpha = \beta$ with $c = d$, and δ with d in A', then one can deduce by paramodulation the clause

$$f(c) \neq f(c) \vee \overline{Q}c$$

and, by resolution, the clause $\overline{Q}c$.

Thus, intuitively, paramodulation provides a way to make use of the substitutivity property of equality. The reflexivity property does not, in E-resolution, require special axioms, and if α and δ have no most-general unifier, the program tries to find one for β and δ (with the same definition for α, δ, and β as in the paramodulation definition). Each clause may generate many distinct paramodulators. One can define, following Ref. 1, the descendants of a clause C from a set S obtained by paramodulating into the literal ℓ of C, in the following manner:

$$P^0(S,C,\ell) = \{C\} \quad ,$$

$$P^1(S,C,\ell) = \text{the set of descendants obtained from C} \quad ,$$

and by induction:

$P^k(S,C,\ell)$ = the set of descendants obtained by paramodulating from the clauses of $P^{k-1}(S,C,\ell)$ into the literal ℓ .

A. E-Resolution Defined

Using the preliminary definition above, one can define E-resolution as follows:

Let $P^\infty(S,C,\ell)$ be the union of the $P^k(S,C,\ell)$ for the different values of k. C_3 is an E-resolvent of two clauses C_1 and C_2 iff there exist a descendant clause C_1' from $P^\infty(S,C_1,\ell_1)$ and a descendant clause C_2' from $P^\infty(S,C_2,\ell_2)$ such that C_3 is a resolvent of C_1' and C_2' and the literals resolved upon in C_1' and C_2' are those descended from ℓ_1 and ℓ_2, respectively.

The intuitive idea behind these concepts is to be able to deal with the transitive property of equality. The two clauses C_1 and C_2 generate two trees of descendant clauses, and a path in one of these trees can be built by a chain of equalities and substitutions. This definition is of little help for programming purposes because of the necessity of developing two trees of paramodulants. It can be shown that a similar definition, but using only one tree, is equivalent. This definition is given below:

> C_3 is an E-resolvent of two clauses C_1 and C_2 iff there exists C_1' from $P^\infty(S,C_1,\ell_1)$ such that C_3 is a resolvent of C_1' and C_2 and the literal resolved upon in C_1' is ℓ_1 or the descendant of ℓ_1.

This way of implementing E-resolution differs from the one used in Ref. 3, but is closer to the formal definition of E-resolution given by Anderson.[1]

B. Completeness for Ground E-Resolution

To show that this modified definition of E-resolution is complete, we will show that it is complete for ground E-resolution and following Ref. 1, lift this result to the general level. Using the terminology of the first definition of E-resolution, let C_3 be a resolvent of the two clauses C_1' and C_2'. Let us denote C_1' by $\{\ell_1'\} \cup L_1'$ and C_2' by $\{\ell_2'\} \cup L_2'$, where L_1' and L_2' are the sets of literals from C_1' and C_2' not deleted by the resolution. C_3 is therefore expressed by $L_1' \cup L_2'$ and, since we have performed ground resolution, ℓ_1' and ℓ_2' are complements. By applying in reverse order to the literal ℓ_1' of the clause C_1', the chain of equality replacements that took place to generate ℓ_2', we can generate the clause $C_1'' \equiv \{\ell_1''\} \cup L_1''$, where $\ell_1'' = \sim\ell_2$. C'' can then resolve against C_2 and as we apply the same chain of paramodulations, the resolvent is C_3. It is shown in Ref. 1 that E-resolution, expressed here in terms of resolution and paramodulation, is complete with or without set of support, under the same condition as paramodulation: If the reflexivity axiom $(FA(x)\ x = x)$ (in which $FA(x)$ stands for $(\forall x)$) is present and all reflectivity functional axioms $(FA(x,y)(x = y \supset f(x) = f(y)))$ are also present.

C. Comments on E-Resolution

If E-resolution can be expressed in terms of paramodulation and resolution, one might wonder to what extent it is a useful technique. In contrast with paramodulation, E-resolution limits the number of clauses on which a theorem prover works. This is an important advantage

because the strategies used to select clauses that are resolved upon are not very successful when the number of clauses increases. The reason is that in E-resolution a clause is added to the set of clauses of the system only if a resolvent is found, while in paramodulation the clauses that would be on the intermediate nodes of the E-resolution tree would be added. However, two clauses may yield more than one resolvent, and E-resolution is complete only if from two clauses one can generate all the possible distinct E-resolvents. To generate all the E-resolvents from two clauses C_1 and C_2, one would have to grow from C_1 or C_2 a tree $P^{\infty}(S,C_1,\ell_1)$ or $P^{\infty}(S,C_2,\ell_2)$ until all the possible distinct paramodulants of C_1 or C_2 into ℓ_1 or ℓ_2 have been found. In practice, these trees are almost never generated entirely. They could sometimes be infinite trees and, at any rate, the expansion of these trees is time consuming. Furthermore, in most cases not all the E-resolvents of two clauses are needed to obtain a proof. Instead, as in Ref. 3, one might use a tree-level bound on the depth of the E-resolution tree. This bound limits the number of nodes to be generated, and it is increased progressively until a proof is found. Of course, then some procedure to save the partially expanded trees of paramodulated clauses should be implemented. If a proof is not found, the tree-level bound is incremented and the search can continue using the saved trees. This tree-level bound serves also the purpose of limiting the search when it happens that two clauses have no E-resolvents. To further limit the search, Morris's E-resolution program[3] was activated only if the two literals ℓ_1 and ℓ_2 of two clauses C_1 and C_2 did not unify. Although this limitation seems fairly natural, it made the system incomplete, as was shown by Anderson[1] using the following set of clauses:

(1) $P_{f(x)g(y)} \vee P_{h(x)i(y)}$

(2) $\sim P_{f(a)g(b)}$

(3) $\sim P_{h(b)1(b)}$

(4) $f(a) = f(c)$

(5) $h(c) = h(b)$.

The only possible resolvents obtained, if E-resolution is called only iff two literals do not unify, are:

$$P_{h(a)1(b)}$$

and

$$P_{f(b)g(b)} \quad .$$

However, by using the general E-resolution, one can generate the nil clause:

(6) $Ph(c)1(b)$ E-resolvent from (1) and (2) obtained by paramodulation of (1) using (4)

(7) nil E-resolvent from (6) and (3) obtained by paramodulation into (6) using (5).

D. The EQA3 E-Resolution System

The E-resolution program EQA3 was designed to be a package that could be added to QA3.[2] QA3 is a question-answering system based on the resolution principle, and it uses the set-of-support and unit-preference strategy. EQA3 does not differ in principle from the system described in Ref. 4 but actually suffers from its implementation in a theorem-proving system whose conception and structure do not lend themselves to improvement and refinement. However, QA3 will probably be rewritten or replaced by a more flexible theorem prover. With this purpose in mind, we have tried to keep EQA3 as general as possible. The descendant tree generator, which is the core of the system, could

eventually be used to generate any type of clause that could be inferred using a rule other than paramodulation. For example, to express that the predicate P(x,y,z) is such that the order in which its arguments appear is irrelevant, one can use the tree generator with a rule of inference consisting of a permutation of the arguments. Special permutations such as cyclic permutation can be used. For example, when the orientation of a line is irrelevant, one wants to express that the two predicates LINE(A,B) and LINE(B,A) have the same truth value. A predicate may have only a few ground instances. A model for this predicate could then be the list of the ground instances for which the predicate is true. Each clause containing a model evaluable predicate can be resolved against or subsumed by a model unit clause.

One can imagine that the tree generator could select, depending on the problem, different rules of inference to produce descendant clauses. The selection can be simply as in E-resolution, e.g., the failure of rule 1 (resolution) implies the use of rule 2 (E-resolution). Another possibility is that each predicate has a property list that tells what rule of inference has to be used.

In its actual implementation, EQA3 makes use of an evaluation function or reluctance function to select the next node to be expanded. The system actually uses only paramodulation to infer new nodes in the tree. Not all the descendants of clauses obtained by paramodulation into a literal are generated. Some of them would be of no use in trying to get an E-resolvent. The substitution takes place only in the terms of the literal or descendant of the literal when the unification algorithm fails. Thus, this implementation suffers from the same incompleteness as Morris's system (see Section II-C), but this limitation has no practical consequences. The reflexivity axiom X = X does not have to be added as

an axiom to the set of clauses. It is "built into" the system and used to resolve against inequality literals.

Each clause containing an equality literal is collected on a list of equalities (EQLIST). This list is ordered by length of clause. Thus equalities belonging to shortest clauses will be tried first for possible application of the E-resolution rule. This was done in an effort to keep the length of the eventual E-resolvent to a minimum (cf. unit preference strategy).

The next section describes the structure of the tree generator and the reluctance function in more detail.

III THE EQUALITY TREE

The essence of E-resolution is that each time two literals with the same predicate but opposite sign do not unify, a special procedure is invoked to show these two terms to be equal using unknown equalities. The special procedure generates a tree of modified clauses obtained by substituting terms in the literal of the clauses until they unify, using a list of positive equalities. This tree is called the "equality tree."

The procedure is a rather general one given:

(1) A start node, a string of symbols, e.g., p(a).

(2) A goal node, also a string of symbols, e.g., p(b).

(3) A list of equalities, e.g., (a = c, c = b). We can replace part of a string by another string known to be its equal by a most-general common instance, and form in this way other nodes (grow a tree), e.g., we can form the nodes p(c) and p(b); the last node is equal to the goal node.

The procedure tries to find a path between the start and goal nodes. In our example the path found is p(a), p(c), p(b). In our description we showed only nodes consisting of single literals. In general, nodes have more complex values (clauses), although the search is done for specific literals in the start and goal clauses.

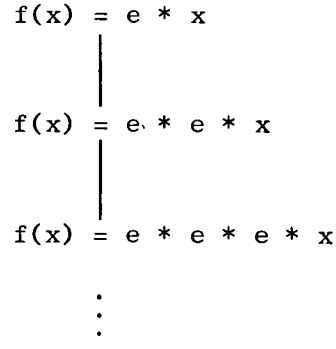
A. Search Procedures

Several difficulties arise if we want to implement such a procedure:

(1) A path between two nodes does not have to exist; in this case we should be able to end the search.

(2) Some branches of the tree must be recognized as unsuccessful, and the search stopped in favor of other branches.

Because of such problems, we cannot use a "depth-first" search technique as we are unable to recover from a single wrong decision in an infinite tree, e.g., we grow a branch from the node f(x) = e * x and repeatedly apply the equality x = e * x. Then we get the branch



An alternative is a "breadth-first" search; we avoid the difficulty associated with infinite branches, but now we cannot use heuristic information in deciding which branch to develop first.

The method used in this system is search controlled by a reluctance function. In this method we may think of a "frontier" of those nodes whose successors have not been examined. This frontier is extended by choosing any node in it and examining the node's successors. The node chosen will be that which has the minimum value of some function called a "reluctance function." It is easy to see that breadth-first and depth-first search are special cases of this last search method.

B. How to Grow a Tree

Several factors have to be considered when growing a tree.

(1) Control of the size of the tree; there are bounds on:

- Breadth
- Depth
- Processing time spent working on this specific problem.

(2) Successors or sons of the node. Not all of the sons of a node are developed at once because the number of sons may be unreasonably large, for instance, when a long list of equalities has to be used. Also, we may reach a goal node without having to find all the successors.

(3) Some nodes are thrown away if associated cost values are above a "cutoff" criterion. In

our system this is a limiting of the length of the literal relative to the length of the goal literal used. If the global variable LIMIT LENGTH is set to four, then any node with literals whose number of symbols (length) is four times the length of the goal literal will be thrown away.

(4) Order of the evaluation of the nodes, the reluctance function: the essential function is EVALCOST.

The tree-growing program is written in an elegant recursive form as suggested by Burstall.[5] The controlled search therefore could be programmed in a manner very similar to depth-first search.

C. The Reluctance Function

Each time a node is to be selected for expanding, the candidates are "open" nodes--nodes that do not have their maximum number of sons (limited by the breadth bound). The node selected is the one with minimal associated cost. The reluctance function should have a minimal value for the chosen node. The cost given by the reluctance function "EVALCOST" is a combination of several "features." A feature f is a function that measures some properties of a node. EVALCOST makes use of the linear combination

$$C = C_1 f_1 + C_2 f_2 \ldots + C_n f_n \quad .$$

Of course, nonlinear combinations are possible, but for our system the linear reluctance function is adequate.

D. Features Used in the Reluctance Function

The features are all functions of the string (literal) associated with the node under investigation. The goal literal is the string that is the ultimate goal of the tree search. The features are:

(1) Length relative to the length of the goal literal

(2) Number of constants in common with the goal literal

(3) Number of function symbols in common with the goal literal

(4) Degree of nesting relative to degree of nesting of the goal literal

(5) Length of the clause of which the literal is an element

(6) Probability that the literal and the goal literal will unify.

E. Detailed Description of the Features

(1) Length: number of symbols in the string (literal) including parentheses, e.g., (f(e)3) → 7.

(2) Number of constants: A list of constants occurring in the literal is made and compared with the list of constants occurring in the goal literal. An integer expressing the number of shared constants is computed. The algorithm gives, in this way, a maximal value for literals with an equal number of the same constants, while lower values are

obtained for a smaller or larger shared number of constants.

(3) Number of function symbols: each substring of the form '(⟨atom⟩ ⟨atom or list⟩' contains the occurrence of a function symbol, here, '⟨atom⟩'. The procedure for the number of constants is re-applied, this time with the two lists of function symbols.

(4) Degree of nesting: this feature is defined as ΣK_x, where x is an element of the string under consideration; x is not '('or')'; K_x is the number of bracket pairs enclosing x--e.g., '(g(f a)(e))' → 7.

(5) Length of clause: the literal associated with the node is an element of a clause. The resolution system has a built-in strategy with a preference for short clauses. In the E-resolution part, too, nodes with long clauses are penalized.

(6) Probability that the literal and the goal literal will unify: normally if two literals do not unify, the unification algorithm fails and leaves us without information on how "well" the unification was doing. If the algorithm in this system fails, it reports the degree to which the laterals did match. The algorithm adds

- For each term that matches [1/number of terms], the weight of the term, to a running count

- Inside a term, for each subterm, [weight of the term/number of subterms] to the running count.

The algorithm tries to unify the two literals and adds each time that the unification succeeds on a subterm the weight of the term or subterm of a term to the running count, e.g.,

(P(f x)(a)), (P(g x)(a)) → 0.5

(P(f x)(a)), (P(f y) z) → 1

(P(f(a))x), (P(f(b))(a)) → 0.25 .

F. Performance of EVALCOST

Not much is known about the influence of the different features. The sample runs are made with a setting in which the length of the literal, and to a lesser degree the length of the clause of a node, determine the expansion of the tree. The user will have to experiment which setting to use for each problem. A semi-interactive use with tracing, printing, and checking of the growth of the tree seems the best approach.

G. Structure of the Tree

1. Structure of the Tree

The tree is built with atoms generated by GENSYM. Each node has a property list with the following flags and information:

VALUE, the literal associated with the node

FATHER, a backpointer to the father node

SONS, a list of pointers to son nodes

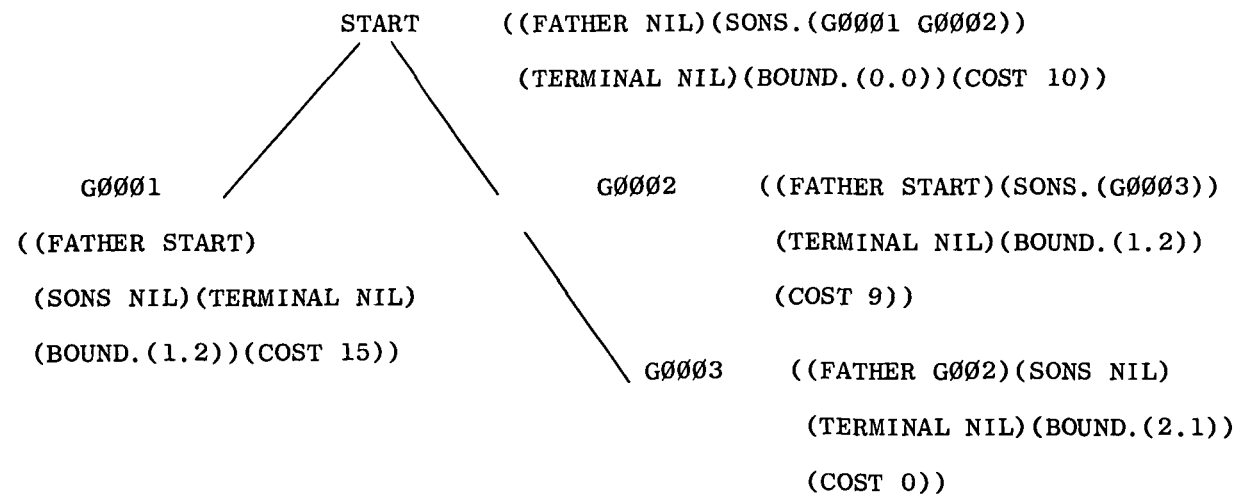
EXPBY, a pair of pointers to the terms of the literal and the equality, used in the substitution

TERMINAL, T if node is terminal, otherwise NIL

BOUND, dotted pair of current depth and breadth (number of sons) (in this order)

COST, cost as computed by EVALCOST.

2. An Example of a Small Tree



IV EXAMPLES OF RUNS

Three of the following examples come from elementary group theory. '*' denotes the binary group operator. E denotes the identity of the group and INV denotes the inverse operator. One example is about the induction proof for the synthesis of the reverse function. REV denotes the reverse function, and AP, LIST, and CDR denote the LISP functions APPEND, LIST, and CDR. For each proof that implied only one E-resolution, the penetrance--the number of nodes developed on the path divided by the

total number of nodes developed in the tree--is given. In the sample runs the theorems to be proven are preceded by TQ and the axioms by AX. Literals derived by E-resolution from a part of the negation of the theorem are preceded by NEG-THM.

Example 1. (See sample printout on page 72). The theorem proven is: the identity element of a commutative group is unique. The negation of the theorem is (el * x = x) & el $\neq$ e, or in prefix notation as used in the printouts: = (*(El,X)X) & $\neq$ (El,E). EQA3 generates a contradiction by paramodulating into $\neq$ (El,E) and resolving against the reflexivity axiom = (X,X). A measure of goal directedness of the proof is the ratio of the length of the path and the total number of nodes generated during the proof. This measure is called penetrance. The penetrance in example 1 was 3/8.

Example 2. In the proof shown on page 73 the group is restricted such that for all elements X, (X(* X X)E). The theorem proven is $(\forall x)\ x \cdot x^{-1} = e$. Penetrance 8/22.

Example 3. Page 74 gives a sample printout for the proof of the theorem $(\forall x)(\forall y)(\forall z)x \cdot (y \cdot (x^{-1} \cdot y^{-1})) = e$. The penetrance was extremely low, 7/104. It seems that the main reason for such a bad performance was the great number of unproductive paramodulants that were generated by using the commutativity axiom (FA(X,Y)(=(* X Y)(* Y X))).

Example 4. In the sample printout on page 75, SK45, SK46, and SK47 denote the constants that replace the universally quantified variables Y1, Y2, and X. As the system starts from the negation of the theorem to find a contradiction,

the universal quantifiers of the theorem become existential quantifiers and the variables are replaced by Skolem constants. The instantiation of Y2*, not given by the system, is Y2* = AP(LIST(CAR(SK45)),SK46)) or for all Y1, Y2, and X the theorem is true with Y2* = AP(LIST(CAR(Y1),Y2)). Penetrance 3/5.

V CONCLUSION

After some experimentation with our implementation of the equality rule several things became clear to us:

(1) An equality rule without any guidance is doomed to fail on any nontrivial problem.

(2) A heuristically guided search gives good results for a limited class of problems for which the reluctance function features are properly "tuned."

(3) For a wider range of problems, watching the theorem prover in the process of proving an equality and introducing simple special rules of inference in case of failure or bad performance turns out to be the best solution.

```
 (QAS)
EXECUTIVE MODE

←RESET

←AX(AX1 AX2)
AX1  (FA (X Y) (= (* X Y) (* Y X)))
AXIOM

AX2  (FA (X) (= (* F X) X))
AXIOM


←TQ(IF(FA(X)(=(* E1 X) X))(= E1 E))

1. NEG-THM        0.   =(*(E1,X),X)

2. NEG-THM        0.    -=(F1,E)

3. NEG-THM        0.    -=(*(E,E1),E)

CLAUSE 3. EQUAL.

4. NEG-THM        0.    -=(*(E1,E),E)

CLAUSE 4. EQUAL.

5. NEG-THM        0.    -=(E,E)

CLAUSE 5. EQUAL.

6. AXIOM          0.   =(X,X)

7. RES(5. 6.)     1.   CONTRADICTION

   YES
```

Example 1

```
 (OAS)
EXECUTIVE MODE

←RESET

←AX(AX2 AX3 AX4 AX5)
AX2  (FA (X) (= (* E X) X))
AXIOM

AX3  (FA (X) (= (* X X) E))
AXIOM

AX4  (FA (X) (= (* X (INV X)) E))
AXIOM

AX5  (FA (X Y Z) (= (* X (* Y Z)) (* (* X Y) Z)))
AXIOM


←TQ(FA(X)(= X (INV X)))

1. NEG-THM        0.    -=(SK45,INV(SK45))

2. NEG-THM        0.    -=(SK45,*(E,INV(SK45)))

CLAUSE 2. EQUAL.

3. NEG-THM        0.    -=(SK45,*(*(X,X),INV(SK45)))

CLAUSE 3. EQUAL.

4. NEG-THM        0.    -=(SK45,*(Y,*(Y,INV(SK45))))

CLAUSE 4. EQUAL.

5. NEG-THM        0.    -=(SK45,*(SK45,E))

CLAUSE 5. EQUAL.

6. NEG-THM        0.    -=(SK45,*(SK45,*(X,X)))

CLAUSE 6. EQUAL.

7. NEG-THM        0.    -=(SK45,*(*(SK45,Z),Z))

CLAUSE 7. EQUAL.

8. NEG-THM        0.    -=(SK45,*(E,SK45))

CLAUSE 8. EQUAL.

9. NEG-THM        0.    -=(SK45,SK45)

CLAUSE 9. EQUAL.

10.AXIOM          0.   =(X,X)

11.RES(9. 10.)    1.   CONTRADICTION

   YES
```

```
 (OAS)
EXECUTIVE MØDE

←RESET

←AX(AX1 AX2 AX4 AX5)
AX1  (FA (X Y) (= (* X Y) (* Y X)))
AXIØM

AX2  (FA (X) (= (* E X) X))
AXIØM

AX4  (FA (X) (= (* X (INV X)) E))
AXIØM

AX5  (FA (X Y Z) (= (* X (* Y Z)) (* (* X Y) Z)))
AXIØM


←TO(FA(X Y)(= E (* X(* Y(* (INV X)(INV Y))))))

1. NEG-THM        0.    -=(E,*(SK45,*(SK46,*(INV(SK45),INV(SK46)))))

2. NEG-THM        0.    -=(E,*(*(SK46,*(INV(SK45),INV(SK46))),SK45))

CLAUSE 2. EQUAL.

3. NEG-THM        0.    -=(E,*(*(SK46,*(INV(SK46),INV(SK45))),SK45))

CLAUSE 3. EQUAL.

4. NEG-THM        0.    -=(E,*(*(*(SK46,INV(SK46)),INV(SK45)),SK45))

CLAUSE 4. EQUAL.

5. NEG-THM        0.    -=(E,*(*(E,INV(SK45)),SK45))

CLAUSE 5. EQUAL.

6. NEG-THM        0.    -=(E,*(INV(SK45),SK45))

CLAUSE 6. EQUAL.

7. NEG-THM        0.    -=(E,*(SK45,INV(SK45)))

CLAUSE 7. EQUAL.

8. NEG-THM        0.    -=(F,E)

CLAUSE 8. EQUAL.

9. AXIØM          0.   =(X,X)

10.RES(8. 9.)     1.   CØNTRADICTIØN

   YES
```

Example 3

```
 (OAS)
EXECUTIVE MØDE

*RESET

*AX(AX2 AX3)
AX2  (FA (U V W) (= (AP U (AP V W)) (AP (AP U V) W)))
AXIØM

AX3  (FA (U) (IF (NØT (NULL U)) (= (REV U) (AP (REV (CDR U)) (LIST (C
AR U))))))
AXIØM


*TPRØVE Ø1
(FA (Y1 Y2 X) (IF (AND (NØT (NULL Y1)) (= (AP (REV Y1) Y2) (REV X)))
(EX (Y2*) (= (AP (REV (CDR Y1)) Y2*) (REV X)))))
1. NEG-THM       0.   -NULL(SK45)

2. NEG-THM       0.   =(AP(REV(SK45),SK46),REV(SK47))

3. NEG-THM       0.   -=(AP(REV(CDR(SK45)),Y2*),REV(SK47))

4. NEG-THM       0.   -=(AP(REV(CDR(SK45)),Y2*),AP(REV(SK45),SK46))

CLAUSE 4. EQUAL.

5. NEG-THM       0.   -=(AP(REV(CDR(SK45)),Y2*),AP(AP(REV(CDR(SK45)),L
IST(CAR(SK45))),SK46))   NULL(SK45)

CLAUSE 5. EQUAL.

6. NEG-THM       0.   -=(AP(REV(CDR(SK45)),Y2*),AP(REV(CDR(SK45)),AP(L
IST(CAR(SK45)),SK46)))   NULL(SK45)

CLAUSE 6. EQUAL.

7. AXIØM         0.   =(X,X)

8. RES(6. 7.)    1.   NULL(SK45)

9. PFS(1. 8.)    2.   CØNTRADICTIØN

   YES
```

Example 4

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Appendix B

REASONING BY ANALOGY AS AN AID TO HEURISTIC THEOREM PROVING

by

Robert E. Kling

Appendix B

REASONING BY ANALOGY AS AN AID TO HEURISTIC THEOREM PROVING

ABSTRACT

When heuristic problem-solving programs are faced with large data bases that contain numbers of facts far in excess of those needed to solve any particular problem, their performance rapidly deteriorates. In this paper, the correspondence between a new unresolved problem and a previously solved analogous problem is computed and invoked to tailor large data bases to manageable sizes. This appendix describes a particular set of algorithms for generating and exploiting analogies between theorems posed to a resolution-logic system. These algorithms are believed to be the first computationally feasible development of reasoning by analogy to be applied to heuristic theorem proving.

Any contemporary heuristic deductive theorem-proving system that proves theorems by applying some rules of inference to an explicit set of axioms must use a carefully tailored data base. Most search procedures will generate many irrelevant inferences when seeking the proof of some nontrivial theorem even when they are given a minimal set of axioms. Generally, the effective power of a search procedure is limited by the memory capacity of a particular system: most theorem provers run out of space (absorbed by irrelevant inferences) before they run out of time when they fail to prove a hard theorem.*

Consider a particular theorem P that can be solved with a set of axioms D. Suppose that a theorem-prover S can prove P within its memory limitations. Suppose D is expanded to D′ by adding axioms that include many of the same relations that appear in D. If S attempts P again, it will generate many new irrelevant inferences that are derived from the axioms in D′ - D. In fact, the size of D′ need not be too much larger than that of D to render P unprovable by S. Typical theorem provers work with a D composed of less than 20 axioms. If P is hard for S, then just a few additional axioms may add a sufficient number of inferences to the search space to exhaust the memory before a solution is found. In the '60's, most research focused on the organization of S and the development of a variety of ever-more-efficient search procedures. Consequently, researchers could choose an optimal D for each particular theorem without sacrificing their research goals. In contrast, as heuristic deductive systems are being proposed to solve real-world problems, such as robot manipulation,[3] larger nonoptimal data bases are necessary.

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*This observation is based upon my own experience with resolution systems and is corroborated by other researchers using different paradigms.[1,2†]

†References are listed at the end of this appendix.

Suppose we have a theorem P, and a large data base D'. In general, there is no way to choose a small subset D of D' such that $D \Rightarrow P$. Suppose we had previously solved some theorem P_1 that is analogous to P in so far as analogs of the axioms used in the proof of P_1 will be required in the proof of P. If we could generate the analogy between P and P_1 to find the set of axioms and use them as D', then we could let S attempt P with greater hope of success. This appendix describes a set of algorithms for generating an analogy between some given pair of P and P_1 and for exploiting this relationship to estimate D'.

The preceding discussion has been rather general and applies to any heuristic theorem prover such as LT[2] and resolution.[4] However, each paradigm will require slightly variant representations and methods for generating and using analogical information. Effective research demands working with a specific theorem prover; for reasons of convenience, I have chosen QA3,[5] a resolution-based theorem prover. QA3 and the algorithm ZORBA-I, described below, are implemented in LISP on a PDP-10 at Stanford Research Institute.

Before describing ZORBA-I abstractly, I want to exemplify the kinds of theorems that it tackles. Briefly, they are theorem-pairs in domains without constants (e.g., mathematics) that have close to one-to-one analogies. The theorems include those that are fairly hard for QA3 to solve even with an optimal memory. For example, ZORBA-I will be given the proof of the theorem

T_1. The intersection of two abelian groups is an abelian group,

and is asked to generate an analogy with

T_2. The intersection of two commutative rings is a commutative ring;

or, given

T_3. A factor group G/H is simple iff H is a maximal normal subgroup of G,

and its proof, ZORBA-I is asked to generate an adequate analogy with

T_4. A quotient ring A/C is simple iff C is a maximal ideal in A.

None of these theorems is trivial for contemporary theorem provers. T_1 has a 35-step proof and T_3 has a 50-step proof in a good axiomatization. A good theorem prover (QA3) generates about 200 inferences in searching for either proof when its data base is minimized to the 10 to 15 axioms required for each proof. If the data base is increased to 20 to 30 reasonable axioms, the theorem prover may generate 500 to 600 clauses and run out of space before a proof is found. Note also that the predicates in the problem statement of these theorems contain only a few of the predicates used in the proof. Thus, T_1 can be stated using only the predicates {INTERSECTION; ABELIAN}, but a proof, in addition {GROUP; IN; TIMES; SUBSET; SUBGROUP; COMMUTATIVE}. Thus, while the first set must map into {INTERSECTION, COMMUTATIVERING}, the second set can map into anything.

Figure B-1 shows a relational space R covering all the relations in the data base. Let R_1' and R_2' be the set of relations in the statements of the new and old theorems (T_1 and T_2, for example). In addition, we know the relations R_1 in some proof of T_1 (since we have a proof at hand). We need to find the set R_2 that contains the relations we expect in some proof of T_2, and we want a map G: $G(R_1) = R_2$.

Clearly, a wise method would be to find some G', a restriction of G to R_1' such that $G'(R_1) = R_2'$, and then incrementally extend G' to G_1', G_2', ... each on larger domains until some $G'(R_1) = R_2$. ZORBA-I performs in such a way that each incremental extension picks up new clauses that

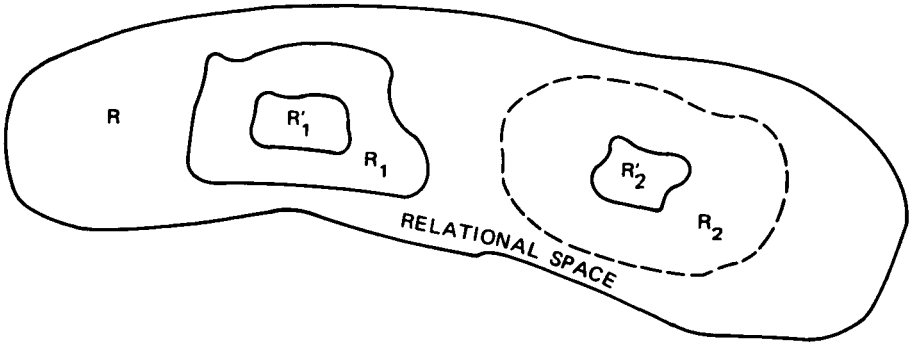

FIGURE B-1 VENN DIAGRAM OF RELATIONS IN STATEMENTS T, T_A, AND D

could be used in a proof of T_2. In fact, if we get no new clauses from an extended G'_J, that may be reason to believe that G'_J is faulty. I now will describe the generation algorithm in more detail.

The user presents ZORBA-I with the following information:

(1) A new theorem, T_A, to prove.

(2) An analogous theorem, T (chosen by the user), that has already been proved.

(3) Proof [T], which is an ordered set of clauses C_k such that $\forall k$, C_k is either

(a) A clause in $\neg$ T

(b) An axiom

(c) Derived by resolution from two clauses

c_i and c_j $\quad j < k$ and $i < k$.

These three items of information are problem-dependent. It accesses a large data base which includes more axioms than it needs for T or T_A and is, in this sense, problem independent. In addition, the user *specifies a "semantic template" for each predicate in his language.* This template associates a (semantic) type with each predicate and predicate-place and is used to help constrain the predicate mappings to be meaningful. For example, (STRUCTURE SET OPERATOR) is associated with the predicate "group." Thus, ZORBA-I knows that "group" is a structure, "A" is a set, and "*" is an operator when it sees group [A;*]. Currently, the predicate types (for algebra) are STRUCTURE, RELATION, MAP, and RELSTRUCTURE; the variable types are SET, OPERATOR, FUNCTION, and OBJECT.

ZORBA-I can make up a description descr[c] of any clause c according to the following rules:

(1) $\forall_p$ If p and $\neg$ p appear in c, then impcond[p] ϵ descr[c].

(2) $\forall_p$ If p appears in c, then pos[p] ϵ descr[c].

(3) $\forall_p$ If $\neg$ p appears in c, then neg[p] ϵ descr[c].

Thus, the axiom, "every abelian group is a group," e.g.,

$$\forall(x\ *)\ \text{abelian}\ [x;*] \Rightarrow \text{group}\ [x;*] \quad ,$$

is expressed by the clause

$$\neg\ \text{abelian}\ [x;*] \vee \text{group}\ [x;*] \quad ,$$

which is described by

$$\text{neg}\ [\text{abelian}];\ \text{pos}\ [\text{group}] \quad .$$

The theorem, "the homomorphic image of a group is a group," e.g.,

$$\forall\ (X\ Y\ *_1\ *_2\ \varphi)$$
$$\text{hom}\ [\varphi;X;Y]\ \wedge\ \text{group}\ [X;*_1]$$
$$\Rightarrow \text{group}\ [Y;*_2] \quad ,$$

is expressed by the clause

$$\neg\ \text{hom}\ [\varphi;X;Y]\ \vee\ \neg\ \text{group}\ [X;*_1]\ \vee\ \text{group}\ [Y;*_2]$$

and is described by

$$\text{neg}\ [\text{hom}],\ \text{impend}\ [\text{group}] \quad .$$

The semantic templates are used during both the INITIAL-MAP (when the predicates and variables in the theorem statements are mapped) as well as in EXTENDER, which adds additional predicates needed for the proof of T_A and a candidate set of axioms for the data base. The clause descriptions are used only by EXTENDER.

The INITIAL-MAP uses a rule of inference called ATOMMATCH[atom 1; atom 2; ANA], which extends analogy by adding the predicates and mapped variables of $atom_1$ and $atom_2$ to analogy ANA. ATOMMATCH now limits ZORBA-I to analogies where atoms* map one-to-one. But a slight generalization of ATOMMATCH can be made so that ATOMMATCH can accept many-many maps of atoms. INITIAL-MAP is a sophisticated search program that sweeps ATOMMATCH over likely pairs of atoms, one

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*Atoms, not predicates.

from the statement of T, the other from the statement of T_A. Alternative analogies are kept in parallel (no backup), and INITIAL-MAP terminates when it has found some analogy that includes all the predicates in theorem statements. Usually, this is the only analogy generated.*

EXTENDER accepts a partial analogy G_1 generated by INITIAL-MAP and the (unordered) axioms used in the proof P. In addition, EXTENDER has access to the data base D used by the theorem prover. It partitions this axiom-list, called AXLIST, into three distinct subsets, ALL, SOME, and NONE (AXLIST = ALL $\cup$ SOME $\cup$ NONE).

If all the predicates on an axiom Ax_k are in G_1, $ax_k \in$ SOME; and if none of its predicates are in G_1, $ax_k \in$ NONE. This partition is trivial to compute, and initially, none or a few $ax_k \in$ ALL, and some $ax_k \in$ SOME and NONE. When EXTENDER has satisfactorily completed G, ALL = AXLIST, SOME = NONE = $\emptyset$.

EXTENDER wants to pick up the analogs of each $ax_k \in$ AXLIST and in doing so incrementally extend the analogy. For the clauses in ALL, the analog descriptions are complete since the analog of each predicate is known. Thus, for all $ax_k \in$ ALL, its analog ax_k' is the set of all clauses that satisfy the analog descriptions. This process is rather pat. In contrast the clauses in SOME are a bridge between the known (restricted) analogy and some additional unmapped predicates. Thus, if I know the analog of a clause in SOME, I have an opportunity to extend the analogy to cover one or more unknown predicates. EXTENDER focuses its attention upon clauses in SOME that have a unique image under the current analogy.

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*In addition, it is rather fast. It generates the analogies for T_1 - T_2 with about 2 seconds of PDP-10 CPU time.

These clauses are used to extend the analogy, provide a new portion of AXLIST into ALL, SOME, and NONE, and incrementally complete the analogy by iteration. Thus the game becomes one of finding some way to move axioms systematically from NONE to SOME to ALL in a way that for each ax_k moved, some image set $G_J(ax_k) = ax'_k$ is found that can be used in the proof of T_A. Moreover, each new image should help extend $G_J \rightarrow G_{J+1}$.

When image clauses are sought, all the clauses that satisfy a particular description are sieved out of the data base. Theorem T_1 described above required the axiom:

$$\neg \text{ int}[x;y;z] \vee \text{subset}[x;y] \quad ,$$

which is described by: pos[subset], neg[int]. When the system searches memory for all clauses that satisfy this description, it finds, in addition

$$\neg \text{ int}[x;y;z] \vee \text{subset}[x;z] \quad ,$$

which has an identical description. ZORBA-I discriminates clauses only in terms of their descriptions and does not discriminate between these two clauses. Most clauses have but one image, but a few have two or three.

Given a clause $ax_k \in$ SOME with description d_k, its image set ax'_k, and the partial analogy G_J developed at this point, EXTENDER picks up the analog information regarding the new predicates appearing in ax_k and ax'_k by deleting from d_k and d'_k all the terms referencing the predicates G_J. If there is one term left in d_k and d'_k, the corresponding predicates are mapped by default. If more terms are left, the predicates

are mapped in a way that preserves (1) description features (e.g., pos terms are associated with pos terms) and (2) semantic types of predicates.

If the system knows that

$$\text{abelian} \rightarrow \text{cring}$$

and wants to associate

$$\neg\, \text{abelian}\,[x;*] \vee \text{commutative}\,[*;x]$$

with

$$\neg\, \text{cring}\,[x;*;+] \vee \text{commutative}\,[*;x]$$

it compares the description

$$\text{neg[abelian]},\ \text{pos[commutative]}$$

with

$$\text{neg[cring]},\ \text{pos[commutative]}$$

and extends the analogy to include commutative $\leftrightarrow$ commutative.

The preceding discussion provides an introduction to the ZORBA-I algorithm, a complete description of which would be too lengthly for inclusion here. It is developed in full detail elsewhere.[6] Figure B-2 describes the relationship between ZORBA-I and QA3. While EXTENDER iterates through the partitions of AXLIST to create a final analogy, it accesses D' and builds up a small set of images of the clauses on AXLIST.

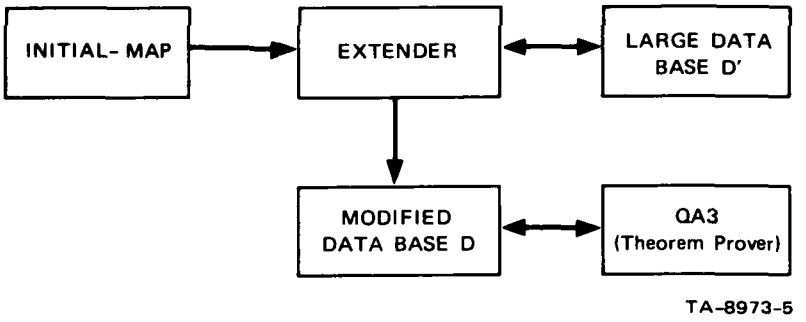

FIGURE B-2 RELATIONSHIP BETWEEN SECTION OF ZORBA-I AND QA3

When it terminates (all clauses have images), it passes this image set into the memory of QA3, which then attempts to prove P using the restricted data base.

At this time, the INITIAL-MAP and EXTENDER run on problem pairs in algebra such as T_1-T_2, T_3-T_4. A large data base of 250 clauses includes the axioms needed for these proofs but is much too large for QA3 to use in any effective way. In effect, without ZORBA-I, QA3 cannot prove any of these theorems using the full data base.

Theorems T_1 and T_2 each require 13 axioms, whereas T_3 and T_4 require 12. When ZORBA-I is asked to find an axiom set for T_2 given the proof of T_1 and the 250 clause algebraic data base, it finds 16 axioms, which include the necessary 13. When it is applied to T_4 given a proof of T_3, it finds 15 axioms, including all the necessary 12. In both cases, the QA3 is able to prove the new theorems (T_2 and T_4) with little more search than a humanly selected optimal data base would generate.

Summary

The preceding sections described a specific (implemented) algorithm for generating the analogy between a new and an old problem, extracting pragmatically important information from this analogy to aid a problem solver in its search for the solution to the new problem. The system knows none of the associations that constitute the analogy in advance, although it does have a description of some of the semantics (templates) of the language. It can generate analogies that involve many relations (predicates) but is implemented to meet several severe restrictions. In particular

(1) The problem solver is a resolution-logic based system with one rule of inference.

(2) The extracted information takes only the form of a problem-dependent data base.

(3) The analogies are nearly one to one.

None of the restrictions is necessary, and weakening is quite possible. In general, ZORBA-I restricts the environment that its associated problem solver (QA3) operates. Using this approach circumvents the need for a sequential planning language and detailed information specifying exactly how each (analog) axiom is to be used. Nevertheless, the analogy generator is nontrivial and needs only a simple semantic type theory represented by templates to supplement the problem-solving language (first-order predicate calculus). Although the resultant analogies are noninformal, they still can be developed in a way as to be used by a highly formal problem solver with extremely weak semantics.

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Appendix C

STRIPS: A NEW APPROACH TO THE APPLICATION OF THEOREM PROVING TO PROBLEM SOLVING

by

Richard E. Fikes and Nils J. Nilsson

Appendix C

STRIPS: A NEW APPROACH TO THE APPLICATION OF THEOREM PROVING TO PROBLEM SOLVING

ABSTRACT

We describe a new problem solver called STRIPS that attempts to find a sequence of operators in a space of world models to transform a given initial world model into a model in which a given goal formula can be proven to be true. STRIPS represents a world model as an arbitrary collection of first-order predicate calculus formulas and is designed to work with models consisting of large numbers of formulas. It employs a resolution theorem prover to answer questions of particular models and uses means-ends analysis to guide it to the desired goal-satisfying model.

DESCRIPTIVE TERMS

Problem solving, theorem proving, robot planning.

I INTRODUCTION

A. Overview of STRIPS

This appendix describes a new problem-solving program called STRIPS (STanford Research Institute Problem Solver). The program has been implemented in LISP on a PDP-10 and is being used in conjunction

with robot research at SRI. (See the paper by Munson[1]* for a discussion of the relationships among STRIPS and the robot executive and monitoring functions.) STRIPS belongs to the class of problem solvers that search a space of "world models" to find one in which a given goal is achieved. For any world model, we assume there exists a set of applicable operators each of which transforms the world model to some other world model. The task of the problem solver is to find some composition of operators that transforms a given initial world model into one that satisfies some particular goal condition.

This framework for problem solving, discussed at length by Nilsson,[2] has been central to much of the research in Artificial Intelligence. A wide variety of different kinds of problems can be posed in this framework.† Our primary interest here is in the class of problems faced by a robot in rearranging objects and in navigating. The robot problems we have in mind are of the sort that require quite complex and general world models compared to those needed in the solution of puzzles and games. Usually in puzzles and games, a simple matrix or list structure is adequate to represent a state of the problem. The world model for a robot problem solver, however, needs to include a large number of facts and relations dealing with the position of the robot and the positions and attributes of various objects, open spaces, and boundaries.

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*References are listed at the end of this appendix.

†It is true that many problems do not require search and that specialized programs can be written to solve them. Our view is that these special programs belong to the class of available operators and that a search-based approach can be used to discover how these and other operators can be chained together to solve even more difficult problems.

Thus, the first question facing the designer of a robot problem solver is how to represent the world model. A convenient answer is to let the world model take the form of statements in some sort of general logical formalism. For STRIPS we have chosen the first-order predicate calculus mainly because of the existence of computer programs for finding proofs in this system. Presently, STRIPS uses the QA3 theorem-proving system[3] as its primary deductive mechanism.

Goals (and subgoals) for STRIPS are stated as first-order predicate calculus wffs (wee formed formulas). For example, the task "push a box to place b" might be stated as the wff $(\exists u)[BOX(u) \wedge AT(u,b)]$, where the predicates have the obvious interpretation. The task of the system is to find a sequence of operators that will produce a world model in which the goal can be shown to be true. The QA3 theorem prover will be used to determine whether or not a wff corresponding to a goal or subgoal is a theorem in a given world model.

Although theorem-proving methods play an important role in STRIPS, they are not used as the primary search mechanism. A graph of world models (actually a tree) is generated by a search process that can best be described as GPS-like (Ernst and Newell[4]). Thus it is fair to say that STRIPS is a combination of GPS and formal theorem-proving methods. This combination allows objects (world models) that can be much more complex and general than any of those used in previously implemented versions of GPS. This use of world models consisting of sets of logical statements causes some special problems that are now the subject of much research in Artificial Intelligence. In the next and following sections we will describe some of these problems and the particular solutions to them that STRIPS employs.

B. The Frame Problem

When sets of logical statements are used as world models, we must have some deductive mechanism that allows us to tell whether or not a given model satisfies the goal or satisfies the applicability conditions of various operators. Green[5] implemented a problem-solving system based on the QA3 theorem-proving system[3] using the resolution principle. In his system, Green expressed the results of operators as logical statements. Thus, for example, to describe an operator goto(x,y) whose effect is to move a robot from any place x to any other place y, Green would use the wff

$$(\forall x,y,s)[ATR(x,s) \Rightarrow ATR(y,goto'(x,y,s))] \quad ,$$

where ATR is a predicate describing the robot's position. Here, each predicate has a state term that names the world model to which the predicate applies. Our wff above states that for all places x and y and for all states s, if the robot is at x in state s then the robot will be at y in the state goto'(x,y,s) resulting from applying the goto operator to state s. (If f is the name of an operator, we denote the corresponding state-mapping function by f'.)

With Green's formulation, any problem can be posed as a theorem to be proved. The theorem will have an existentially quantified state term, s. For example, the problem of pushing a box B to place b can be stated as the wff

$$(\exists s)\ AT(B,b,s) \quad .$$

If a constructive proof procedure is used, an instance of the state proved to exist can be extracted from the proof (Green,[3] Luckham and

Nilsson[3]). This instance, in the form of a composition of operator functions acting on the initial state, then serves as a solution to the problem.

Green's formulation has all the appeal (and limitations) of any general-purpose problem solver and represents a significant step in the development of these systems. It does, however, suffer from some serious disadvantages that our present system attempts to overcome. One difficulty is caused by the fact that Green's system combines two essentially different kinds of searches into a single search for a proof of the theorem representing the goal. One of these searches is in a space of world models; this search proceeds by applying operators to these models to produce new models. The second type of search concerns finding a proof that a given world model satisfies the goal theorem or the applicability conditions of a given operator. Searches of this type proceed by applying rules of inference to wffs within a world model. When these two kinds of searches are combined in the largely syntactically guided proof-finding mechanism of a general theorem prover, the result is gross inefficiency. Furthermore, it is much more difficult to apply any available semantic information in the combined search process.

The second drawback of Green's system is even more serious. The system must explicitly describe, by special axioms, those relations <u>not</u> affected by each of the operators. For example, since typically the positions of objects do not change when a robot moves, one must include the statement

$$(\forall u,x,y,z,s)[\mathrm{OBJECT}(u,s) \wedge \mathrm{AT}(u,x,s) \Rightarrow \mathrm{AT}(u,x,\mathrm{goto}'(y,z,s))] \quad .$$

Thus, after every application of goto in the search for a solution, one may need to prove that a given object B remains in the same position in the new state if the position of B is important to the completion of the solution.

The problem posed by the evident fact that operators affect certain relations and don't affect others is sometimes called the frame problem.[7,8] Since, typically, most of the wffs in a world model will not be affected by an operator application, our approach will be to name only those relations that are affected by an operator and to assume that the unnamed relations remain valid in the new world model. Since proving that certain relations are still satisfied in successor states is tedious, our convention can drastically decrease the search effort required.

Because we are adopting special conventions about what happens to the wffs in a world model when an operator is applied, we have chosen to take the process of operator application out of the formal deductive system entirely. In our approach, when an operator is applied to a world model, the computation of the new world model is done by a special extra-logical mechanism. Theorem-proving methods are used only within a given world model to answer questions about it concerning which operators are applicable and whether or not the goal has been satisfied. By separating the theorem proving that occurs within a world model from the search through the space of models we can employ separate strategies for these two activities and thereby improve the overall performance of the system.

II OPERATOR DESCRIPTIONS AND APPLICATIONS

The operators are the basic elements out of which a solution is built. For robot-like problems we can imagine that the operators

correspond to routines or subprograms whose execution causes a robot to take certain actions. For example, we might have routines that cause the robot to turn and move, a routine that causes it to go through a doorway, a routine that causes it to push a box and perhaps dozens of others. When we discuss the application of problem-solving techniques to robot problems, the reader should keep in mind the distinction between an operator and its associated action routine. Execution of routines actually causes the robot to take actions. Application of operators to world models occurs during the planning (i.e., problem solving) phase when an attempt is being made to find a sequence of operators whose associated routines will produce a desired state of the world. Since routines are programs, they can have parameters that are instantiated by constants when the routines are executed. The associated operators will also have parameters, but as we shall soon see, these can be left free at the time they are applied to a model.

In order to chain together a sequence of operators to achieve a given goal, the problem solver must have descriptions of the operators. The descriptions used by STRIPS consist of three major components:

(1) Name of the operator and its parameters

(2) Preconditions

(3) Effects.

The first component consists merely of the name of the operator and the parameters taken by the operator. The second component is a formula in first-order logic. The operator is applicable in any world model in which the precondition formula is a theorem. For example, the operator push(u,x,y) which models the action of the robot pushing an object u

from location x to location y might have as a precondition formula

$$(\exists x,u)[AT(u,x) \wedge ATR(x)] \quad .$$

The third component of an operator description defines the effects (on a set of wffs) of applying the operator. We shall discuss the process of computing effects in some detail since it plays a key role in STRIPS. When an operator is applied, certain wffs in the world model are no longer true (or at least we cannot be sure that they are true) and certain other wffs become true. Thus to compute one world model from another involves copying* the world model and in this copy deleting some of the wffs and adding others. Let us deal first with the set of wffs that should be added as a result of an operator application.

The set of wffs to be added to a world model depends on the results of the routine modeled by the operator. These results are not completely specified until all of the parameters of the routine are instantiated by constants. For example, the operator goto(x,y) might model the robot moving from location x to location y for any two locations x and y. When this operator's routine is executed, the parameters x and y must be instantiated by constants. However, we have designed STRIPS so that an operator can be applied to a world model with any or all of the operator's parameters left uninstantiated. For example, suppose we apply the operator goto(a,x) to a world model in which the robot is at some location† a. If the parameter x is unspecified, so will be the resulting

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*In our implementation of STRIPS we employ various bookkeeping techniques to avoid copying; these will be described in a later section.

†We shall adopt the convention of using letters near the beginning of the alphabet (a,b,c, etc.) to stand for constants and letters near the end of the alphabet (u,v,w,x, etc.) as variables.

world model. We could say that the application of goto(a,x) creates a family or schema of world models parameterized by x. The power and efficiency of STRIPS is increased by searching in this space of world model families rather than in the larger space of individual world models.

If we are to gain this reduction in search space size, then we must be able to describe with a single set of predicate calculus wffs the world model family resulting from the application of an operator with free parameters. One way in which this can be done is to use a state term in each literal of each wff. Thus, the principal effect of applying the operator goto(a,x) to some world model s_o, say, is to add the wff

$$(\forall x)(\exists s)\mathrm{ATR}(x,s)$$

which states that for all values of the parameter x, there exists a world model s in which the robot is at x. With expressions of this sort, a set of wffs can represent families of world models. Selecting specific values for the parameters selects specific members of the family.

Anticipating the use of a resolution-based theorem prover in STRIPS, we shall always express formulas in clause form.[1] Then the formula above would be written

$$\mathrm{ATR}(x,\mathrm{goto}'(a,x,s_o))$$

where $\mathrm{goto}'(a,x,s_o)$ is a function of x replacing the existentially quantified state variable. The value of $\mathrm{goto}'(a,x,s_o)$, for any x, is that world model produced by applying the operator goto(a,x) to world model s_o. Recall that any variables (such as x in the formula above) occurring in a clause have implicit universal quantification.

The description of each operator used in STRIPS contains a list of those clauses to be added when computing a new world model. This list is called the add list.

The description of an operator also includes information about which clauses can no longer be guaranteed true and must therefore be deleted in constructing a new world model. For example, if the operator goto(a,x) is applied, we must delete any clause containing the atom* ATR(a). Each operator description contains a list of atoms, called the delete list, that is used to compute which clauses should be deleted. Our rule for creating a new world model is to delete any clauses containing atoms (negated or unnegated) that are instances of atoms on the delete list. We also delete any clauses containing atoms of which the atoms on the delete list are instances. The application of these rules might sometimes delete some clauses unnecessarily, but we want to be guaranteed that the new world model will be consistent if the old one was.

When an operator description is written, it may not be possible to name explicitly all the atoms that should appear on the delete list. For example, it may be the case that a world model contains clauses that are derived from other clauses in the model. Thus from AT(B1,a) and from AT(B2,a+Δ) we might derive NEXTTO(B1,B2) and insert it into the model. Now, if one of the clauses on which the derived clause depends is deleted, then the derived clause must be deleted also.

We deal with this problem by defining a set of primitive predicates (e.g., AT, ATR, BOX) and relating all other predicates to this primitive

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*An atom is a single predicate letter and its arguments.

set. In particular, we require the delete list of an operator description to indicate all the atoms containing primitive predicates which should be deleted when the operator is applied. Also, we require that any nonprimitive clause in the world model have associated with it those primitive clauses on which its validity depends. (A primitive clause is one which contains only primitive predicates.) For example, the clause NEXTO(B1,B2) would have associated with it the clauses AT(B1,a) and AT(B2,a+Δ).

By using these conventions we can be assured that primitive clauses will be correctly deleted during operator applications, and that the validity of nonprimitive clauses can be determined whenever they are to be used in a deduction by checking to see if all of the primitive clauses on which the nonprimitive clause depends are still in the world model.

In the next section, we shall describe the search process for STRIPS and also present a specific example in which the process of operator application is examined in detail.

III THE OPERATION OF STRIPS

A. Computing Differences and Relevant Operators

In a very simple problem-solving system we might first apply all of the applicable operators to the initial world model to create a set of successor models. We would continue to apply all applicable operators to these successors and to their descendants until a model was produced in which the goal formula was a theorem. Checking to see which operators are applicable and to see if the goal formula is a theorem are theorem-proving tasks that could be accomplished by a deductive system such as QA3. However, since we envision uses in which the number of operators applicable to any given world model might be

quite large, such a simple system would generate an undesirably large tree of world models and would thus be impractical.

Instead we have adopted the GPS strategy of extracting "differences" between the present world model and the goal and of identifying operators that are "relevant" to reducing these differences.[4] Once a relevant operator has been determined, we attempt to solve the subproblem of producing a world model to which it is applicable. If such a model is found then we apply the relevant operator and reconsider the original goal in the resulting model.

Note that in the GPS strategy, when an operator is found to be relevant, it is not known where it will occur in the completed plan, that is, it may be applicable to the initial model and therefore be the first operator applied, its effects may imply the goal so that it is the last operator applied, or it may be some intermediate step toward the goal. The STRIPS search strategy maintains this flexibility and therefore combines many of the advantages of both forward search (from the initial model toward the goal) and backward search (from the goal toward the initial model).

Two key steps in this strategy involve computing differences and finding operators relevant to reducing these differences. One of the novel features of our system is that it uses a theorem prover as an aid in these steps. The following description of these processes assumes that the reader is familiar with the terminology of resolution-based theorem-proving systems.

Suppose we have a world model consisting of a set, S, of clauses, and that we have a goal formula whose negation is represented by the set, G, of clauses. The difference-computing mechanism attempts to find a contradiction for the set $S \cup G$ using a resolution theorem

prover such as QA3. (The theorem prover would likely use, at least, the set-of-support strategy with G the set receiving support.) If a contradiction is found, then the "difference" is nil and STRIPS would conclude that the goal is satisfied in S.

Our interest at the moment though is in the case in which QA3 cannot find a contradiction after investing some prespecified amount of effort. Let R be the set consisting of the clauses in G and the resolvents produced by QA3 that are descendants of clauses in G. Any set of clauses D in R can be taken as a "difference" between S and the goal in the sense that if a world model were found in which a clause in D could be contradicted, then it is likely* that the proof of the goal could be completed in that model.

STRIPS creates differences by heuristically selecting subsets of R, each of which acts as a difference. The selection process considers such factors as the number of literals in a clause, at what level in the proof tree a clause was generated, and whether or not a clause has any descendants in the proof tree.

The quest for relevant operators proceeds in two steps. In the first step an ordered list of candidate operators is created for each difference set. The selection of operators for this list is based on a simple comparison of the clauses in the difference set with the add lists in the operator descriptions. For example, if a difference set contained a clause having in it the robot position predicate ATR, then the operator goto would be considered a candidate operator for that difference.

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*That is, a proof could be completed if this new model still allows a deduction of this clause in D.

The second step in finding an operator relevant to a given difference set involves employing QA3 to determine if clauses on the add list of a candidate operator can be used to "resolve away" (i.e., continue the proof of) any of the clauses in the difference set. If, in fact, QA3 can produce new resolvents which are descendants of the add list clauses, then the candidate operator (properly instantiated) is considered to be a relevant operator for the difference set.

To complete the operator-relevance test STRIPS must determine which instances of the operator are relevant. For example, if the difference set consists of the unit clauses -ATR(a) and -ATR(b), then goto(x,y) is a relevant operator only when y is instantiated by a or b. Each new resolvent which is a descendant of the operator's add list clauses is used to form a relevant instance of the operator by applying to the operator's parameters the same instantiations that were made during the production of the resolvent. Hence the consideration of one candidate operator may produce several relevant operator instances.

One of the important effects of the difference-reduction process is that it usually produces specific instances for the operator parameters. Furthermore, these instances are likely to be those occurring in the final solution, thus helping to narrow the search process. So, although STRIPS has the ability to consider operators with uninstantiated parameters, it also has a strong tendency toward instantiating these parameters with what it considers to be the most relevant constants.

B. The STRIPS Executive

STRIPS begins by attempting to form differences between the initial world model, s_0, and the main goal (as described in the previous section). If no differences are found, then the problem is trivially

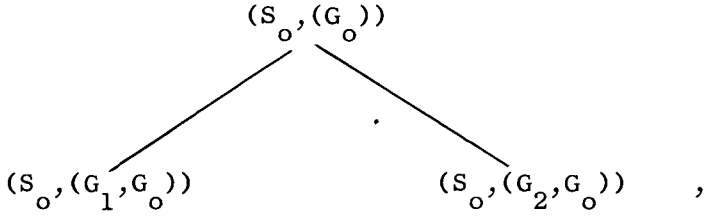
solved. If differences are found, then STRIPS computes a set of operators relevant to reducing those differences.

Suppose, for example, that STRIPS finds two instantiated operators, OP_1 and OP_2, relevant to reducing the differences between s_o and the main goal. Let the (instantiated) precondition formulas for these operators be denoted by PC_1 and PC_2, respectively. Thus STRIPS has found two ways to work on the main problem:

(1) Produce a world model to which OP_1 is applicable, apply OP_1, and then produce a world model in which the main goal is satisfied, or

(2) Produce a world model to which OP_2 is applicable, apply OP_2, and then produce a world model in which the main goal is satisfied.

STRIPS represents such solution alternatives as nodes on a search tree. The tree for our example can be represented as follows:



where G_o, G_1, and G_2 are sets of clauses corresponding to the negations of the main theorem, PC_1 and PC_2, respectively.

In general, each node of the search tree has the form (⟨world model⟩,⟨goal list⟩). The subgoal being considered for solution at each node is the first goal on that node's goal list. The last goal on each list is the negation of the main goal, and each subgoal is the negation of the preconditions of an operator. Hence, each subgoal in a

goal list represents an attempt to apply an operator which is relevant to achieving the next goal in the goal list.

Whenever a new node, $(s_1,(G_m,G_{m-1},\ldots,G_1,G_o))$, is constructed and added to the search tree as a descendant of some existing node, the new node is tested for goal satisfaction. This test is performed by QA3 which looks for a contradiction to $s_1 \cup G_m$.

If a contradiction is found and G_m is G_o--i.e., the node has the form $(s_1,(G_o))$--then the main goal is satisfied in s_1 and the problem is solved. If a contradiction is found and G_m is not G_o, then G_m is the negation of a precondition formula for an operator that is applicable in s_1. STRIPS produces a new world model, s_1', by applying to s_1 the operator corresponding to G_m. The node is changed to $(s_1',(G_{m-1},\ldots,G_1,G_o))$ and the test for goal satisfaction is performed on it again. This process of changing the node continues until a goal is encountered which is not satisfied or until the problem is solved.

If no contradiction is found in the goal satisfaction test, QA3 will return a set R of clauses consisting of the clauses in G_m and resolvents that are descendants of clauses in G_m. This set of resolvents is attached to the node and is used for generating successors to the node.

The process for generating the successors of a node $(s_1,(G_m,G_{m-1},\ldots,G_1,G_o))$ with R attached involves forming difference sets $\{D_1\}$ from R and finding operator instances relevant to reducing these differences (as described in the previous section). For each operator instance found to be relevant, a new offspring node is created. This new node is formed with the same world model and goal list as its parent node, then, the goal of finding a world model in which the relevant operator instance can be applied is added to the new node. This

is done by creating the appropriate instance of the operator's preconditions and adding the negation of the instantiated preconditions to the beginning of the new node's goal list.

Since the number of operators relevant to reducing sets of differences might be rather large in some cases, it is possible that a given node in the search tree might have a large number of successors. Even before the successors are generated, though, we can order them according to the heuristic merit of the operators and difference sets used to generate them. The process of computing a successor node can be rather lengthy, and for this reason STRIPS actually computes only that single next successor judged to be best. STRIPS adds this successor node to the search tree, performs a goal-satisfaction test on it, and then selects another node from the set of nodes which still have uncomputed successors. STRIPS must therefore associate with each node the sets of differences and candidate operators it has already used in creating successors.

STRIPS has a heuristic mechanism to select nodes with uncomputed successors to work on next. For this purpose we use an evaluation function that takes into account such factors as the number and types of literals in the remaining goal formulas, the number of remaining goals, and the number and types of literals in the difference sets.

A simple flowchart of the STRIPS executive is shown in Figure C-1.

C. An Example

Let us next trace through a simple example contrived to illustrate the main features in the operation of STRIPS. Consider the configuration shown in Figure C-2, consisting of two objects B and C and a robot R at places b, c, and a, respectively. The problem given to STRIPS

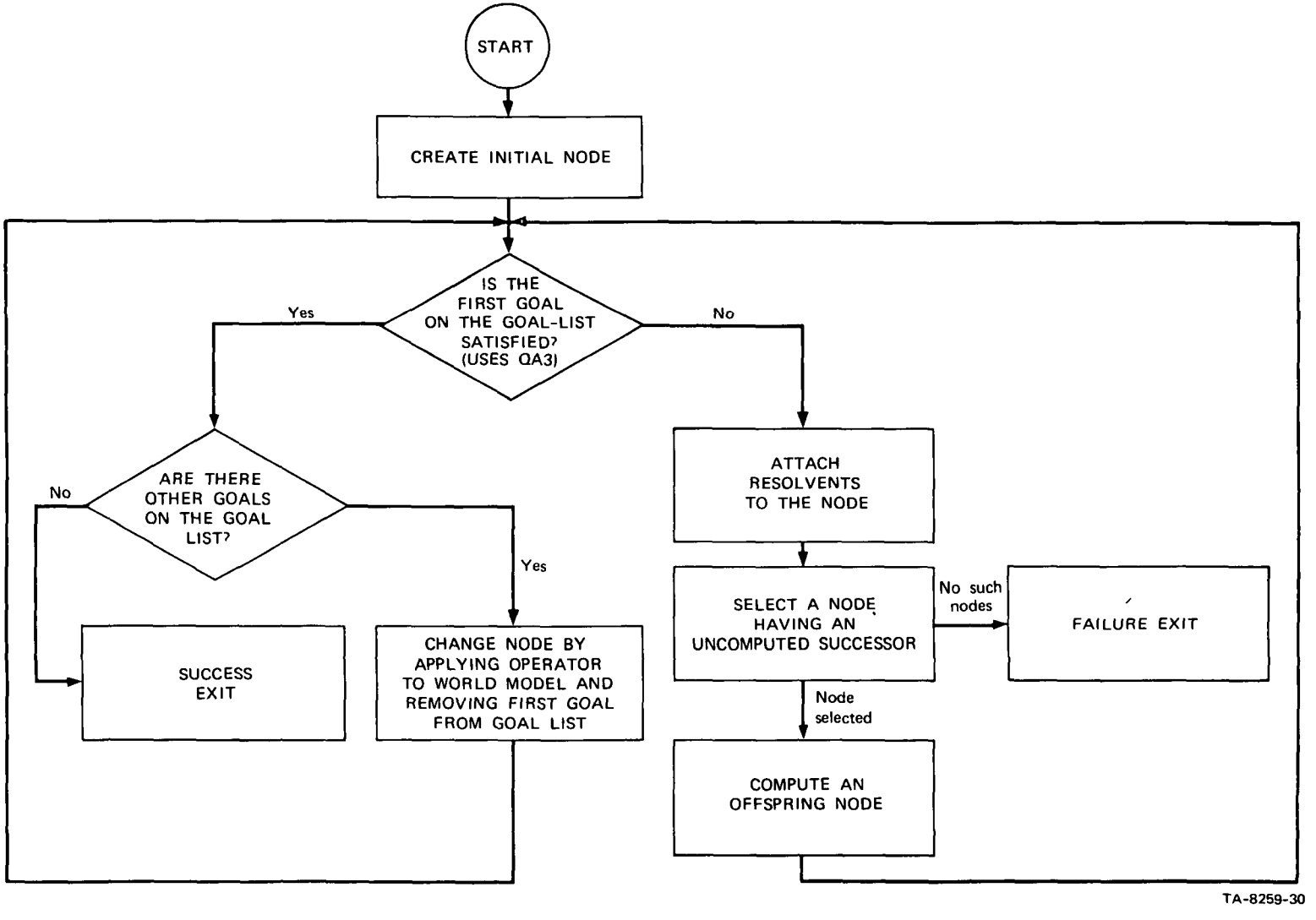


FIGURE C-1 FLOWCHART FOR THE STRIPS EXECUTIVE

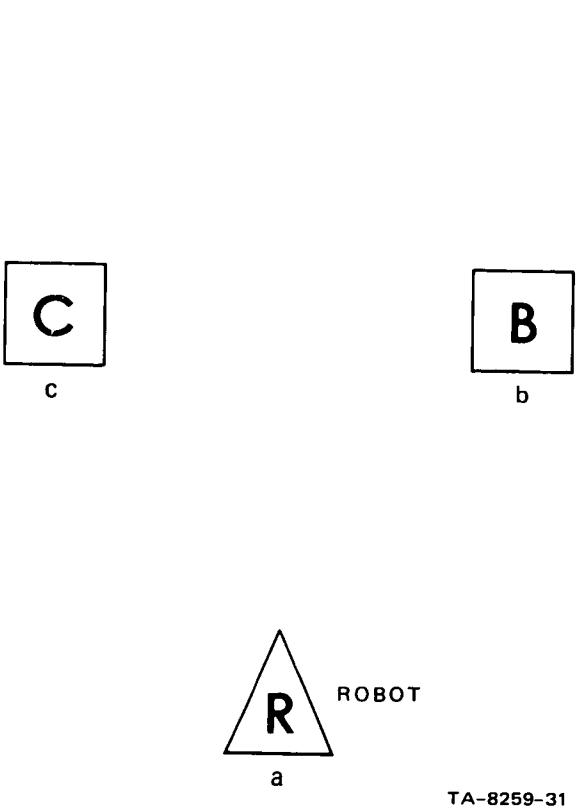


FIGURE C-2 CONFIGURATION OF OBJECTS AND ROBOT FOR EXAMPLE PROBLEM

is to achieve a configuration in which object B is at place k and in which object C is <u>not</u> at place c.

The existentially quantified theorem representing this problem can be written

$$(\exists s)[AT(B,k,s) \wedge \sim AT(C,c,s)] \quad .$$

If we can find an instance of s (in terms of a composition of operator applications) that satisfies this theorem, then we will have solved the problem. The negation of the theorem is

$$G_o: \quad \sim AT(B,k,s) \vee AT(C,c,s) \quad .$$

Let us suppose that STRIPS is to compose a solution using the two operators goto and push. These operators can be described as follows:

(1) push(u,x,y): Robot pushes object u from place x to place y.

Precondition formula:

$$(\exists u,x,s)[AT(u,x,s) \wedge ATR(x,s)]$$

Negated precondition formula:

$$\sim AT(u,x,s) \vee \sim ATR(x,s)$$

Delete list:

$$AT(u,x,s)$$

$$ATR(x,s)$$

Add list:

$$AT(u,y,push'(u,x,y,s^*))$$

$$ATR(y,push'(u,x,y,s^*))$$

where s^* is the state to which the operator is applied.

(2) goto(x,y): Robot goes from place x to place y.

Precondition formula:

$$(\exists x,s)ATR(x,s)$$

Negated precondition formula:

$$\sim ATR(x,s)$$

Delete list:

$$ATR(x,s)$$

Add list:

$$ATR(y,goto'(x,y,s^*)) \quad .$$

The initial configuration can be described by the following world model:

$$s_o: \quad ATR(a,s_o)$$
$$AT(B,b,s_o)$$
$$AT(C,c,s_o) \quad .$$

In addition, we have a universal formula, true in all world models, that states if an object is in one place, then it is not in a different place:

$$F: \quad (\forall u,x,y,s)[AT(u,x,s) \wedge (x \neq y) \Rightarrow \sim AT(u,y,s)] \quad .$$

The clause form of this formula is

$$F': \ \sim AT(u,x,s) \vee (x=y) \vee \sim AT(u,y,s) \quad .$$

We assume that F' is adjoined to all world models.

A portion of STRIPS' solution trace relating to the final plan is given in Figure C-3. The remainder of this section is a commentary on that trace. STRIPS first constructs the node N_o, consisting of the list $(s_o,(G_o))$, as the root of the problem-solving tree and tests it for a solution by attempting to find a contradiction for the set $s_o \cup \{G_o\}$. No contradiction is found but some resolvents can be obtained; among them is the resolvent R_1 of G_o and F':

$$\sim AT(B,k,s) \vee (c=y) \vee \sim AT(C,y,s) \quad .$$

Next STRIPS selects a node (N_o is now the only one available) and begins to generate successors. First it selects a difference set D_1 from the set of resolvents attached to N_o. In this case it sets $D_1 = \{R_1\}$. Then STRIPS composes a list L_1 of candidate operators for reducing D_1. Here L_1 would consist of the single element push.

Next STRIPS attempts to reduce D_1 using clauses on the add list of push. Again using theorem-proving methods we obtain two resolvents from D_1 and $AT(u,y,push'(u,x,y,s^*))$:

$$\sim AT(B,k,push'(C,x,y,s^*)) \vee (c=y)$$

and

$$\sim AT(C,y,push'(B,x,k,s^*)) \vee (c=y) \quad .$$

Assuming that these resolutions represent acceptable reductions in the difference, we extract the state terms of the resolvents to yield

```
Begin STRIPS trace
Create negated goal G_o:  ~AT(B,k,s) V AT(C,c,s)
Form model s_o:  ATR(a,s_o)
                 AT(B,b,s_o)
                 AT(C,c,s_o)
                 ~AT(u,x,s) V (x=y) V ~AT(u,y,s)
Form node N_o:  (s_o,(G_o))
Perform goal satisfaction test on node N_o
     Goal G_o not satisfied; resolvents formed:
          R_1:  ~AT(B,k,s) V (c=y) V ~AT(C,y,s)
          R_2:  ...
          .
          .
          .
Select node N_o
Compute offspring node of N_o
     Create difference D_1:  {R_1}
     Create candidate operators list L_1:  (push)
     Test relevancy of push
          Relevant instances of push found:
               OP_1:  push(C,x,y)
               OP_2:  push(B,x,k)
     Create negated goal G_1:  ~AT(C,x,s) V ~ATR(x,s)
     Create node N_1:  (s_o,(G_1,G_o))
Perform goal satisfaction test on node N_1
     Goal G_1 not satisfied; resolvents formed:
          R'_3:  ~ATR(c,s)
          R'_4:  ...
          .
          .
          .
```

FIGURE C-3 SOLUTION TRACE FOR EXAMPLE PROBLEM

Select node N_1

Compute offspring node of N_1

Create difference D_2: $\{R_3'\}$

Create candidate operators list L_2: (goto)

Test relevancy of goto

Relevant instances of goto found

OP_3: goto(x,c)

Create negated goal G_2: $\sim ATR(x,s)$

Create node N_2: $(s_o,(G_2,G_1,G_o))$

Perform goal satisfaction test on node N_2

Goal G_2 satisfied

$x = a,\ s = s_o$

Apply operator goto(a,c)

Create model s_1: $ATR(c,goto'(a,c,s_o))$

$AT(B,b,goto'(a,c,s_o))$

$AT(C,c,goto'(C,c,goto'(a,c,s_o))$

$\sim AT(u,x,s) \vee (x=y) \vee \sim AT(u,y,s)$

Goal G_1 satisfied

$x = c,\ s = goto(a,c,s_o)$

Apply operator push(C,c,y)

Create model s_2: $ATR(y,push'(C,c,y,goto'(a,c,s_o)))$

$AT(B,b,push'(C,c,y,goto'(a,c,s_o)))$

$AT(C,y,push'(C,c,y,goto'(a,c,s_o)))$

$\sim AT(u,x,s) \vee (x=y) \vee \sim AT(u,y,s)$

Goal G_o not satisfied; resolvents formed

R_5': $\sim AT(B,k,s) \vee (c=y)$

R_6': ...

FIGURE C-3 SOLUTION TRACE FOR EXAMPLE PROBLEM (Continued)

Select node N_2

Compute offspring node of N_2

Create difference D_3: $\{R_5'\}$

Create candidate operators list L_3: (push)

.
.
.

etc.

FIGURE C-3 SOLUTION TRACE FOR EXAMPLE PROBLEM (Concluded)

appropriate instances of the relevant operator. This gives us:

$$OP_1: \ \underline{push}(C,x,y)$$

and

$$OP_2: \ \underline{push}(B,x,k) \quad .$$

For brevity, let us consider just OP_1 and construct G_1, the negated version of the precondition formula for OP_1:

$$G_1: \ \sim AT(C,x,s) \vee \sim ATR(x,s) \quad .$$

This formula is then used to construct a successor node

$$N_1: \ (s_o,(G_1,G_o)) \quad .$$

STRIPS then performs a goal test on N_1 by attempting to find a contradiction for $s_o \cup G_1$.

Again no contradiction is found, but the following resolvents are obtained:

$$R_3: \sim ATR(c,s_o) \text{ from } G_1 \text{ and } AT(C,c,s_o)$$

and

$$R_4: \sim AT(C,a,s_o) \text{ from } G_1 \text{ and } ATR(a,s_o) \quad .$$

Although these clauses represent differences between s_o and G_1, we do not insist that these differences be reduced in s_o. We would accept a reduction occurring in any world model, so STRIPS rewrites the clauses as:

$$R_3': \sim ATR(c,s)$$

and

$$R_4': \sim AT(C,a,s) \quad .$$

Next STRIPS selects a node for consideration. When it selects N_1, it sets the difference set, D_2, to $\{R_3'\}$.

The list of operators useful for reducing D_2 consists only of goto. STRIPS now attempts to perform resolutions between the clauses on the add list of goto and D_2. The clause in D_2 resolves with $ATR(y,goto'(x,y,s^*))$ to yield nil, and answer extraction produces the instance substituted for the state term, namely

$$s = goto'(x,c,s^*) \quad .$$

Thus STRIPS identifies the following instance of goto:

$$OP_3: \quad goto(x,c) \quad .$$

The associated negated precondition is

$$G_2: \ \sim ATR(x,s) \quad .$$

STRIPS then constructs the successor node

$$N_2: \ (s_o,(G_2,G_1,G_o))$$

and immediately attempts to find a contradiction for $s_o \cup G_2$. Here a contradiction is obtained, and answer extraction yields the state term:

$$goto'(a,c,s_o) \quad .$$

Thus STRIPS applies goto(a,c) to s_o to yield

$$\begin{array}{ll} s_1 & ATR(c,goto'(a,c,s_o)) \\ & AT(B,b,goto'(a,c,s_o)) \\ & AT(C,c,goto'(a,c,s_o)) \quad . \end{array}$$

Node N_2 is then changed to

$$(s_1,(G_1,G_o))$$

and STRIPS immediately checks for a contradiction for $s_1 \cup G_1$. Again a contradiction is found; answer extraction produces the following instances for x and s:

$$x = c$$

and

$$s = goto'(a,c,s_o) \quad .$$

Thus STRIPS applies the following instance of OP_1:

$$\underline{\text{push}}(C,c,y) \quad .$$

The result is the world model family s_2 consisting of the following clauses.

s_2: $ATR(y,push'(C,c,y,goto'(a,c,s_o)))$

$AT(B,b,push'(C,c,y,goto'(a,c,s_o)))$

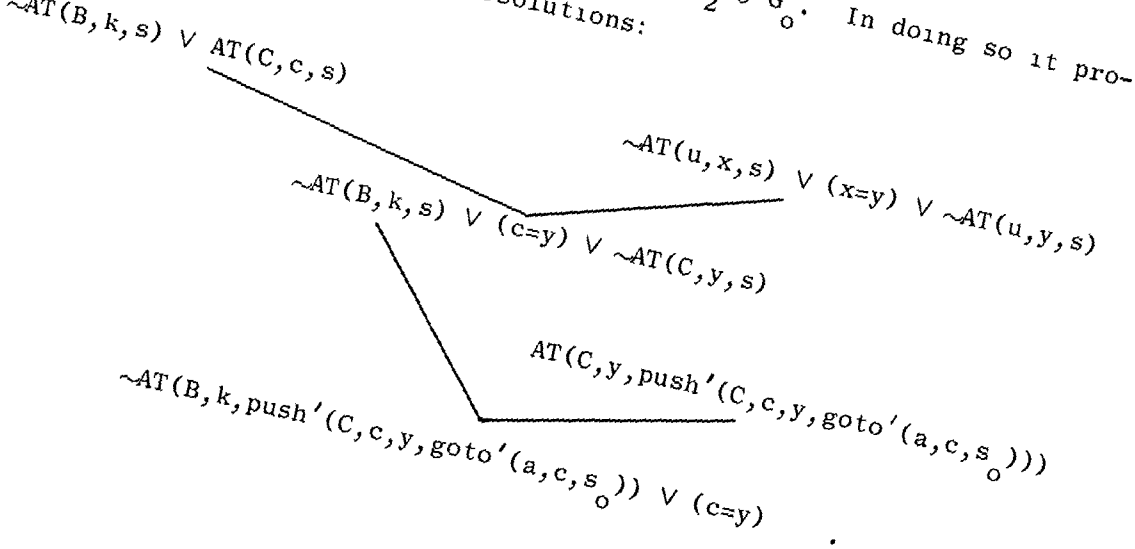
$AT(C,y,push'(C,c,y,goto'(a,c,s_o)))$.

Note that this application of the operator $\underline{\text{push}}$ involved an uninstantiated parameter, y.

Node N_2 is then changed to

$$(s_2,(G_o)) \quad .$$

and STRIPS checks for a contradiction for $s_2 \cup G_o$. In doing so it produces the following tree of resolutions:



.

The clause at the root produces one of the resolvents to be attached to N_2, namely

$$R_5: \ \sim AT(B,k,s) \vee (c=y) \quad .$$

When STRIPS selects N_2, it begins generating successors based on a difference $D_3 = \{R_5'\}$. The operator list for this difference consists solely of push, and the relevant instance of push is found to be

$$OP_4: \ \underline{push}(B,x,k) \quad .$$

Its (negated) precondition is

$$G_3: \ \sim AT(B,x,s) \vee \sim ATR(x,s) \quad .$$

A successor node to N_2 is then

$$N_3: \ (s_2,(G_3,G_o)) \quad .$$

STRIPS finds a contradiction between s_2 and G_3, and extracts

$$s = push'(C,c,b,goto'(a,c,s_o))$$

and $x = b$. Therefore, it applies $\underline{push}(B,b,k)$ to an instance of s_2 (with $y = b$) to yield

$$\begin{aligned} s_3: \ & ATR(k,push'(B,b,k,push'(C,c,b,goto'(a,c,s_o)))) \\ & AT(B,k,push'(B,b,k,push'(C,c,b,goto'(a,c,s_o)))) \\ & AT(C,b,push'(B,b,k,push'(C,c,b,goto'(a,c,s_o)))) \quad . \end{aligned}$$

Node N_3 is then changed to

$$(s_3,(G_o))\quad .$$

STRIPS can find a contradiction between s_3 and G_o [assuming that the equality predicate (b = c) can be evaluated to be false] and exits successfully. The successful plan is embodied in the state term for s_3.

D. Efficient Representation of World Models

A primary design issue in the implementation of a system such as STRIPS is how to satisfy the storage requirements of a search tree in which each node may contain a different world model. We would like to use STRIPS in a robot or question-answering environment where the initial world model may consist of hundreds of wffs. For such applications it is infeasible to recopy completely a world model each time a new model is produced by application of an operator.

We have dealt with this problem in STRIPS by first making the assumption that most of the wffs in a problem's initial world model will not be changed by the application of operators. This is certainly true for the class of robot problems we are currently concerned with. For these problems most of the wffs in a model describe rooms, walls, doors, and objects, or specify general properties of the world which are true in all models. The only wffs that might be changed in this robot environment are the ones that describe the status of the robot and any objects which it manipulates.

Given this assumption, we have implemented the following scheme for handling multiple world models. All the wffs for all world models are stored in a common memory structure. Associated with each

wff (i.e., clause) is a visibility flag, and QA3 has been modified to consider only clauses from the memory structure which are marked visible. Hence, we can "define" a particular world model for QA3 by marking that model's clauses visible and all other clauses invisible. When clauses are entered into the initial world model they are marked visible and given a variable as a state term. Clauses not changed will remain visible throughout STRIPS' search for a solution.

Each world model produced by STRIPS is defined by two clause lists. The first list, DELETIONS, names all those clauses from the initial world model which are no longer present in the model being defined. The second list, ADDITIONS, names all those clauses in the model being defined which are not also in the initial model. These lists represent the changes in the initial model needed to form the model being defined, and our assumption implies they will contain only a small number of clauses.

To specify a given world model to QA3, STRIPS marks visible the clauses on the model's ADDITIONS list and marks invisible the clauses on the model's DELETIONS list. When the call to QA3 is completed, the visibility markings of these clauses are returned to their previous settings.

When an operator is applied to a world model, the DELETIONS list of the new world model is a copy of the DELETIONS list of the old model plus any clauses from the initial model which are deleted by the operator. The ADDITIONS list of the new model consists of the clauses from the old model's ADDITIONS list as transformed by the operator plus the clauses from the operator's add list.

To illustrate this implementation design we list below the way in which the world models described in the example of the previous section are represented:

s_o: ATR(a,s)

AT(B,b,s)

AT(C,c,s)

s_1: DELETIONS: ATR(a,s)

ADDITIONS: ATR(c,goto'(a,c,s_o))

s_2: DELETIONS: ATR(a,s)

AT(C,c,s)

ADDITIONS: ATR(y,push'(C,c,y,goto'(a,c,s_o)))

AT(C,y,push'(C,c,y,goto'(a,c,s_o)))

s_3: DELETIONS: ATR(a,s)

AT(C,c,s)

AT(B,b,s)

ADDITIONS: ATR(k,push'(B,b,k,push'(C,c,b,goto'(a,c,s_o))))

AT(B,k,push'(B,b,k,push'(C,c,b,goto'(a,c,s_o))))

AT(C,b,push'(B,b,k,push'(C,c,b,goto'(a,c,s_o)))) .

IV FUTURE PLANS AND PROBLEMS

The current implementation of STRIPS can be extended in several directions. These extensions will be the subject of much of our problem-solving research activities in the immediate future. We shall conclude this note by briefly mentioning some of these.

We have seen that STRIPS constructs a problem-solving tree whose nodes represent subproblems. In a problem-solving process of this sort, there must be a mechanism to decide which subproblem to work on next.

We have already mentioned some of the factors that might be incorporated in an evaluation function by which subproblems can be ordered according to heuristic merit. We expect to devote a good deal of effort to devising and experimenting with various evaluation functions and other ordering techniques.

Another area for future research concerns synthesis of more complex procedures than those consisting of simple linear sequences of operators. Specifically we want to be able to generate procedures involving iteration (or recursion) and conditional branching. In short, we would like STRIPS to be able to generate computer programs. Several researchers[5,9,10] have already considered the problem of automatic program synthesis and we expect to be able to use some of their ideas in STRIPS.

Our implementation of STRIPS is designed to facilitate the definition of new operators by the user. Thus the problem-solving power of STRIPS can gradually increase as its store of operators grows.

An idea that may prove useful in robot applications concerns defining and using operators to which there correspond no execution routines. That is, STRIPS may be allowed to generate a plan containing one or more operators that are fictitious. This technique essentially permits STRIPS to assume that certain subproblems have solutions without actually knowing how these solutions are to be achieved in terms of existing robot routines. When the robot system attempts to execute a fictitious operator, the subproblem it represents must first be solved (perhaps by STRIPS). (In human problem solving, this strategy is employed when we say: "I won't worry about that [sub] problem until I get to it.")

We are also interested in getting STRIPS to define new operators for itself based on previous problem solutions. One reasonable possibility is that after a problem represented by $(S_o,(G_o))$ is solved,

STRIPS could automatically generate a fictitious operator to represent the solution. It would be important to try to generalize any constants appearing in G_o; these would then be represented by parameters in the fictitious operator. The structure of the actual solution would also have to be examined in order to extract a precondition formula, delete list, and add list for the fictitious operator.

A more ambitious undertaking would be an attempt to synthesize automatically a robot execution routine corresponding to the new operator. Of course, this routine would be composed from a sequence of the existing routines corresponding to the individual existing operators used in the problem solution. The major difficulty concerns generalizing constants to parameters so that the new routine is general enough to merit saving. Hewitt[11] discusses a related problem that he calls "procedural abstraction." He suggests that from a few instances of a procedure, a general version can sometimes be synthesized. We expect that our generalization problem will be aided by an analysis of the structure of the preconditions and effects of the individual operators used in the problem solution.

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Appendix D

A LANGUAGE FOR WRITING PROBLEM-SOLVING PROGRAMS

by

Johns F. Rulifson, Richard J. Waldinger and Jan A. Derksen

Appendix D

A LANGUAGE FOR WRITING PROBLEM-SOLVING PROGRAMS

ABSTRACT

This appendix describes a language for constructing problem-solving programs. The language can manipulate several data structures, including ordered and unordered sets. Pattern matching facilities may be used in various ways, including the binding of variables. Implicit backtracking facilitates the compact representation of search procedures. Expressions are treated analogously to atoms in LISP. A "context" device is used to implement variable bindings, to effect conditional proofs, and to solve the "frame" problem in robot planning.

I BACKGROUND

In order to design a deductive problem-solving program, we are constructing a new formal language that can express complex inferential mechanisms concisely. This language, called the QA4 language, is being used to build a proposed intelligent system, called the QA4 system, that will be able to organize and use a large body of specialized knowledge. The selection of three specific applications--automatic program synthesis, automaton planning, and theorem proving--permits a concentration of effort within a framework of generality. All three applications, however, share a common basis that encompasses natural language dialogue, question answering, and inference, as well as many other areas of Artificial Intelligence.

There is strong motivation for the development of a new language for problem-solving programs. Earlier systems have been constrained by fixed inference mechanisms, built-in strategies, awkward languages for problem statement, and rigid overall structure. They relied on one or two rules of inference that could not be changed. To modify a strategy required a complete reprogramming of the system. It was sometimes harder to express a program-synthesis problem in a language the system could understand than it was to write the program yourself. Systems were limited to the use of a single paradigm that might be applicable to some types of problems and inappropriate for others. Theorem-proving strategies have used syntactic properties of the expressions being manipulated, but have been unable to use semantic knowledge or pragmatic, intuitive information. They have been unable to employ the sort of pattern recognition the human problem solver relies on so heavily.

The basic approach of the QA4 project is to develop natural, intuitive representations of specific problems and their solutions. The specification for a computer program, for example, is a blend of procedural and declarative information that includes explicit instructions, intuitive advice, and semantic definitions. A QA4 interpreter will execute programs in the transparent but precise language we have chosen for these representations; and the interpreter, together with an initial collection of QA4 "bootstrapping" programs, will constitute the basic QA4 system. The system will attempt to assimilate new advice and facts and attempt to solve problems with continually increasing agility.

The project has revolved around the construction and reworking of hand simulations of a proposed final QA4 system. Each simulation includes a problem statement, relevant definitions and advice, and a protocol for the solution. These simulations have provided a focus

for the language development and prompted explorations into theoretical foundations of the problem areas.[1]* Table D-1 summarizes the scope of the simulations and indicates the problem areas attacked.

Table D-1

PROBLEM AREAS

Program Synthesis

- Generate recursive and iterative programs from declarative axiomatic specifications (problems taken from a LISP primer).
- Generate an iterative program from a recursive procedural definition (see Fibonacci example in Ref. 2).
- Verify the correctness of programs with respect to input/output relations. These relations may be defined in terms of executable programs, as well as in terms of declarative axioms.

Automaton Planning

- Generate plans for simple robot problems.

Theorem Proving

- Prove simple algebraic identities over the integers.
- Derive simple algebraic laws from Peano's axioms.
- Prove properties of axiomatically defined groups.
- Accommodate general rules of inference, applicable to any logical system.

The QA4 language is derived from more conventional programming languages and mathematical languages, and yet differs from both in many ways. The basic data structures include sets, sets with repeated elements ("bags"), ordered bags ("tuples"), and lambda expressions. Data

*References are listed at the end of this appendix.

may also be represented implicitly; for example, the set of even integers, although infinite, may still be described and manipulated in the system. Every expression in the language may have a variety of properties associated with it. This feature serves as the basis for describing the role of each expression and thus directing the processes that operate on the expression. Program control is often directed by matching patterns against expressions. Sometimes, for example, the syntactic form of a problem suggests the use of a certain strategy. Ambiguous patterns lead to nondeterministic programs and the need for automatic backtracking.[3] Other control features include parallel search and iteration through sets. Space does not permit a full presentation of our current, preliminary version of the QA4 syntax. Table D-2 lists some features of the language.

The system changes continuously as it is used. The programmer types commands in the form of QA4 expressions to a top-level function. The commands may input or modify expressions or properties of expressions; define, modify, or execute programs; or perform debugging tasks.

The input system of QA4 is a parser that transforms QA4 infix expressions into internal prefix format. The parser uses the input translater BIP,[4] and has the advantage of being readily modified. Similarly, an output function takes the internal expression form and produces a corresponding infix output stream. Thus the user always communicates with QA4 in an infix mathematical-style notation.

The QA4 interpreter is a function resembling LISP EVAL.[5] It accepts QA4 expressions and, with the aid of an extensive library of primitive functions, executes them. Unlike LISP programs, QA4 expressions may succeed or fail and do not necessarily have values. The interpreter performs its task in small steps, and may, between any two steps, redirect its attention to other parallel processes or search programs.

Table D-2

SOME LANGUAGE FEATURES

Data Manipulation
• Arithmetic and Boolean operations
• Set, bag, and tuple operations
• Expression decomposition and construction
Pattern Matching
• Actual argument decomposition
• Data base queries
• Monitoring expression properties
• Invoking of strategies and inference rules
Control
• Standard serial and conditional statements (prog's, labels, go's, and if's)
• Iterative forms for sets, bags, and tuples
• Automatic backtracking
• Strategy controlled parallel interpretation

II DATA CONTROL STRUCTURES

Every operator in QA4 has a single operand. The data type of each primitive operator has been chosen to eliminate a proliferation of rules governing algebraic properties, such as associativity, commutativity, and transitivity. The Boolean connective "and," for example, has a set as its operand. The finix expression A & B & C is translated into the internal representation AND{A, B, C} (where braces denote the data type "set"). Since sets are independent of the order of their elements, this representation makes the statement of the commutativity law unnecessary.

Bags in QA4 are unordered tuples or, equivalently, sets with repeated elements. They play an important role in the definition of arithmetic operators, such as addition. The operand of PLUS cannot be a set, because the set {1, 1} is equal to {1}, but we would not want PLUS{1, 1} to equal PLUS{1}. Instead, the infix expression X + Y + Z becomes PLUS[X, Y, Z] internally, where [X, Y, Z] is a bag. Bags are evaluated by first evaluating their members. The resulting values are collected together into a bag, elements being duplicated when appropriate. Thus, if X, Y, and Z all had value 1, our expression would equal PLUS[1, 1, 1], and its value would be 3.

Some expressions, infinite sets, for example, cannot always be explicitly evaluated. Finite sets may also be inconvenient to evaluate: A program may wish to search the Cartesian product of two sets, even when the entire set is too large to generate. The interpreter can perform the search by indexing through the original two sets. In cases such as this expressions are said to have implicit values.

QA4 has iterative, parallel, and backtracking control structures. The iterative statement forms of the language operate over sets, bags, and tuples. The order of iteration may be controlled by relations. During theorem proving experiments, for example, pairs of logical expressions are analyzed in an order specified both in terms of syntactic properties, such as length, and of pragmatic properties, such as frequency of use. Parallel structures, in the form of coroutines and WHEN statements, are used in the construction of problem solving strategies. For example, in order to prove a theorem of the form A $\vee$ B, we may wish to establish two processes, one to prove A and the other to prove B. If either terminates successfully, the proof is complete. Nondeterministic programs give rise to backtracking. If a point of indeterminacy occurs, a choice determined by a prespecified strategy is made. If the program

later fails, control is reestablished at the choice point, and a different selection is made.

Without explaining all the notations we use, we illustrate the power of the QA4 language with a program that sorts bags:

```
SORT = CASES

       ⟨λ [ ], ⟨ ⟩,

       λ X·B ↑ MIN⟨X,B⟩, X·SORT(B)⟩;     .
```

When this function is applied to a bag, say B′, it first checks to see whether B′ is empty ([ ]); if so, it returns the empty tuple (⟨ ⟩). If the bag is not empty, it finds an element X of B′ such that X is less than or equal to all the elements of B, the bag remaining when X is deleted from B′. Then it sorts B (recursively) and adjoins X to the front of the resulting tuple. Thus the bound variables of a lambda expression may be patterns, and variable binding must then be done by pattern matching. The search for a pattern match may be directed by an associated strategy.

III EXPRESSIONS

The data base for QA4 programs is made up of QA4 expressions. An expression is represented internally by a list of properties, one of which is the syntactic component that uniquely distinguishes it from all other QA4 expressions. This list stores arbitrary properties, and each property is, in turn, a QA4 expression. These properties fall into three categories: syntactic, semantic, and pragmatic. Table D-3 is a brief example of an expression. Table D-4 lists commonly used properties

Table D-3

A SAMPLE EXPRESSION

Syntactic component	⟨X, Y⟩
Value	⟨3, 4⟩
Length	2
Result when the function F is applied to the expression	27

Table D-4

EXPRESSION PROPERTIES

Syntactic

- The form
- The logical type (e.g., a function mapping numbers into truth values)
- The data type (e.g., a set of 3-tuples)
- Frequently used information (e.g., the length)

Semantic

- The value
- An implicit value (e.g., a coroutine[6] that generates the value)
- A set of expressions equal to this one
- Constraints (e.g., a range or interval for the value)

Pragmatic

- Historical information
- Intuitive evaluation advice
- Success/failure indicators

Expression manipulation is accomplished by decomposition and construction. In QA4 decomposition means naming parts or components of an expression. The naming is done by the pattern matcher. Patterns may occur at many points in the language: in formal arguments of functions, in assignment statements, and in conditional tests. Table D-5 illustrates some of the more useful facets of the pattern matching notation. Transformation of expressions is done through a complete set of constructors,[7] such as: add an element to a set, add onto tuples, or construct a lambda expression.

Table D-5

SOME PATTERN MATCHER FEATURES

• Transparent template notation	⟨X,4,3⟩ matches ⟨5,4,3⟩ with X = 5
• Matching of internal or external notation	⟨X,4⟩ matches (tuple 3 4) with X = 3
• Fragment variables	⟨2, * Y⟩ matches ⟨2,3,4,5⟩ with Y = ⟨3,4,5⟩
• Type constraints on variables	X/integer matches 3 with X = 3
• Predicate constraints	⟨X ↑ X ≥ 4,5,6⟩ does not match ⟨2,5,6⟩
• "Occurs in" matching	.. + .. matches A * 2 + B

Given the syntactic component for an expression, a fundamental operation is to retrieve the entire expression so as to find the properties already assigned or known about it. In this way, LISP's atom property feature is extended to expressions in general. When an expression is stored, whether the expression has been stored before is determined. If it has been, the old expression is returned; if not, the new expression is retained by the system.

The storage mechanism is a discrimination net. Each node of the net consists of a feature selector and a set of labeled branches. A syntactic component is retrieved by applying the topmost selector, choosing a branch based on the outcome of the selector, and repeating the process until either a terminal node is reached or there is no appropriate branch. When conflicts occur at a terminal node, a new selector is automatically generated and installed at the new node. The next time the same syntactic component is retrieved, the expression that has just been added will be returned. The net also serves as a pruning device for the pattern matcher.

If two QA4 expressions are identical except for the names of their bound variables, they have the same internal representation. Thus bound variables are not used as discrimination features. Moreover, in order to store sets and bags in the net, an index is assigned to each element of a set or bag expression the first time the expression is stored. If the same set is then stored a second time (perhaps with some elements permuted), the elements are first ordered by their index numbers and then discriminated upon syntactically. If a user types in the set {A, B, C}, the elements might be assigned indices A←1, B←2, C←3. If the set {C, B, A} is entered, it is sorted into {A, B, C} and then found to occur already. The storage and retrieval functions also maintain extensive statistics concerning the number of references made to each expression for use in future optimization.

Variable bindings are implemented in the QA4 interpreter with a "context" mechanism--a method of storing all the changeable properties of expressions which simplifies backtracking and executing parallel processes. The same facilities, moreover, are made available to users and are especially useful in programs dealing with conditional proofs or robot planning programs confronted with the "frame" problem.[8]

IV CONCLUSION

Certain structures and mechanisms have found repeated application in deductive problem solvers. It is our goal to give these concepts concise notations. We expect this effort to have several desirable consequences·

- Existing problem-solving techniques should become more easily representable and modifiable.
- A large store of special-purpose knowledge could be embodied in a program.
- Systems would be more likely to rely on strategies than on blind search if such strategies were easily expressed and incorporated.

We have found the QA4 language a suitable vehicle for our own work in program synthesis, robot planning, and theorem proving.

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Appendix E

FAILURE TESTS AND GOALS IN PLANS

by

Richard E. Fikes

Appendix E

FAILURE TESTS AND GOALS IN PLANS

I INTRODUCTION

This appendix describes a proposal for the form that plans for the Stanford Research Institute mobile automaton might take and the rules an interpreter might use to execute these plans. We are particularly concerned here with adding tests to a plan that allow the executor to determine whether execution of a plan is succeeding and that specify what is to be done when a failure occurs.

We proceed by developing a syntax and semantics for plans in the context of STRIPS (STanford Research Institute Problem Solver),[1]* the program that acts as a planner for the automaton system. Subsequently, we present an algorithm that STRIPS can use to create the tests for the executor to use.

We assume that the reader has some familiarity with the capabilities of our robot vehicle and our means of modeling both the robot's external environment and its action routines (or operators). See Refs. 1 and 2 for this background material.

II SYNTAX AND SEMANTICS OF A STRIPS PLAN

The role of the planner in our system is to determine what the robot should do to solve a given task. We may consider the output of

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*References are listed at the end of this appendix.

the planner to be a program each of whose steps is an operator to be executed or a test to be made on the world model. One simple form that a plan might have is the following:

```
BEGIN
     DO operator_1,
     GOAL preconditions for operator_2;
     DO operator_2,
     GOAL preconditions for operator_3;
     .
     .
     .
     GOAL preconditions for operator_k;
     DO operator_k,
     GOAL task statement
END.
```

The executor of the plan will call the operator routines contained in the DO statements and will employ a theorem prover such as QA3.5[3,4] (a resolution-based deductive system) to determine whether the predicates contained in the GOAL statements are true in the world model at each step.

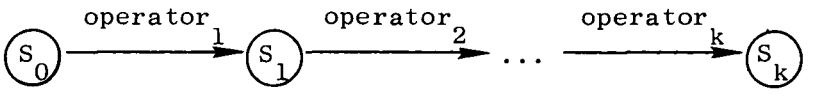
The GOAL statements in a plan provide a means of testing whether execution of the plan is proceeding successfully. We assign to the planner the responsibility of generating the information needed for these tests. In the form for a plan given above this information is merely the GOAL statements that determine whether the next operator in the plan can be applied, and a final GOAL statement to determine whether the task has been completed.

We would like the planner to provide statements in the plan that will allow the executor to determine as soon as possible when execution of the plan is failing. For example, if the success of some operator

in a plan depends on a box B1 being at some location LA and a side effect of execution of some earlier operator in the plan is the determination that B1 is not located at LA, then we would like the plan to contain statements that would allow the executor to realize that the new location of B1 is going to cause an eventual failure. Execution of the plan could then be discontinued without incurring the costs of doing the operations that precede the point in the plan where the actual failure would occur.

To see how STRIPS provides this type of information in its plans, we first note that it employs a means-ends analysis search strategy similar to that of GPS[5] to grow a search tree whose nodes specify world models and some of whose arcs represent planned operator applications. The means-ends analysis strategy directs search by creating subgoals and determining relevant operators. The theorem prover, QA3.5, is used to ask questions about world models, such as whether a goal is true in a model or whether an operator's preconditions are true in a model. A complete description of STRIPS can be found in Ref. 1.

STRIPS can create a plan when there is a path through its search tree of the following form:



,

where S_0 is the initial world model, each S_i is the world model that would be produced by applying operator$_i$ to model S_{i-1}, and S_k is the model in which the task statement is satisfied. The operators on this path define the DO statements for the plan; each operator's preconditions and the task statement define the plan's GOAL statements.

STRIPS forms additional tests for the plan by extracting information from the proofs produced by QA3.5. For the search-tree path we

are considering, QA3.5 will have been used to prove that the task statement is true in S_k, and that the preconditions for each $operator_i$ are true in S_{i-1}. For each of these proofs, STRIPS determines which axioms from the world model were used. Any of these axioms from a given model that were not added to the model as one of the effects of the previous operator in the plan must also have been in the model before that operator was executed. This implies that STRIPS can add a test to the plan before the DO statement for that operator that will prevent the DO statement's execution if one of these axioms is missing from the model. This process can be iterated backwards through the plan so that tests can be inserted before each DO statement indicating what axioms the remainder of the plan assumes exist in the model at that point. Figure E-1 shows an example plan into which test indicators have been inserted.

To include these new tests in the plan, we first surround each DO statement and the preceding preconditions GOAL statement by a labeled BEGIN statement and an END statement to form ALGOL-like blocks as follows:

```
BEGIN
    B1:BEGIN
       GOAL preconditions for operator1;
       DO operator1
    END;
    B2:BEGIN
       GOAL preconditions for operator2;
       DO operator2
    END;
    .
    .
    .
    Bk:BEGIN
       GOAL preconditions for operatork;
       DO operatork
    END;
    GOAL task statement
END
```

```
BEGIN
     (Test for A1)
     (Test for A2 and A4)
     (Test for A6)
     (Test for A7 and A3)
     GOAL preconditions for op1,    (Proof used axioms A8 and A5)
     DO op1                         (Adds axiom A9)

     (Test for A1)
     (Test for A6)
     (Test for A7 and A3)
     GOAL preconditions for op2,    (Proof used axioms A9, A2, and A4)
     DO op2                         (Adds axioms A12 and A10)

     (Test for A1 and A12)
     (Test for A7 and A3)
     GOAL preconditions for op3,    (Proof used axioms A10 and A6)
     DO op3                         (Adds axiom A11)

     (Test for A1 and A12)
     GOAL preconditions for op4;    (Proof used axioms A11, A7, and A3)
     DO op4                         (Adds axioms A10 and A13)

     GOAL task statement            (Proof used axioms A1, A12, and A13)
END
```

FIGURE E-1 ABSTRACT PLAN INDICATING POSSIBLE TESTS

Each new test in the plan is represented by a FAILTEST statement having the following form:

$$\text{FAILTEST } A_1 \wedge A_2 \wedge \ldots \wedge A_n \text{ FOR } B_J, B_{J+1}, \ldots, B_m \quad ;$$

where each A_i is an axiom used by QA3.5 in a proof and each B_i is the label of a BEGIN statement in the plan. When the executor encounters a FAILTEST statement it attempts to determine whether the conjunction of axioms is true in the current state. If the proof attempt succeeds,

then execution continues with the next statement in the plan; if the proof attempt fails, then those blocks which begin with the labels listed in the right side of the FAILTEST statement are deleted from the plan before execution continues.

When deletions occur during the execution of a FAILTEST statement, the plan is no longer complete and its execution will almost certainly fail to satisfy some GOAL statement remaining in the plan. When the executor encounters an unsatisfied GOAL statement, it can recall the planner to create a plan that will achieve the unsatisfied goal. If the planner successfully produces such a plan, then the new plan can be executed to "get back onto the track" of the original plan. If the planner fails and the goal is the task-statement goal, then the system cannot accomplish the task. If the planner fails with any other goal, then the executor may still be able to retain some of the original plan by continuing execution at the next block.*

To determine which blocks should be listed in a FAILTEST statement, the planner assumes that if some axiom that it intends to be true at some point in a plan is not true at that point when the plan is being executed, then any proof in which that axiom participated is invalid. This assumption implies that the FAILTEST statement at that point in the plan can indicate deletion of any block whose only function in the plan is to add axioms used in the invalidated proofs.

Figure E-2 shows an instantiation of the example plan from Figure E-1 in the form that STRIPS would produce it. The task for the instantiated plan is to push the three boxes BOX1, BOX2, and BOX3 to the same location.

---

*At this point execution of the plan is in deep trouble, and in most cases FAILTEST statements will be encountered that will cause deletion of the remainder of the plan.

```
BEGIN
B1:BEGIN
     FAILTEST AT(BOX1,LA) FOR B1,B2,B3,B4;
     FAILTEST AT(BOX2,LB)∧SAMEROOM(LB,LA) FOR B1,
     IF AT(ROBOT,LD)∧SAMEROOM(LD,LB) THEN DO GO(LD,LB)
          ELSE GOAL AT(ROBOT,LB)
   END;
B2:BEGIN
     FAILTEST AT(BOX1,LA) FOR B2,B3,B4;
     IF AT(ROBOT,LB)∧AT(BOX2,LB)∧SAMEROOM(LB,LA) THEN DO PUSH(BOX2,LB,LA)
          ELSE GOAL AT(ROBOT,LA)∧AT(BOX2,LA)
   END;
B3:BEGIN
     FAILTEST AT(BOX1,LA)∧AT(BOX2,LA) FOR B3,B4;
     FAILTEST AT(BOX3,LC)∧SAMEROOM(LC,LA) FOR B3,
     IF AT(ROBOT,LA)∧SAMEROOM(LA,LC) THEN DO GO(LA,LC)
          ELSE GOAL AT(ROBOT,LC)
   END,
B4:BEGIN
     FAILTEST AT(BOX1,LA)∧AT(BOX2,LA) FOR B4;
     IF AT(ROBOT,LC)∧AT(BOX3,LC)∧SAMEROOM(LC,LA) THEN DO PUSH(BOX3,LC,LA)
          ELSE GOAL AT(BOX3,LA)
   END;
   GOAL (Ex)(AT(BOX1,x)∧AT(BOX2,x)∧AT(BOX3,x))
END
```

FIGURE E-2 PLAN FOR THE THREE BOXES PROBLEM

The GO(x,y) operator used in the plan moves the robot from location x to location y where x and y are constrained to be in the same room. The PUSH(b,x,y) operator in the plan causes the robot to push an object b from location x to location y, where both the robot and the object are assumed to begin at location x.

Note that in the Figure E-2 plan each pair of statements

GOAL preconditions for op_1

DO op_1

has been replaced by an IF statement. STRIPS produces these IF statements in the following form:

IF preconditions for op_1 THEN DO op_1

ELSE GOAL relevant results of op_1 ,

where the relevant results of an operator are those axioms added by the operator that were used during the creation of the plan in the proof of some subsequent operator's preconditions or the task-statement goal. Hence the IF statement indicates to the executor that if the operator can be applied then it should be, otherwise a new plan should be found and executed that will produce the same results that the operator was to achieve. For example, in the Figure E-2 plan if the robot is not initially at location LD, then GO(LD,LB) will not be applied; instead a new plan will be created to move the robot to location LB, since that was the desired result of applying GO(LD,LB). Also, consider the case where the robot is at LD initially so that GO(LD,LB) is applied; if GO(LD,LB) fails to move the robot to LB, then the preconditions for PUSH(BOX2,LB,LA) will not be satisfied in block B2 and a new plan will be created to achieve the desired results of pushing BOX2 to LA.

Note also in Figure E-2 the implications of the assumption that a single missing axiom invalidates any proofs in which the axiom participated. This assumption causes the first FAILTEST statement in the plan to indicate deletion of the entire plan if BOX1 is not at location LA. One might argue that when a particular axiom is not true as expected an attempt should be made to generate and execute a plan that would make the axiom true so that the original plan could still be used. That strategy can easily lead to nonoptimal plans. For example, if BOX1 is not initially at LA during execution of the plan for the three boxes problem, then this strategy would dictate that a new plan be constructed and executed to move BOX1 to LA; once this was accomplished, the original plan could be executed. This solution of the problem would require moving all three boxes to a new location; the strategy proposed here of

deleting the entire original plan would cause creation and execution of a new plan involving the movement of two boxes to the third. Hence, this strategy prefers to expend greater replanning effort so that the resulting plan will require less execution effort.

Finally, note that some of the tests indicated in the Figure E-1 plan have disappeared in the Figure E-2 plan. The deleted tests were determined by STRIPS to be redundant. For example, a FAILTEST statement could have been inserted in block B1 to assure that BOX3 was at location LC; but since failure of that test would cause only block B3 to be deleted from the plan, the test need not be made in any of the blocks preceding block B3.

III THE STRIPS ALGORITHM FOR ADDING TESTS TO A PLAN

In this section we present and illustrate an algorithm for creating the FAILTEST statements and IF statements for a STRIPS plan. The input to the algorithm is a plan consisting of a sequence of blocks followed by a GOAL statement containing the task statement. Each block in the input plan has the following form:

```
B1:BEGIN
     GOAL preconditions for operator1,
     DO operator1
   END
```

The algorithm also knows which axioms were used to prove each operator's preconditions and the task statement while the plan was being created by STRIPS. Finally, the algorithm knows from the operator descriptions the axioms added to the world model by each operator in the plan.

The algorithm is as follows:

1. For each GOAL statement in the plan do the following procedure:

1.1 Create an axiom list, AXL, consisting of the axioms used by QA3.5 in the goal's proof during the creation of the plan.

1.2 Proceed backwards through the plan from the GOAL statement to the initial BEGIN and execute the following procedure at each DO statement encountered:

1.2.1 Determine whether the DO statement's operator added to the model any of the axioms on the list, AXL. If it did not, then take no action at this DO statement. If it did, then continue at the next step.

1.2.2 Delete from AXL those axioms added to the model by the operator and store at the DO statement a list of the deleted axioms.

1.2.3 Mark the block in which the DO statement occurs as being relevant to the goal under consideration by storing at the block the goal and a copy of the list, AXL.

2. For each GOAL statement in the plan, do the following procedure:

2.1 Create a null goal list, GL.

2.2 Create a null block list, BL.

2.3 Proceed backwards through the plan from the GOAL statement to the initial BEGIN and execute the following procedure at each block encountered:

2.3.1 Determine whether the block is marked as being relevant to the goal under consideration. If it is then continue at the next step. If it is not, then continue at step 2.3.3.

2.3.2 Set AXL to be the list of axioms stored at the block with the goal under consideration.

2.3.3 Determine whether the block is marked relevant to any goal that is either not on the list GL or is not the goal under consideration. If it is, then take no further action at this block. If it is not, then continue at the next step.

2.3.4 If there is a GOAL statement in the block under consideration, then add the goal to the list GL.

2.3.5 Add the block under consideration to the list BL.

2.3.6 Insert a FAILTEST statement at the beginning of the block under consideration to test for the conjunction of the axioms on AXL and to delete the blocks on list BL.

3. For each block on the plan, do the following procedure:

3.1 Form a wff, RELRESULTS, by conjoining all the axioms stored at the block's operator (in step 1.2.2 of the algorithm).

3.2 Replace the statements

GOAL preconditions for op_1,
DO $operator_1$

in the block by the statement

IF preconditions for op_1 THEN DO operator$_1$
ELSE GOAL RELRESULTS .

We will illustrate the operation of this algorithm with the following input plan:

```
BEGIN
B1:BEGIN
     DO op1                          (Adds axioms A7 and A10)
   END
B2:BEGIN
     GOAL preconditions for op2,     (Proof used axioms A5 and A7)
     DO op2                          (Adds axioms A4 and A11)
   END,
B3:BEGIN
     DO op3                          (Adds axioms A1 and A12)
   END,
B4·BEGIN
     DO op4                          (Adds axioms A2, A6, and A13)
   END;
B5·BEGIN
     GOAL preconditions for op5;     (Proof used axioms A1, A6, and A8)
     DO op5                          (Adds axioms A3 and A14)
   END;
   GOAL task statement;              (Proof used axioms A2, A3, A4, and A9)
END
```

The parenthesized comments in the plan indicate the axioms that are added by each operator (as given in the operator descriptions) and the axioms used to prove each of the goals during creation of the plan. Operators op_1, op_3, and op_4 are assumed to have no preconditions.

The algorithm begins by executing the step 1 procedure for each GOAL statement in the plan. Consider first the GOAL statement in block B2. We shall refer to the goal in this statement as G2. In step 1.1 AXL will be created as the list (A5,A7). Next the procedure of step 1.2 is executed for the DO statement in block B1. Op_1 added axiom A7 to the model,

and A7 is an element of AXL. Hence, in step 1.2.2 list AXL becomes (A5) and the list (A7) is stored at the DO statement. In step 1.2.3 block B1 is marked relevant to goal G2 by storing the pair (G2,(A5)) at the block. This completes the step 1 processing for goal G2.

For the goal in block B5, which we shall refer to as G5, the list AXL is created as (A1 A6 A8). The first DO statement encountered is in block B4, at step 1.2.2 AXL becomes (A1 A8) and the list (A6) is stored at the DO statement. In step 1.2.3 the pair (G5;(A1 A8)) is stored at block B4. For the DO statement in block B3, AXL becomes (A8), the list (A1) is stored at the DO statement, and the pair (G5;(A8)) is stored at block B3. Since neither of the DO statements in blocks B2 and B1 add axiom A8 to the model, no further action is taken for goal G5.

For the task-statement goal, which we shall refer to as Gt, the list AXL is created as (A2 A3 A4 A9). The first DO statement encountered is in block B5; it causes AXL to become (A2 A4 A9), the list (A3) to be added to it, and the pair (Gt;(A2 A4 A9)) to be stored at block B5. For the DO statement in block B4, AXL becomes (A4 A9), the list (A2) is added to the statement, and the pair (Gt,(A9)) is stored at the block B2. Since the DO statement in block B1 does not add axiom A9, no further action is taken for goal Gt.

This completes the step 1 processing and leaves the plan in the following form:

```
BEGIN
B1:BEGIN                              (G2;(A5))
     DO op1;                          (Adds axioms A7 and A10) (A7)
   END;
B2:BEGIN                              (Gt,(A9))
     GOAL preconditions for op2.      (Proof used axioms A5 and A7)
     DO op2                           (Adds axioms A4 and A11) (A4)
   END;
```

```
B3:BEGIN                                (G5;(A8))
     DO op3                             (Adds axioms A1 and A12) (A1)
   END;
B4:BEGIN                                (G5;(A1 A8))(Gt,(A4 A9))
     DO op4                             (Adds axioms A2, A6, and A13) (A6) (A2)
   END;
B5:BEGIN                                (Gt;(A2 A4 A9))
     GOAL preconditions for op5;        (Proof used axioms A1, A6, and A8)
     GO op5                             (Adds axioms A3 and A14) (A3)
   END;
   GOAL task statement;                 (Proof used axioms A2, A3, A4, and A9)
END
```

Step 2 of the algorithm makes a second pass through the plan by again considering each GOAL statement. For goal G2, the step 2.3 process is executed once at block B1. At step 2.3.1 we determine that block B1 is marked relevant to G2. At step 2.3.2, AXL becomes (A5). The block passes the test at step 2.3.3, no action is taken at step 2.3.4, and list BL becomes (B1) at step 2.3.5. At step 2.3.6 the following statement is added to block B1:

FAILTEST A5 FOR B1 .

No further action is taken for goal G2.

For goal G5, B4 is the first block considered in the step 2.3 process. Since B4 is marked as being relevant to G5, step 2.3.2 is executed and sets AXL to be (A1 A8). Since block B4 is marked relevant to Gt and Gt is not an element of list GL, no further action is taken for block B4. For block B3, AXL becomes (A8) in step 2.3.2, BL becomes (B3) in step 2.3.5, and the following statement is added to block B3 in step 2.3.5:

FAILTEST A8 FOR B3 .

Since blocks B2 and B1 are not marked relevant to G5, no further action is taken for G5.

For goal Gt, block B5 is marked relevant and therefore AXL is set to be (A2 A4 A9). The test is passed at step 2.3.3, list GL is set to be (G5) at step 2.3.4, list BL is set to be (B5) at step 2.3.5, and the following statement is added to block B5 at step 2.3.6:

FAILTEST A2^A4^A9 FOR B5 .

At block B4, AXL becomes (A4 A9), the test in step 2.3.3 is passed since G5 is on list GL, BL becomes (B4 B5), and the following statement is added to B4:

FAILTEST A4^A9 FOR B4,B5 .

At block B3, the test in step 2.3.1 causes step 2.3.2 to be skipped, BL becomes (B3 B4 B5), and the following statement is added:

FAILTEST A4^A9 FOR B3,B4,B5 .

At block B2, AXL becomes (A9), GL becomes (G2 G5), BL becomes (B2 B3 B4 B5), and the following statement is added:

FAILTEST A9 FOR B2,B3,B4,B5 .

At block B1, the test in step 2.3.1 causes step 2.3.2 to be skipped, BL becomes (B1 B2 B3 B4 B5), and the following statement is added:

FAILTEST A9 FOR B1,B2,B3,B4,B5 .

No further action is taken for goal Gt.

The algorithm's final pass through the plan occurs in step 3. At that time IF statements are added to blocks B2 and B5. Note that in blocks B1, B3, and B4 the operators have no preconditions, so that the IF statements for those blocks collapse into DO statements and leave the blocks unchanged.

This completes the algorithm and produces the following plan:

```
BEGIN
B1:BEGIN                              (G2;(A5))
     FAILTEST A9 FOR B1,B2,B3,B4,B5,
     FAILTEST A5 FOR B1;
     DO op1                           (Op1 adds axioms A7 and A10)
   END;                               (RELRESULTS for op1 is (A7))
B2:BEGIN                              (Gt;(A9))
     FAILTEST A9 FOR B2,B3,B4,B5;
     IF preconditions for op THEN     (Preconditions proof used axioms A5
          DO op2 ELSE GOAL A4          and A7)
   END;                               (Op2 adds axioms A4 and A11)
                                      (RELRESULTS for op2 is (A4))
B3·BEGIN                              (G5,(A8))
     FAILTEST A4∧A9 FOR B3,B4,B5;
     FAILTEST A8 FOR B3;
     DO op3                           (Op3 adds axioms A1 and A12)
   END;                               (RELRESULTS for op3 is (A1))
B4:BEGIN
     FAILTEST A4∧A9 FOR B4,B5,
     DO op4                           (Op4 adds axioms A2, A6, and A13)
   END;                               (RELRESULTS for op4 is (A2 A6))
B5:BEGIN
     FAILTEST A2∧A4∧A9 FOR B5;
     IF preconditions for op5 THEN    (Preconditions proof used axioms A1,
          DO op5 ELSE GOAL A3          A6, and A8)
   END;                               (Op5 adds axioms A3 and A14)
                                      (RELRESULTS for op5 is (A3))
   GOAL task statement;               (Proof of task statement used axioms
                                       A2, A3, A4, and A9)
END
```

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Appendix F

ISUPPOSEW--A COMPUTER PROGRAM THAT FINDS REGIONS IN THE PLAN MODEL OF A VISUAL SCENE

by

Kazuhiko Masuda

Appendix F

ISUPPOSEW--A COMPUTER PROGRAM THAT FINDS REGIONS IN THE PLAN MODEL OF A VISUAL SCENE

ABSTRACT

This appendix describes the nature and structure of the computer program ISUPPOSEW and some of its results. ISUPPOSEW is designed to enable a robot to make conjectures, on the basis of its visual information, about elements of its environment that it cannot see. The process of conjecture employed is analogous to that which a human employs in similar circumstances.

I INTRODUCTION

Suppose you visit someone's house and your visit is confined to one room--say, the living room. After you have returned home, it may be interesting to conjecture, on the basis of your memory of the visual information acquired from seeing only one room, where the other rooms of the house are located. Similarly, we often guess the locations of elevators or exits in places such as department stores or halls. As a matter of fact, the results remain as conjectures unless one finally confirms the locations by seeing for oneself. A person tries to reduce the problem by conjecturing as reasonably as possible with the help of his empirical knowledge.

The computer program described in this appendix provides a means for conjecturing how the environment of a robot is constructed of

regions by taking into account the unseen elements of the plan model of the scene that the robot now has as its model of the environment.

Let us first consider some applications. Suppose that you command a robot located in a large room to do a job that requires some information that the robot does not yet have. For example, you might give the command, "Turn in the corridor to the right and go into the third room," but the robot does not know where the corridor is. If, however, he can guess the most likely location of the corridor through his already-known information, he goes there, confirms its location, and solves the problem. If he finds that his first conjecture is wrong, he moves to the second possible point and looks for the corridor.

We can consider another example. Suppose a robot asks the receptionist at the entrance of the university building, "Where is Professor K's office?" The receptionist may answer, "Turn to the right at the corner, and go straight on. You'll see a big office behind a smaller office in front." The robot must find the large room with a small office in front. When he finds an office that fits the description, he conjectures that he has solved the problem.

This type of conjecture will not be done by only one means. The exit of the building to the outside will be more easily conjectured by sound, wind, or light, but the visual model may also be important for that purpose.

Buildings usually consist of comparatively regular structures of a particular type. That is, very few homes are built with round rooms. A theater, however, may be circular, with the corridor surrounding the hall, hence, when a person is in a theater, he applies different conjectures with the knowledge that he is now in a theater. This process must be something like a global conjecture based on an elementary one

by adding a different strategy and different information to the basic conjecture method.

Now, the author thought that it would be valuable to try to construct the more complete environmental model of a robot from the visual scene by following as closely as possible the process that a person does in making such conjectures.

The estimation of the results is related so much to the purpose of action and accumulation of empirical knowledge that simple programming is difficult. Regretfully, this program conjectures only by following several elementary rules given to the program beforehand and does not include any estimation of its procedure and results. For this reason the author named the program ISUPPOSEW--"W" means "DOUBLE," for the program and for the author. In addition, since the program technique of the author is very rudimentary, algorithms are elementary and need to be improved. Although the program requires a rather long running time, example data examined are rather more complicated than actual data, for the author expects that this type of conjecture must be limited to several local areas of the model.

II HEURISTICS

As described in the Introduction, this program does not follow any theorem or axiom, nor does it have any estimation function to monitor the procedure of conjecture. It follows only the human way to conjecture as naturally as possible. Consequently, there may be some people who doubt the results. For these people, several rules that the program follows are given below.

First of all, the basic terminology--EPOINT, VIEWZONE, and VIEWLINE--is explained. Figure F-1 shows a part of the plan model of visual scenes.

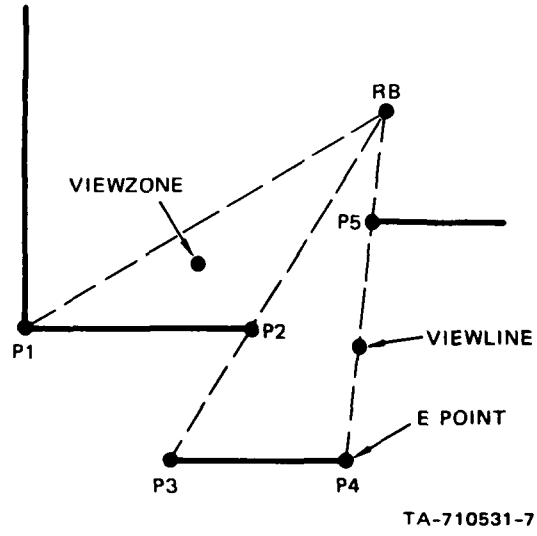


FIGURE F-1 PART OF THE PLAN MODEL OF VISUAL SCENES

Triangles constructed by three points including RB such as Δ(RB P1 P2) and Δ(RB P3 P4) are called VIEWZONEs, where RB signifies the location point of a robot. The lines constructing those triangles such as $\overline{RBP1}$, $\overline{RBP2}$, and $\overline{P1P2}$ are called VIEWLINEs. Lines such as $\overline{P1P2}$ are elements of models at the same time. Points such as P2, P3, P4, and P5 that are edges of only one element of a model are called EPOINTs.

The rules of the program are given as follows:

Rule 1--The elements of a model are thought to be related to each other by right angles or parallelism.

Rule 2--The conjecture procedure is applied only to all EPOINTs.

Rule 3--Conjecture elements of a model must not be drawn in VIEWZONEs, except in the special case of Rule 4(a).

Rule 4--There are three kinds of conjectures applied to EPOINTs:

(a) When two lines that contain the opposite EPOINTs are colinear with each other, these two EPOINTs are connected.

(b) The line that contains an EPOINT can be extended as long as the extended line segment does not violate Rule 3.

(c) In the case where Rule 4(b) cannot be applied because an EPOINT is in contact with a VIEWZONE, the line that contains the EPOINT is turned with a right angle to the direction in which the extended line does not cross the VIEWZONE and is extended in the same way as in Rule 4(b).

Rule 5--The extended or turned and extended line from an EPOINT is connected to the line that crosses the former one or may cross it if extended at the closest point to the EPOINT on the former one.

Rule 6--The conjecture procedure is repeated until no new conjectured line is created with regard to all EPOINTs.

Rule 7--The region surrounded by a single closing curve is thought to be a structural region of a model.

ISUPPOSEW is an algorithm that carries those rules into effect. A brief explanation about rules is added below.

In application of Rule 4(a), we can consider four cases shown in Figure F-2. Figures F-2(b) and (d) indicate cases where there are several VIEWZONEs between opposite EPOINTs with lines colinear to each other. If a strict definition such as "GATE" or "DOORWAY" is preferred, Rule 4(a) may have to be applied only to cases (a) and (b), but because

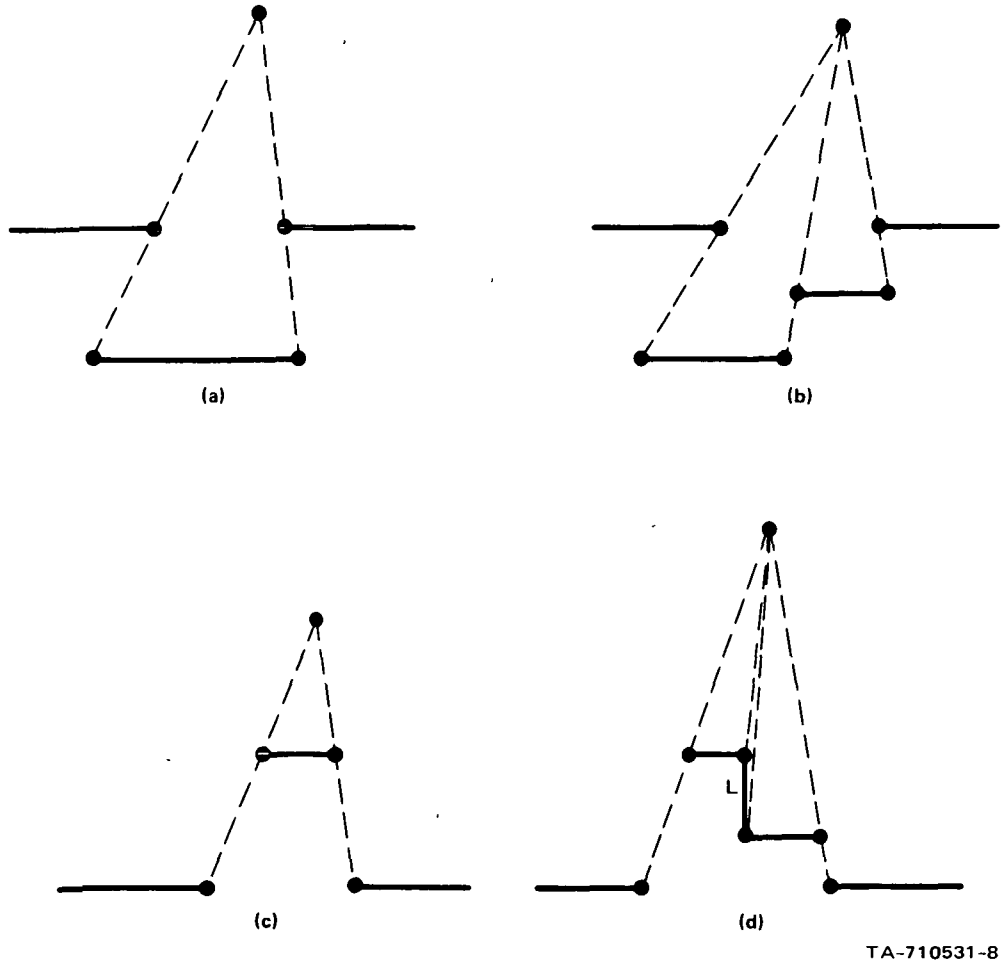


FIGURE F-2 CASES FOR APPLICATION OF RULE 4(a)

of inconvenience described later in ISUPPOSEW, Rule 4(a) is applied to all four cases. However, in a case such as (d), since EPOINTs should be considered to be connected to line L, ISUPPOSEW treats those paired EPOINTs as NGATE (a structure that is not like a gate) and considers application of Rule 4(b) to them simultaneously.

Consider the configuration of Figure F-3. With regard to points P2, P5, P7, Rule 4(b) can also be applied, but as is seen in the case of P5, infinite extension of the line is not allowable. The same thing may be considered also with regard to P2 or P7. P8 is the point to which Rule 4(c) is applied. The extension of the line must be done

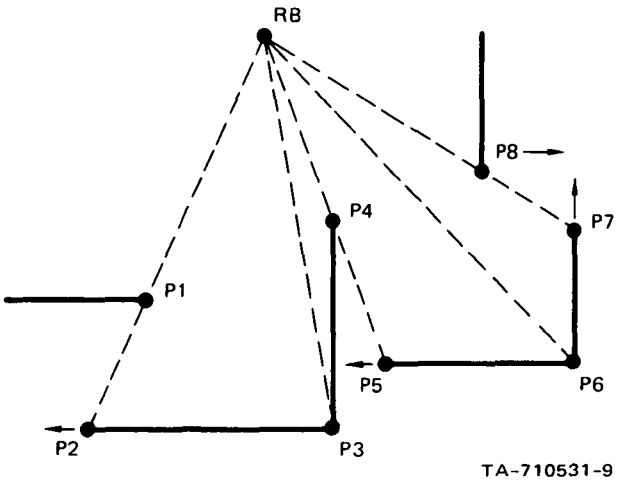


FIGURE F-3 CASE FOR APPLICATION OF RULE 4(b)

after turning to the right at the point, P8, and the line is connected to the extended line of P7. At P1 and P4, any conjecture is impossible. When only those points are left, the algorithm terminates.

Figure F-4(a) illustrates Rule 6. Rule 4(a) is thought to be applied to P1, but unless P2 and P3 are connected, the extended line from P1 will cross a VIEWZONE. The sequence of consideration of EPOINTs is optional, and so we must withhold any conjecture about P1 until

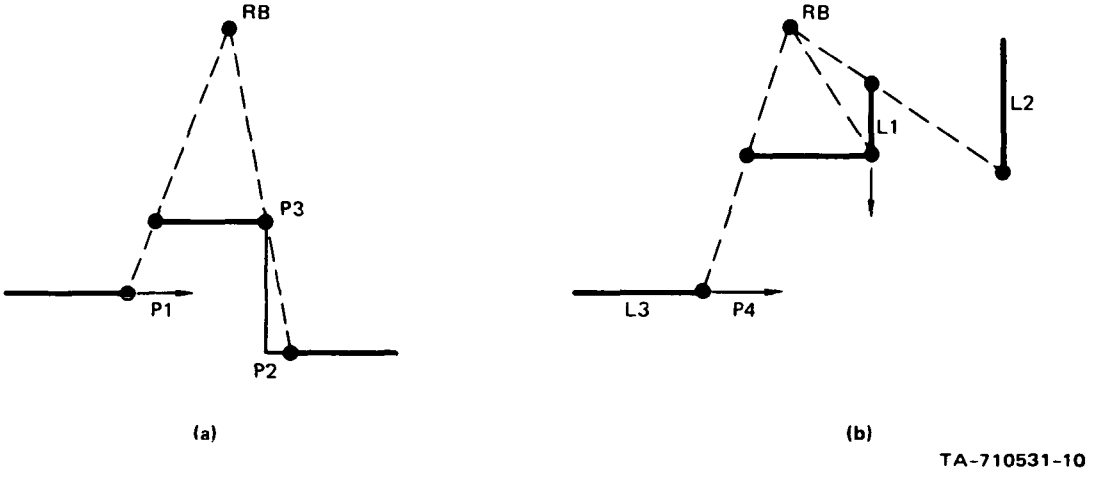


FIGURE F-4 DIAGRAM ILLUSTRATING RULES 5 AND 6

consideration on P2 or P3 is completed. This suggests that the conjecture process must be repeated.

When line L3 is extended from P4 in Figure F-4(b), it must terminate at the crossing point of the extended line of L1, rather than at that of L2. That is what Rule 5 explains; and this makes the program rather conservative.

III PROGRAM

A. Structure

This program can be divided into two parts: Part I consists of functions EX2IN, CONJECT 1, and CONJECT 2, Part II consists of functions EX2IN* and RGNFND. Part I is the program that creates a new model of scenes by drawing possible conjectured lines in a given data model by following the rules, Part II is the program that separates a created model into several closed regions. Each part of the program is explained below.

B. EX2IN

Since the author dealt with only hand-written experimental data, a program to transform input data into internal format is needed. EX2IN is the program that transforms the input data shown in Figure F-5 and Table F-1 into the internal format shown in Table F-2.

The input data must have an assumed boundary region that covers all the territory of an original model. It is a square region surrounded by four straight lines L, T, R, and B, that connect points POO, POY, PXY, and PXO, where POO is not necessarily the origin, the origin is allowed anywhere.

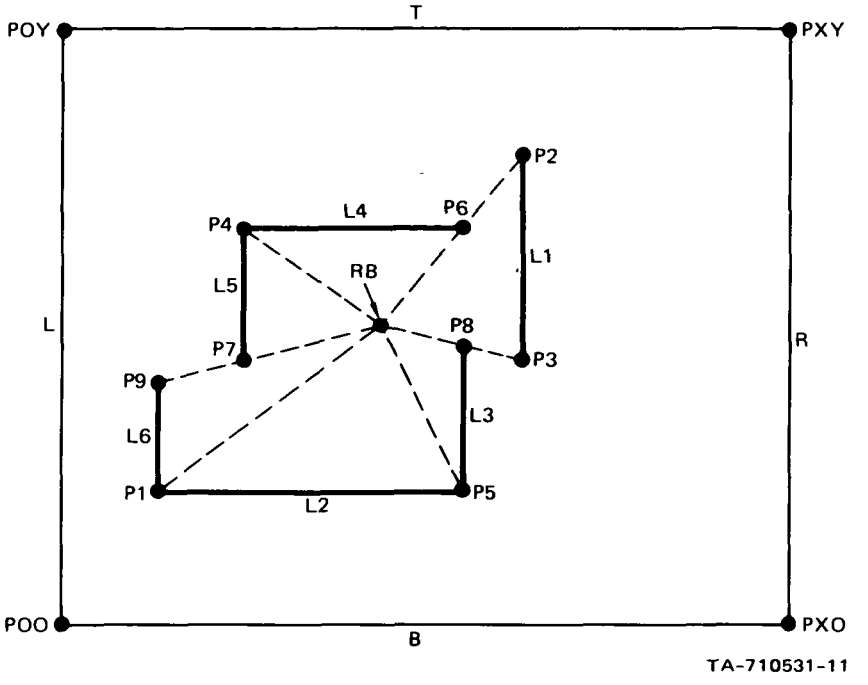


FIGURE F-5 EXAMPLE INPUT DATA

The first line of the input format clarifies the location of a robot (RB signifies ROBOT). The values of X-Y coordinates of RB are put in parentheses next to RB. Then the arbitrary names of lines that are the elements of a model including assumed boundary lines are listed in optional sequence, followed by a list of end points of each line and their X-Y coordinate values after each name of a line.

The original data are named VIEW, and all the lines and points except RB are put into the property lists of VIEW with identifier LINES and POINTS. Each line has one property list identified by ORT, where the list of both end points of the line are propped. Each point has property lists identified by XCOR, YCOR, TYPE, NLNS, NPTS, and NVZNS, but RB has only the properties XCOR and YCOR. XCOR and YCOR are values of X-coordinates and Y-coordinates of each point, respectively. TYPE indicates the type of points such as E for EPOINT and C for corner. NLNS is the abbreviation of neighbor lines; the list of lines diverging from

Table F-1

EXAMPLE INPUT DATA

```
(  (RB (15.0 13.0))
    L1 (P2 (21.0 21.0) P3 (21.0 12.0))
    L2 (P1 ( 5.0  6.0) P5 (18.0  6.0))
    L3 (P8 (18.0 12.5) P5 (18.0  6.0))
    L4 (P4 ( 9.0 18.0) P6 (18.0 18.0))
    L5 (P4 ( 9.0 18.0) P7 ( 9.0 12.0))
    L6 (P1 ( 5.0  6.0) P9 ( 5.0 11.3))
    L  (POO( 0.0  0.0) POY( 0.0 99.0))
    T  (POY( 0.0 99.0) PXY(99.0 99.0))
    R  (PXY(99.0 99.0) PXO(99.0  0.0))
    B  (PXO(99.0  0.0) POO( 0.0  0.0))
```

Table F-2

INTERNAL FORMAT

```
VIEW--POINTS--(P1 P2 ... P9 POO PXO PXY POY)
    |   LINES--(L1 L2 ... L6  L   T   R   B)
    |
    |
  RB--XCOR--15.0
    |   YCOR--13.0
    |
  P1--XCOR--5.0
    |   YCOR--6.0
    |   TYPE--C
    |   NLNS--(L2 L6)
    |   NPTS--(P5 P9)
    |  NVZNS--((RB P9 P1)(RB P1 P5))
    |
    |
    |
 POY--XCOR--0.0
    |   YCOR--99.0
    |   TYPE--C
    |   NLNS--(L T)
    |   NPTS--(POO PXY)
    |  NVZNS--(NIL NIL)
    |
    |
  L1--ORT--(P2 P3)
    |
    |
    B--ORT--(POO PXO)
```

the point is put into NLNS. NPTS means neighbor points, and it identifies the list of points connected to the point by NLNS. Finally, NVZNS signifies neighbor viewzones. One point in a model always has one viewline that is attached by two viewzones on both sides. The list of those viewzones is put under the identifier NVZNS. In the case of P2 in Figure F-1, NVZNS has the list, ((RB P1 P2), (RB P3 P4)). EX2IN computes NVZNS of each point at its final stage, using the already transformed internal format.

ISUPPOSEW outputs EX2INED when the transformation is completed.

C. CONJECT 1

This is the program that applied Rule 4(a) to the model. Before entering CONJECT 1, ISUPPOSEW prepares the data list named ELIST, which is a list of all points whose types are E. CONJECT 1 creates all the possible pairs of EPOINTs and judges whether or not the pairs meet Rule 4(a). If such a pair is found, the new line that connects both points is created in such a manner that the function GENSYM names the line, the paired points are put into the property list of the new line (identified by ORT), and the new line is APPENDed to the list MODEL, which was prepared beforehand. The list MODEL is constructed in the form of the list of lines and their end points, though coordinate values of points and the list of RB are not listed.

The implementation of Rule 4(a) is done by the function named GLISTF. First of all, both points of a pair must have NLNS colinear to each other, and the pair connected in the original data--namely, elements of a model--or the pair that includes other colinear lines between them is deleted. Then whether or not both points have one common NVZNS is checked. If so, they are the pairs shown in Figures F-2(a) and (c).

Next, to distinguish case (b) from case (d), the function checks whether or not the connecting line of points crosses more than one viewline.

CONJECT 1 deletes the EPOINTs that meet Rule 4(a) from the ELIST and puts the left ones into the new list, E*LIST, but the EPOINTs considered to be NGATE are still left in E*LIST for further consideration.

ISUPPOSEW outputs the new current model created by CONJECT 1.

D. CONJECT 2

CONJECT 2 is one program that applies Rules 4(a) and (b), Rule 5, and Rule 6 to the EPOINTs listed in E*LIST. The algorithm is shown in Figure F-6. According to Rule 5, the repeated conjecture is required for the EPOINTs from which adequate conjecture is not extracted through each path. Consequently, E**LIST is set for those points, and the same process is repeated until the contents of both E*LIST and E**LIST become the same--namely, no more conjecture can be extracted.

The following are brief explanations of each stage of the algorithm.

1. Setting Candidate Lines

As is shown in Figure F-7, we prepare three lines, LX, LY1, and LY2, starting from P and terminating at crossing points of border lines. Each of these lines is at a right angle to the next one. That procedure is done by three functions: CANDLX creates the list of three lines, LX, LXB1, and LXB2, computing the crossing point, XNP1, of the extended line, LX, with one of border lines, L, T, R, or B; the function CANDLY1 does the same computation with regard to the imaginary line, LR, which is the assumed line of L shifted to the right in a right angle against L with the center, P; and the function CANDLY2 does the

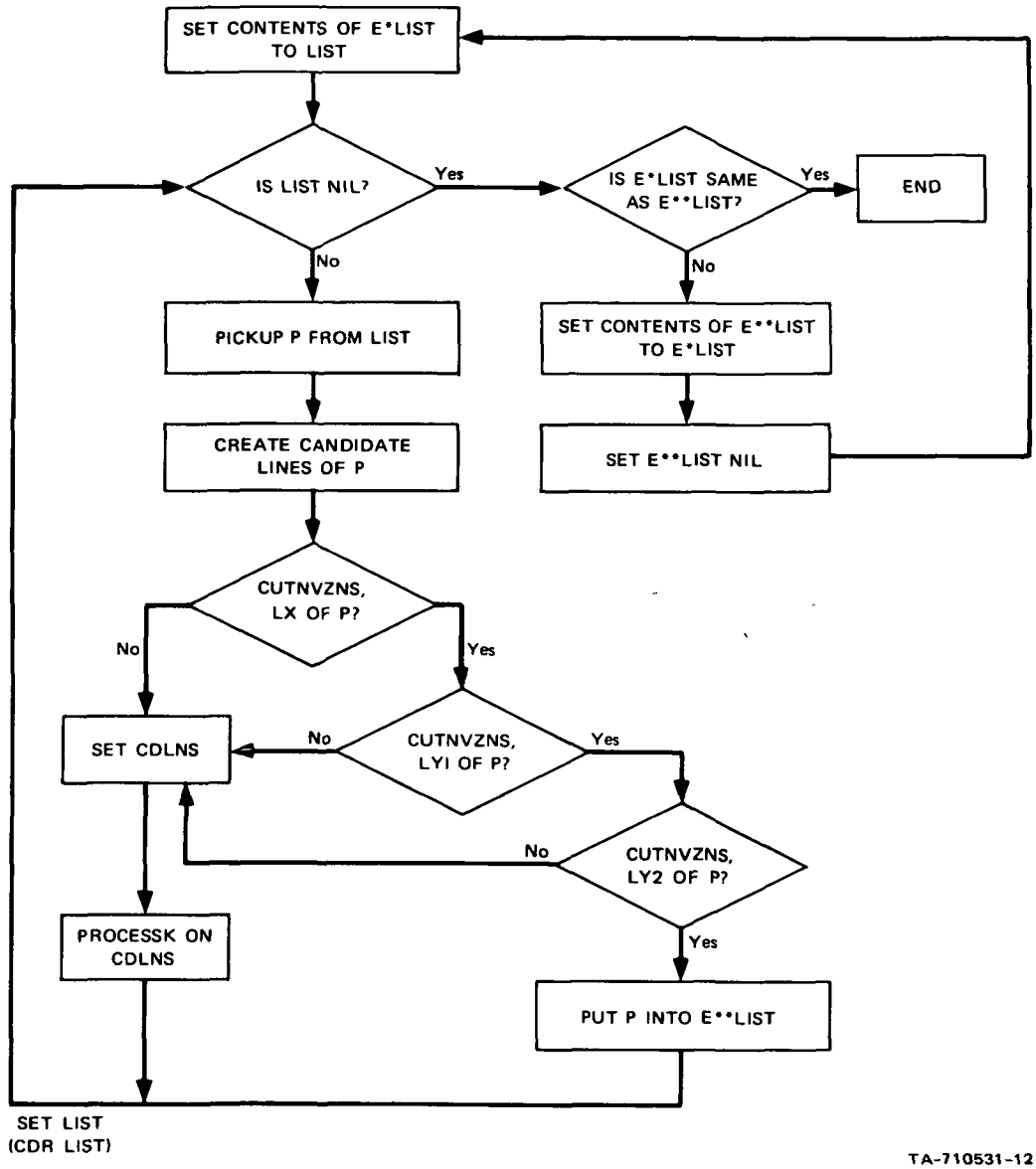


FIGURE F-6 ALGORITHM OF CONJECT 2

same with regard to the assumed line, LL, the shifted line of L to the left. Three sets of lines (LX, LXB1, LXB2), (LY, LY1B1, LY1B2), and (LY2, LY2B1, LY2B2) are prepared. The internal format of those lines and newly created points such as XNP1, XNP2, XNP3, PR, and PL are temporarily made with property lists of ORT for lines and XCOR and YCOR for points for convenience of computation.

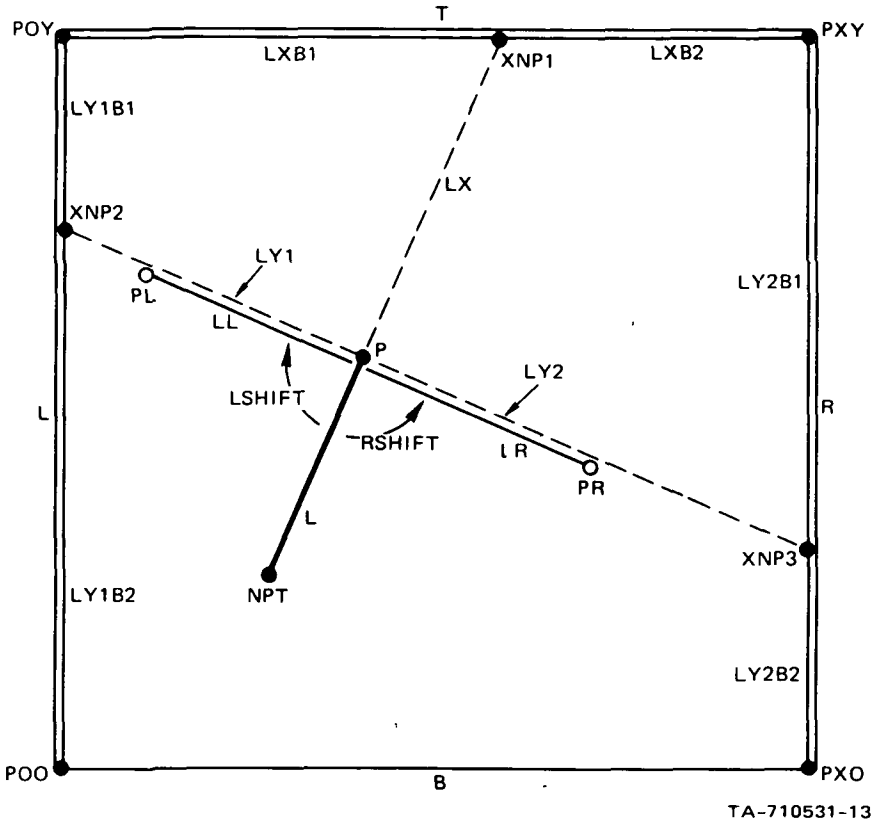


FIGURE F-7 EXPLANATORY DIAGRAM FOR CONJECT 2

2. Determining Whether a Candidate Line Crosses NVZNS

The function CUTNVZNS determines whether a candidate line crosses NVZNS. One of three lines, LX, LY1, and LY2, that does not cross NVZNS of P is chosen. The priority is given to LX first and then either to LY1 or to LY2. In the case of P5 in Figure F-3, LX crosses the NVZNS of P5, but it is possible to extend the line as far as the crossing point. Therefore, the criterion of CUTNVZNS is whether or not the extended line crosses only one VIEWLINE of NVZNS.

One extended line chosen from LX, LY1, and LY2 is called a candidate line of P and its set, i.e., (LX, LXB1, LXB2), is bound to CDLNS, and each element of the CDLNS is called CDLN, CDLN1, and CDLN2, respectively.

3. PROCESSK

This is a program to apply Rule 5, namely, to modify the current model, using the result of the judgment of whether the proposed CDLNS must be used as new elements of the model or whether they must be modified. The algorithm is shown in Figure F-8. First of all, the list LNS, which consists of all lines picked up from the current MODEL, is prepared. Then, picking up each line from the list, the program judges the relationship between the line and CDLN. This judgment is carried on by the following four functions.

OVERLAPL [Figure F-9(a)]--This function judges whether or not CDLN overlaps the line L. The definition of OVERLAP here is either that both ends of L are inside CDLN or that only one of them is inside. Both lines must be colinear with each other. If so, the new line whose new end is the closer NPTS of L to P is bound to CDLN, and CDLN1 and CDLN2 are bound to NIL.

XNL* [Figure F-9(b)]--If the line L crosses the CDLN, the crossing point is calculated, and the new set of CDLN, CDLN1, and CDLN2 is created instead of the old ones, as is shown in Figure F-9(b).

XN2L [Figure F-9(c)]--This function is a little complicated. When the extended line of L crosses the current CDLN, unless the extended segment crosses or overlaps any other line or crosses any VIEW-LINE on its way to the assumed crossing point of CDLN, new CDLN and CDLN1 are created, and CDLN2 is set to be NIL, as is shown in Figure F-9(c).

COVER [Figure F-9(d)]--This is also for a very special case. The value of this function becomes T in the reverse case of OVERLAPL, namely, when the CDLN is overlapped by L because the already created line, L, in the current model connecting P to the other, exists. This situation sometimes occurs for EPOINTs such as the part of NGATE

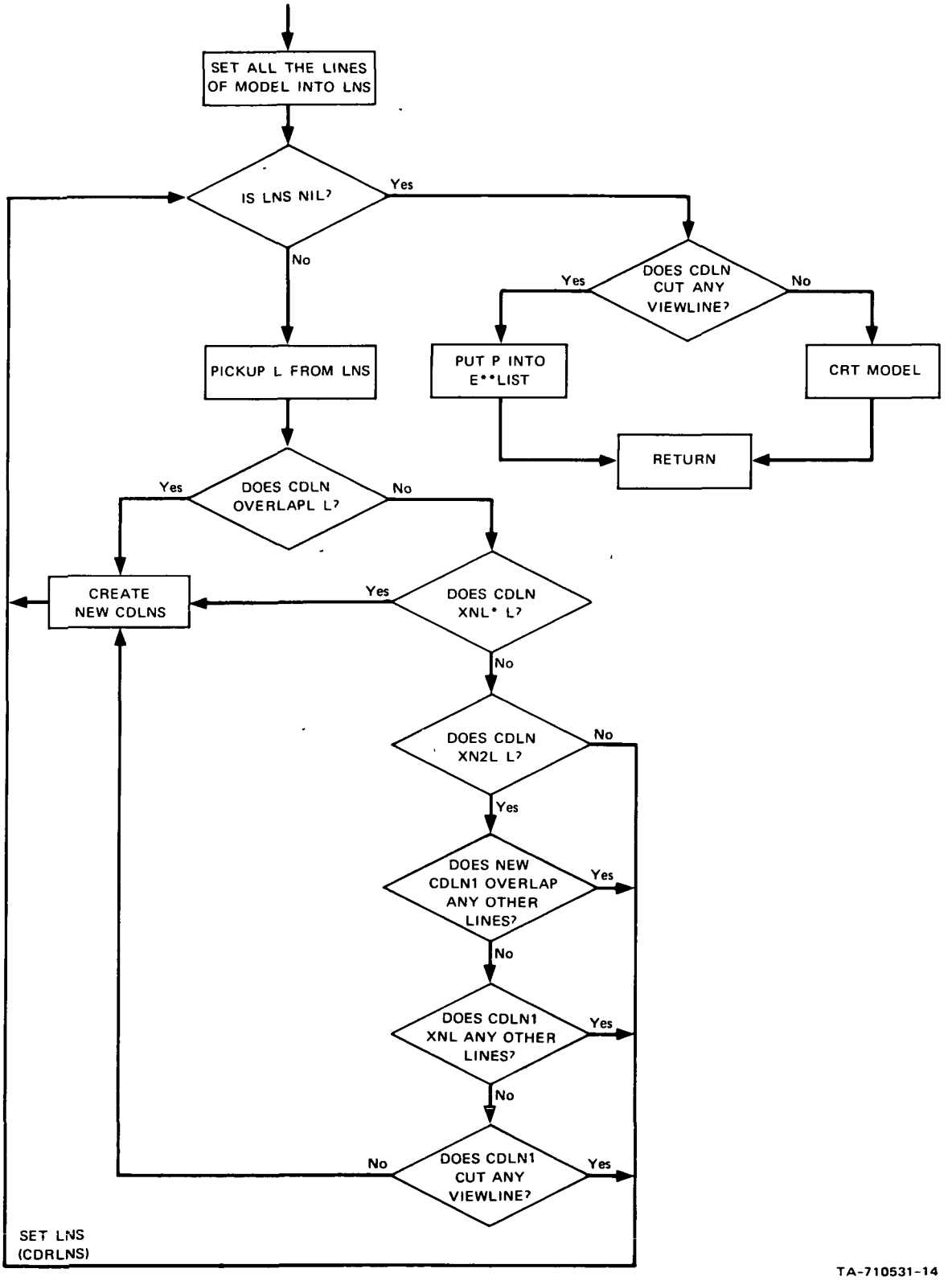


FIGURE F-8 ALGORITHM OF PROCESSK

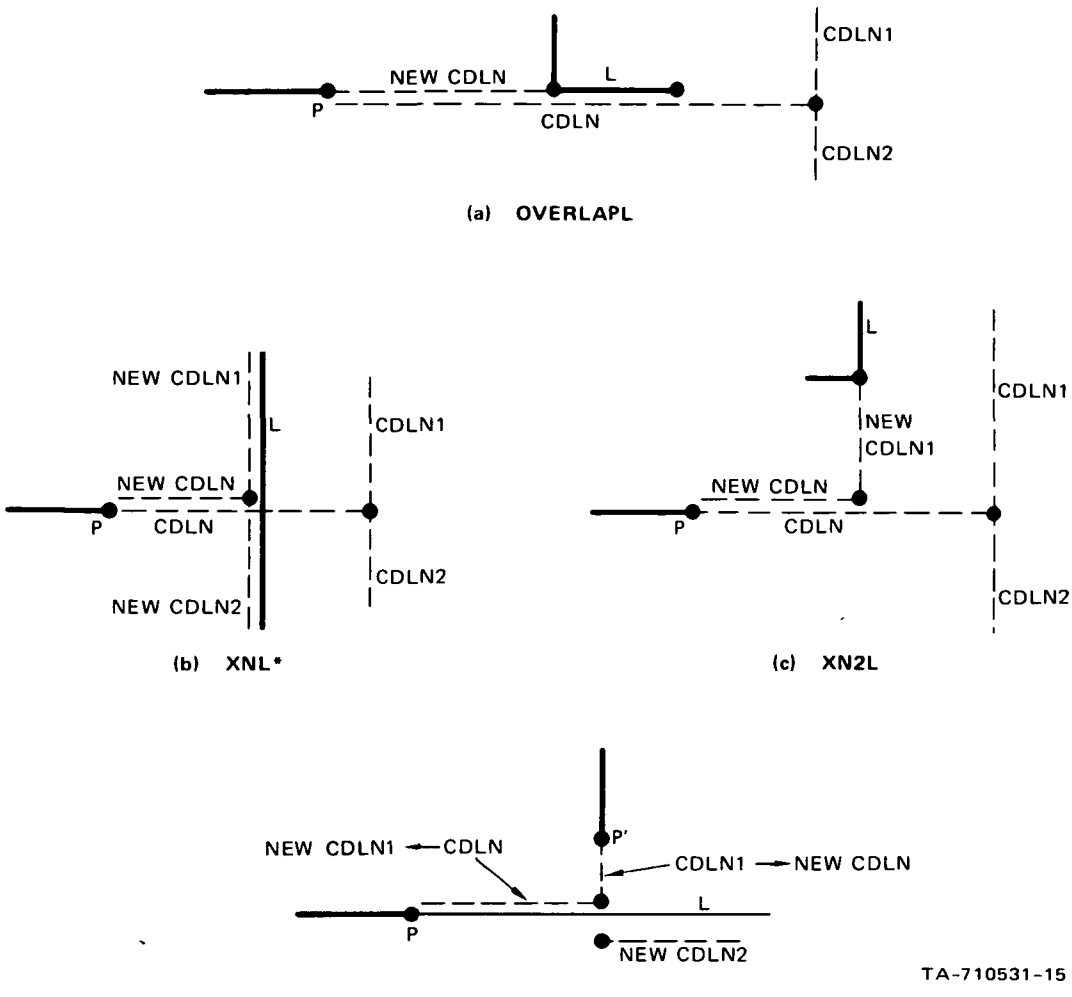


FIGURE F-9 FUNCTIONS FOR JUDGING THE RELATIONSHIP BETWEEN A LINE AND CDLNs

judged by CONJECT 1 or the point already chosen in the current model as the opposite part against the crossing point of the CDLN1 when XN2L worked through the process of conjecture on the other EPOINT before. So, as is shown in Figure F-7(d), the new set of CDLNs is the shifted one as the point P′ is conjectured by XNL*, for convenience of computation.

After the above judgments have been made, the new set of candidate lines, CDLNs, is formed, or it may be the same as the original one. Then, it is checked as to whether or not the CDLN crosses any VIEW-LINE in the model. This seems ridiculous, but it must be checked after

all the above conjectures or simultaneously, because otherwise, it makes the above conjectures insignificant. Consider P in Figure F-10. Perhaps, if EPOINT P1 has not been conjectured yet, P will be connected to the line L only with the above four conjectures.

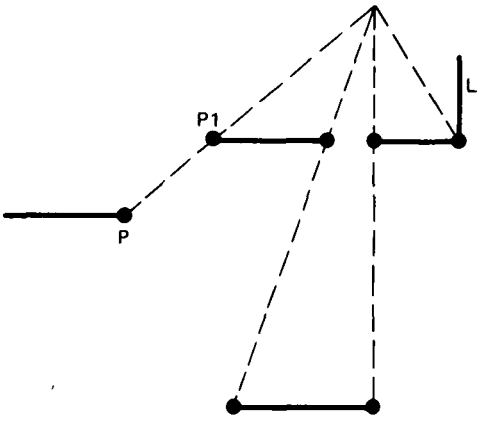


FIGURE F-10 DIAGRAM ILLUSTRATING THE NECESSITY OF CHECKING WHETHER CDLN CROSSES ANY VIEWLINE

All through the process, all new elements of CDLNs and their created crossing points, if any, are named by the function GENSYM but at this stage no internal format for them is made.

When any CDLN is negated and we find that the questionable point is not to be conjectured on the current MODEL, the point is put into E**LIST and prepared for the second path of CONJECT 2.

ISSUPOSEW outputs the newly created MODEL after CONJECT 2 is completed.

E. EX2IN*

As for the list MODEL, created by CONJECT 1 and CONJECT 2, only ORT of new lines and values of X-Y coordinates of new points are

put in their property lists in internal format. Consequently, EX2IN*, almost the same function as EX2IN, works on MODEL to make properties NPTS, NLNS, and TYPE of points.

EX2IN* results in the new internal format such that the old points have properties XCOR, YCOR, new NPTS, new NLNS, and NVZNS, the new points have properties XCOR, YCOR, NPTS, and NLNS, all the lines have their ORT, and the point RB remains the same. The property lists of VIEW, LINES, and POINTS are left as they were, although the elements of LINES must have different properties from the old ones. (The author has not yet developed a function to modify LINES.)

The new property of points, NPTS, is different from the old one in a way. EX2IN* has the function called FOOP, which lists the neighbor points of a certain point in the manner of traversing clockwise, as shown in Figure F-11. The algorithm is shown in Figure F-12.

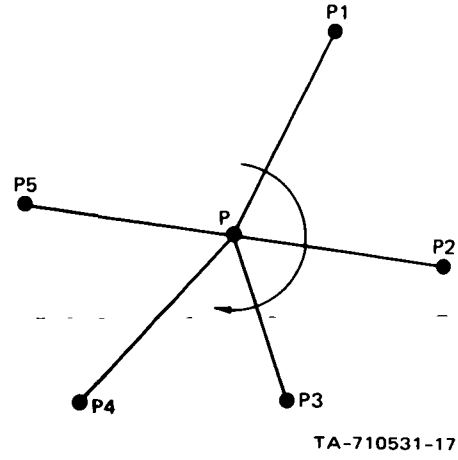
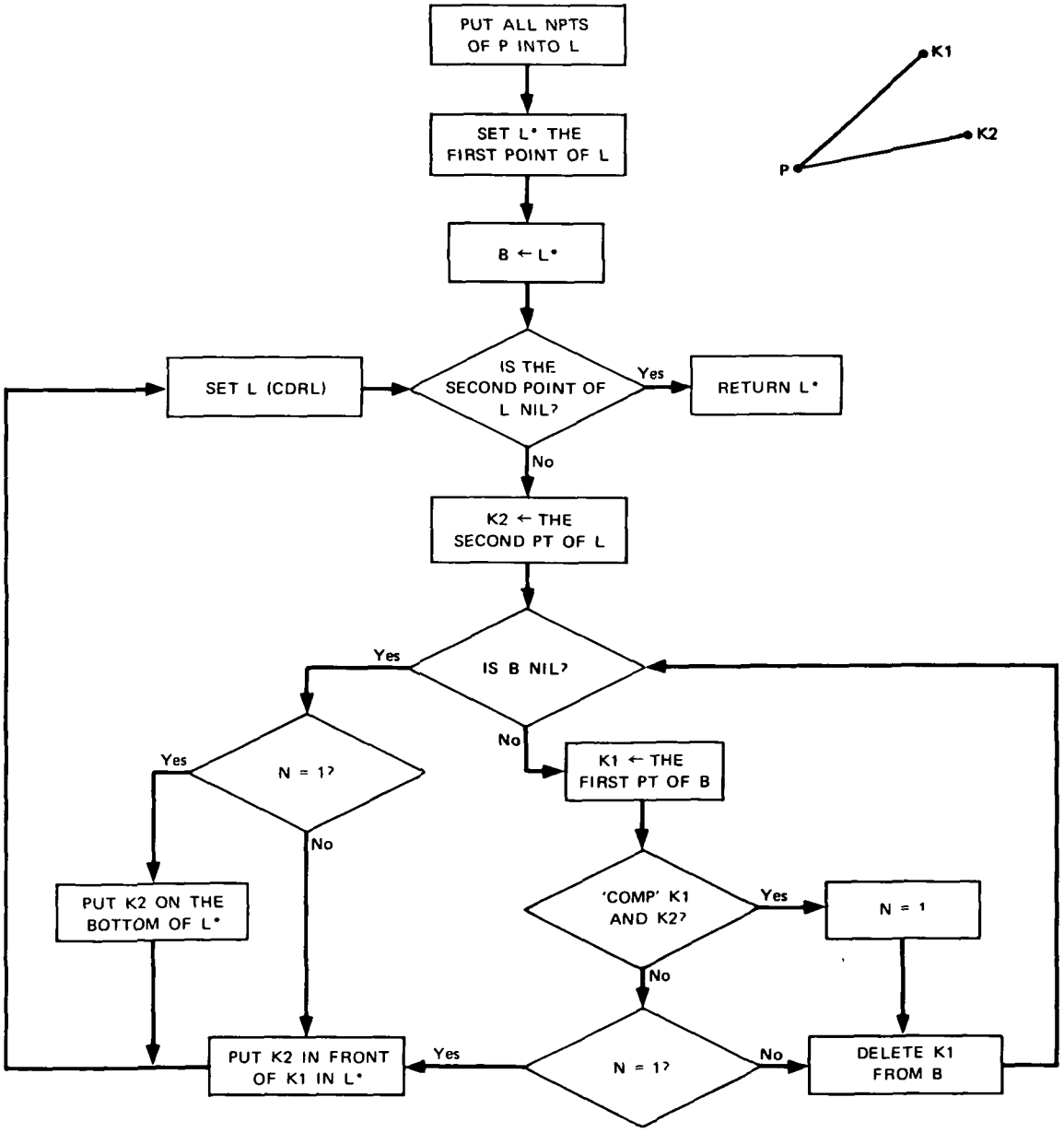


FIGURE F-11 EXPLANATORY DIAGRAM FOR FUNCTION FOOP

F. RGNFND

The function RGNFND works on the list of all points of the model to find out the closed region in the model.



NOTE 'COMP is T when angle $<$K1PK2 is less than or equal to be π with regard to the direction shown by an arrow

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FIGURE F-12 ALGORITHM OF FOOP

Whenever one closed region is found, the name of the region is given by GENSYM and put into the property list of MODEL identified by REGIONS. Each created region has the property list of all lines and the list of all points that define that region listed in the order that we can see the region on the left as we follow the contour. ISUPPOSEW outputs the lists of all regions and its points as shown in the results (see Figures F-13 to F-17).

The RGNFND program is still incomplete, it has not yet been developed so that it can delete the region outside the border lines and unite two regions created by outer and inner boundaries when one large region holds the small one.

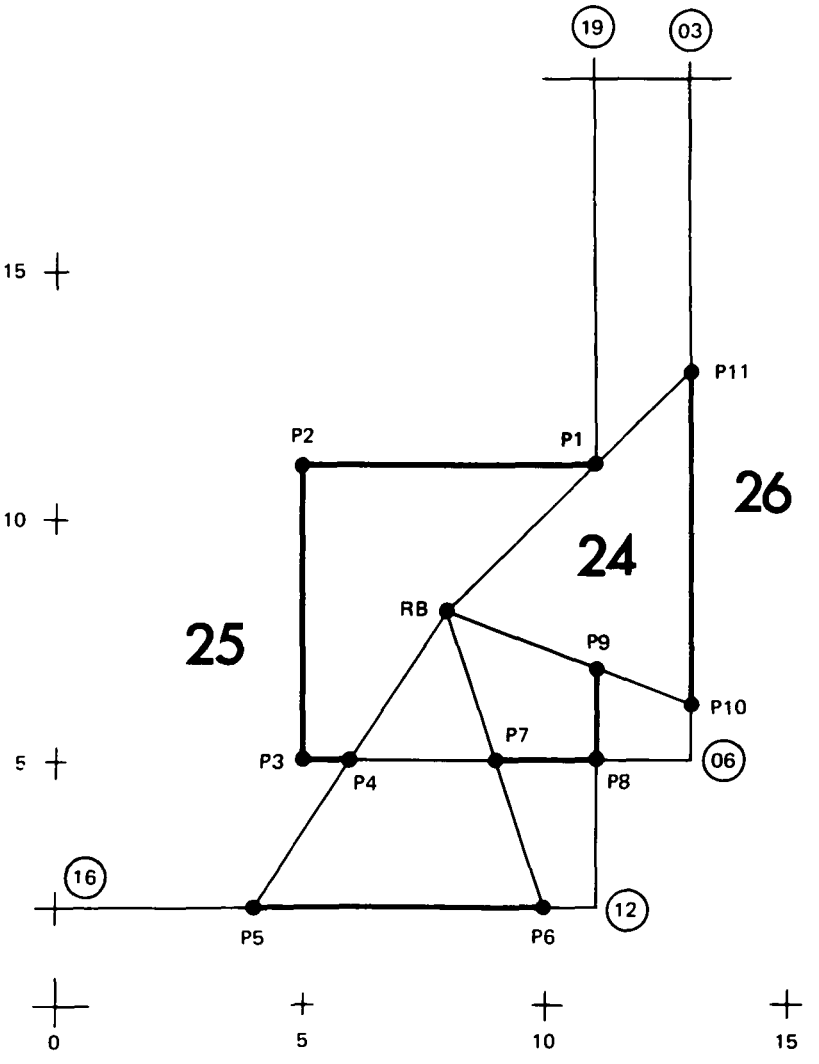
IV RESULTS

The examined data and their results are shown in Figures F-13 to F-17. Figure F-16 shows the whole output of ISUPPOSEW.

Some questionable points of the program should be considered.

A. Necessity of NGATE and Singularity of Solution

Even in the case of Figure F-2(d), CONJECT 1 connects both EPOINTs in pairs. Strictly speaking, they may not have to be connected. However, the author gave the program the characteristic that it make as many closed regions as possible. See Figure F-18. If CONJECT 1 is defined strictly, the region R2 in Figure F-18(a) and the region R6 in Figure F-18(b) may be left as open regions, for the lines L and L′ are not created in some circumstances, whether they are created depends on the sequence of EPOINTs that CONJECT 1 is given. Case (a) may be thought to be natural without R2, whereas in case (b) the preference is to close the region R6. The present CONJECT 1 closes both regions, unfortunately,



RESULTS [G0026 (G0016 P00 PXO PXY G0003 P11 P10
G0006 P8 G0012 P6 P5))
(G0025 (G0019 POY G0016 P5 P6 G0012 P8
P7 P4 P3 P2 P1))
(G0024 (G0019 P1 P2 P3 P4 P7 P8 P9 P8
G0006 P10 P11 G0003))
(G0023 (G0019 G0003 PXY PXD P00 G0016
POY))]

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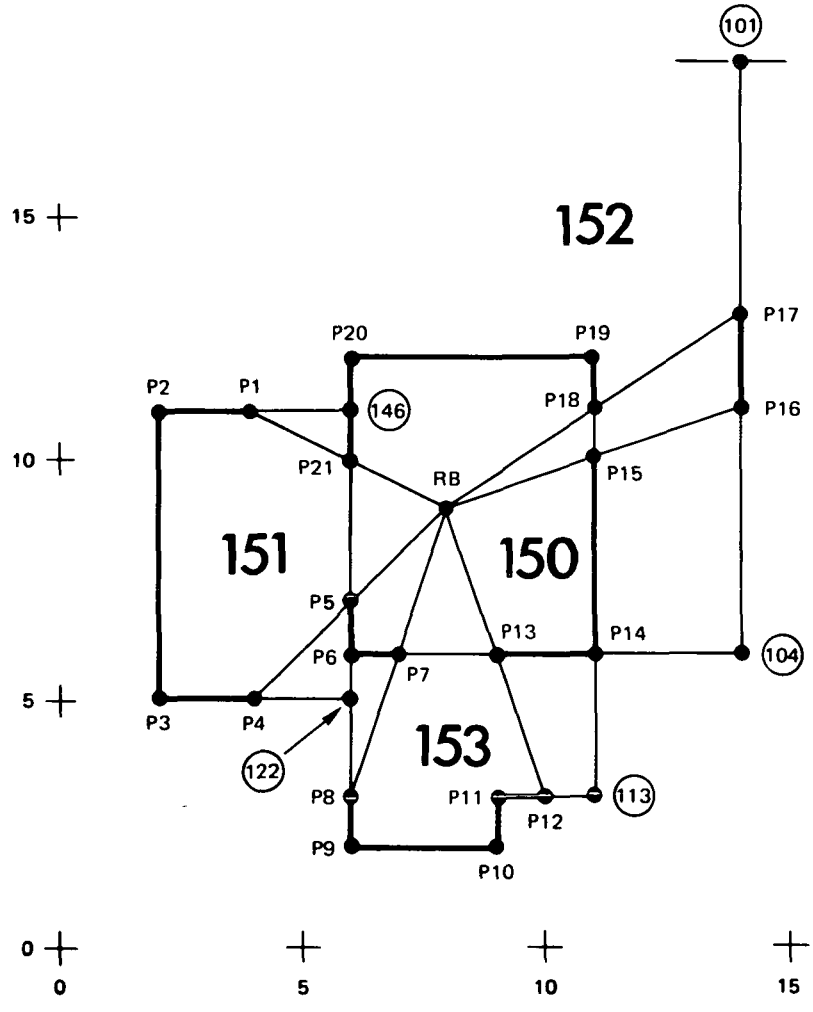
FIGURE F-13 DATA 1 RESULTS




```
RESULTS  [(G0154 (G0101 PXY PXO P00 POY))
          (G0153 (G0122 P8 P9 P10 P11 P12 G0113 P14
             P13 P7 P6))
          (G0152 (G0146 P20 P19 P18 P15 P14 G0104 P16
             P17 G0101 POY P00 PXO PXY G0101 P17
             P16 G0104 P14 G0113 P12 P11 P10 P9
             P8 G0122 P4 P3 P2 P1))
          (G0151 (G0146 P1 P2 P3 P4 G0122 P6 P5 P21))
          (G0150 (G0146 P21 P5 P6 P7 P13 P14 P15 P18
             P19 P20))]
```

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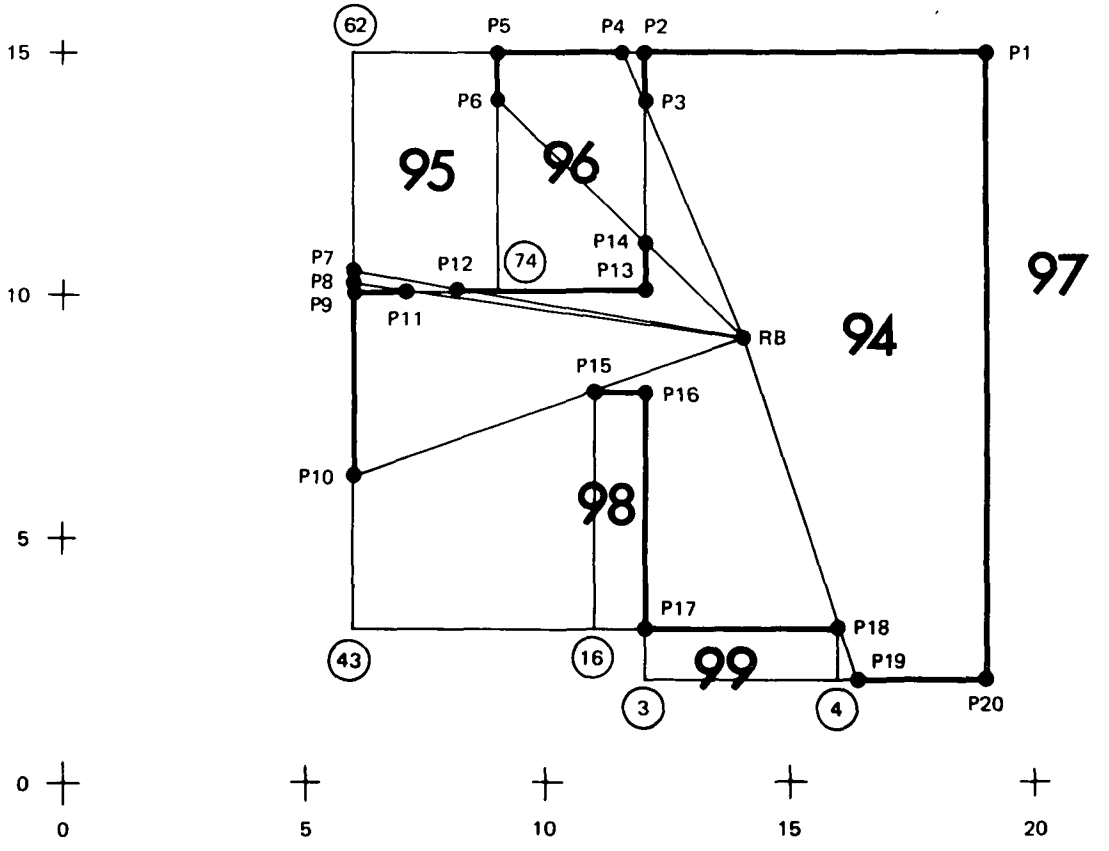
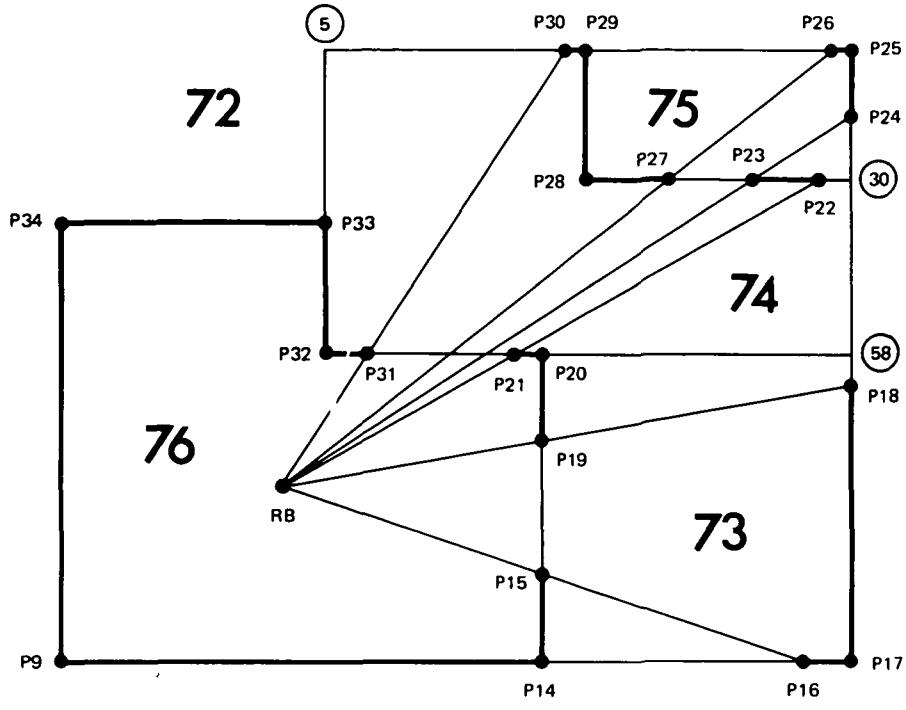
FIGURE F-14 DATA 2 RESULTS



RESULTS (MAPCAR (FUNCTION RGNLIST) (RGNFND (GET VIEW @POINTS$
((G0101 (POY POO PXO PXY)) (G0100 (POY PXY PXO POO))
(G0099 (G0009 P1 8 P17 G0003)) (G0098 (G0016 P17 P16 P15))
(G0097 (G0062 P5 P4 P2 P1 P 20 P19 G0009 G0003 P17 G0016 G0043
P10 P9 P8 P7)) (G0096 (G0074 P13 P14 P3 P2 P4 P5 P6)) (G0095
(G0074 P6 P5 G0062 P7 P8 P9 P11 P12)) (G0094 (G0074 P12 P11 P9
P10 G0043 G0016 P15 P16 P17 P18 G0009 P19 P20 P1 P2 P3 P14 P13)))

TA-710531-21

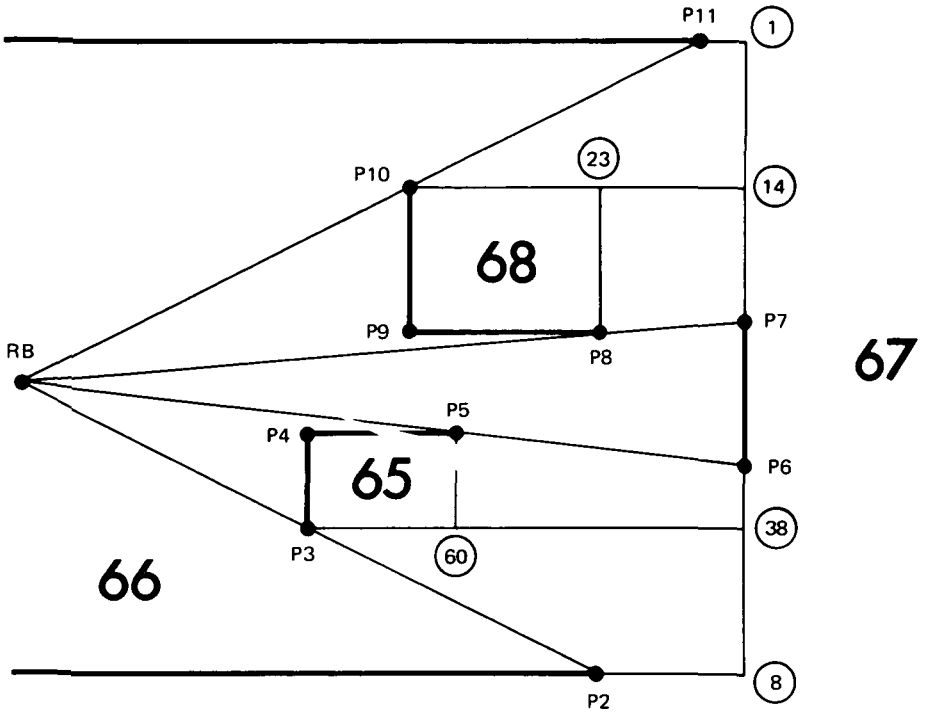
FIGURE F-15 DATA 3 RESULTS




```
RESULTS   *(DSKIN DATA4$
          ...
          *(I SUPPOSEW DATA4$
          EX2INED
          MODEL
          (B (PXO POO) R (PXY PXO) T (POY PXY) L (POO POY) L23 (P33 P34)
          L22 (P32 P33) L21 (P31 P32) L20 (P29 P30) L19 (P28 P29) L18 (P27
          P28) L17 (P25 P26) L16 (P24 P25) L15 (P22 P23) L14 (P20 P21) L13
          (P19 P20) L12 (P17 P18) L11 (P16 P17) L10 (P14 P15) L2 (P9 P14)
          L1 (P34 P9))
          CONJECT1
          (B (PXO POO) R (PXY PXO) T (POY PXY) L (POO POY) L23 (P33 P34)
          L22 (P32 P33) L21 (P31 P32) L20 (P29 P30) L19 (P28 P29) L18 (P27 P28)
          L17 (P25 P26) L16 (P24 P25) L15 (P22 P23) L14 (P20 P21) L13 (P19 P20)
          L12 (P17 P18) L11 (P16 P17) L10 (P14 P15) L2 (P9 P14) L1 (P34 P9)
          G0001 (P31 P21) G0002 (P27 P23) G0003 (P24 P18) G0004 (P19 P15)
          CONJECT 2
          (B (PXO POO) R (PXY PXO) T (POY PXY) L (POO POY) L23 (P33 P34)
          L22 (P32 P33) L21 (P31 P32) L20 (P29 P30) L19 (P28 P29) L18 (P27 P28)
          L17 (P25 P26) L16 (P24 P25) L15 (P22 P23) L14 (P20 P21) L13 (P19 P20)
          L12 (P17 P18) L11 (P16 P17) L10 (P14 P15) L2 (P9 P14) L1 (P34 P9)
          G0001 (P31 P21) G0002 (P27 P23) G0004 (P19 P15) G0006 (P30 G0005)
          G0007 (G0005 P33) G0020 (P26 P29) G0031 (P24 G0030) G0040 (P22
          G0030) G0060 (G0058 P20) G0061 (G0058 G0030) G0059 (P18 G0058)
          G0071 (P16 P14))
          EX2INED*
          REGIONS
          ((G0078 (POY POO PXO PXY)) (G0077 (POY PXY PXO POO)) (G0076
          (P9 P14 P15 P19 P20 P21 P31 P32 P33 P34)) (G0075 (G0030 P24 P25
          P26 P29 P28 P27 P23 P22)) (G0074 (G0058 G0030 P22 P23 P27 P28 P29
          P30 G0005 P33 P32 P31 P21 P20)) (G0073 (G0058 P20 P19 P15 P14 P16
          P17 P18)) (G0072 (G0058 P18 P17 P16 P14 P9 P34 P33 G0005 P30 P29
          P26 P25 P24 G0030)))
```

TA-710531-22

FIGURE F-16 DATA 4 RESULTS




```
RESULTS  [(G0070 (POY P00 PXO PXY))
          (G0069 (POY PXY PXO P00))
          (G0068 (G0023 P10 P9 P8))
          (G0067 (G008 P2 P1 P12 P11 G001 G0014 P7 P6
             G0038))
          (G0066 (G0060 G0038 P6 P7 G0014 G0023 P8 P9
             P10 G0023 G0014 G0001 P11 P12 P1 P2
             G0008 G0038 G0060 P3 P4 P5))
          (G0065 (G0060 P3 P4 P5))]
```

TA-710531-23

FIGURE F-17 DATA 5 RESULTS

and deletes the trouble of singularity of the result of the kind caused by the proposed sequence of EPOINTs.

If we examine the result of DATA 3, we see that the regions 98 and 99 were created, but the situation is very similar to the case in Figure F-18(a). That is, these regions have no evidence such as VIEW-ZONES inside them. Regions 98 and 99 are also created on account of the sequence of EPOINTs given to CONJECT 2. That type of difference of solution is not excluded from the program. ISUPPOSEW cannot guarantee the singularity of solutions of this kind in the present stage. The

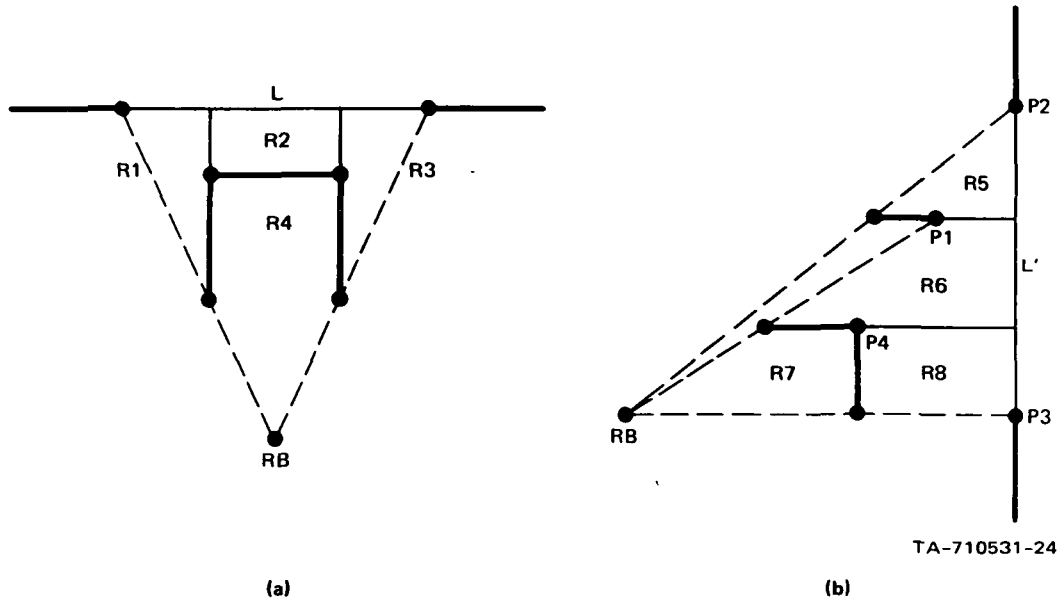


FIGURE F-18 EXPLANATORY DIAGRAM FOR CLOSING REGIONS

program that defines the relationship between regions must be added to. Then inconvenient regions may be deleted from the results or may be merged by the other (as they are most likely to be), but it must be another problem concerned with the global conjecture.

B. The Problem of Overlap of Lines

The algorithm of CONJECT 2 has the problem of overlap of created lines. ISUPPOSEW always replaces the old line in the current model by the newest line. It does conjecture procedures evenly on all the EPOINTs listed in E*LIST at first, without deleting any that happen to be considered to be connected as the result of the conjecture of other points. The case (b) in Figure F-18 has three points, P1, P2, and P3, to be dealt with by CONJECT 2. Assume the sequence given in (... P1 ... P2 ... P3 ...). When CONJECT 2 works on P1, the set of lines such that the extended line of P1 crosses L′ is created in the model, CONJECT 2 is applied to P2, and the result becomes the same.

ISUPPOSEW replaces the old set in the model with the new result. This is the way that ISUPPOSEW avoids the overlap problem, but it drives the program to meaningless calculations.

C. Questionable Conjecture, Impossible Conjecture, and Necessity of CONJECT 3

The basic concept of ISUPPOSEW includes the idea that an EPOINT like P9 in DATA 1 seldom exists, which has no opposite EPOINT to which it can be connected, in the building of the average kind. This gives the basic reason to case (a) in Figure F-19 that the line must be

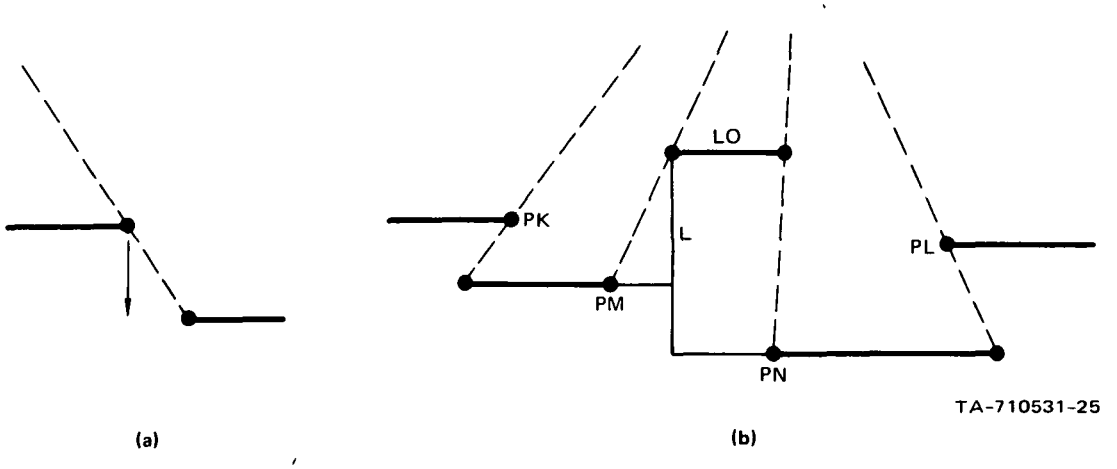


FIGURE F-19 DIAGRAM FOR QUESTIONABLE CONJECTURE

extended in the direction shown by an arrow, for if that point is one part of the doorway, it must be connected to the opposite one by CONJECT 1. The problem occurs when such opposites cannot be found because of obstacles. Such a case occurs in rather complicated data, as is shown in Figure F-19(b). Both points PK and PL must cross NVZNS to make closed regions, because the opposite EPOINTs of them may be somewhere behind LO. This is one point at which the author fears that CONJECT 3 is necessary.

We can consider more impossible conjectures. P3 in DATA 1 is one of them. ISUPPOSEW has treated only EPOINTs. Consequently, although they are in almost the same situation, conjecture on P5 in DATA 1 is different from other points such as P11 and P10 in DATA 1.

Suppose the line LO in Figure F-19(b) is connected to the other by CONJECT 1. There is left no possibility that the conjectured line L is drawn. Then point PM has no chance to be connected to any other point. Furthermore, who can guarantee that line L is right? The best answer may be that the line L connects to LO on the central point of LO. Now, it is impossible for ISUPPOSEW to make the above conjectures, and the author thinks it is the limit of ISUPPOSEW and that of human beings at the same time so long as we consider only the plan model of a visual scene.

Appendix G

ROBOT COMMUNICATIONS BETWEEN THE PDP-15 AND THE PDP-10

by

B. Michael Wilber

Appendix G

ROBOT COMMUNICATIONS BETWEEN THE PDP-15 AND THE PDP-10

I INTRODUCTION

There are an inconceivable number of links in the chain from a person typing English sentences on a Teletype to Shakey shaking, tweeting, and occasionally moving from place to place. One of those links is a package of subroutines through which the LISP part communicates with the robot program in the PDP-15, via the PDP-10 monitor, the infamous inter-computer interface, and a set of PDP-10 communication routines on the PDP-15. In this document, we will characterize the robot vehicle as it is seen from LISP via this subroutine package; when we refer to the PDP-15, it should be understood that we refer to the robot program within the PDP-15.

This appendix is one of three documents describing the robot from more or less the same point of view; the others are John Munson's Technical Note 35[1] and a forthcoming description of the robot as seen from the next level up.[2] Technical Note 35 describes the overall design considerations of this software and was written before any of the software. Here we describe the implementation of the "lower end" (as previously detailed) of that software, as well as characterizing the

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[1] "Bottom-Level PDP-10 Software for the SRI Robot," August 1970.

[2] Further details on the workings of the PDP-15 can be gleaned from Ed Pollack's memos of 11 February 1971 and 18 March 1971 (two memos).

concomitant hardware as viewed through the software. The third document will complete the description by telling how to use the robot from the viewpoint central to Technical Note 35. The last two documents, telling how to use the robot, go into considerable detail superfluous to Technical Note 35; areas of contradiction of Technical Note 35, however, represent implementation-motivated changes in the design.

We will characterize the robot as having two levels of protocol. The "PDP-15 protocol" is concerned with messages between LISP and the robot (or at least the PDP-15), while the "PDP-10 protocol" treats the ways of inducing the PDP-10 subroutine package to handle those messages.

The PDP-10 protocol is by far the simpler, so we shall consider it first. A conversation with the robot program in the PDP-15 is initiated or terminated by a call to INIT15 or REL15, respectively, about these two nothing more need be said. During a conversation, messages are sent to the PDP-15 by calls on START15; these messages typically start activities aboard the robot. Status reports are elicited from the PDP-15 by calls on READ15. Finally, the subroutine package provides a fifth entry point called STOP15, which sends a "stop" message; it is a specialized entry to START15 and thus needs little further special consideration.

Before further exploring the peculiarities of START15 and READ15, we will touch upon the PDP-15 protocol--the content of the messages transmitted between PDP-10 LISP and the PDP-15 robot program. Munson's Technical Note 35 introduces the concept of an "activity" as one of ten motor or sensory actions that the PDP-15 can be asked or told about. In communication with the PDP-15, these activities are designed by code numbers called "activity codes." There are certain other kinds of messages sent between the two computers (e.g., "stop" above) which artificially fit into the protocol by the use of dummy "activity" codes. We

will however, try to restrict our use of the word "activity" to Munson's sense and use "action" to denote this more general sense.

In order to further isolate the PDP-10 protocol from the PDP-15 messages, we have stylized the PDP-15 messages into two formats--one for the orders sent to the PDP-15 (via START15), and another for the status reports elicited from the PDP-15 (via READ15). Each of these routines, of course, needs an activity code to identify the action under consideration. The (START15) orders also contain an additional optionally used parameter giving--for example--a distance to turn. The (READ15) status reports contain a value called the "activity status value" (ASV) and two additional values (which may or may not be used). The ASV summarizes the status of the action in a fairly uniform way, while the additional values give additional information in a manner peculiar to the particular action under consideration.

There are two additional facets of READ15 that will bear passing mention. For completeness, we should mention that READ15 sends the activity code to the PDP-15 in the request for a status report, so it is not entirely passive with respect to the PDP-15 robot program. Far more important is the observation that some of the actions do not directly affect the vehicle, but are instead handled completely by the PDP-15 robot program. For these actions there is no corresponding status report; in fact, we do not consider the case of READ15 being given one of the corresponding activity codes.

II THE PDP-10 PROTOCOL

A. The LISP Functions in the PDP-10 Protocol

We will now specify the precise LISP constructs used in the PDP-10 protocol. The reader may be interested to note that this is a LISP adaptation of the FORTRAN-oriented protocol.[1]

1. Establishing the Connection: (INIT15)

This must be done when the program is started or re-started. Thus it must be done whenever the PDP-10 monitor detects an error and stops the program. Spurious execution of this form should do no harm.

2. Breaking the Connection: (REL15)

This is the complement of (INIT15).

3. Sending an Order: (START15 actcode param)

Execution of this form will send an order to the PDP-15 robot program; the order will contain the values of "actcode" and "param." The PDP-15 will then usually start the action represented by "actcode," with "param" specifying, say, a distance to turn; details are further specified by the PDP-15 protocol.

4. Reading the Status of an Activity: (READ15 actcode)

This is a pseudo-function in that it returns values via global variables as well as communicating with the PDP-15. It sends a

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[1] Cf. Ann Robinson's memo of 26 June 1970.

request for a status report to the PDP-15 and then reads the resulting report from the PDP-15, the request contains the value "actcode." The activity status value is returned as the value of both the function and the LISP atom ACTASV, while the first and second additional activity status values are returned as the values of the LISP atoms ACTV1 and ACTV2, respectively. (These three values replace the values current when the READ15 function is entered at the same level of binding. Thus the effect is the same as if the atoms had been SETQ-ed to the values in the calling function.) Further details are given by the PDP-15 protocol.

5. Stopping an Activity: (STOP15 actcode)

A "stop" order is sent to the PDP-15, the order contains the value "actcode." While this is not a separate activity[1] in the PDP-10 protocol, it is a separate action in the PDP-15 protocol, to which the reader is referred for further details.

B. How to Use the LISP Functions in the PDP-10 Protocol

1. The Connection--INIT15 and REL15

Before a conversation between LISP and the PDP-15 robot program can take place, a connection must be established by INIT15. This connection is broken by REL15 and also by the monitor or the LISP system on a large number of monitor commands, such as RUN, SAVE, START, etc., and must subsequently be reestablished.

Ideally, one will break the connection with REL15, but the monitor's (and LISP's) predilection to do this automatically as a by-product of many frequently used operations reduces REL15 to near-vestigial status.

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[1] In the sense of Technical Note 35.

2. Using the PDP-15 Protocol--START15, READ15, STOP15

A conversation, as specified in the PDP-15 protocol, is carried out by means of the START15, READ15, and STOP15 functions. As previously mentioned, these functions can only be used after an INIT15, any further restrictions on their use is the domain of the PDP-15 protocol.

III PDP-15 PROTOCOL

A. The PDP-15 Actions in the PDP-15 Protocol

There are twelve actions that the PDP-15 can be commanded to perform, eight of these actions are just the PDP-15 ends of Technical Note 35 activities, while the others serve other purposes. All twelve actions are detailed below. Eight of these actions directly cause the PDP-15 to send orders to the robot and receive responses from the robot, while the others affect various aspects of the operations of the eight robot actions. We will now briefly describe the PDP-15 actions, but we defer details to our summary. Many of the actions executed by the robot can terminate abnormally; we defer discussion of that point to a succeeding section.

1. Stop

The indicated activity is stopped. The activity must be tilt, pan, iris, focus, roll, or turn. The activity status value for the stopped activity is set to 7, and the rest of the report will correctly reflect its terminal status.

2. Tilt

The robot's head tilts by the indicated amount.

3. Pan

The robot's head pans (relative to its body) by the indicated amount.

4. Turn

The entire robot turns by the indicated amount. Note that roll and turn conflict in their use of the wheels.

5. Roll

The entire robot rolls forward or backward by the indicated amount. Note that roll and turn conflict in their use of the wheels.

6. Override

The catwhiskers and pushbar are overridden according to a code word supplied by the most recent override order. This override is effective on rolls and turns.

7. Range

This is a complex action, which we will describe in terms of its components. Upon receipt of the START15-order, the rangefinder is turned on and allowed to start warming up. When the rangefinder finishes warming up, the PDP-15 reads the value from the rangefinder into its own memory. At this time, the PDP-15 starts timing an interval after which, barring another START15-order from the PDP-10, it will automatically turn off the rangefinder. If another START15-order comes from the PDP-10 during this interval, the PDP-15 reads the then-current rangefinder value into its memory and resets the interval to turn off

the rangefinder. Thus a sufficiently rapid succession of rangefinder START15-orders will keep the rangefinder turned on. READ15 will always report the value resulting from the START15 rather than directly reading the rangefinder, so READ15's will normally be paired to START15-orders.

8. Emergencyfinished

This "action" cannot be the subject of a START15-order but supplies a means by which the PDP-15 can supply (via READ15) information to the PDP-10 regarding its "emergency" recovery status. Further details are given below.

9. Tvpoweron

This is a complex action quite similar to range in that it entails a warmup phase and a "kept-on" phase that is reinitialized on subsequent START15-orders. This action, however, does not directly read a TV picture, owing to problems in handling the enormous volume of data that would result therefrom.

10. Iris

The TV camera's iris setting is changed by the indicated amount.

11. Focus

The TV camera's focus setting is changed by the indicated amount.

12. Initialize

The PDP-15 resets itself to its initial state. Note that this involves turning off the overrides. No orders are sent to the robot because no on-board initialization is necessary. Note that any on-board actions can thus be in progress. The PDP-15 will not become confused about this. This action is used in system initialization and also in certain error recoveries (see below).

B. How to Use the PDP-15 Protocol

1. Establishing and Terminating Rapport

When first establishing contact with the PDP-15, it is advisable, though by no means necessary, to send it an initialize order. Then the PDP-15 and the robot will be in a more-or-less well-known state. No means is provided by which the contact can be broken because there is no need for such an action.

2. Normal Operations

Any PDP-15 action except emergencyfinished can be the subject of a START15-order whenever there is no conflict with an in-progress action, this is not quite true in the case of emergency recoveries, as we will discuss below. Emergencyfinished can never be START15-ed. The conflicts are as follows.

(1) Override and initialize are completely executed in the PDP-15 and thus are never in progress.

(2) Stop sends orders to the robot but works by affecting other actions and is thus never in progress itself.

(3) Each of the remaining eight START15-able actions conflicts with itself while it is in progress.

(4) Roll and turn conflict with each other while they are in progress.

Any of the eight on-board actions--as well as emergency-finished (i.e., any action but stop, override, or initialize)--can be reported by READ15 at any time. The range of values that can be taken by the activity status variable changes from action to action, but there are five standard values with roughly the same meaning for each of the actions. They are:

-1. The action is in progress. For range and tvpoweron, this means that the on-board equipment is warming up.

0: The action has completed normally.

6: The action did not complete in the time the PDP-15 allowed it. The PDP-15 then took other measures to terminate the action.

7: This action was specified in a stop order.

8: An "emergency" was noted by the robot, the PDP-15, or by the telemetry interface between them. Recovery from this condition is further discussed below.

Other conditions can give rise to values from 1 to 5 as individually noted in the summary below.

3. Coping with an "Emergency"

Under certain drastic conditions (e.g., transmission error or low robot power) the PDP-15 may report an activity status of 8. Owing to the gravity of this condition, the PDP-15 will not completely reset itself until it has received acknowledgment that the PDP-10 has noticed. For example, the PDP-10 cannot presume correct execution of recent orders or even nonexecution of nonorders. The PDP-15 will attempt to reset the states of the robot, as well as some of its internal tables, but will not complete the job until receipt of an initialize order from the PDP-10.

In addition, we must consider timing. The PDP-15 takes several seconds in its attempts to reset the state of the robot. It tells the PDP-10 about the progress of this recovery by means of a special activity code--and the associated activity status variable. This special activity is the "emergencyfinished" action. Its activity status variable is set to 8 (just as all the others) when the PDP-15 perceives an emergency, but it is automatically set to zero when the PDP-15 and the robot have again established communications.

Thus there are two things the PDP-10 must do upon perceiving a PDP-15 "emergency" (i.e., activity status variable = 8). It must send an initialize order, and it must wait until the emergency-finished activity status value goes to 0. These can be done in either order, but both must be done. It should be noted that successful completion of this part of the protocol does not guarantee absence of the offending condition, e.g., low power on board the robot.

C. Abnormal Terminations on Board the Robot

We have discussed PDP-15 conditions under which actions can terminate abnormally (e.g., timeout, emergency). There remain, however,

conditions on board the robot that can also abnormally terminate actions--for example, bumping into an unexpected obstacle. Whenever a stepping motor is thus abnormally stopped, the residual count is accurately reported in the corresponding status report. These conditions are discussed below.

1. Tilt, Pan, Iris, Focus

These four motions are restricted to definite ranges by limit switches. Whenever the indicated count would cause motion past a limit switch, then motion is stopped at the limit switch and the status report reflects this state.

2. Roll and Turn

There are four principal ways in which a roll or turn can terminate abnormally, these are denoted by distinct values of the READ15 activity status variable. First, the robot can engage a catwhisker and stop because of that. Secondly, the pushbar can come free (because an object the robot is pushing has slipped off), causing the PDP-15 to stop the robot. Also, the robot can encounter an immobile obstacle while pushing (or preparing to push). (This case will be treated more fully below.) These three circumstances all involve the robot stopping; however, the status reports also distinguish a fourth case in which the robot covers the entire distance ordered by the PDP-10, in spite of the catwhiskers being engaged sometime during or before the roll. This could happen because the catwhiskers are overridden or because the catwhiskers became free either before the robot had finished decelerating to a stop or before the roll started.[1]

[1] See Ed Pollack's memo of 18 March 1971, "Robot Emergencies," Note that his "pushbar emergency" is just the "hard contact" referred to herein.

When the robot encounters an immobile obstacle it backs away: if it was rolling, it backs up to free itself, if it was turning (unlikely, but still a distinct possibility), it turns back to its original heading. This is a reflex in the PDP-15 because of the way the hard-contact pushbar switch is connected to the PDP-15. That is, the PDP-15 can sense the event of making hard contact but not the state of being in hard contact. Consistent with our philosophy of removing all possible computational burden from the PDP-15, we adopted this solution, rather than have the PDP-15 ensure that a subsequent roll or turn be in a direction appropriate to releasing the hard contact. At any rate, the status report of a roll or turn correctly reflects the terminal status of the activity.

IV SUMMARY

A. Introduction

A LISP program communicates with the robot through the PDP-10 monitor and various programs in the PDP-15. We break the protocol into two pieces, which we call the PDP-10 protocol and the PDP-15 protocol. We can think of the PDP-15 protocol as treating the messages to and from the robot, while we can view the PDP-10 protocol as treating the way a LISP program gets the PDP-10 monitor to handle these messages. Thus in this discussion, the robot is viewed as part of the implementation of the PDP-15 protocol. In previous sections we have emphasized the meanings of messages at the expense of their precise forms, now we will focus on precise formats and allude to the meanings only in passing.

B. PDP-10 Protocol

1. The Connection

(a) Execution of the form

(INIT15)

will establish a channel to the robot program.

(b) Whenever the form

(REL15)

is executed, the channel is disestablished. In practice there should be little need to execute this form.

2. The Messages

(a) LISP can send an order by executing

(START15 actcode param)

where the order contains actcode and param and is subject to the rules of the PDP-15 protocol.

(b) Whenever a LISP function is curious about the state of a PDP-15 action, it need only execute

(READ15 actcode) ,

where actcode specifies the action according to the PDP-15 protocol. The activity status value is returned as the value of the function and of the atom ACTASV, while the first and second additional values are returned as the values of ACTV1 and ACTV2, respectively.

(c) A LISP function can stop some actions by executing

(STOP15 actcode) ,

which in the PDP-15 protocol is equivalent to

(START15 stopcode actcode) , .

with "stopcode" being the activity code for the "stop" action of the PDP-15 protocol.

C. PDP-15 Protocol

1. Formats of Parameters, Results, and Other Diverse Quantities

We frequently include in PDP-15 messages various numeric and coded values. We will briefly digress to explain the formats of the code words for the catwhiskers and the overrides as well as the peculiar formats for stepping motor counts and residual counts.

a. Catwhiskers

The states of the catwhiskers and pushbar (after a roll or turn) are encoded into a word called the "whisker word." The pushbar and each catwhisker is associated with a unique bit position in the whisker word, and the value of any given bit is 1 when (and only when) the associated catwhisker is in contact with something (presumably a box, wall, another robot, etc.). All unused bits in the whisker word contain zeroes, so the entire word is zero when the robot is in an empty area. The following table gives the correspondence between whiskers and bits, of course, the pushbar bit reflects the "ready to push" switch, not the "immovable object" switch.

Bit No.	Octal Code	Meaning of "1"
21	040000	Pushbar is engaged
23	010000	Left front whisker is engaged
25	002000	Front horizontal whisker is engaged
26	001000	Right front whisker is engaged
28	000200	Right rear whisker is engaged
30	000040	Rear whisker is engaged
33	000004	Left rear whisker is engaged
35	000001	Front vertical whisker is engaged

b. Overrides

The inhibition of rolling or turning due to the pushbar becoming free or a catwhisker being engaged is overridden as shown by this table.

Code Word	Pushbar	Catwhisker
0	Enabled	Enabled
1	Enabled	Overridden
2	Overridden	Enabled
3	Overridden	Overridden

c. Stepping Motor Counts

In the robot, motor counts are expressed in sign-magnitude notation of various formats tailored to the individual activities. Because we have removed all possible computational burdens from the PDP-15, this variability of format is carried up to the interface between START15 and READ15 on the one hand and the lower-level LISP functions on the other. We can characterize one of these sign-magnitudes by two field widths: the width of the entire number and the width of the significant part of the magnitude. Thus a 12-bit wide number of 11 significant bits has no bits ignored, while a 12-bit wide number of 7 significant bits has 4 bits (to be ignored) between the sign bit and the most significant magnitude bit.

d. Residual Counts

Those actions involving a stepping-motor count all return a residual motor count at the end of the action. (We expect that on a normal completion, the residual count will be zero.) The residual counts are treated nonuniformly for the following reasons.

The robot has two distinct ways of handling residual motor counts: in the cases of a tilt, pan, iris, or focus action running into a limit switch and stopping because of the limit switch, the sign bit is inverted; in all other cases, the sign bit is correct. Fortunately,

these four actions can never overshoot their targets, and thus the residual's sign bit is dispensable. (Of course, these four actions could be aborted by the stop action or a PDP-15 emergency so the sign bit is not even necessarily reversed.) On the other hand, the vehicle can build up considerable momentum while rolling (e.g., down a ramp) or even turning, causing it to overshoot and then back up to the target. Of course, there is nothing preventing, for example, the pushbar coming free on the overshoot, and so the robot could be on either side of the target when it finally stops rolling (or turning). Then it is very important to preserve the sign bit associated with the residual count of a roll or turn.

The way residual counts are returned (via READ15), then, is this: For the roll and turn activities, the residual count is the correct signed residual count, while the other activities return the magnitude of the residual count.

2. Formats of the Messages

The formats of the messages themselves are presented in abbreviated fashion in Table G-1.

Table G-1

FORMATS OF THE MESSAGES

Activity	Activity Code	START15 Parameter	READ15 Status Report: Activity Status Variable (ACTASV)[1]	READ15 Status Report: First Additional Activity Status Variable (ACTV1)	READ15 Status Report: Second Additional Activity Status Variable (ACTV2)	Conversion Factor, Limit Positions (approximate)
Stop	0	Activity code[2]	None[3]			None
Tilt	1	Motor counts (6/12 bits)[4]	1 limit switch	Residual count[5]	None	+10 counts/degree up -45, +35 degrees up
Pan	2	Motor counts (8/12 bits)[4]	1 limit switch	Residual count[5]	None	+105 counts/90 degrees left -105, +115 degrees left
Turn	3	Motor counts (14/18 bits)[4]	1 ignored bump 2 stopped-bump 3 stopped-dropped object 4 stopped-immovable object (backed off)	Residual count	Whisker word[6]	-650 counts / 90 degrees left
Roll	4	Motor counts (14/18 bits)[4]		Residual count	Whisker word[6]	+5000 counts / 13 5 feet forward
Override	5	Code word[7]	None[3]			None
Range	6	None[8]	-1 warming up 0 off 1 warmed up and ready	Rangefinder counts	None	353 feet / 326-counts
Emergency-finished	7	None[9]	0 talking to robot 8 ignoring robot (no other values)	None	None	None
Tvpoweron	8	None[8]	-1 warming up 0 off 1 warmed up and ready	None	None	None
Iris	9	Motor counts (7/12 bits)[4]	1 limit switch	Residual count[5]	None	To be determined
Focus	10	Motor counts (10/12 bits)[4]	1 limit switch	Residual count[5]	None	To be determined
Initialize	64	None[8]	None[3]			None

[1] In addition to (unless otherwise specified) -1 in progress, 0 normal completion, 6 timed out, 7 stopped by PDP-10, 8 emergency

[2] Must be one of tilt, pan, roll, turn, iris, or focus.

[3] It is meaningless to read the status of stop, override, or initialize.

[4] The meaning of the notation "(m/n) bits" is that the number is n bits wide, of which m are significant.

[5] The residual count is the magnitude only in the case of tilt, pan, iris, and focus

[6] The format of the catwhisker word is given above

[7] The interpretation of the override code word is given above

[8] The START15 parameter is required by the PDP-10 protocol but ignored by the PDP-15 protocol in the cases of range, tvpoweron, and initialize

[9] It is meaningless to do a START15 specifying emergencyfinished

Appendix H

FORTRAN DISPLAY PACKAGE

by

John Bender

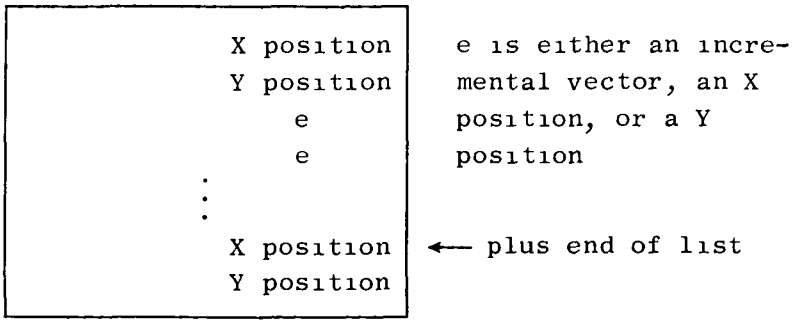
Appendix H

FORTRAN DISPLAY PACKAGE

This appendix is a follow-up to the User Display Software Memo of October 1970, with corrections and specifics for using the display from FORTRAN.

The current implementation is a minidisplay package that gives the user the basic routines needed to display a figure. No light pen facility has been implemented. A satisfactory handle for indicating the location of a light pen hit within a user's sublist has not been worked out. The ability to save, retrieve, and manipulate a complete frame is not possible, and may not be a desirable low-level FORTRAN facility. See the attached pages for a rewritten edition of pages 4, 5, and 6 of the October memo.

The format of a sublist has been simplified and is as follows:



The left half of all sublist words is ignored. All sublists must contain at least one end of list.

The operating procedure for using the display is as follows:

(1) Reserve the PDP-15 for your use, using the signup sheet.

(2) Turn on the power to the Adage display.

(3) Put the newest version of the bootstrap program in the PDP-15 papertape reader.

(4) Put 07600 in the address switches.

(5) Press the following PDP-15 console buttons in order (located in upper left-hand corner):

STOP

RESET

READIN.

(6) Log in on the PDP-10 and get on your disk areas, DISMON.BIN and DIS10.MAC, from user area [20,26].

(7) Type the underlined:

```
.R TO15↵
FILE TO GO TO 15↵
DISMON.BIN↵
↑C
.
```

(8) Along with your FORTRAN program, load the file DIS10.MAC. The display is now yours.

(9) When finished with the display, turn off its power and hit the STOP switch on the PDP-15.

To: AI Group October 1970

From: Systems Programming

Subject: User Display Software

The following memo is divided into three parts:

Part I is a description of the way the display works at the lowest level. It is provided for information only; it is not expected that LISP or FORTRAN programmers will use this information directly.

Part II is a description of the display commands that are accessible from FORTRAN or MACRO.

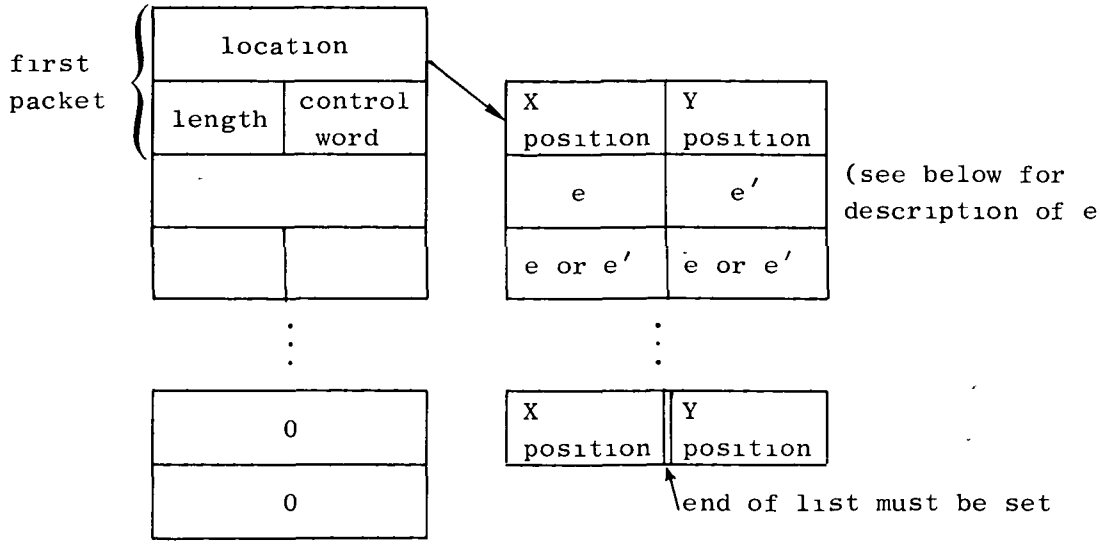
Part III is a discussion of a display user system (the user being a LISP robot programmer) that we envision as the final working system.

We urge everyone to read this and offer criticisms. We do not wish to omit any obvious functions and would like to accommodate all users if possible.

LJC/kls

In the PDP-10 a display list is defined as a list of two-word packets that describe sublists, where a sublist is a list of PDP-10 words that are the coordinates of a point on the user's screen. The user's screen is a two-dimensional 10" x 10" area. For the purposes of this description, any point outside this area is not visible. The X and Y coordinates have the origin at the center of the screen.

The structure of a display list is as follows:

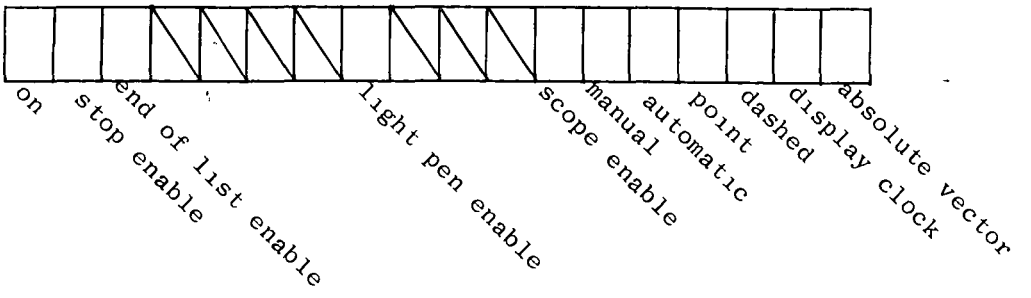


The move bit is set if the vector is to be displayed at the intensity specified in the Y portion of the position word.

The preceding description of a display list did not include any mention of the various modes available to the user. The available modes are: point, dashed, and line. The line mode is normally used to describe a figure in a frame.

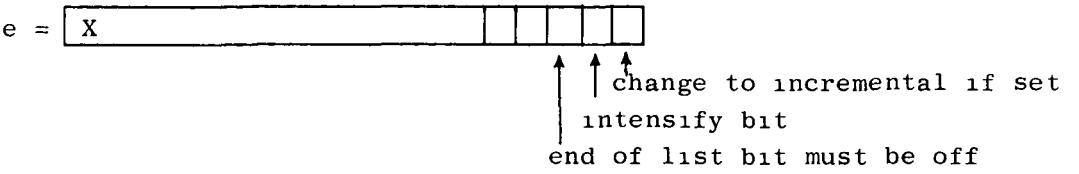
The control word contains the bits that indicate in which mode a sublist is to be displayed. The entire sublist must be displayed in the same mode. There exist two submodes for line: absolute vector and incremental vector.

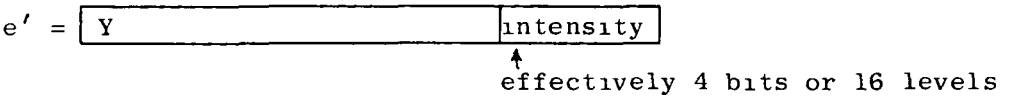
The control word bit definition is as follows:



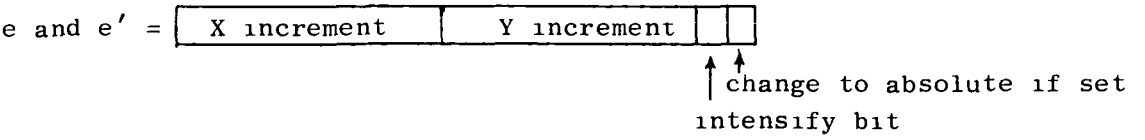
e is an element that is either a description of an incremental vector or the X portion of an absolute vector. e′ is either an incremental vector or the Y portion of an absolute vector. Note that a sublist must start with an absolute vector. This requirement ensures that the position of the display beam is well defined before the display enters the incremental mode. Also, the sublist must end with the display in absolute vector mode, because only in the absolute mode is it possible to have the end of list bit. End of list bit set defines the end of a sublist.

An absolute vector has the following form:





In incremental mode,



The only functions available to user programs are: light pen enable, line mode, point mode, and dashed mode. The user cannot disable, on, end of list enable, absolute vector automatic, or display clock. The user cannot enable, stop enable, or manual. Scope enable may be indirectly effected by the blink function. If the display is to be capable of blinking a sublist, this function will have to be performed in the PDP-15.

The MACRO subroutine calls that are available to the user are:

CREFRM(framename)	Create frame, where frame name is a block of storage in which the display list packets will be stored, or are stored if first entry is nonzero.
ADDSL(name,length,mode)	Add sublist; name is the address of a sublist, length is the absolute number of contiguous PDP-10 words used in the sublist, and mode is one of the following: 1 line 2 dashed line 3 point 4 blink line 5 blink dashed line 6 blink point
DELSL(name)	Delete sublist, deletes the entry and moves up the bottom of the list.
REPSL(oldname,newname,length,mode)	Replace sublist.
MODE(name,mode)	New mode, changes the mode of an existing sublist.
LPON(name) LPOFF(name)	Light pen on/off, enables or disables the light pen for this sublist.
SETINT(name,value)	Set intensity; changes intensity in an existing sublist. The values can be from 0 to 15_{10}.
DISPLA	Display; will display the list at a refresh rate of 40 frames a second, using all entries in the array referred to by CREFRM.

HIT — Hit, queries the PDP-15 if a light pen hit has occurred since the last time it was interrogated and returns a sublist reference and an index into the sublist; 0 otherwise. This is not presently implemented.

STOP — Stop, turns off the scope. This does not have to be done before changing what is currently appearing on the display.

A copy of the current display is kept by the user. The only information that he can get back from the display is light pen hit information.

Some routines that can help a user in building up a sublist are:

INCVEC(location,Xincrement,Yincrement,action)

Incremental vector puts the X and Y increment values in the specified location. Action has values of:

0 Don't change vector mode, don't intensify

1 Change vector mode, don't intensify

2 Don't change vector mode, intensify

3 Change vector mode, intensify.

Changing vector mode only affects vectors that follow the vector in which it occurs.

ABSVEC(location,Xposition,Yposition,action)

Absolute vector puts X position and action value in left half of location, and puts Y position and implied intensity in right half. The action values are the same as for incremental plus end of list action:

4 End of list

5 End of list and intensify.

INTENS(value)

Implied intensity in constructing a sublist intensity is an implied parameter and is needed by ABSVEC.

GETINT

Get implied intensity returns the value of the assumed intensity if no intensity value is ever defined and an assumed value of 10_{10} is used. This is a FORTRAN function.

PART III

A. Introduction

This proposed display system is plagiarized from the BBN 940 LISP system. That system, however, seemed to be designed around the BBN's displays. Ours, we hope, is somewhat display-independent. Since our display is quite primitive, this doesn't hurt.

The system centers around an internal LISP representation for structured pictures. Simple objects such as lines, quadratic curves, and character strings are combined, translated, rotated, scaled, etc. by combining them into lists together with key words and necessary parameters. Currently, the system is designed to handle only two-dimensional coordinates, but we hope everything will be easily extended to homogeneous coordinates. Our system is unsuited for displays of large numbers of unstructured points, say, a display of unprocessed TV pictures. But for interactive systems displaying line drawings, such as plots or pictures of rooms, the system offers flexibility of data structure with a minimum of space and computation.

B. Noninteractive Picture Display

To display a picture the user must first construct the internal representation. The proposed primitive figures are:

(1) (DVECTOR X_0 Y_0 X_1 Y_1) represents a vector from (X_0,Y_0) to (X_1,Y_1)

(2) (DPLOT A) (where A is a list of Y values, say $A = (Y_1,Y_2,\ldots,Y_n)$) represents a plot of the elements of A at unit intervals along the X-axis

(3) (DPLOT AT) similarly represents a plot where A is interpreted as X values

(4) (DCIRCLE X Y RDT) represents a circle with origin (X,Y) of radius R, approximated by cords spanning an angle of DT

(5) (DTREE E) represents a tree-like display of the s-expr E

(6) Character strings; that will be discussed later.

To define a unit interval the display is thought of as a coordinate system with the origin in the middle and extending one unit on each axis. All numbers may, in normal list fashion, be fixed or floating.

A figure is either a primitive figure or modified figure. The following list of modifications always apply to both kinds:

1. (TRANSLATE: F X Y) represents F translated by X Y

2a. (SCALE: F S) represents F scaled by S in both axes

2b. (SCALE: F X Y) represents F scaled by X in the X-axis and Y in the Y-axis

2c. (ISCALE: F S) represents F scaled by 1/S in both axes

2d. (ISCALE: F X Y) represents F scaled by 1/X in the X-axis and 1/Y in the Y-axis

3a. (MOVE: F A_{11} A_{12} A_{21} A_{22}) represents the transformation of F by the obvious matrix

3b. (MOVE: F R) represents F rotated by R radians

4. (INTENSITY: F I) represents F displayed in intensity I

5. (DASH: F), (SOLID: F) (BLINKING: F) represents F displayed point in the appropriate mode

6. Finally, the list (F_1 F_2 ... F_n) represents the combination of the figures in the list.

Before we discuss the process of displaying an internal representation, let's consider an example. Suppose we have a list A = (Y_1 Y_2 ... Y_n) of values we want to plot. We would like everything to fit on display and fill the screen. We also want to start plotting along the X-axis at the origin. If DY is the maximum difference in Y values, then

```
(TRANSLATE:
     (ISCALE:
          (DPLOT A)
          N
          DY)
1 0)
```

is a possible representation. The LISP code to generate the figure might simply be

```
(SETQ F (LIST (QUOTE TRANSLATE:)
        (LIST (QUOTE ISCALE:)
             (LIST (QUOTE DPLOT) A)
             (LENGTH A)
             (MAXDIF A))
        0 1))
```

To convert an internal representation to a bit-string in the style of the display the user might execute

```
(SETQ G (DISPLAY F A))
```

where F is a figure, A is the array in which the bits will go, and G is a variable that will be used to store all sorts of good information about A for later reference. G is thought of as a piece of glass and may be shown at any time. The command (SHOW G) does just that. (KILL G) removes G from the display. It is recommended that these pieces of glass not be used as small picture parts but rather as major overlays. For example, they might be a coordinate grid, a light button panel, an unsmoothed picture, a smoothed picture, etc. It is planned that there will also be a mechanism for modifying a piece of glass, but the specifications of such modification requests will be closely linked to final implementation procedures.

The primitive figures for character strings are close to the LISP print functions:

DPRIN1, DPRINC, and DTERPRI .

They will be interpreted as the appropriate strings with character height and width being some standard proportion of the display screen size. DTERPRI will cause teletype-like lines to appear. The extra function (DSPACES N) inserts N blanks. All the standard figure modifiers will also work on character strings, permitting vertical printing and various sizes.

C. Interactive Features

Since we are not yet sure just which selection devices will ultimately be used, this proposal discusses everything in terms of the light pen. Two facilities are offered for interactive graphics: the ability to specify which figures may be selected and functions which will wait in the PDP-10 until certain selections have been made through the PDP-15.

When a figure F modified by the list (ITEM: F), is processed by DISPLAY special information is included in the bit buffer for the PDP-15 and notes are kept on the piece of glass in the PDP-10. Later, if the figure is shown and the function (PENSELECT) is executed, the value will be a pointer to the ITEM list in the internal representation of the figure selected by the user.

This system is a compromise, and due to the cost of interaction between the machines it appears especially suited for light button panels, selection of one from a few relatively disjoint figures, for drawing with only a few lines. But since this is the anticipated kind of usage the system should be adequate.

For drawing, two more interactive functions are needed:

(1) TRACE--which tracks the pen and returns as a value a coordinate

(2) RUBBERBAND--which tracks to the first select, and rubberbands until the second. It's value is the list of the two selected coordinates.