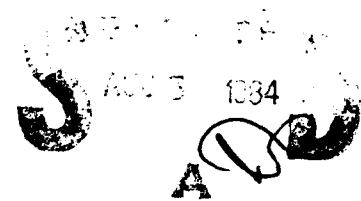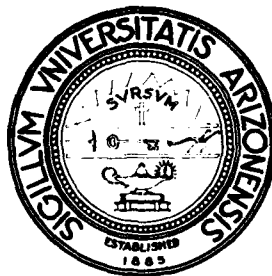| 1.0	4.5 5.0 5.6 6.3 7.1	2.8 3.2 3.6 4.0	2.5 2.2 2.0
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A Simulation Model for Procedure Inference

From a Mental Model for a Simple Device

David E. Kieras

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Earlier work has demonstrated that knowledge of the internal structure of a simple control panel device enables people to more quickly learn how to operate the device, or to infer how to operate it in the absence of explicit instructions. An experiment is reported that shows that the important aspect of the knowledge about the device is the information about the system topology. This is information about the pattern of connections between the

internal components and the operating controls and indicators. In contrast, information about the overall function of the system and the principles that the system is based on is not important. The basic conclusion is that the device model information is helpful because it supports the inference of the exact procedures required to operate the device. A simulation model based on this principle was developed, and is described in detail. The model makes predictions about the latencies between individual control actions, based on the amount of inferential processing required at each step. The predictions were supported by an analysis of the detailed response latencies from the experiment.

ABSTRACT

Earlier work has demonstrated that knowledge of the internal structure of a simple control panel device enables people to more quickly learn how to operate the device, or to infer how to operate it in the absence of explicit instructions. An experiment is reported that shows that the important aspect of the knowledge about the device is the information about the system topology. This is information about the pattern of connections between the internal components and the operating controls and indicators. In contrast, information about the overall function of the system and the principles that the system is based on is not important. The basic conclusion is that the device model information is helpful because it supports the inference of the exact procedures required to operate the device. A simulation model based on this principle was developed, and is described in detail. The model makes predictions about the latencies between individual control actions, based on the amount of inferential processing required at each step. The predictions were supported by an analysis of the detailed response latencies from the experiment.

A Simulation Model for Procedure Inference
From a Mental Model for a Simple Device

David E. Kieras

Kieras and Bovair (1983,in press) presented a set of results in which subjects who understood how a simple device worked could learn and infer how to operate it much more efficiently than subjects who did not have this information. Figure 1 presents a sketch of the control panel of the device used in those studies. Figure 2 presents a block diagram which the subjects studied in order to acquire knowledge of how the device worked, along with a few pages of written material which explained the diagram. The subjects were told that the device was the control panel of a "phaser bank" on the "Starship Enterprise," although the fantasy aspect of this information was shown to be unimportant. According to Kieras and Bovair, it is important for subjects to understand the role of power flow in how this device operates. Referring to the diagram, it is explained how power starts from the ship's power source and flows through the energy booster, and to the main and secondary accumulators, and then can be routed to the phaser bank. The various switches and controls along the way control where the power can flow to, and the indicator lights show where the power is present. According to these results, the critical information is the system topology information (what is connected to what), together with the principle of power flow.

The purpose of this report is to present a simulation model for the process of inferring how to operate a device of this type based on the system topology information along with the power flow concept. Some results will be presented in which the specific processing aspects of the model will be compared to response latencies from the human subjects. The goal of this effort was to demonstrate that the concept of a mental model could be put on a rigorous basis. That is, despite all of the interest and activity in the realm of mental models at this time (e.g., Gentner & Stevens, 1983; Halasz & Moran, 1982, 1983; Kieras & Bovair, in press), there has in fact been very little in the way of rigorously stated theoretical models for how a mental model can be used. Thus, this simulation model, together with its comparison to performance data, provides at least one case of where the mental model concept has been worked through in detail.

This paper is divided into three sections. The first section describes the experiment whose data will be compared to the simulation model. This experiment is briefly reported in Kieras and Bovair (in press), but not in Kieras and Bovair (1983). Thus it is reported in full detail here, although two of the four conditions are not immediately relevant for the simulation work. The second section describes the simulation model. The third
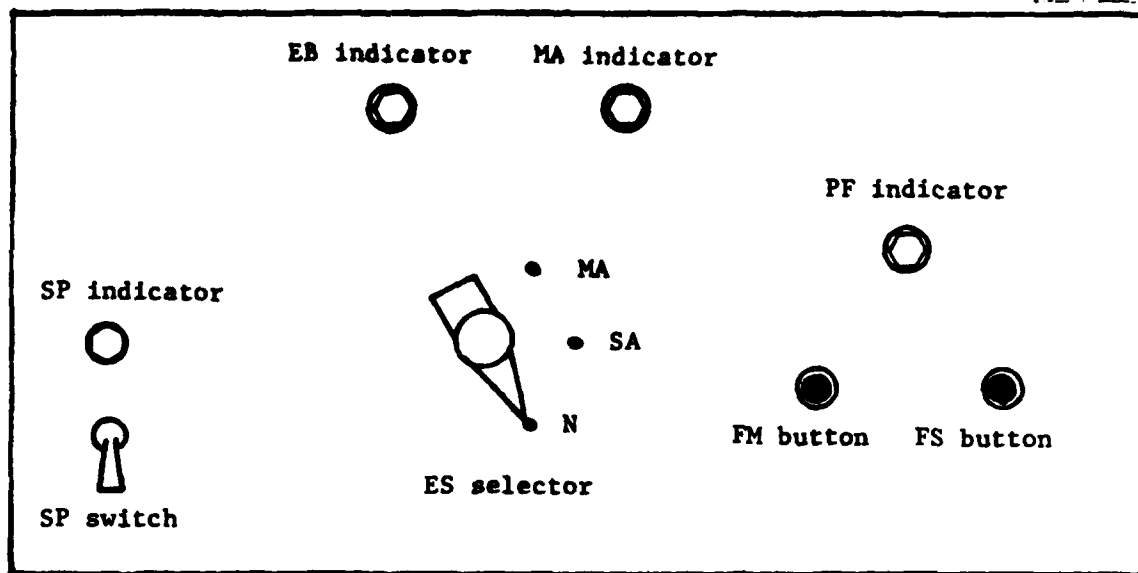
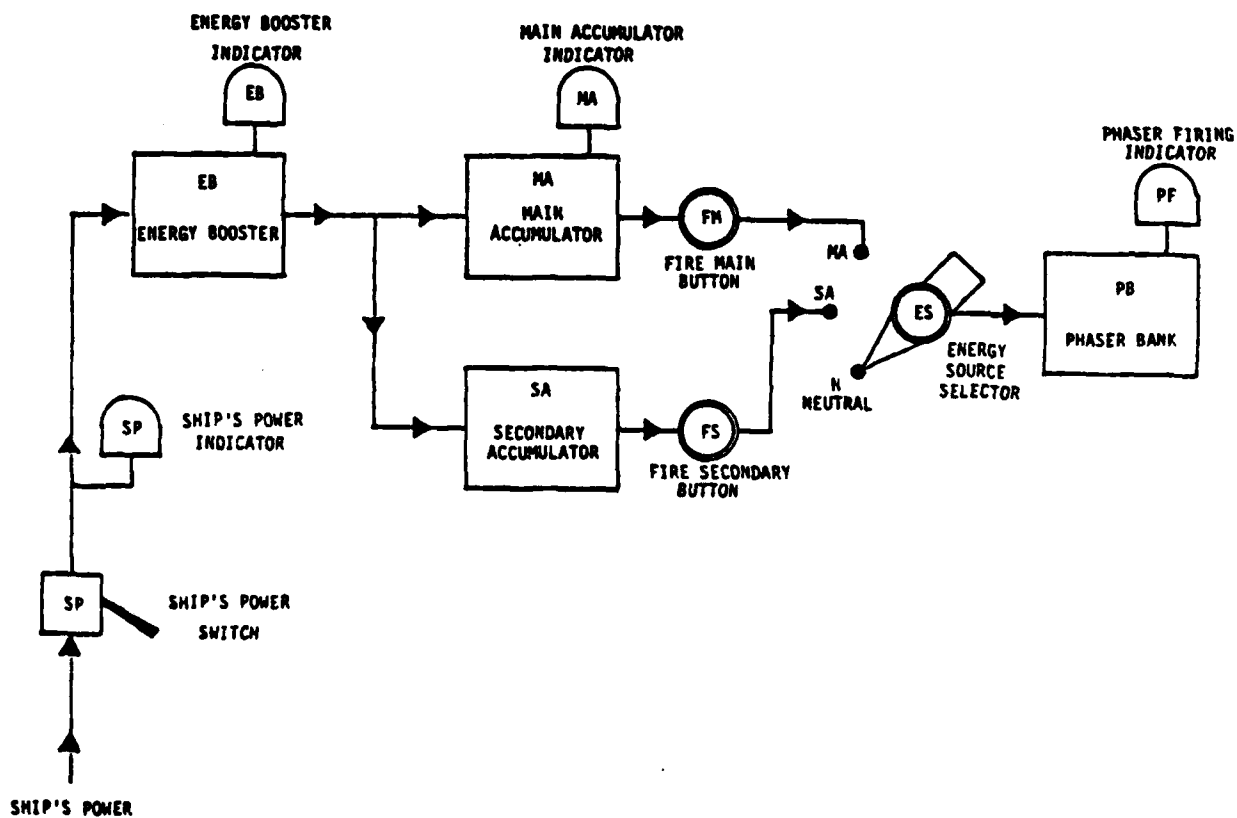Figure 1. Sketch of the control panel of the device.

Figure 2. The block diagram representation of the device model.

section presents the results in which the simulation model is compared to the data from the experiment.

EXPERIMENT

The results of the two experiments reported in Kieras and Bovair (1983) suggest very strongly that the model subjects are able to efficiently infer the procedures, while the rote subjects must proceed by trial and error and rote memorization. However, the device model material in these first studies contained many different types of information. It placed the device in an interesting and familiar fantasy context, which may have been more motivating than the rote condition. It also provided some general principles and design rationale information, such as why an energy booster is necessary. Finally, the device model contained information on the system topology and made use of the principle of power flow.

The analysis in the form of a computer simulation described below suggests that it is the system topology together with the power flow concept that makes inference of the procedures possible. But this is true only if the topology information describes specifically which controls are on what power-flow paths. Thus, the critical how-it-works information is the specific descriptions of the controls and their path relations to the internal components. Therefore, neither the fantasy context, nor details about the nature of the components, nor general principles about how the system works, should be of value in enabling subjects to infer the procedures. This set of assertions was tested in this Experiment, which was also designed to collect detailed inter-response times during procedure inference. The time data is compared to the simulation model in the third section of this report.

Method

Materials and Design. The experiment was a 2 x 2 factorial design, with the factors being the presence or absence of the fantasy context and the presence or absence of specific control information. The no-fantasy no-specific condition was identical to the previous rote condition in Kieras and Bovair (1983), and the fantasy specific condition was essentially the same as the model condition in Kieras and Bovair. A sample excerpt of the fantasy-specific materials is shown in Table 1. Figure 2, except for the control labels, is the same as the device model diagram for this condition.

The no-fantasy specific condition subjects studied device model materials identical to the previous materials, except that all references to the Star Trek fantasy were eliminated, along with any discussion of how the system components worked or why they were present. The names of the components were changed to terms that did not convey any particular function for the system,

Table 1
Sample of Materials for the Fantasy Specific Condition

The arrows on the diagram show how power flows through the system. Starting on the lower left of the diagram, you can see that power comes in from the shipboard circuits. Notice on the diagram that this power flows to the energy Booster (B), and from there it flows to the two accumulators (MA and SA). The diagram shows that power can flow from either of the accumulators to the Phaser bank (P). The switch, selector and pushbuttons control the flow of power.

I will first describe the function of each component, and then will describe how the controls relate to the components.

Ship's power cannot be used to fire the phaser directly because it is not at a high enough level. The energy Booster boosts the ship's power to the high level necessary to fire the phaser. Both accumulators store large amounts of power, and if they are used continuously, they are liable to overload and burn out. To prevent continuous use of one accumulator, this system has two: the Main Accumulator (MA) and the Secondary Accumulator (SA). When the Phaser bank receives power, rapid phase shifts take place. These phase shifts cause the emission of the phaser beams, and thus the actual firing.

Now that you have seen what each component does, I will describe how the controls relate to the operation of the components.

On the lower left of the diagram, locate the ship's Power Switch (PS). You can see that the power coming in from the shipboard circuits is controlled by the PS switch. When this switch is off, no power can come in. When the switch is turned on, power flows into the energy Booster (B). Power from the energy Booster then flows into both accumulators. Find the selector on the diagram and notice that the accumulator whose power will be supplied to the Phaser bank is selected by the selector (S). While the selector is set to neutral (N), no power can flow from either accumulator to the Phaser bank. When the selector is set to MA, the power can flow from the Main Accumulator. When the selector is set to SA, then power can flow from the Secondary Accumulator.
----

such as pulser instead of phaser bank. Table 2 contains a sample of these materials that corresponds to Table 1. These subjects studied the same diagram as the fantasy-specific group, with appropriate changes in the labels, as shown in Figure 3.

The fantasy no-specific materials consisted of a fantasy explanation of the pseudo-physics principles underlying the phaser system, along with the major components and general power flow, but without describing any of the controls, indicators, or actual power-flow paths. This material was similar in length to the other device model materials, and was also accompanied by a diagram. The diagram is shown in Figure 4, and a sample of the materials in Table 3. As in the other device model conditions, subjects had to pass a test on the content before proceeding to the rest of the experiment. Complete copies of the materials appear in Appendix A.

Each subject was run in one of the four different device model conditions described above. Five subjects were run in each of the two conditions that had no specific control information. Since response latency data were needed for the two conditions that had specific control information, ten subjects were run in each of these two conditions. Each subject was tested in all ten of the situations described below.

Subjects. Subjects were students of both sexes at the University of Arizona, recruited through campus advertisements. Subjects were paid $5 for participating in the experiment. Of the 39 subjects who participated, the data of nine subjects was discarded, due to problems such as failure to understand the instructions. Subjects were run individually, and were assigned to their conditions at random.

Instructions and Procedure. The subjects were seated before the control panel device and a standard video terminal on which appeared the instructions and other materials. Subjects were first informed of the general purpose of the experiment, then they were allowed to familiarize themselves with the layout of the control panel. If they were in a condition where they were to be given device model information, they then read the appropriate materials and then were quizzed on the content. If they did not answer all the quiz questions correctly, they read the material and tried the quiz again, until they could answer every question correctly. The subjects then were given instructions for the procedure inference phase of the experiment.

In this phase, subjects made one attempt to infer how to operate the device in each of the ten situations used previously in Kieras and Bovair (1983). These situations are listed in the order that they appeared in Table 4. In each situation, the subject was commanded to use a certain setting of the selector switch, and the device was either working "normally," with all of the components functioning, or there was a malfunctioning component. Depending on the component, the device could either be made to work by changing to the alternate selector setting, or

Table 2
Sample of Materials for
the Specific No-Fantasy Condition

The arrows on the diagram show how power flows through the
system. Starting on the lower left of the diagram, you can see
that power comes in from the power source. Notice on the diagram
how this power flows to the Buffer (B), and from there it flows to
the two activators (MA and SA). The diagram shows that power can
flow from either of the activators to the Pulser (P). The switch,
selector, and pushbuttons control the flow of power.

I will now describe how the controls relate to the
components.

On the lower left of the diagram, locate the power switch
(PS). You can see that the power coming in from the power source
is controlled by the PS switch. When this switch is off, no power
can come in. When the switch is turned on, power flows into the
Buffer (B). Power from the Buffer then flows into both
activators. Find the selector on the diagram, and notice that the
activator whose power will be supplied to the Pulser (P) is
selected by the selector (S). While the S selector is set to
neutral (N), no power can flow from either activator to the Pulser
(P). When the selector is set to MA, the power can flow from the
Main Activator. When the selector is set to SA, then power can
flow from the Secondary Activator.

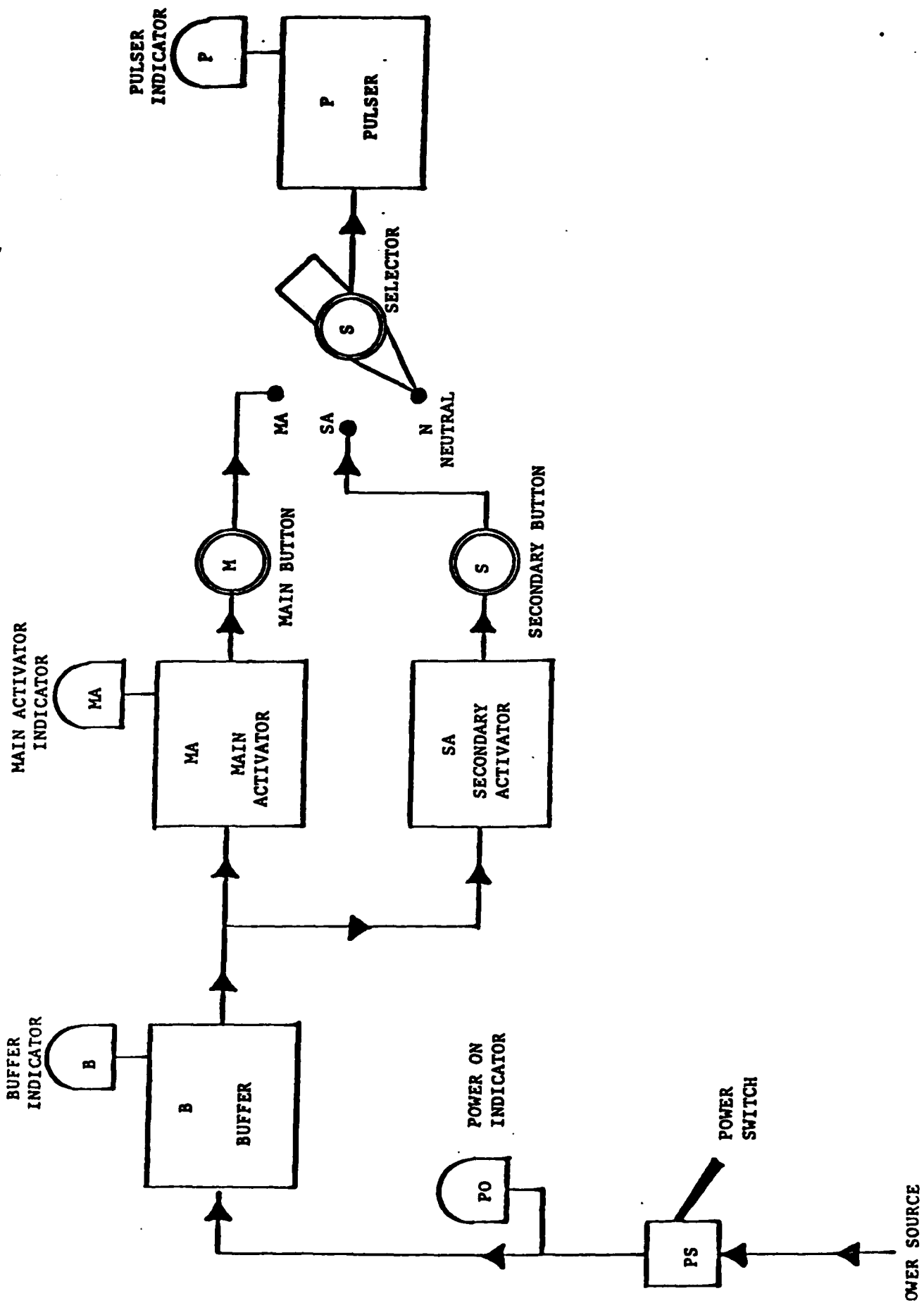---

Figure 3. The diagram used for the condition with no fantasy and specific information.

Table 3
Sample of Materials for the
Fantasy with no Specific Information Condition

The phaser system is based on several important principles in physics that were discovered in the last decade of the 20th century. These were applied to produce a powerful weapon system for use aboard interstellar spaceships. Such a system became necessary to defend Federation ships from the aggression of the sophisticated warships of the hostile Klingon and Romulan empires.

The key characteristic of the phaser system is its need for very high energy levels that are available on short notice. The basic energy source is the violent interaction of matter and antimatter, which is controlled by means of a catalytic plasma produced from ionized dilithium crystals. Find the matter-antimatter power source on the diagram. The normal result of contact between matter and anti-matter is a violent explosion. However, the catalytic plasma slows the rate at which energy is released, so that use of this energy becomes practical.

The phaser requires energy of several giga-electron volts to be applied within a few picoseconds. Not even the dilithium-based matter-antimatter system can generate such peak levels, and so the energy that it does produce must be stored. The storage system is an outgrowth of the first successful unified field theory. A circulating field, known as an energon ring, can be collapsed by the injection of large amounts of energy from the matter-antimatter power source. The extent of the collapse is determined by the amount of energy injected. Find the matter-antimatter power source on the diagram, and notice the arrows that show the flow of power into the energon storage system.

Maintenance of a collapsed energon ring requires a supply of vector bosons which is synchronized with the period of energon circulation. When the energon ring is allowed to expand, all of the energy is released almost instantaneously, with a maximum release time of 3-5 picoseconds. Because the energy must be taken out of the energon ring within picoseconds, the energon storage system must be able to operate at very high speeds. By making the energon storage system as compact as possible, the time needed for energy to travel between components of the system is minimized. This need for compactness was a major factor that led to adoption of a toroidal (doughnut-shaped) vessel in which the energon rings circulate. On the diagram, find the energon storage system. You will see the toroidal storage vessel shown with the energon rings circulating inside. Notice that the boson generators are mounted around the outside of the vessel.

HYPERON BURSTS

AIMING MECHANISM

HYPERON STRUCTURE

PHASE SHIFTS

ZIRCONIUM NUCLEI

TOROIDAL VESSEL

BOSON GENERATORS

ENERGON RINGS

MATTER — ANTIMATTER

CATALYTIC PLASMA

DILITHIUM CRYSTALS

MATTER-ANTIMATTER
POWER SOURCE

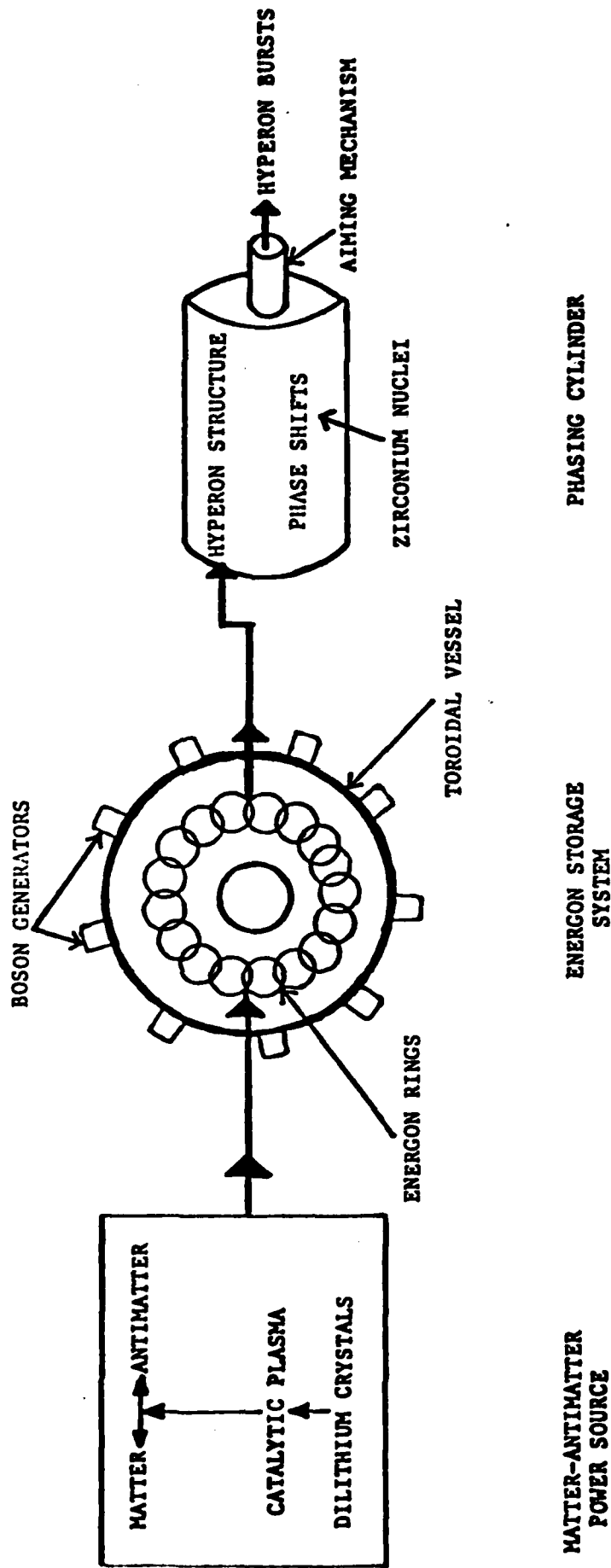ENERGON STORAGE
SYSTEM

PHASING CYLINDER

Figure 4. The diagram for the condition with fantasy and no specific control information.

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else the malfunction could not be compensated for. Thus there are four malfunction states, one normal state, and two commands, giving a total of ten situations. The subject's task was to attempt to get the P indicator to flash by operating the controls. If they succeeded, they were to conclude the trial by typing the letter S (for success) on a computer terminal. But if they concluded that the could not compensate for a malfunction, they were to end by typing N (for non-compensatable malfunction). After completing each situation, the subject was prompted for a retrospective report; however, these data will not be reported. Appendix B contains other details that are important for experiments of this sort, but are not necessary for the immediate purposes of this report.

Results

The basic measure of how easy it was to infer a procedure is the number of actions, defined as a change in control settings, tried before arriving at the appropriate goal state. Table 5 shows the mean number of actions tried by each group, averaged over situations. There is a strong main effect of specific information ($p<.01$), while the effect of the fantasy context and the interaction failed to reach significance ($ps>.1$).

Discussion

These results show that the effectiveness of the device model instructions in the first two experiments was not due to either the motivational interest of the fantasy, nor to the how-it-works information about the system components, nor to the general principles underlying the system. Rather, the critical how-it-works information is the specific items of system topology that relate the controls to the components and to the possible paths of power flow. The simulation model described below makes use of exactly this information and is able to infer the procedures for operating devices of this type in a simple and general way.

THE SIMULATION MODEL

The results of the above experiment and those in Kieras and Bovair (1983) suggest that the inference process that subjects use must be relatively simple, because ordinary subjects, with no apparent technical background, can acquire the model and make good use of it in a short amount of time. A simulation model was devised to explore this idea and to see if it provides a reasonable account of what subjects actually do.

The model consists of a representation of the device model, essentially a propositional form of the diagram that was shown to the subjects, and a set of production rules for inferring what is taking place in the device in terms of power flow, and how to set the controls to route the power flow through the device to obtain

Table 4
Order of Presentation and Malfunction State
in each Situation

Order Number	Situation Number	Commanded Setting	Malfunctioning Component
1	1	MA	None
2	3	MA	Booster/buffer
3	2	SA	None
4	4	MA	Phaser/pulser
5	7	SA	Booster/buffer
6	5	MA	Main accumulator/activator
7	8	SA	Both accumulators/activators
8	6	MA	Both accumulators/activators
9	9	SA	Secondary accumulator /activator
10	10	SA	Phaser/pulser

Table 5

Mean Number of Actions Tried
While Inferring Procedures

Specific Information Condition	Fantasy Condition		Mean
	No Fantasy	Fantasy	
No Specific Information	24.3	17.7	21.0
Specific Information	6.3	6.3	6.3
Mean	12.3	10.1	11.2

the desired result. Most of the rules in this model are very general and apply to a broad variety of similar devices. This class of devices is that in which some entity such as energy flows along paths in an all-or-none fashion, through all-or-none components and controls. The goal is to get the energy from a starting point to another point by setting the controls properly, taking into account that defective components will block the flow of energy. In the simulation, a different device can be specified by changing only the device representation; the inference rules stay the same. However, many of the production rules in the simulation must be present to allow the model to mimic task-specific strategies that subjects apparently use that are not directly related to the device model.

Implementation

Some information on the implementation environment for the model is important. The model was implemented using a variation of the user-device interaction simulator that is briefly described in Kieras and Polson (in press). The interaction simulator was used to simplify the development of the inference model by making it unnecessary to clutter it with details about the behavior of the actual device. In this system, the actual device is represented by a transition network, and an interpreter uses this network to simulate the behavior of the device in response to inputs from the user. A production system represents the user's procedural knowledge, and an interpreter uses the production rules to determine what the user's responses to the device outputs should be. The device simulation and the user simulation interact, thus simulating the interaction of the user and device. For more detail on the transition network representation of the device, see Kieras and Polson (in press); there is no need to describe it for present purposes. Note that the transition network system is used to simulate the behavior of the <u>actual</u> device; it is a separate representation from the <u>propositional</u> one used in the mental model of the device.

The production system interpreter described in Kieras and Polson is very simple; for this work, it was replaced with a more powerful interpreter based on the one described in Kieras (1982). This production system interpreter is specialized for performing inference on propositional representations in list form, in both a working memory (WM) and a long-term memory (LTM). Each production rule can specify a pattern of propositions both in WM and in LTM that must be present before the rule is fired and the action executed. The interpreter has the useful feature that all possible instantiations of each condition are identified, and then the action executed for each instantiation. A rule can be fired only once on a particular instantiation of its condition. Conditions can contain variables, which can be used to match an individual term in a proposition, and then can specify the corresponding value in an action. The simulation currently runs in CMU UCI LISP on a DEC-10.

In the work in Kieras (1982), this interpreter made it possible to write production rules for constructing passage macrostructure in a very general way, using the propositions in LTM to determine what specific inferences could be made about the propositions in WM. Thus, instead of writing many individual inference rules, one for each pattern of possible specific propositions, it was possible to write a small number of production rules whose conditions contain many variables. Thus, the range of application of the rules is determined by the propositions of general knowledge in LTM.

Working memory contains propositions that describe the model's current goals and its representation of the internal and external state of the device. Propositions can be both added and removed from WM by the actions of the production rules, and by changes in the output of the simulated device. The model's goal structure is defined by the relationships between production rules that test for or manipulate WM propositions that describe goals. More detail will be presented below.

The device representation

Table 6 shows a portion of the 6 representation of the device model; the full representation appears in Appendix C. This is simply a propositional paraphrase of the diagram, in which the various concepts are terminals, components, controls, and the basic relation between them is the connection relation. The labels are the earlier labels for the device, and correspond to Figures 1 and 2, rather than the labels used in the experiment above. Notice that the selector switch has been represented as three individual switches. The constraint that only one of the switches can be on at a time is implicit in the definition of how the device actually behaves. The LTM representation also describes some other aspects of the device, such as the proposition SPECO, which states that the goal of operating the device is to get the PF indicator (PFI) on.

Inference Rules

There are 59 production rules in the current form of the model, which can be described in five groups, based on the type of processing involved. These five groups are listed in full in Appendix C. Here, each group will be briefly described and illustrated with a few examples.

Properties. The first type, illustrated in Table 7, infers certain properties of the controls. For example, the rule P-FIND-POWER-SWITCH identifies which control is the main power switch. It will be described in detail to explain the LISP-based notation. The first term in the rule is the name of the rule. The condition portion of the rule consists of the function TEST, which is the pattern-matching function. The arrow symbol separates the condition from the action. The function BUILD constructs propositions in the specified memory (e.g., WM), and another function, REMOVE, removes propositions from memory. The

Table 6
Definition of Device in Long-Term Memory

CPD1 (ISA SHIP-POWER POWER-SOURCE)
CPD2 (ISA EB COMPONENT)
CPD3 (ISA MA COMPONENT)
. . .
CPDA (ISA SPI INDICATOR)
CPDB (ISA EBI INDICATOR)
. . .
CPDE (AT SPI SP-EB)
CPDF (AT EBI EB)
. . .
CPDI (ISA SP-EB TERMINAL)
CPDJ (ISA EB-OUT TERMINAL)
. . .
CPD6 (ISA SP SWITCH)
CPD7 (ISA FM BUTTON)
CPD8 (ISA FS BUTTON)
CPD9 (ISA ESS-MA SELECTOR)
CPD10 (ISA ESS-SA SELECTOR)
CPD11 (ISA ESS-N SELECTOR)
CONO1 (CONNECTION SHIP-POWER SP-IN)
CONO2 (CONNECTION SP-IN SP)
CONO3 (CONNECTION SP SP-EB)
. . .
CPD23 (CHOICE ESS-MA PREFERRED)
FACT1 (ISA SWITCH CONTROL)
FACT2 (ISA BUTTON CONTROL)
FACT3 (ISA SELECTOR CONTROL)
SPECO (OPERATE-GOAL-STATE PFI ON)
SPEC1 (INITIAL-STATE ESS-N ON)
. . .
INFRN1 (ASSOCIATED MA FM)
. . .
INFRN5 (ISA SP POWER-SWITCH)
ASSUM1 (ISA EB VITAL-COMPONENT)
ASSUM2 (ISA PB VITAL-COMPONENT)

Table 7
Rules that Infer Properties of Controls

```
(P-FIND-POWER-SWITCH
      ($TEST  (*LTM ISA *X1 POWER-SOURCE)
              (*LTM CONNECTION *X1 *Y1)
              (*LTM CONNECTION *Y1 *X2)
              (*LTM ISA *X2 SWITCH)))
=>
      (($BUILD *WM (ISA *X2 POWER-SWITCH))
        ($BUILD *WM (STATE DEVICE OFF)) ))
(P-ASSOCIATE-CONTROL-1
      ($TEST  (*LTM CONNECTION *X1 *Y1)
              (*LTM ISA *X1 COMPONENT)
              (*LTM CONNECTION *Y1 *Y2)
              (*LTM CONNECTION *Y2 *X2)
              (*LTM ISA *X2 *X3)
              (*LTM ISA *X3 CONTROL)))
=>
      (($BUILD *WM (ASSOCIATED *X1 *X2)) ))
(P-ASSOCIATE-CONTROL-2
      ($TEST  (*LTM CONNECTION *X1 *Y1)
              (*LTM ISA *X1 COMPONENT)
              (*LTM CONNECTION *Y1 *Y2)
              (*LTM CONNECTION *Y2 *X2)
              (*LTM ISA *X2 *Z1)
              (*LTM ISA *Z1 CONTROL)
              (*LTM CONNECTION *X2 *Y3)
              (*LTM CONNECTION *Y3 *Y4)
              (*LTM CONNECTION *Y4 *X3)
              (*LTM ISA *X3 *Z2)
              (*LTM ISA *Z2 CONTROL)))
=>
      (($BUILD *WM (ASSOCIATED *X1 *X3)) ))
```

condition in P-FIND-POWER-SWITCH corresponds to finding a power
source, referred to with variable *X1, which is connected to a
terminal, *Y1, which is connected to a switch, *X2. If such a
pattern is found, the action consists of adding a proposition to
WM that states that *X2 is a power switch.

Another example is that it is important for the system to
know that the main Accumulator is associated with the MA setting
of the selector since it is on the same path as the setting.
Thus, the rules, P-ASSOCIATE-CONTROL-1 and -2, simply note such
relations and build the corresponding propositions. Notice that
these rules only need to be performed once, if it is assumed that
their products are stored in long-term memory, as in Table 6. The
subject may well perform these inferences while first learning the
device model.

Energy propagation. The second type of production rule,
shown in Table 8, determines where energy is in the system, as a
function of the control settings, by simulating the flow of energy
along the connections. For example, the production rule
P-CONNECTION-ENERGY determines that if there is energy at a
terminal which is connected to another terminal, then there is
also energy at that point. A more complex rule, P-COMPONENT-GOOD,
is triggered by the pattern of an illuminated indicator (*X2)
connected to a component (*X1). The action is to build
propositions stating that the component is good, and that there is
energy at both the input (*Y1) and output (*Y2) of the component.

Notice that all of the rules in this group contain a test for
the proposition (GOAL PROPAGATE ENERGY) in their condition, and
build a proposition (PROCESS ENERGY PROPAGATING) in their actions.
This is part of the control structure, and will be described more
below.

Path finding. The third type of production rule, shown in
Table 9, is responsible for finding a path through the diagram
that will get energy to a specified point. These rules start with
the goal of energizing the goal component of the device, in this
case the PF indicator, and work backward through the diagram until
they find an energy source. Along the way, the rules construct a
plan for operating the device by making notes in working memory of
which controls need to be put into what state. These rules are
governed by the proposition (GOAL FIND PATH) and build the
proposition (PROCESS FINDING PATH) when triggered. For example,
the production rule P-BACK-CONNECTION is triggered by the pattern
that consists of the goal to energize a certain point, *Y1, which
is "downstream" from a terminal, *Y2. If this pattern is
detected, the production rule action removes the goal of
energizing *Y1, and adds the goal to energize *Y2. Thus, this
rule chains backward over simple connections to find the point
earliest in the diagram that needs to be energized.

The production rule P-BACK-SWITCH illustrates how the
corresponding process is done when a control switch is
encountered. This rule is triggered by the pattern in which the

Table 8
Example Rules for Propagating Energy

```
(P-CONNECTION-ENERGY
      ($TEST  (*WM GOAL PROPAGATE ENERGY)
              (*WM AT ENERGY *Y1)
              (*LTM ISA *Y1 TERMINAL)
              (*LTM CONNECTION *Y1 *Y2)
              (*LTM ISA *Y2 TERMINAL)
              (ABSENT *WM AT ENERGY *Y2)))
=>
      (($BUILD *WM (AT ENERGY *Y2)(PROCESS ENERGY PROPAGATING)) ))
(P-COMPONENT-GOOD
      ($TEST  (*WM GOAL PROPAGATE ENERGY)
              (*LTM AT *X2 *X1)
              (*LTM ISA *X1 COMPONENT)
              (*LTM ISA *X2 INDICATOR)
              (*WM DEVICE *X2 ON)
              (*LTM CONNECTION *Y1 *X1)
              (*LTM ISA *Y1 TERMINAL)
              (*LTM CONNECTION *X1 *Y2)
              (*LTM ISA *Y2 TERMINAL)))
=>
      (($BUILD *WM (STATE *X1 GOOD)(PROCESS ENERGY PROPAGATING)
                    (AT ENERGY *X1)(AT ENERGY *Y1)
                    (AT ENERGY *Y2))))
```

Table 9
Example Rules for Finding Path through Controls

```
(P-BACK-CONNECTION
        ($TEST   (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                 (ABSENT *WM AT ENERGY *Y1)
                 (*LTM CONNECTION *Y2 *Y1)
                 (*LTM ISA *Y2 TERMINAL) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH) (GOAL ENERGIZE *Y2))
         ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-BACK-SWITCH
        ($TEST   (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                 (*LTM ISA *Y1 TERMINAL)
                 (ABSENT *WM AT ENERGY *Y1)
                 (*LTM CONNECTION *X1 *Y1)
                 (*LTM ISA *X1 SWITCH)
                 (*LTM CONNECTION *Y2 *X1) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH)
                       (STEP *X1 ON)(GOAL ENERGIZE *Y2))
         ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-SELECT-PREFERRED
        ($TEST   (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                 (*LTM ISA *Y1 TERMINAL)
                 (ABSENT *WM AT ENERGY *Y1)
                 (*LTM CONNECTION *X1 *Y1)
                 (*LTM ISA *X1 SELECTOR)
                 (*LTM CONNECTION *Y2 *X1)
                 (*LTM CHOICE *X1 PREFERRED)
                 (ABSENT *WM GOAL USE *X1)
                 (*LTM ASSOCIATED *X2 *X1)
                 (ABSENT *WM STATE *X2 BAD) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH)
                       (STEP *X1 ON)(GOAL ENERGIZE *Y2))
         ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-FOUND-ENERGY
        ($TEST   (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *X1)
                 (*WM AT ENERGY *X1)) )
=>
        (($REMOVE *WM (GOAL ENERGIZE *X1)
                       (GOAL FIND PATH)(PROCESS FINDING PATH))
         ($BUILD *WM (GOAL BEGIN OPERATION)) ))
```

to-be-energized point, *Y1, is downstream from the switch, *X1, whose upstream terminal is *Y2. The production rule deletes the goal of energizing *Y1, adds the goal of energizing *Y2, and also adds to working memory the proposition (STEP *X1 ON). This proposition specifies that a step of operating the device will be to put the control *X1 into the ON state.

A similar, but more complex, set of rules is used to deal with the selector switch. The rule P-SELECT-PREFERRED is an example of one of the rules for determining what to do with a selector switch. It is based on which setting is defined in long-term memory as being the preferred setting. It is clear (see Kieras and Bovair, 1983, Exp. 2) that the description of the main accumulator as the "main" accumulator produces an extremely strong tendency for subjects to prefer to use the main accumulator when they are free to do so. The rule can be paraphrased as follows: If the goal is to find the path and to energize terminal *Y1, which is not already energized, and *Y1 is downstream from selector *X1, which is the preferred choice, and the system has not been specifically given the goal of using this selector, and the associated component is not known to be bad, then one of the steps will be to turn the selector on, and the new goal is to energize the upstream point, *Y2.

There are several other rules, listed in Appendix C, for dealing with selectors. P-SELECTION-ALREADY-DONE recognizes when the selector has already been set as part of a starting strategy (see below). P-SELECT-TO-BE-USED handles the situation when the model was given an initial goal of using one of the selectors, which corresponds to the present experiment. P-SELECT-NOT-PREFERRED and P-SELECT-GOOD-NOT-BAD chooses a setting when one of the other rules cannot fire due to a bad component.

Another set of production rules in this group recognizes certain special situations. P-FOUND-ENERGY, shown in Table 9 recognizes when the FIND PATH goal is satisfied, and then changes the goal to BEGIN OPERATION. Other rules, shown in Appendix C, recognize situations involving bad components. For example, P-VITAL-COMPONENT-BAD recognizes that if a component is known to be bad, and this component is also described in long-term memory as being a vital component, then the process of trying to find a path for the energy flow can not succeed. It is assumed that the subject can easily deduce which components are vital and encode the information into long-term memory. As another example, if energy is going into a component that has an indicator, but the indicator is off, then the component must be bad.

Operating strategies. The fourth group of rules concern the overall sequence of activities of the model and its procedure for operating the device. There are some activities subjects apparently can do without inference. These are either specific to the task that subjects are asked to do, or are very general procedures, for operating devices which subjects probably already know. For example, the action of turning on the power switch is often done first, and occurs quite rapidly. This suggests that

subjects do not have to perform extended inference before realizing that the power switch has to be turned on. Another aspect of this strategy knowledge is that once the inference rules have constructed the steps to be performed, these steps must be executed in some order. This order does not seem to be a product of inference, but of conventional ideas for operating equipment.

These strategy production rules, illustrated in Table 10, perform specific strategies for beginning the procedure inference task, and for operating the device once the inference has been completed. Thus, for example, the production rule P-OPERATE-FIRST, which can be triggered only if some other starting strategy has not been specified, begins the entire task by recognizing that the device is off and what the goal state of operating the device is, namely getting the PFl on. It adds to working memory the goal of turning on the device and the goal of energizing the point *Y1, which corresponds to the PFI. The production rule P-STEP-TURN-ON is triggered by the goal of turning on the device, and simply performs the action of turning on the power switch and waiting for the device to complete its state change. The goal is added to working memory of propagating the energy through the device, in order to update the working memory representation of where the energy is in the system.

In order to produce more stable performance from the subjects in the experiment, they were explicitly instructed which setting of the selector to use. That is, they were given the command to "use the MA setting" or "use the SA setting." As will be presented in more detail below, roughly half of the subjects immediately set the selector to the corresponding setting and then turned the device on, while the other half performed the action of turning the device on first, and then setting the selector. It is assumed that subjects could perform these two steps without inference, by using a start-up strategy. Thus, the only inferences that subjects had to make was which of the two buttons to push, and what action to take if the device was not operating normally.

Thus, two start-up strategies are represented in the model. Which starting strategy is used is determined by the value of the variable *START-STRATEGY assigned by the modeler. One strategy beginning with the rule P-START-WITH-TURN-ON, turns the device on, then sets the selector. This rule sets up the goal of turning on the device, which triggers the production rule P-STEP-TURN-ON. Then the goal of setting the selector is added to working memory by P-START-WITH-TURN-ON-2. This triggers the production rule P-SET-SELECTOR (see Appendix C), which is triggered by the goal of setting the selector and also the proposition in working memory of using a certain control at a certain setting. This proposition corresponds to the command to the subject and is assumed to be in working memory when the model begins to run. The second strategy does these two steps in the reverse order, with similar rules.

Logically speaking, there are many possible orders in which the controls could be operated on a device. However, in the experiments done with this particular device, subjects almost

Table 10
Example Rules for Start-Up Strategies

```
(P-OPERATE-FIRST
(AND (EQ *START-STRATEGY NIL)
        ($TEST   (*WM STATE DEVICE OFF)
                 (*LTM OPERATE-GOAL-STATE *Y1 *Y2)))
=>
        (($BUILD *WM (GOAL TURN-ON DEVICE)
                        (GOAL ENERGIZE *Y1)
                        (GOAL FIND PATH))))
(P-START-WITH-TURN-ON
        (EQ *START-STRATEGY 'TURN-ON-FIRST)
        ($TEST   (*WM GOAL START TASK)))
=>
        (($REMOVE *WM (GOAL START TASK))
         ($BUILD *WM (GOAL TURN-ON DEVICE)(GOAL SET-SELECTOR
NEXT)) ))
(P-START-WITH-TURN-ON-2
        (EQ *START-STRATEGY 'TURN-ON-FIRST)
        ($TEST   (*WM GOAL SET-SELECTOR NEXT)
                 (ABSENT *WM GOAL TURN-ON DEVICE)))
=>
        (($REMOVE *WM (GOAL SET-SELECTOR NEXT))
         ($BUILD *WM (GOAL SET SELECTOR)(GOAL BEGIN INFERENCE)) ))
(P-STEP-TURN-ON
        ($TEST   (*WM GOAL TURN-ON DEVICE)
                 (*WM STATE DEVICE OFF)
                 (*LTM ISA *X1 POWER-SWITCH)))
=>
        ((PRINT (LIST '>>>OPERATE *X1 'ON))
         (OPERATE-CONTROL *X1 ON)
         (WAIT-FOR-DEVICE)
           ($REMOVE *WM (STATE DEVICE OFF))
           ($REMOVE *WM (GOAL TURN-ON DEVICE))
           ($BUILD *WM (GOAL PROPAGATE ENERGY)) ))
```

---

always operate the toggle switch first, followed by the selector switch, followed by a pushbutton. If the device fails to work, other actions may be performed but the pushbutton was always the last control operated. This order is consistent both with the hypothesis that subjects work left to right across the device, or with the hypothesis that the nature of the device requires that the pushbuttons be operated last and the power switch should be operated either first or very early in the sequence. The strategy used in the model corresponds to the latter hypothesis; all switches are operated first, followed by all selectors, followed by the pushbuttons.

The actual operation of the device begins when the rule P-BEGIN-OPERATION in Table 11 is triggered by the rule P-FOUND-ENERGY (see Table 9). A sequence of rules, P-STEP-1, P-STEP-2, and so forth, are executed to operate the controls as specified by the STEP propositions placed in working memory by the FIND-PATH rules. The starting strategies may have already operated the power switch or the selector. If this is so, a proposition describing the step to be performed will not be present for the corresponding control, and production rules like P-STEP-1-SKIP (see Appendix C) will simply skip over this part of the operating sequence. Notice that any action of operating a control on the device is always followed by the assertion of the goal to propagate energy through the system. Further steps in operating the device must wait until this goal of propagating energy has been removed, meaning that the simulation always determines what alteration in the internal state of the device has occurred before it goes on to operate another control.

The production rule P-STEP-3 will always be the last production rule fired in the operating sequence. This rule is triggered by the pattern of doing STEP C, the presence of a proposition in working memory to operate a button, and the absence of the goal to propagate energy. The action portion of P-STEP-3 operates the pushbutton, waits for the device to finish changing state, and adds to working memory the goal of propagating energy, and also the proposition that the model expects that the goal has been achieved. The next production rule P-ACHIEVED-GOAL is triggered by this expectation and the pattern that the device is in the state described in long-term memory as the operation goal state of the device. If this pattern appears, then the device has been operated successfully; the model shuts down the device with other rules, and then stops.

Malfunction operation. The fifth group of production rules, illustrated in Table 12, is concerned with what to do when the goal state was not achieved when expected. At this time, the model's knowledge of how to recover from malfunctions is effective, but very crude. The production rule P-DID-NOT-WORK is triggered by the pattern of the expectation that the goal will be achieved and the failure of the device to be in the desired state after the PROPAGATE ENERGY goal has been fulfilled. This rule adds the goal of diagnosing the problem, and reasserts the goal of propagating energy through the system. The production rules

Table 11
Example Rules for Operating Device

```
(P-BEGIN-OPERATION
     ($TEST  (*WM GOAL BEGIN OPERATION)
             (ABSENT *WM GOAL STEP NIL)))
=>
     (($BUILD *WM (GOAL STEP A))
      ($REMOVE *WM (GOAL BEGIN OPERATION)) ))
(P-STEP-1
     ($TEST  (*WM GOAL STEP A)
             (*WM STEP *X1 *Y1)
             (*LTM ISA *X1 SWITCH)))
=>
     ((PRINT (LIST '>>>OPERATE *X1 *Y1))
      (OPERATE-CONTROL *X1 *Y1)
      (WAIT-FOR-DEVICE)
        ($BUILD *WM (GOAL PROPAGATE ENERGY))
      ($REMOVE *WM (GOAL STEP A))
      ($BUILD *WM (GOAL STEP B)) ))
(P-STEP-3
     ($TEST  (*WM GOAL STEP C)
             (*WM STEP *X1 *Y1)
             (*LTM ISA *X1 BUTTON)
             (ABSENT *WM GOAL PROPAGATE ENERGY)))
=>
     ((PRINT (LIST '>>>OPERATE *X1 *Y1))
      (OPERATE-CONTROL *X1 *Y1)
      (WAIT-FOR-DEVICE)
        ($BUILD *WM (GOAL PROPAGATE ENERGY))
        ($BUILD *WM (EXPECT GOAL ACHIEVED))
      ($REMOVE *WM (GOAL STEP C)) ))
(P-ACHIEVED-GOAL
     ($TEST  (*WM EXPECT GOAL ACHIEVED)
             (*LTM OPERATE-GOAL-STATE *X1 *X2)
             (*WM DEVICE *X1 *X2)))
=>
     ((PRINT '">>>SUCCESSFUL OPERATION")
      (PRINT-STATS)(STOP-NOW)
        ($REMOVE *WM (GOAL OPERATE DEVICE)(EXPECT GOAL ACHIEVED)
                     (GOAL PROPAGATE ENERGY))
      ($BUILD *WM (GOAL STEP SHUTDOWN))))
```

Table 12
Example Rules for Handling Unsuccessful Attempt

```
(P-DID-NOT-WORK
     ($TEST  (*WM EXPECT GOAL ACHIEVED)
             (ABSENT *WM GOAL PROPAGATE ENERGY)
             (*LTM OPERATE-GOAL-STATE *X1 *X2)
             (ABSENT *WM DEVICE *X1 *X2) ))
=>
     ((PRINT '"DID NOT WORK WHEN EXPECTED")
       ($REMOVE *WM (EXPECT GOAL ACHIEVED))
      ($BUILD *WM (GOAL PROPAGATE ENERGY)
                     (GOAL DIAGNOSE PROBLEM)) ))
(P-DIAGNOSE-PROBLEM
     ($TEST  (*WM GOAL DIAGNOSE PROBLEM)
             (ABSENT *WM GOAL PROPAGATE ENERGY)
             (*LTM CONNECTION *Y1 *X1)
             (*LTM ISA *Y1 TERMINAL)
             (*LTM ISA *X1 COMPONENT)
             (*WM AT ENERGY *Y1)
             (ABSENT *WM AT ENERGY *X1)
             (*LTM ASSOCIATED *X1 *X2)
             (*WM STEP *X2 *X3) ))
=>
     (($BUILD *WM (STATE *X1 BAD)(GOAL TRY AGAIN))
       ($REMOVE *WM (GOAL DIAGNOSE PROBLEM)))).
(P-DIAGNOSE-VITAL-COMPONENT-BAD
     ($TEST  (*WM GOAL DIAGNOSE PROBLEM) (*WM STATE *X1 BAD)
             (*LTM ISA *X1 VITAL-COMPONENT) ))
=>
     ((PRINT '"VITAL COMPONENT BAD -- DEVICE WILL NOT WORK")
       (PRINT-STATS)(STOP-NOW)))
```

P-DIAGNOSE-PROBLEM and P-DIAGNOSE-VITAL-COMPONENT-BAD represent the troubleshooting knowledge. The first of these two rules simply notes whether energy was present on the input side of a component, but not on the output side, when there was a step involving a control that was associated with the component. If this is the case, the rule specifies that this component must be bad and sets up the goal of trying again. The second rule notices that if a vital component is bad, the device will not work and the model is halted.

Rules shown in Appendix C respond to the goal of trying again by removing all propositions referring to the individual step from working memory, which throws away the results of any previous inferences. The system then simply starts over by setting up the goal to energize the goal point of the device, and finding a path, and propagating energy as required. Thus, the very same production rules for inferring the steps are used again. However, a different solution should result because the faulty component will have been identified, and if there is an alternate power flow route through the system, it will be found in this second attempt. When the new path has been found, the same plan execution rules described above will be used to execute the steps.

Notice that the model in its present form does not attempt to salvage any partial solutions. Thus, if it infers that the selector must be on a certain setting and then a certain button must be pushed, and then determines that the setting did not work, it will not simply try the other setting immediately, but rather will start from scratch and infer that the other setting and the other pushbutton must be used.

Although the production rules presented above have many task-specific components to them, the heart of this simulation is in the production rules for propagating energy, inferring the steps to be performed, carrying out the steps, and diagnosing the problem if a system did not work. Periodically during development of the model, it was tested with a rather different device, whose block diagram is shown in Figure 5. The model can successfully operate this device in various malfunction states as well as the normal states, but systematic explorations of either the model's performance, or subjects' performance, have not been done. The point is, however, that the essence of the model is not specific to any one device, but that the inference rules in the device can be applied to any device of this type.
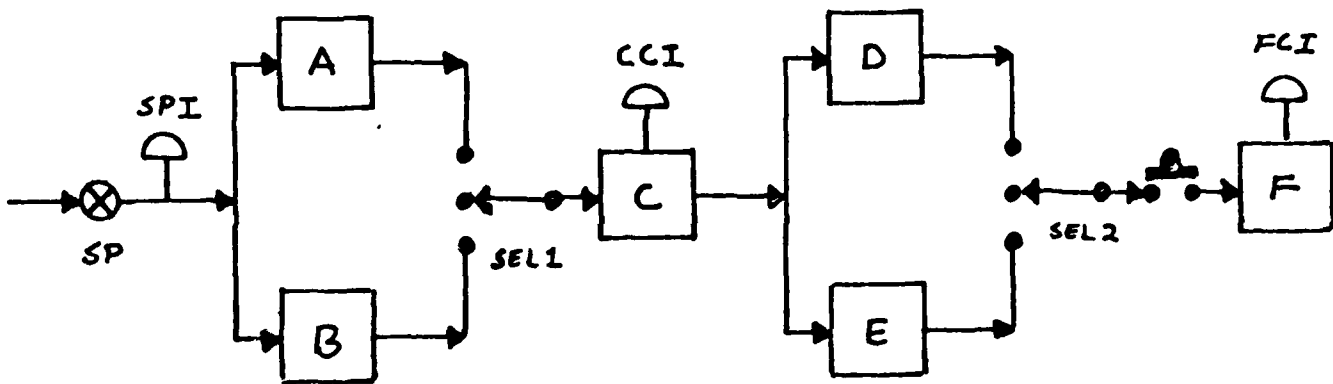
Figure 5. Block diagram of alternate device used during simulation development.

THE RELATION OF THE SIMULATION TO DATA

Behavior Sequences

The data collected in the experiment has two aspects. The first is the sequence of actions that subjects performed in the various situations; the second is the timing of the actions that were performed. The first step in comparing the simulation to the data was to examine the sequences of actions and consider whether the simulation also produces them. The sequences performed by each subject in each situation were grouped together with similar sequences. Only some of the behavioral sequences could be reasonably produced by the model. For example, there were many cases where subjects repeatedly pressed one of the buttons while trying to get the PF indicator to flash. While this "try it again" behavior is a familiar strategy in our interactions with equipment, the model can not produce it. This is because the model is based on the assumption that the device behaves in a nonprobabilistic manner; thus, the device will either work in a certain malfunction state, or it will not work, and repeatedly pressing a button will not result in any change.

There are other cases where the subjects executed sequences that were not consistent with the device model. An example is trying both accumulators when logically the phaser bank must be defective, or pushing buttons when the EB indicator is off. In their retrospective reports in this experiment, and reports in earlier experiments of this type, some subjects appear to perform these illogical actions because they want to "make sure." That is, even though they know that the device will not work, they feel there is no harm in trying. Such behavior is very difficult to prevent in an experiment. On other occasions, this behavior apparently is a result of failure on the part of the subject to completely understand the device model or to reason correctly with it. Again, the model does not address these situations.

Clearly, the model could be elaborated to the point where it could include realistic heuristics, irrational reasoning, and incomplete use of the device model. However, it seems to be more fruitful to consider whether the simple model described here is applicable to the cases where subjects apparently engaged in correct reasoning from a correct device model.

Thus, the subset of behavior sequences that are consistent with the model were selected for additional analysis. Table 13 shows the frequencies of these logical sequences in each of the situations. Notice that the two different start-up strategies corresponding to either setting the selector first or turning on the power first, described above, are allowed. Thus, these sequences are what the simulation does "naturally." In some cases, these sequences are what the majority of subjects performed, but in others, especially the early malfunction situations, this is not so. Thus the simulation produces the same behavior as many subjects do, but, of course, since this behavior considered follows the "logical" pattern, it is quite unremarkable that the

model would also produce it.   Thus, in order to evaluate the empirical quality ·of the model, the sequence of behavior is not relevant. Rather, the timing of the actions is the testable prediction.   If the model produces the actions with the same relative timing as subjects, then the model provides a plausible description of the subjects' inference process.

Latency Analysis

The simulation was run under each of the situations listed in Table 13.   This was done by setting the device simulator to produce a certain malfunction behavior pattern, and running the production system with the appropriate starting strategy selected. The amount of processing done by the model prior to each action on the controls was noted. As described in Kieras (1981, 1982, in press), the amount of processing of various types done by the model can be used to predict the amount of time subjects took to perform the same steps.   The variable POPERS represents the simulation's predictions about the time required to make inferences and caring out the various cognitive activities involved in the task.   This is a measure of the number of propositional operations, defined as the number of propositions that were either added to, or removed from, working memory by the actions of the production rules.   Thus, the total number of propositional operations performed before an overt action is executed is the measure of the amount of processing required before the action can be performed. This measure has also been used before in other production system simulations as a reasonable predictor of processing time (Kieras, 1982). Most of the other aspects of the production system processing can not be easily justified theoretically as good predictors. For example, most theorists assume that the conditions of the production rules are actually tested in parallel, although normally a serial comparison process is used in a simulation. Thus, the number of rules in the system should have no predictive relation to response times.

Note that the simulation by definition had to produce the same behavior sequences as listed in Table 13. The question thus is whether the simulation would perform its inferences in the same place that people did, and whether the amount of inference performed would correspond to the amount of time that subjects required.   This analysis was done in two stages. In the first, the data from all of the logical sequences listed in Table 13 was used.   In the second, a subset of the data was selected whose pattern of latencies corresponded qualitatively to the model's behavior.   Thus, the first analysis gives a lower bound on the quality of the fit of the model to. the data, while the second analysis gives the model every advantage.

All logical sequences. Table 14 describes the results of the regression analysis using the entire set of logical sequence reaction time profiles. The data consist of the latencies for each individual action for each subject whose sequence was included in Table 13, for a total of 439 points.   The overall proportion of variance accounted for is approximately 30%.

Table 13
Frequency of each "Logical" Pattern in each Situation

Trial	Sit.No.	Sit.	f	Pattern					
1	1	MA-NORMAL	8	MA	ON	M	TS		
2	3	MA-EB OUT	3	MA	ON	TN			
3	2	SA-NORMAL	12	SA	ON	S	TS		
			7	ON	SA	S	TS		
4	4	MA-PB OUT	2	MA	ON	M	TN		
			2	ON	MA	M	TN		
5	7	SA-EB OUT	7	SA	ON	TN			
			2	ON	SA	TN			
6	5	MA-MA OUT	7	MA	ON	SA	S	TS	
			3	ON	MA	SA	S	TS	
7	8	SA-MA,SA OUT	2	SA	ON	S	TN		
			3	ON	SA	S	TN		
8	6	MA-MA,SA OUT	5	MA	ON	SA	S	TN	
			2	ON	MA	SA	S	TN	
9	9	SA-SA OUT	11	SA	ON	S	MA	M	TS
			6	ON	SA	S	MA	M	TS
10	10	SA-PB OUT	7	SA	ON	S	MA	M	TN
			5	ON	SA	S	MA	M	TN

Table 14
Regression Analysis of Response Times
Using Simulation and Nuisance Variables

Final R-Square = .30, N = 439.

Variable	Final Coefficient	Final Std. Coefficient	F-to-Remove
CONSTANT	-1.787		
SMEAN	.993	.314	60.73
FIRST	.956	.094	4.06
LAST	1.592	.156	7.18
POPERS	.050	.205	18.44
TNSTP	4.729	.325	38.72

This is not necessarily a low proportion of variance, given that the data consists of the latencies of individual actions from many subjects engaged in a problem-solving task. Such tasks are notorious for producing highly variable time data.

The key result is the significance of the variable POPERS, along with a reasonably large standardized regression coefficient. This shows that the amount of processing by the model has some relation to the response latencies. There are several nuisance variables that were represented in the analysis. The first is each subjects' mean latency (see Pedhazur, 1977, 1982). The presence of the dummy coded variables FIRST and LAST indicate that first and last steps take longer to execute than others. These elevated times could simply be due to the nature of the equipment and procedure. In order to execute the first step the subjects had to orient themselves from the video terminal, on which the command to execute the procedure was displayed, to the control panel, and bring their hand to the controls. Similarly, the last step consisted of typing either an S or an N on the terminal; this would require the subject to reorient from the control panel back to the terminal.

However, the step of typing an N takes a very long time, as shown by the dummy variable TNSTP, beyond that involved in final steps inference processes that are represented in the simulation. This suggests that there are some very time-consuming processes that POPERS does not reflect. These processes are not necessarily mysterious; subjects may simply think the entire problem over again, before committing themselves to this response. Notice that while it is easy to decide on the action of typing an S the decision of typing an N is much harder. The subject has not been able to get the indicator to flash, and must decide that it is not possible to do so. It seems quite reasonable that many subjects may think this over before committing themselves; since the model does not lack confidence in its own reasoning, it would never do this.

Strategy differences. The low proportion of variance accounted for could be due to two factors: There is a large amount of noise in the data; second, the simulation many not always be using the same strategy as subjects do. For example, in Figure 6 is shown the predicted and observed response time profile for a subject where the model apparently provides a good account, and in Figure 7 is shown a case where the subject is apparently using a rather different strategy. The data contains a mixture of profiles that are qualitatively the same as the model's and profiles that are rather different.

The basic strategy that the model uses is illustrated in Figure 8. This is to first execute a start-up strategy, which is determined by what the subject's first response is, then to infer a plan which button is to be pressed, then execute the plan. If the plan does not succeed, the model does additional inference, and makes up a new plan and executes it. Regardless of the actual parameter values and coefficients involved, this strategy makes
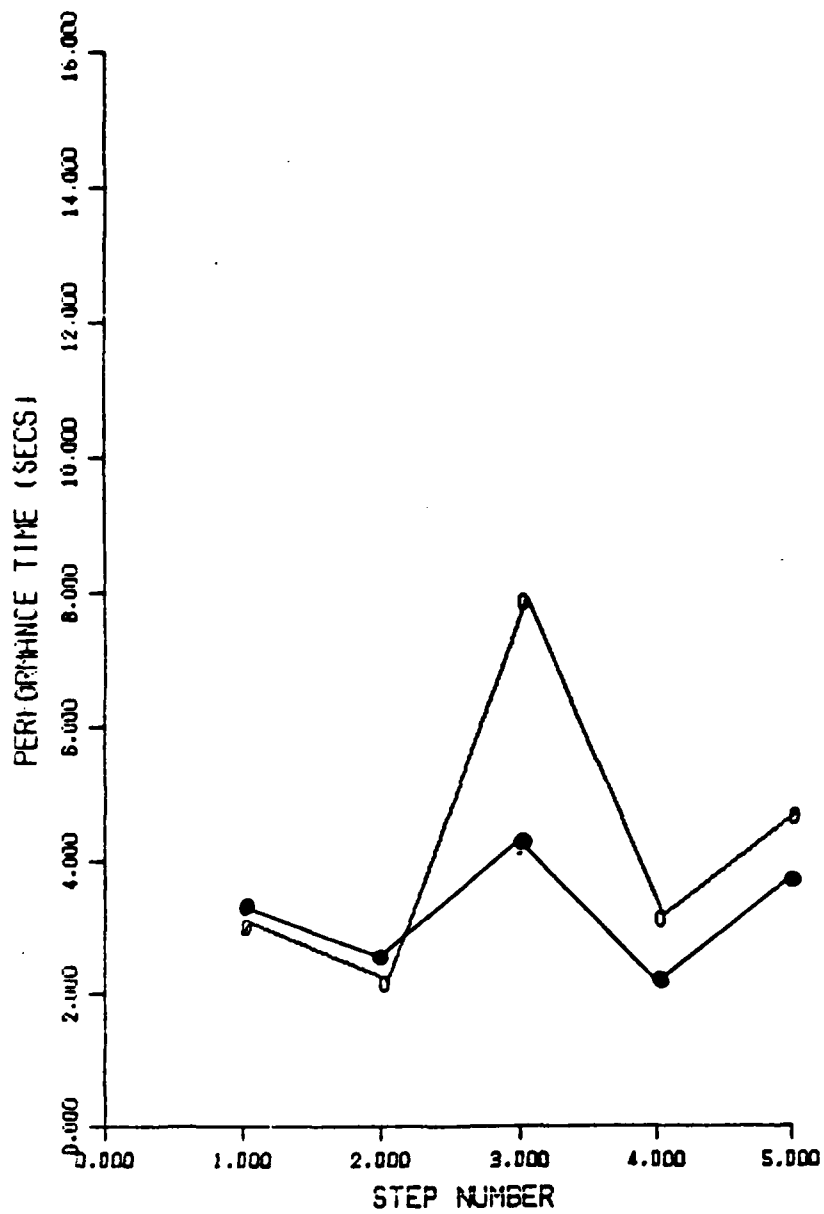
Figure 6. Observed (open circles) and Predicted (closed circles)
latencies based on all logical sequences.

PERFORMANCE TIME (SECS)

STEP NUMBER
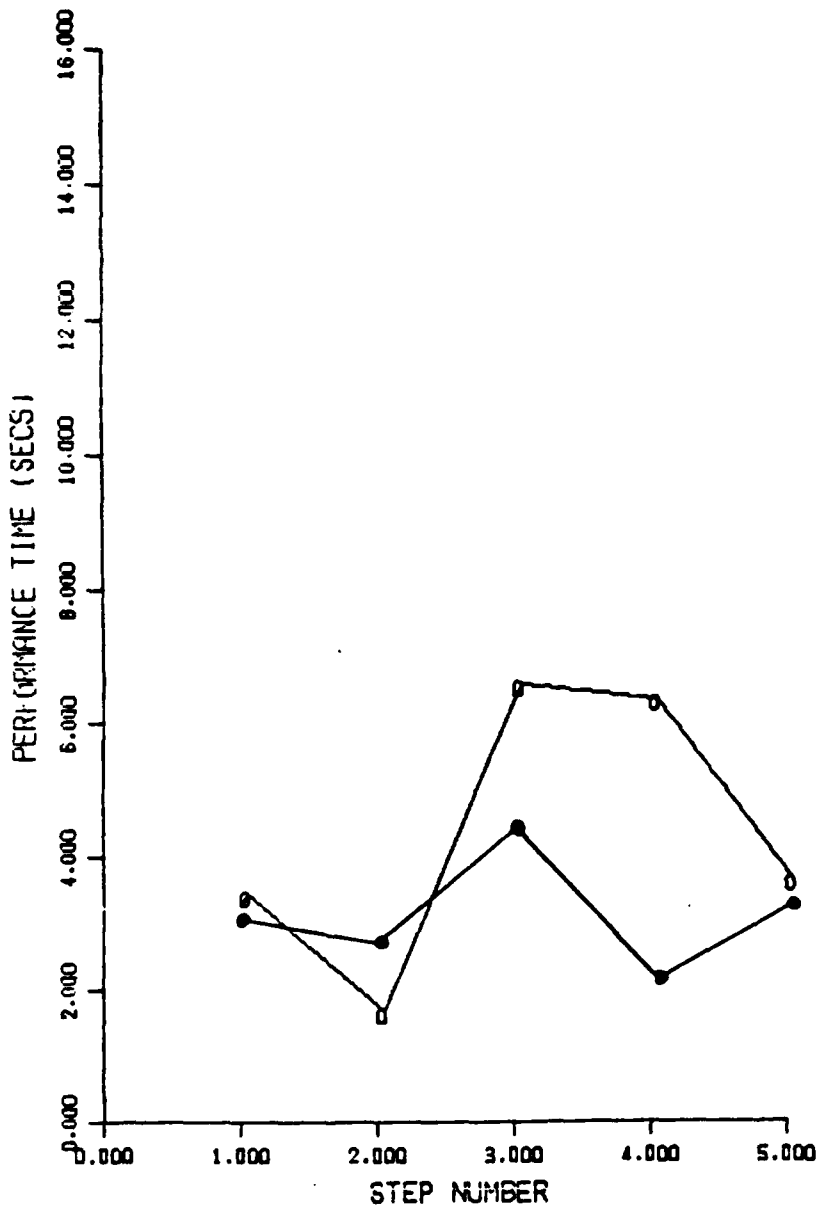
P 5 (MA ON SA S TS) SUB 22

Figure 7. Observed (open circles) and predicted (closed circles) latencies based on all logical sequences. Note the qualitatively different pattern.
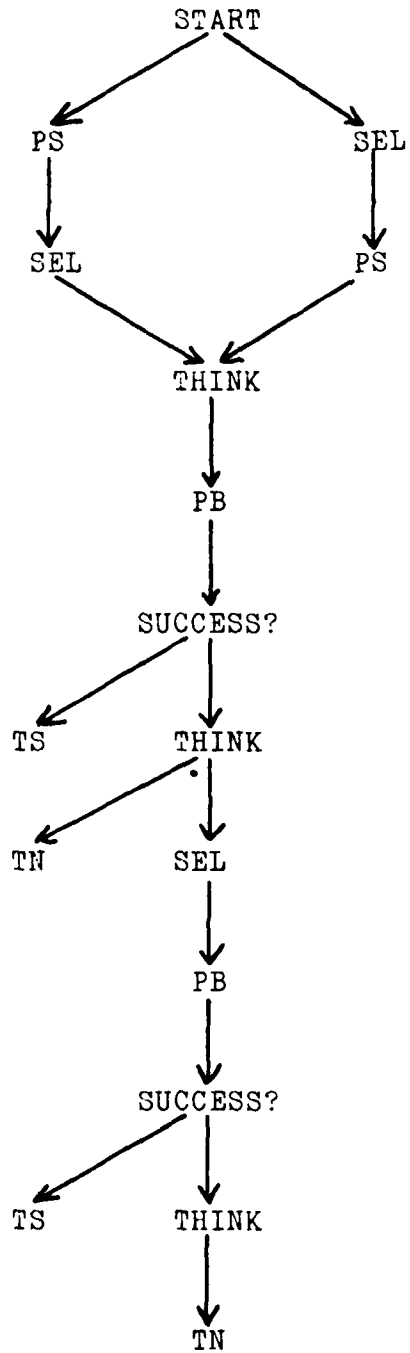
Figure 8. Flowchart showing the basic strategy followed by the simulation model.

certain predictions about the qualitative nature of the response time profile. For example, the two steps involved in the start-up strategy (PS and SEL in Figure 8) should be relatively fast because there is no inference involved, and there should be a long pause before a pushbutton (PB) is pressed. If the device operates successfully, then the time to type an S (TS) should be relatively short. If the device does not work, then again there must be a long time spent in the inference and planning stages, followed by a rapid plan execution phase. Note that if this second plan involves two steps, which it often will because of the need to both change the selector setting and press a button, the prediction is that the time to perform the first of these actions will be quite long because of the THINK process shown in Figure 8, but the time to perform the second will be short, because executing the plan is very quick. If at any point the model concludes that the device can not be made to work, then the last action taken is to type the N (TN). This should always be preceded by a fairly long inference time.

Clearly, the example shown in Figure 7 does not correspond to the proper qualitative pattern. Of course, since the profile is based on a single observation from a single subject for each response time, it is impossible to tell whether the discrepancies between the model and the subject's profile are due to sampling error or to the subject following a systematic strategy. The first analysis in Table 14 provides a lower limit on the quality of fit in that no allowance is made for whether or not the subject's strategy agrees with the model's strategy. Thus, lack of fit in the first analysis is being attributed only to sampling error, and not systematic sources.

Similar profile sequences. How well would the model fit if it were applied only to the sequences from subjects who are apparently following the same strategy as the model? A relatively objective method of selecting such data was devised based on cluster analysis. The problem was to select response time profiles on the basis of their qualitative pattern of increases and decreases in time, as opposed to their average absolute values. This was done by using a standard cluster analysis program, to classify cases consisting of using the within-profile standardized response times. That is, the mean and standard deviation of the response time in each individual response time profile was determined and the data for each profile transformed into z-scores using the mean and standard deviation for that profile. This has the effect of removing differences in location and scale for all profiles. Thus, the only differences between profiles will be in terms of the shape of the curve rather than the actual numerical sizes involved.

The output of the clustering program was then used to define groups of similar profiles. This was done somewhat intuitively, but a basic rule was that clusters formed by aggregating over an aggregated distance measure of more than 2.0 in the BMDP2M output were considered to form distinct clusters. On this basis, the data for a typical situation tended to fall into roughly three

clusters. One contained cases whose latency profile had the same pattern as the simulations. The distribution of these cases is shown in Table 15. Another cluster contained profiles that were different from the simulation's pattern. Figure 7 is an example. There are large excursions in latency that fall in different places than predicted by the model. This suggests that this subject was following a definite inference strategy that was different from the model's strategy.

But contrary to expectation, the departures fror the model's profile did not consist mainly of these different-strategy cases. Rather, most of the discrepant cases appeared in the third cluster, which consisted of profiles that were essentially flat, and whose raw times were short, less than about 2 seconds. Apparently, in these cases, little or no inference was going on. These cases became more frequent in the last situations that subjects performed. Thus, subjects were learning how to operate the device on a procedural knowledge basis, as opposed to an inferential basis. For example, in Procedures 9 and 10, subjects could use a "try the other accumulator" strategy: If the phaser could not be made to fire using the main accumulator, switch immediately to the secondary accumulator and press the corresponding button. It is not unreasonable that subjects could devise such procedures in the course of the experiment; it is perhaps remarkable that their abilities to devise and learn procedures on this basis are so powerful. However, further exploration of this process is a matter for separate line of research.

As can be seen in Table 15, out of the original 94 sequences listed in Table 13, 41 sequences have response latency profiles similar to the model's. This subset of the data, consisting of a total of 166 points, was subjected to a multiple regression analysis using the same predictor variables as before. The times were standardized on an ipsative basis; the mean and standard deviation for each subject represented in the data was used to convert the subject's data into z-scores. This removes between-subject variability, making the SMEAN variable unnecessary, but leaves within-subject variance.

Table 16 shows the results of this analysis. Notice that the same variables are important, and the final proportion of variance accounted for has increased to 43%. Especially noteworthy is the large standardized regression coefficient given to POPERS. Thus although there are other effects in the data, the amount of inferential processing done by the model is closely related to the subject's pattern of latencies.

Table 15

Frequency of Response Time Profiles Resembling Simulation

Trial	Sit.No.	Sit.	f	Pattern					
1	1	MA-NORMAL	5	MA	ON	M	TS		
2	3	MA-EB OUT	2	MA	ON	TN			
3	2	SA-NORMAL	7	SA	ON	S	TS		
			5	ON	SA	S	TS		
5	7	SA-EB OUT	6	SA	ON	TN			
			2	ON	SA	TN			
6	5	MA-MA OUT	2	MA	ON	SA	S	TS	
			2	ON	MA	SA	S	TS	
7	8	SA-MA,SA OUT	2	SA	ON	S	TN		
			1	ON	SA	S	TN		
8	6	MA-MA,SA OUT	4	MA	ON	SA	S	TN	
			2	ON	MA	SA	S	TN	
10	10	SA-PB OUT	1	SA	ON	S	MA	M	TN

Table 16

Regression Analysis of Within-S Standardized Response Times
Simulation Profile Cases Only

Final $\underline{R}$-Square = .43, $\underline{N}$ = 166.

Variable	Final Coefficient	Final Std. Coefficient	$\underline{F}$-to-Remove
CONSTANT	-.907		
FIRST	.608	.262	14.01
LAST	1.046	.451	24.79
POPERS	.027	.420	34.95
TNSTP	.717	.233	7.78

CONCLUSION

The model, together with some additional variables, is able to account for at least 30% of the variance in response time for situations where it produces the same sequences of actions as the subjects, and more than 40% of the variance when it is required to predict only those cases in which the subjects are apparently using the same general inference strategy as the model. It should be kept in mind, of course, that the strategy used in the model was relatively arbitrary, and so the model's failure to describe other strategies is not so much a criticism of the basic approach of the model, but rather of the arbitrary decision made as to which of many possible strategies to implement in the model.

Clearly, it would be possible to build an arbitrary number of arbitrary strategies into the model and provide it with some basis for choosing which strategy to use for which subject. The model would then fit the data quite well. However, this would not be a particularly useful exercise. The point of developing the simulation model and comparing it to subjects' data was not to support the claim that a specific strategy of inferring procedures from a device model is the exact strategy that subjects use. Rather, it was to demonstrate that procedural inference could in fact be done on the basis of the device model in a simple and straightforward fashion.

Since the model shows the same pattern of processing times as do many subjects, it is a reasonable hypothesis for how subjects make use of a device model. The fact that some subjects could use a mixture of planning, inference, and execution stages that is different from the model does not argue that the modelling effort has not succeeded in these goals. Likewise, the fact that many subjects could quickly and efficiently devise procedures that eliminate the need for inference does not argue that the model is not a good description of how the inferences could be performed. Rather, it shows that subjects are capable of procedural induction which was not anticipated under the conditions used.

The most intriguing suggestion resulting from the success of the model is that there may be many situations involving learning how to operate equipment in which the inference of procedures is relatively simple. If so, the construction of an inference model could be used as a basis for deciding which particular items of device model information need to be provided to subjects in order to allow them to infer the procedures. For example, Polson, Kieras, Englebeck, and Willer (1983) conducted an experiment very similar to these reported in Kieras and Bovair (1983, in press). However, like many other researchers, they found only weak and inconsistent effects of the device model; in some tasks there is clearly no effect. The device model in that study was developed intuitively. But upon examining the model in light of the results, it became clear that the device model provided the information required to infer only some of the operating procedures. Future work based on a corrected version of the device model should be successful.

But the practical problem that the Polson et al. (1983) work demonstrates is that for a system of any complexity it may be exceedingly difficult to determine what aspects of the of system are actually required to support inference of procedures. Rather than making such decisions intuitively, it may be worthwhile to construct an inference model for the procedures. If this can be done, it would allow a relatively rigorous specification of what device knowledge is actually required. In the case of systems like a word processor, this may in fact be easier than it would appear at first glance. Many of the processes involved with interacting with a computer at the system monitor level consist of moving information from one place to another. This is very similar to the flow of power through a device like the one studied here. If so, modelling inference of procedures for information transfer may not be much more complicated than that involved in modeling inference of power flow. Thus, the effort to build a procedural inference model could provide a practical means of describing what information users should actually be provided for how a system works.

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APPENDIX A

DEVICE MODEL MATERIALS

FANTASY, NO SPECIFIC CONTROL INFORMATION

To help make the device meaningful to you, we have based it on Gene Roddenberry's "Star Trek". I will explain how the device works in terms of this fantasy. This device is a phaser-bank control from the Starship "Enterprise", and you will figure out several procedures for firing the phasers.

I will explain how the phaser bank works. After I have given you this information, there will be a short quiz on the important points. You must answer all the questions correctly before we can go on to the next part of the experiment. If you answer a question incorrectly, I will present the information to you again, and then you will do the quiz again. We will repeat this until you can answer all the questions correctly.

Notice that there is a diagram to the right of the terminal. This diagram shows the major components of the phaser system, and will help you to understand the system. You should locate on the diagram every part that is mentioned in the text, and pay special attention to the arrows that show the flow of power through the system. By doing this you will find it easier to answer the questions on the quiz correctly.

The phaser system is based on several important principles in physics that were discovered in the last decade of the 20th century. These were applied to produce a powerful weapon system for use aboard interstellar spaceships.

Such a system became necessary to defend Federation ships from the aggression of the sophisticated warships of the hostile Klingon and Romulan empires.

The key characteristic of the phaser system is its need for very high energy levels that are available on short notice.

The basic energy source is the violent interaction of matter and antimatter, which is controlled by means of a catalytic plasma produced from ionized dilithium crystals. Find the matter-antimatter power source on the diagram.

The normal result of contact between matter and anti-matter is a violent explosion. However, the catalytic plasma slows the rate at which energy is released, so that use of this energy becomes practical.

The phaser requires energy of several giga-electron volts to be applied within a few picoseconds. Not even the dilithium-based matter-antimatter system can generate such peak levels, and so the energy that it does produce must be stored.

The storage system is an outgrowth of the first successful unified field theory. A circulating field, known as an energon ring, can be collapsed by the injection of large amounts of energy from the matter-antimatter power source. The extent of the collapse is determined by the amount of energy injected.

Find the matter-antimatter power source on the diagram, and notice the arrows that show the flow of power into the energon storage system.

Maintenance of a collapsed energon ring requires a supply of vector bosons which is synchronized with the period of energon circulation. When the energon ring is allowed to expand, all of the energy is released almost instantaneously, with a maximum release time of 3-5 picoseconds.

Because the energy must be taken out of the energon ring within picoseconds, the energon storage system must be able to operate at very high speeds.

By making the energon storage system as compact as possible, the time needed for energy to travel between components of the system is minimized. This need for compactness was a major factor that led to adoption of a toroidal (doughnut-shaped) vessel in which the energon rings circulate.

On the diagram, find the energon storage system. You will see the toroidal storage vessel shown with the energon rings circulating inside. Notice that the boson generators are mounted around the outside of the vessel.

The phaser itself is perhaps the most conventional aspect of the system, being a direct extension of the traditional laser technology developed in the mid-20th century.

A phaser uses phase-shifting to convert energy into a stream of hyperons.

Energy is pumped from the energon storage system into a zirconium-filled phasing cylinder, and this energy causes phase-shifts in the hyperon structure of the zirconium nuclei. When the phase shifts come to a peak, a burst of hyperons is emitted in a stream through the aiming mechanism. This burst of hyperons excites the nuclei into further phase-shifts which in turn, cause another burst of hyperons. After four bursts of hyperons, the energy is depleted to a level where phase-shifting is not possible, and so phasing terminates.

Find the phasing cylinder on the diagram. Note the arrows showing the flow of power from the energon storage system into the phasing cylinder, and also the arrow representing the bursts of hyperons through the aiming mechanism.

Test questions

What is the key characteristic of the phaser system?

(1) It must be shielded to protect the operator from radiation. (2) It needs very high energy levels available on short notice. (3) It cannot be operated without tachyon reactors.

What is the basic energy source for the phaser system?

(1) The interaction between matter and antimatter. (2) A circulating system of ionized dilithium crystals. (3) A plasma produced from energon rings.

What role is played by the catalytic plasma produced from dilithium crystals?

(1) It maintains circulating energon rings in their collapsed state so that energy can be stored. (2) It enables matter and antimatter to release energy when they are brought into contact with each other. (3) It controls the rate of release of energy from the interaction of matter and antimatter, so that the energy can be used.

Where does the energy that is stored in the energon storage system come from?

(1) It comes from the matter-antimatter power source. (2) It comes from the zirconium-filled phasing cylinder. (3) It comes from the boron generators.

What determines the amount of collapse of the energon rings?

(1) The size of the vessel in which the rings are circulating. (2) The amount of energy injected from the matter-antimatter power source. (3) The number of vector bosons injected from the matter-antimatter power source.

What happens when energon rings are allowed to expand?

(1) Dilithium crystals produce a catalytic plasma. (2) Vector bosons undergo rapid phase-shifts. (3) They release all their stored energy almost instantaneously.

What is required to maintain energon rings in their collapsed state?

(1) Modulated vector bosons synchronized with the period of energon circulation. (2) A stream of hyperons produced from ionized dilithium crystals. (3) A catalytic plasma that causes phase shifts in the nuclei.

Why is the energon storage system as compact as possible?

(1) So that the distance, and thus the time, between components is minimized. (2) So that the phaser system can be easily moved out of the ship for planet-based operation. (3) So that the number of boson generators needed to operate it is as small as possible.

Where does the phasing cylinder get its energy from?

(1) From the matter-antimatter power source. (2) From the energon storage system. (3) From boson generators.

The phaser is a direct extension of which 20th century technology?

(1) Energon storage systems. (2) Meson generators. (3) Laser technology.

Where do the phase-shifts within the phasing cylinder take place?

(1) In the circulating energon rings. (2) In the hyperon structure of zirconium nuclei. (3) In the catalytic plasma produced from dilithium crystals.

Why does phasing terminate after four bursts of hyperons?

(1) Because zirconium nuclei only contain four hyperons. (2) Because the energon rings are not in synchrony with the vector bosons. (3) Because the energy in the phasing cylinder is depleted, after four bursts.

NO FANTASY, SPECIFIC CONTROL INFORMATION

I will explain how the device works and what the controls do. After I have given you this information, there will be a short quiz on the important points.

You must answer all the questions correctly before we can go on to the next part of the experiment. If you answer a question incorrectly, I will present the information to you again, and then you will do the quiz again.

We will repeat this until you can answer all the questions correctly.

Notice that there is a diagram above the control panel. This diagram shows the major components of the system and is intended to help you to understand the system. You will find that by carefully studying the diagram and locating on it every part that is mentioned in the text, the questions on the quiz will be easy to answer.

The system consists of four components, four controls, and four indicator lights.

On the diagram, find the four components which are shown as the boxes labeled Buffer (B), Main Activator (MA), Secondary Activator (SA), and Pulser (P).

Now find on the diagram the four controls: the switch labeled Power Switch (PS), the Selector (S) and the two pushbuttons, M and S.

Finally, find the four indicators labeled: Power-ON indicator (PO indicator), Buffer indicator (B indicator), Main Activator indicator (MA indicator), and Pulser indicator (P indicator).

It is important to realize that this device can sometimes malfunction.

However, the only parts that can break down are the components: the Buffer, the Main and Secondary Activators, and the Pulser. The lights, the controls, and the connecting wires between the components are completely reliable.

Thus, if the device malfunctions, the cause must be a malfunction in the components, and not a problem in the wiring, switches, or defective indicator lights.

The arrows on the diagram show how power flows through the system.

Starting on the lower left of the diagram, you can see that power comes in from the power source.

Notice on the diagram how this power flows to the Buffer (B), and from there it flows to the two activators (MA and SA).

The diagram shows that power can flow from either of the activators to the Pulser (P).

The switch, selector, and pushbuttons control the flow of power.

I will now describe how the controls relate to the components.

On the lower left of the diagram, locate the power switch (PS). You can see that the power coming in from the power source is controlled by the PS switch.

When this switch is off, no power can come in. When the switch is turned on, power flows into the Buffer (B).

Power from the Buffer then flows into both activators.

Find the selector on the diagram, and notice that the activator whose power will be supplied to the Pulser (P) is selected by the selector (S). While the S selector is set to neutral (N), no power can flow from either activator to the Pulser (P).

When the selector is set to MA, the power can flow from the Main Activator. When the selector is set to SA, then power can flow from the Secondary Activator.

Find the M and S buttons on the diagram, and notice that the flow of power from the selected activator to the Pulser is controlled by the buttons. When the Main Activator has been selected, the Main (M) button controls the flow of power to the Pulser. When the Secondary Activator has been selected, then the Secondary (S) button controls the flow of power to the Pulser.

Finally, the control panel is provided with four indicator lights.

The diagram shows that each indicator is attached to a particular component in the system.

The indicator will only light if the component that it is connected to is both receiving power and working properly.

The PO indicator will light if the system is receiving power from the power source. Thus the Power-ON indicator (PO indicator) will light when you turn on the power switch (PS).

The Buffer indicator (B indicator) will light if the Buffer is receiving power, and operating correctly and putting out power.

The Main Activator indicator (MA indicator) will light if the Main Activator is receiving power from the Buffer, and the Main Activator is working properly and putting out power.

Note that there is no indicator for the Secondary Activator.

Lastly, the Pulser indicator (P indicator) will light if the Pulser is receiving power and is working properly. Because the Pulser works in pulses, the P indicator will flash four times, when the Pulser receives power.

Test questions

Where does the Buffer get its power from?

(1) from the activators. (2) from the power source. (3) from its own special power supply.

Where does the Main Activator get its power from?

(1) from the Buffer. (2) directly from the power source. (3) from the Secondary Activator.

Where does the Secondary Activator get its power from?

(1) directly from the power source. (2) from the Pulser. (3) from the Buffer.

Where does the Pulser get its power from?

(1) from either one of the two activators. (2) from the Main Activator only. (3) directly from the Buffer.

What is the PS for?

(1) It controls which activator will be used. (2) It controls whether the system gets power from the power source. (3) It controls the flow of power from an activator to the Pulser.

What does the selector do?

(1) It selects which activator the Buffer will send power to.
(2) It selects whether power will be received from the Buffer or
not. (3) It selects which activator will be used to power the
Pulser.

Assume that the system is in full working order, that the PS
is on, and that the selector is set to MA.

Now, what will happen if the M button is pressed?

(1) The Main Activator will send power to the Pulser. (2)
The Pulser will receive power from the Secondary Activator. (3)
The Pulser will receive power directly from the Buffer.

Assume that the system is in full working order, that the PS
is on, and that the selector is set to MA.

Now, what will happen if the S button is pressed?

(1) Nothing. The selector must be set to SA for power to
flow to the Pulser when the S button is pressed. (2) The Main
Activator will send power to the Pulser. (3) The Secondary
Activator will send power to the Pulser.

What does the PO indicator indicate?

(1) It indicates whether the Pulser is ready to operate. (2)
It indicates whether or not the system is receiving power from the
power source. (3) It indicates whether the Secondary Activator is
working and receiving power.

What does it mean if the B indicator is on?

(1) It means that the Buffer is not receiving power from the
power source. (2) It means that the Buffer is receiving power
from the power source, but the Buffer may or may not be working.
(3) It means that the Buffer is both receiving power from the
power source and is functioning properly.

What does it mean if the MA indicator is on?

(1) It means that the Pulser is receiving power from the Main
Activator. (2) It means that the Main Activator is working and is
receiving power from the Buffer. (3) It means that both
activators are receiving power and working properly.

What can you tell if the P indicator flashes?

(1) The Pulser is ready to operate, but is not getting power. (2) The Pulser is not working. (3) The Pulser is working and receiving power.

FANTASY, SPECIFIC CONTROL INFORMATION

To help make the device meaningful to you, we have based it on Gene Roddenberry's "Star Trek". I will explain how the device works in terms of this fantasy.

This device is a phaser-bank control from the Starship "Enterprise", and you will figure out several procedures for firing the phasers.

I will explain how the phaser bank works. After I have given you this information, there will be a short quiz on the important points.

You must answer all the questions correctly before we can go on to the next part of the experiment. If you answer a question incorrectly, I will present the information to you again, and then you will do the quiz again.

We will repeat this until you can answer all the questions correctly.

Notice that there is a diagram to the right of the terminal. This diagram shows the major components of the phaser control system and is intended to help you to understand the system. You will find that by carefully studying the diagram and locating on it every part that is mentioned in the text, the questions in the quiz will be easy to answer.

The system consists of four components, four controls, and four indicator lights.

On the diagram, find the four components which are shown as the boxes labeled energy Booster (B), Main Accumulator (MA), Secondary Accumulator (SA), and Phaser bank (P).

Now find on the diagram the four controls: the switch labeled Power Switch (PS), the Selector (S), and the two pushbuttons, M and S.

Finally, find the four indicators labeled: Power-ON indicator (PO indicator), energy Booster indicator (B indicator), Main Accumulator indicator (MA indicator), and Phaser bank indicator (P indicator).

It is important to realize that this device can sometimes malfunction.

However, the only parts that can break down are the components: the Booster, the Main and Secondary Accumulators, and the Phaser bank. The lights, the controls, and the connecting wires between the components are completely reliable.

Thus, if the device malfunctions, the cause must be a malfunction in the components, and not a problem in the wiring, switches, or defective indicator lights.

The arrows on the diagram show how power flows through the system.

Starting on the lower left of the diagram, you can see that power comes in from the shipboard circuits.

Notice on the diagram that this power flows to the energy Booster (B), and from there it flows to the two accumulators (MA and SA).

The diagram shows that power can flow from either of the accumulators to the Phaser bank (P).

The switch, selector and pushbuttons control the flow of power.

I will first describe the function of each component, and then will describe how the controls relate to the components.

Ship's power cannot be used to fire the phaser directly because it is not at a high enough level. The energy Booster boosts the ship's power to the high level necessary to fire the phaser.

Both accumulators store large amounts of power, and if they are used continuously, they are liable to overload and burn out. To prevent continuous use of one accumulator, this system has two: the Main Accumulator (MA) and the Secondary Accumulator (SA).

When the Phaser bank receives power, rapid phase shifts take place. These phase shifts cause the emission of the phaser beams, and thus the actual firing.

Now that you have seen what each component does, I will describe how the controls relate to the operation of the components.

On the lower left of the diagram, locate the ship's Power Switch (PS). You can see that the power coming in from the shipboard circuits is controlled by the PS switch. When this switch is off, no power can come in. When the switch is turned on, power flows into the energy Booster (B).

Power from the energy Booster then flows into both accumulators.

Find the selector on the diagram and notice that the accumulator whose power will be supplied to the Phaser bank is selected by the selector (S). While the selector is set to neutral (N), no power can flow from either accumulator to the Phaser bank.

When the selector is set to MA, the power can flow from the Main Accumulator. When the selector is set to SA, then power can flow from the Secondary Accumulator.

Find the M and S buttons on the diagram, and notice that the flow of power from the selected accumulator to the Phaser bank is controlled by the firing buttons. When the Main Accumulator has been selected, the fire Main (M) button controls the flow of power to the Phaser bank.

When the Secondary Accumulator has been selected, then the fire Secondary (S) button controls the flow of power to the Phaser bank.

Finally, the control panel is provided with four indicator lights.

The diagram shows that each indicator is attached to a particular component in the system.

The indicator will only light if the component that it is connected to is both receiving power and working properly.

The PO indicator will light if the phaser system is receiving power from the ship. Thus the Power-ON indicator (PO indicator) will light when you turn on the power switch (PS).

The energy Booster indicator (B indicator) will light if the energy Booster is receiving power, and operating correctly and putting out the boosted energy.

The Main Accumulator indicator (MA indicator) will light if the Main Accumulator is receiving power from the energy Booster, and the Main Accumulator is working properly and putting out power.

Note that there is no indicator for the Secondary Accumulator.

Lastly, the Phaser indicator (P indicator) will light if the Phaser bank is receiving power and is working properly.

Because the Phaser fires in pulses, the P indicator will flash four times, when the Phaser bank receives power.

Test questions

Where does the energy Booster get its power from?

(1) from the accumulators. (2) from the shipboard power circuits. (3) from its own special power supply.

Where does the Main Accumulator get its power from?

(1) from the energy Booster. (2) directly from the shipboard circuits. (3) from the Secondary Accumulator.

Where does the Secondary Accumulator get its power from?

(1) directly from the shipboard circuits. (2) from the Phaser bank. (3) from the energy Booster.

Where does the Phaser bank get its power from?

(1) from either one of the two accumulators. (2) from the Main Accumulator only. (3) directly from the energy Booster.

What is the PS for?

(1) It controls which accumulator will be used. (2) It controls whether the phaser system gets power from the ship. (3) It controls the flow of power from an accumulator to the Phaser bank.

What does the selector do?

(1) It selects which accumulator the energy Booster will send power to. (2) It selects whether power will be received from the energy Booster or not. (3) It selects which accumulator will be used to power the Phaser bank.

Assume that the phaser control system is in full working order, that the PS is on, and that the selector is set to MA.

Now, what will happen if the M button is pressed?

(1) The Main Accumulator will send power to the Phaser bank. (2) The Phaser bank will receive power from the Secondary Accumulator. (3) The Phaser bank will receive power directly from the energy Booster.

Assume that the phaser control system is in full working order, that the PS is on, and the selector is set to MA.

Now, what will happen if the S button is pressed?

(1) Nothing. The selector must be set to SA for power to flow to the Phaser bank when the S button is pressed. (2) The Main Accumulator will send power to the Phaser bank. (3) The Secondary Accumulator will send power to the Phaser bank.

What does the PO indicator indicate?

(1) It indicates whether the Phaser bank is ready to operate. (2) It indicates whether or not the phaser system is receiving power from the shipboard circuits. (3) It indicates whether the Secondary Accumulator is working and receiving power.

What does it mean if the B indicator is on?

(1) It means that the energy Booster is not receiving power from the shipboard power circuits. (2) It means that the energy Booster is receiving power from the shipboard power circuits, but the energy Booster may not be working. (3) It means that the energy Booster is both receiving power from the shipboard circuits and is working properly.

What does it mean if the MA indicator is on?

(1) It means that the Phaser bank is receiving power from the Main Accumulator. (2) It means that the Main Accumulator is working and is receiving power from the energy Booster. (3) It means that both accumulators are receiving power and working properly.

What can you tell if the P indicator flashes?

(1) The Phaser bank is ready to operate, but is not getting power. (2) The Phaser bank is not working. (3) The Phaser bank is receiving power and is working.

APPENDIX B
Details of Instructions and Procedure

This section contains details that the reader may want to skip. These details are important for conducting experiments of this type, however.

Subjects were told that the initial or starting state of the device was: PS down, S selector set at N, and no buttons being pushed, and that when they were figuring out how to operate the device, they would be asked to always begin with the device in the initial state. They were also told that the behavior of the device in response to what they did with the controls was controlled by the computer outside the room, and that the computer was programmed to make the device simulate a real device. Thus, although the device was not a real device, the computer made it behave as if it was, and so they should think of the device as a real piece of equipment, and not part of a computer.

Subjects were told that their task was to figure out how to operate the device both when it was working normally, and when it was malfunctioning, and that each time they finished operating the device, they would be asked to report on what they were thinking about while they were working. The instructions on the experimental procedure were similar for all subjects except that the instructions for the subjects in the two fantasy conditions used terms from the fantasy such as "firing the phasers".

Subjects were told that the goal of operating the device was to make the P indicator flash, and that their task was to figure out how to set the controls to make this happen. Because the device was specially built for the experiment, they were not expected to immediately know how to operate it, but would have to think about what they were doing and perhaps use trial and error. They were instructed to type an "S" for "success" on the keyboard of the terminal when they got the P indicator to flash.

They were told that because the device behaved like a real device, that it would sometimes malfunction, and that there were several different ways in which it could malfunction. When the device worked normally, certain control settings would cause the P indicator to flash, but when it malfunctioned, the same settings might or might not work, depending on the malfunction. If the device did malfunction, then there were two possible courses of action. One was that there was no possible way to set the controls to get the indicator to flash. If they were sure that this was the case, they should signal this by typing an "N" for Not-compensated malfunction on the terminal keyboard. In the second possibility, they were told that although the P indicator might not flash using some control settings, it would flash using other settings. If this were the case, they would type "S" for Success on the keyboard. Thus, the subject would have to decide both if there was a malfunction and if it was possible to make the P indicator flash.

They were told that in some of the situations the device would be working normally, and in some there would be some type of malfunction, with a total of ten different situations. For all situations, they should try to operate the device in as few steps as possible, so that it was important that they did not "fiddle" with the device any more than necessary. It was also important that they get the P indicator to flash if it was possible to do so, or recognize that it was not possible to make it flash.

They were told that typing the "S" or "N" signalled that they had finished operating the device in the given situation. The experimenter would then ask them to say what they were thinking about when they were operating the controls. They were told that for each step that they did, they should say what they remembered actually thinking at the time. They should not try to "second-guess" themselves; if they could not remember or were not sure what they actually thought at the time, then they should simply say that they could not remember, or were not sure.

For each situation, they were first asked to check that the device was in its initial state, and then tap the space bar on the terminal. When they tapped the space bar either "Use the MA setting", or "Use the SA setting" appeared on the screen. They were told that the messages referred to the setting of the selector that we wished them to try to use. If there was a malfunction, that setting might not work and they might need to change the setting, or even not use it at all, but that setting was the preferred one, and they should use it if they felt that they could.

They were also told that in the first situation that they saw, the device would be working normally, so that they would definitely be able to get the P indicator to flash. After the first situation, then they would also see malfunction situations.

After the first few subjects were run, a few modifications were made to the instructions to eliminate some problems caused for a few of the subjects. Reference to the exact numbers of normal and malfunction situations was deleted after one subject said that he tried an alternate setting than the one asked for because he knew that there were only two normal situations, and he had already seen them. The "story" instructions were also modified to encourage subjects to make use of the diagram provided.

The experimenter observed the subject's performance and, when the subject was finished with a situation prompted the subject for their recall with the questions: "Do you remember what steps you did?", and "Do you remember what you were thinking at the time you did each step?".

For two procedures, (MA-MA out and SA-SA out), it was possible to make the P indicator flash although there was a malfunction in each case that meant that the asked-for settings would not work. In such cases, it was possible that the subject would give up trying after the initial settings did not work, and just tap "N". If "N" was tapped for these two procedures, then the message: "Typing an "N" here means that you think that you cannot get the P indicator to flash, no matter what control settings you use. Are you sure that you have tried all the possible settings?" would appear and the subject would try again for this situation.

APPENDIX C

*** DEFINITION OF DEVICE IN LONG-TERM MEMORY ***

```
CPD1  (ISA SHIP-POWER POWER-SOURCE)
CPD2  (ISA EB COMPONENT)
CPD3  (ISA MA COMPONENT)
CPD4  (ISA SA COMPONENT)
CPD5  (ISA PB COMPONENT)
CPDA  (ISA SPI INDICATOR)
CPDB  (ISA EBI INDICATOR)
CPDC  (ISA MAI INDICATOR)
CPDD  (ISA PFI INDICATOR)
CPDE  (AT SPI SP-EB)
CPDF  (AT EBI EB)
CPDG  (AT MAI MA)
CPDH  (AT PFI PB)
CPDI  (ISA SP-EB TERMINAL)
CPDJ  (ISA EB-OUT TERMINAL)
CPDL  (ISA MA-FM TERMINAL)
CPDN  (ISA SA-FS TERMINAL)
CPDP  (ISA SP-IN TERMINAL)
CPDS  (ISA FM-ESS TERMINAL)
CPDU  (ISA FS-ESS TERMINAL)
CPDX  (ISA ESS-N-IN TERMINAL)
CPDY  (ISA ESS-PB TERMINAL)
CPD6  (ISA SP SWITCH)
CPD7  (ISA FM BUTTON)
CPD8  (ISA FS BUTTON)
CPD9  (ISA ESS-MA SELECTOR)
CPD10 (ISA ESS-SA SELECTOR)
CPD11 (ISA ESS-N SELECTOR)
CON01 (CONNECTION SHIP-POWER SP-IN)
CON02 (CONNECTION SP-IN SP)
CON03 (CONNECTION SP SP-EB)
CON05 (CONNECTION SP-EB EB)
CON06 (CONNECTION EB EB-OUT)
CON09 (CONNECTION EB-OUT MA)
CON10 (CONNECTION MA MA-FM)
CON11 (CONNECTION EB-OUT SA)
CON12 (CONNECTION SA SA-FS)
CON14 (CONNECTION MA-FM FM)
CON15 (CONNECTION FM FM-ESS)
CON16 (CONNECTION SA-FS FS)
CON18 (CONNECTION FS FS-ESS)
CON19 (CONNECTION FM-ESS ESS-MA)
CON21 (CONNECTION FS-ESS ESS-SA)
CON23 (CONNECTION ESS-MA ESS-PB)
CON24 (CONNECTION ESS-SA ESS-PB)
CON25 (CONNECTION ESS-N-IN ESS-N)
CON26 (CONNECTION ESS-N ESS-PB)
CON28 (CONNECTION ESS-PB PB)
CPD23 (CHOICE ESS-MA PREFERRED)
FACT1 (ISA SWITCH CONTROL)
```

```
FACT2 (ISA BUTTON CONTROL)
FACT3 (ISA SELECTOR CONTROL)
SPECO (OPERATE-GOAL-STATE PFI ON)
SPEC1 (INITIAL-STATE ESS-N ON)
SPEC2 (INITIAL-STATE ESS-SA OFF)
SPEC3 (INITIAL-STATE ESS-MA OFF)
SPEC4 (INITIAL-STATE SP OFF)
INFRN1 (ASSOCIATED MA FM)
INFRN2 (ASSOCIATED SA FS)
INFRN3 (ASSOCIATED MA ESS-MA)
INFRN4 (ASSOCIATED SA ESS-SA)
INFRN5 (ISA SP POWER-SWITCH)
ASSUM1 (ISA EB VITAL-COMPONENT)
ASSUM2 (ISA PB VITAL-COMPONENT)
```

PRODUCTION RULES USED IN THE SIMULATION

```
   *** SUBSYSTEM TO INFER PROPERTIES OF CONTROLS ***
(P-FIND-POWER-SWITCH
        ($TEST (*LTM ISA *X1 POWER-SOURCE)
               (*LTM CONNECTION *X1 *Y1)
               (*LTM CONNECTION *Y1 *X2)
               (*LTM ISA *X2 SWITCH)))
=>
      (($BUILD *WM (ISA *X2 POWER-SWITCH))
         ($BUILD *WM (STATE DEVICE OFF)) ))
(P-ASSOCIATE-CONTROL-1
        ($TEST (*LTM CONNECTION *X1 *Y1)
               (*LTM ISA *X1 COMPONENT)
               (*LTM CONNECTION *Y1 *Y2)
               (*LTM CONNECTION *Y2 *X2)
               (*LTM ISA *X2 *X3)
               (*LTM ISA *X3 CONTROL)))
=>
      (($BUILD *WM (ASSOCIATED *X1 *X2)) ))
(P-ASSOCIATE-CONTROL-2
        ($TEST (*LTM CONNECTION *X1 *Y1)
               (*LTM ISA *X1 COMPONENT)
               (*LTM CONNECTION *Y1 *Y2)
               (*LTM CONNECTION *Y2 *X2)
               (*LTM ISA *X2 *Z1)
               (*LTM ISA *Z1 CONTROL)
               (*LTM CONNECTION *X2 *Y3)
               (*LTM CONNECTION *Y3 *Y4)
               (*LTM CONNECTION *Y4 *X3)
               (*LTM ISA *X3 *Z2)
               (*LTM ISA *Z2 CONTROL)))
=>
      (($BUILD *WM (ASSOCIATED *X1 *X3)) ))
```

```
*** SUBSYSTEM TO PROPAGATE ENERGY ALONG CONNECTIONS ***
(P-PROPAGATE-CONTROL
        ($TEST (*WM GOAL PROPAGATE ENERGY)
               (*WM PROCESS ENERGY PROPAGATING)))
=>
      (($REMOVE *WM (PROCESS ENERGY PROPAGATING)) ))
(P-CONNECTION-ENERGY
        ($TEST (*WM GOAL PROPAGATE ENERGY)
               (*WM AT ENERGY *Y1)
               (*LTM ISA *Y1 TERMINAL)
               (*LTM CONNECTION *Y1 *Y2)
               (*LTM ISA *Y2 TERMINAL)
               (ABSENT *WM AT ENERGY *Y2)))
=>
      (($BUILD *WM (AT ENERGY *Y2)(PROCESS ENERGY PROPAGATING)) ))
(P-CONNECTION-ENERGY-BACK
        ($TEST (*WM GOAL PROPAGATE ENERGY)
               (*WM AT ENERGY *Y1)
               (*LTM ISA *Y1 TERMINAL)
               (*LTM CONNECTION *Y2 *Y1)
               (*LTM ISA *Y2 TERMINAL)
               (ABSENT *WM AT ENERGY *Y2)))
=>
      (($BUILD *WM (AT ENERGY *Y2)(PROCESS ENERGY PROPAGATING)) ))
(P-CONTROL-ENERGY
        ($TEST (*WM GOAL PROPAGATE ENERGY)
               (*WM AT ENERGY *Y1)
               (*LTM ISA *Y1 TERMINAL)
               (*LTM CONNECTION *Y1 *X1)
               (*LTM ISA *X1 *X2)
               (*LTM ISA *X2 CONTROL)
               (*WM DEVICE *X1 ON)
               (*LTM CONNECTION *X1 *Y2)
               (*LTM ISA *Y2 TERMINAL)
               (ABSENT *WM AT ENERGY *Y2)))
=>
      (($BUILD *WM (AT ENERGY *Y2)(PROCESS ENERGY PROPAGATING)) ))
(P-CONTROL-ENERGY-BACK
        ($TEST (*WM GOAL PROPAGATE ENERGY)
               (*WM AT ENERGY *Y1)
               (*LTM ISA *Y1 TERMINAL)
               (*LTM CONNECTION *X1 *Y1)
               (*LTM ISA *X1 *X2)
               (*LTM ISA *X2 CONTROL)
               (*WM DEVICE *X1 ON)
               (*LTM CONNECTION *Y2 *X1)
               (*LTM ISA *Y2 TERMINAL)
               (ABSENT *WM AT ENERGY *Y2)))
=>
      (($BUILD *WM (AT ENERGY *Y2)(PROCESS ENERGY PROPAGATING)) ))
(P-INDICATOR-ENERGY
        ($TEST (*WM GOAL PROPAGATE ENERGY)
               (*LTM AT *X1 *X2)
               (ABSENT *WM AT ENERGY *X2)
               (*LTM ISA *X1 INDICATOR)
```

```
                        (ABSENT *LTM ISA *X2 COMPONENT)
                        (*WM DEVICE *X1 ON)))
        =>
                (($BUILD *WM (AT ENERGY *X2)(PROCESS ENERGY PROPAGATING)) ))
        (P-COMPONENT-WORKING
                ($TEST (*WM GOAL PROPAGATE ENERGY)
                        (*WM AT ENERGY *Y1)
                        (*LTM ISA *Y1 TERMINAL)
                        (*LTM CONNECTION *Y1 *X1)
                        (ABSENT *WM AT ENERGY *X1)
                        (*LTM ISA *X1 COMPONENT)
                        (*LTM CONNECTION *X1 *Y2)
                        (*WM AT ENERGY *Y2)))
        =>
                (($BUILD *WM (AT ENERGY *X1)(STATE *X1 GOOD))))
        (P-COMPONENT-GOOD
                ($TEST (*WM GOAL PROPAGATE ENERGY)
                        (*LTM AT *X2 *X1)
                        (*LTM ISA *X1 COMPONENT)
                        (*LTM ISA *X2 INDICATOR)
                        (*WM DEVICE *X2 ON)
                        (*LTM CONNECTION *Y1 *X1)
                        (*LTM ISA *Y1 TERMINAL)
                        (*LTM CONNECTION *X1 *Y2)
                        (*LTM ISA *Y2 TERMINAL)))
        =>
                (($BUILD *WM (STATE *X1 GOOD)(PROCESS ENERGY PROPAGATING)
                                (AT ENERGY *X1)(AT ENERGY *Y1)
                                (AT ENERGY *Y2))))
        (P-COMPONENT-BAD
                ($TEST (*WM GOAL PROPAGATE ENERGY)
                        (*LTM AT *X2 *X1)
                        (*LTM ISA *X1 COMPONENT)
                        (*LTM ISA *X2 INDICATOR)
                    (*LTM CONNECTION *Y1 *X1)
                        (*LTM ISA *Y1 TERMINAL)
                        (*WM AT ENERGY *Y1)
                        (ABSENT *WM DEVICE *X2 ON)))
        =>
                (($BUILD *WM (STATE *X1 BAD))))
        (P-PROPAGATE-CONTROL-2
                ($TEST (*WM GOAL PROPAGATE ENERGY)
                        (ABSENT *WM PROCESS ENERGY PROPAGATING)))
        =>
                (($REMOVE *WM (GOAL PROPAGATE ENERGY)) ))


*** SUBSYSTEM TO FIND PATH FROM TO-BE-ENERGIZED POINT ***
        (P-FIND-PATH-CONTROL
                ($TEST (*WM GOAL FIND PATH)
                        (*WM PROCESS FINDING PATH)))
        =>
                (($REMOVE *WM (PROCESS FINDING PATH)) ))
        (P-BACK-CONNECTION
                ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
```

```
                        (ABSENT *WM AT ENERGY *Y1)
                        (*LTM CONNECTION *Y2 *Y1)
                        (*LTM ISA *Y2 TERMINAL) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH) (GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-BACK-CONNECTION-INDICATOR
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *X2)
                        (*LTM ISA *X2 INDICATOR)
                        (ABSENT *WM AT ENERGY *X2)
                        (*LTM AT *X2 *X1)
                        (*LTM ISA *X1 COMPONENT)
                        (ABSENT *WM STATE *X1 BAD) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH) (GOAL ENERGIZE *X1))
          ($REMOVE *WM (GOAL ENERGIZE *X2)) ))
(P-BACK-SWITCH
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                        (*LTM ISA *Y1 TERMINAL)
                        (ABSENT *WM AT ENERGY *Y1)
                        (*LTM CONNECTION *X1 *Y1)
                        (*LTM ISA *X1 SWITCH)
                        (*LTM CONNECTION *Y2 *X1) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (STEP *X1 ON)(GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-BACK-BUTTON
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                        (*LTM ISA *Y1 TERMINAL)
                        (ABSENT *WM AT ENERGY *Y1)
                        (*LTM CONNECTION *X1 *Y1)
                        (*LTM ISA *X1 BUTTON)
                        (*LTM CONNECTION *Y2 *X1) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (STEP *X1 ON)(GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-BACK-GOOD-COMPONENT
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                        (*LTM ISA *Y1 TERMINAL)
                        (ABSENT *WM AT ENERGY *Y1)
                        (*LTM CONNECTION *X1 *Y1)
                        (*LTM ISA *X1 COMPONENT)
                        (ABSENT *WM STATE *X1 BAD)
                        (*LTM CONNECTION *Y2 *X1)))
=>
        (($BUILD *WM (PROCESS FINDING PATH) (GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-SELECTION-ALREADY-DONE
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                        (*LTM ISA *Y1 TERMINAL)
                        (ABSENT *WM AT ENERGY *Y1)
                        (*LTM CONNECTION *X1 *Y1)
                        (*LTM ISA *X1 SELECTOR)
```

```
                        (*LTM CONNECTION *Y2 *X1)
                        (*WM DEVICE *X1 ON)
                        (*LTM ASSOCIATED *X2 *X1)
                        (ABSENT *WM STATE *X2 BAD) ))
    =>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-SELECT-TO-BE-USED
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                (*LTM ISA *Y1 TERMINAL)
                (ABSENT *WM AT ENERGY *Y1)
                (*LTM CONNECTION *X1 *Y1)
                (*LTM ISA *X1 SELECTOR)
                (*LTM CONNECTION *Y2 *X1)
                (*WM GOAL USE *X1)
                (*LTM ASSOCIATED *X2 *X1)
                (ABSENT *WM STATE *X2 BAD) ))
    =>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (STEP *X1 ON)(GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-SELECT-PREFERRED
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                (*LTM ISA *Y1 TERMINAL)
                (ABSENT *WM AT ENERGY *Y1)
                (*LTM CONNECTION *X1 *Y1)
                (*LTM ISA *X1 SELECTOR)
                (*LTM CONNECTION *Y2 *X1)
                (*LTM CHOICE *X1 PREFERRED)
                (ABSENT *WM GOAL USE *X1)
                (*LTM ASSOCIATED *X2 *X1)
                (ABSENT *WM STATE *X2 BAD) ))
    =>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (STEP *X1 ON)(GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-SELECT-NOT-PREFERRED
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                (*LTM ISA *Y1 TERMINAL)
                (ABSENT *WM AT ENERGY *Y1)
                (*LTM CONNECTION *X1 *Y1)
                (*LTM ISA *X1 SELECTOR)
                (*LTM CONNECTION *Y2 *X1)
                (ABSENT *LTM CHOICE *X1 PREFERRED)
                (ABSENT *WM GOAL USE *X1)
                (*LTM ASSOCIATED *X2 *X1)
                (ABSENT *WM STATE *X2 BAD) ))
    =>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (STEP *X1 ON)(GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-SELECT-GOOD-NOT-BAD
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                (*LTM ISA *Y1 TERMINAL)
```

```
                        (ABSENT *WM AT ENERGY *Y1)
                        (*LTM CONNECTION *X1 *Y1)
                        (*LTM ISA *X1 SELECTOR)
                        (*LTM CONNECTION *X3 *Y1)
                        (*LTM ISA *X3 SELECTOR)
                        (*LTM CONNECTION *Y2 *X1)
                        (*LTM CONNECTION *Y3 *X3)
                        (*LTM ASSOCIATED *X2 *X1)
                        (*LTM ASSOCIATED *X4 *X3)
                        (*WM STATE *X2 GOOD)
                        (ABSENT *WM STATE *X4 BAD) ))
=>
        (($BUILD *WM (PROCESS FINDING PATH)
                        (STEP *X1 ON)(GOAL ENERGIZE *Y2))
          ($REMOVE *WM (GOAL ENERGIZE *Y1)) ))
(P-BACK-CONNECTION-INDICATOR-BAD
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *X2)
                (*LTM ISA *X2 INDICATOR)
                (ABSENT *WM AT ENERGY *X2)
                (*LTM AT *X2 *X1)
                (*LTM ISA *X1 COMPONENT)
                (*WM STATE *X1 BAD) ))
=>
        (($BUILD *WM (GOAL TRY AGAIN))
          ($REMOVE *WM (GOAL ENERGIZE *X2)) ))
(P-BACK-BAD-COMPONENT
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *Y1)
                (*LTM ISA *Y1 TERMINAL)
                (ABSENT *WM AT ENERGY *Y1)
                (*LTM CONNECTION *X1 *Y1)
                (*LTM ISA *X1 COMPONENT)
                (*WM STATE *X1 BAD)))
=>
        ((PRINT (LIST '"CAN NOT GET ENERGY TO" *Y1))
          ($REMOVE *WM (GOAL ENERGIZE *Y1))
          ($BUILD *WM (GOAL TRY AGAIN)) ))
(P-VITAL-COMPONENT-BAD
        ($TEST (*WM GOAL FIND PATH) (*WM STATE *X1 BAD)
                (*LTM ISA *X1 VITAL-COMPONENT) ))
=>
        ((PRINT '"VITAL COMPONENT BAD -- DEVICE WILL NOT WORK")
          (PRINT-STATS)
          (STOP-NOW)))
(P-FOUND-ENERGY
        ($TEST (*WM GOAL FIND PATH) (*WM GOAL ENERGIZE *X1)
                (*WM AT ENERGY *X1)) )
=>
        (($REMOVE *WM (GOAL ENERGIZE *X1)
                        (GOAL FIND PATH)(PROCESS FINDING PATH))
          ($BUILD *WM (GOAL BEGIN OPERATION)) ))
(P-FIND-PATH-CONTROL-2
        ($TEST (*WM GOAL FIND PATH)
                (*WM GOAL ENERGIZE *X1)
                (ABSENT *WM PROCESS FINDING PATH)))
=>
```

```
        (($REMOVE *WM (GOAL FIND PATH)(GOAL ENERGIZE *X1))
           (PRINT (LIST '"CAN NOT FIND PATH FROM" *X1))
           (PRINT '"CAN NOT GET DEVICE TO WORK")
           (PRINT-STATS)(STOP-NOW) ))


*** SUBSYSTEM TO OPERATE DEVICE WITH FIRST STEP STRATEGIES ***
  (P-OPERATE-FIRST
  (AND NIL  (EQ *START-STRATEGY NIL)
        ($TEST (*WM STATE DEVICE OFF)
              (*LTM OPERATE-GOAL-STATE *Y1 *Y2)))
  =>
        (($BUILD *WM (GOAL TURN-ON DEVICE)
                    (GOAL ENERGIZE *Y1)
                    (GOAL FIND PATH))))
  (P-BEGIN-INFERENCE
        ($TEST (*WM GOAL BEGIN INFERENCE)
              (*LTM OPERATE-GOAL-STATE *Y1 *Y2)))
  =>
        (($REMOVE *WM (GOAL BEGIN INFERENCE))
         ($BUILD *WM (GOAL ENERGIZE *Y1)
                    (GOAL FIND PATH))))
  (P-START-WITH-TURN-ON
  (AND T (EQ *START-STRATEGY 'TURN-ON-FIRST)
        ($TEST (*WM GOAL START TASK)))
  =>
        (($REMOVE *WM (GOAL START TASK))
          ($BUILD *WM (GOAL TURN-ON DEVICE)
                    (GOAL SET-SELECTOR NEXT)) ))
  (P-START-WITH-TURN-ON-2
  (AND T (EQ *START-STRATEGY 'TURN-ON-FIRST)
        ($TEST (*WM GOAL SET-SELECTOR NEXT)
              (ABSENT *WM GOAL TURN-ON DEVICE)))
  =>
        (($REMOVE *WM (GOAL SET-SELECTOR NEXT))
          ($BUILD *WM (GOAL SET SELECTOR)(GOAL BEGIN INFERENCE)) ))
  (P-START-WITH-SET-SELECTOR
  (AND T (EQ *START-STRATEGY 'SET-SELECTOR-FIRST)
        ($TEST (*WM GOAL START TASK)))
  =>
        (($REMOVE *WM (GOAL START TASK))
          ($BUILD *WM (GOAL SET SELECTOR)(GOAL TURN-ON NEXT)) ))
  (P-START-WITH-SET-SELECTOR-2
  (AND T (EQ *START-STRATEGY 'SET-SELECTOR-FIRST)
        ($TEST (*WM GOAL TURN-ON NEXT)
              (ABSENT *WM GOAL SET SELECTOR)))
  =>
        (($REMOVE *WM (GOAL TURN-ON NEXT))
          ($BUILD *WM (GOAL TURN-ON DEVICE)(GOAL BEGIN INFERENCE))
  ))
  (P-STEP-TURN-ON
        ($TEST (*WM GOAL TURN-ON DEVICE)
              (*WM STATE DEVICE OFF)
              (*LTM ISA *X1 POWER-SWITCH)))
  =>
```

```
        ((PRINT (LIST '>>>OPERATE *X1 'ON))
         (OPERATE-CONTROL *X1 ON)
         (WAIT-FOR-DEVICE)
           ($REMOVE *WM (STATE DEVICE OFF))
           ($REMOVE *WM (GOAL TURN-ON DEVICE))
           ($BUILD *WM (GOAL PROPAGATE ENERGY)) ))
(P-SET-SELECTOR
        ($TEST (*WM GOAL SET SELECTOR)
               (*WM USE *X1 *Y1)))
=>
        ((PRINT (LIST '>>>OPERATE *X1 *Y1))
         (OPERATE-CONTROL *X1 *Y1)
         (WAIT-FOR-DEVICE)
           ($REMOVE *WM (GOAL SET SELECTOR))
           ($BUILD *WM (GOAL PROPAGATE ENERGY)) ))
(P-BEGIN-OPERATION
        ($TEST (*WM GOAL BEGIN OPERATION)
               (ABSENT *WM GOAL STEP NIL)))
=>
        (($BUILD *WM (GOAL STEP A))
         ($REMOVE *WM (GOAL BEGIN OPERATION)) ))
(P-STEP-1
        ($TEST (*WM GOAL STEP A)
               (*WM STEP *X1 *Y1)
               (*LTM ISA *X1 SWITCH)))
=>
        ((PRINT (LIST '>>>OPERATE *X1 *Y1))
         (OPERATE-CONTROL *X1 *Y1)
         (WAIT-FOR-DEVICE)
           ($BUILD *WM (GOAL PROPAGATE ENERGY))
         ($REMOVE *WM (GOAL STEP A))
         ($BUILD *WM (GOAL STEP B)) ))
(P-STEP-1-SKIP
        ($TEST (*WM GOAL STEP A)
               (*WM STEP *X1 *Y1)
               (ABSENT *LTM ISA *X1 SWITCH)))
=>
        (($REMOVE *WM (GOAL STEP A))
         ($BUILD *WM (GOAL STEP B)) ))
(P-STEP-2
        ($TEST (*WM GOAL STEP B)
               (*WM STEP *X1 *Y1)
               (*LTM ISA *X1 SELECTOR)
               (ABSENT *WM GOAL PROPAGATE ENERGY)))
=>
        ((PRINT (LIST '>>>OPERATE *X1 *Y1))
         (OPERATE-CONTROL *X1 *Y1)
         (WAIT-FOR-DEVICE)
           ($BUILD *WM (GOAL PROPAGATE ENERGY))
         ($REMOVE *WM (GOAL STEP B))
         ($BUILD *WM (GOAL STEP C)) ))
(P-STEP-2-SKIP
        ($TEST (*WM GOAL STEP B)
               (*WM STEP *X1 *Y1)
               (ABSENT *LTM ISA *X1 SELECTOR)))
```

```
=>
        (($REMOVE *WM (GOAL STEP B))
         ($BUILD *WM (GOAL STEP C)) ))
(P-STEP-3
        ($TEST (*WM GOAL STEP C)
               (*WM STEP *X1 *Y1)
               (*LTM ISA *X1 BUTTON)
               (ABSENT *WM GOAL PROPAGATE ENERGY)))
=>
        ((PRINT (LIST '>>>OPERATE *X1 *Y1))
         (OPERATE-CONTROL *X1 *Y1)
         (WAIT-FOR-DEVICE)
           ($BUILD *WM (GOAL PROPAGATE ENERGY))
           ($BUILD *WM (EXPECT GOAL ACHIEVED))
         ($REMOVE *WM (GOAL STEP C)) ))
(P-ACHIEVED-GOAL
        ($TEST (*WM EXPECT GOAL ACHIEVED)
               (*LTM OPERATE-GOAL-STATE *X1 *X2)
               (*WM DEVICE *X1 *X2)))
=>
        ((PRINT '">>>SUCCESSFUL OPERATION")
         (PRINT-STATS)(STOP-NOW)
           ($REMOVE *WM (GOAL OPERATE DEVICE)(EXPECT GOAL ACHIEVED)
                           (GOAL PROPAGATE ENERGY))
  ($BUILD *WM (GOAL STEP SHUTDOWN))))


            *** SUBSYSTEM TO SHUT DEVICE DOWN ***
(P-STEP-SHUTDOWN
        ($TEST (*WM GOAL STEP SHUTDOWN)
               (*WM AT ENERGY *X1)))
=>
        (($REMOVE *WM (GOAL STEP SHUTDOWN)(AT ENERGY *X1))
         ($BUILD *WM (GOAL STEP SHUTDOWN-1)) ))
(P-STEP-SHUTDOWN-1
        ($TEST (*WM GOAL STEP SHUTDOWN-1)
               (*WM STEP *X1 *X2)
               (*LTM ISA *X1 BUTTON) ))
=>
        (($REMOVE *WM (GOAL STEP SHUTDOWN-1)(STEP *X1 *X2))
           (OPERATE-CONTROL *X1 OFF)
         (WAIT-FOR-DEVICE)
         ($BUILD *WM (GOAL STEP SHUTDOWN-2)) ))
(P-STEP-SHUTDOWN-2
        ($TEST (*WM GOAL STEP SHUTDOWN-2)
               (*LTM INITIAL-STATE *X1 *X2)
               (*WM STEP *X1 NIL)
           (*LTM ISA *X1 SELECTOR)))
=>
        (($REMOVE *WM (STEP *X1 NIL)(GOAL STEP SHUTDOWN-2))
         (OPERATE-CONTROL *X1 *X2)
         (WAIT-FOR-DEVICE)
         ($BUILD *WM (GOAL STEP SHUTDOWN-3)) ))
(P-STEP-SHUTDOWN-3
        ($TEST (*WM GOAL STEP SHUTDOWN-3)
```

```
                        (*LTM INITIAL-STATE *X1 *X2)
                        (*LTM ISA *X1 SWITCH)))
        =>
                ((SREMOVE *WM (STEP *X1 NIL)(GOAL STEP SHUTDOWN-3))
                 (OPERATE-CONTROL *X1 *X2)
                 (WAIT-FOR-DEVICE)
                 ($BUILD *WM (GOAL STEP SHUTDOWN-LAST)) ))
        (P-STEP-SHUTDOWN-LAST
                ($TEST (*WM GOAL STEP SHUTDOWN-LAST) ))
        =>
                (($REMOVE *WM (GOAL STEP SHUTDOWN-LAST))
                 (STOP-NOW)))


*** SUBSYSTEM TO FIGURE OUT WHAT TO DO IF UNSUCCESSFUL ATTEMPT ***
        (P-DID-NOT-WORK
                ($TEST (*WM EXPECT GOAL ACHIEVED)
                        (ABSENT *WM GOAL PROPAGATE ENERGY)
                        (*LTM OPERATE-GOAL-STATE *X1 *X2)
                        (ABSENT *WM DEVICE *X1 *X2) ))
        =>
                ((PRINT '"DID NOT WORK WHEN EXPECTED")
                   ($REMOVE *WM (EXPECT GOAL ACHIEVED))
                 ($BUILD *WM (GOAL PROPAGATE ENERGY)(GOAL DIAGNOSE PROBLEM))
        ))
        (P-DIAGNOSE-PROBLEM
                ($TEST (*WM GOAL DIAGNOSE PROBLEM)
                        (ABSENT *WM GOAL PROPAGATE ENERGY)
                        (*LTM CONNECTION *Y1 *X1)
                        (*LTM ISA *Y1 TERMINAL)
                        (*LTM ISA *X1 COMPONENT)
                        (*WM AT ENERGY *Y1)
                        (ABSENT *WM AT ENERGY *X1)
                        (*LTM ASSOCIATED *X1 *X2)
                        (*WM STEP *X2 *X3) ))
        =>
                (($BUILD *WM (STATE *X1 BAD)(GOAL TRY AGAIN))
                 ($REMOVE *WM (GOAL DIAGNOSE PROBLEM))))
        (P-DIAGNOSE-VITAL-COMPONENT-BAD
                ($TEST (*WM GOAL DIAGNOSE PROBLEM) (*WM STATE *X1 BAD)
                        (*LTM ISA *X1 VITAL-COMPONENT) ))
        =>
                ((PRINT '"VITAL COMPONENT BAD -- DEVICE WILL NOT WORK")
                   (PRINT-STATS)
                   (STOP-NOW)))
        (P-STEP-TRY-AGAIN
        (AND NIL  ($TEST (*WM GOAL TRY AGAIN)
                        (*WM AT ENERGY *X1)))
        =>
                (($REMOVE *WM (GOAL STEP TRY-AGAIN)(AT ENERGY *X1))
                 ($BUILD *WM (GOAL STEP TRY-AGAIN-1)) ))
        (P-STEP-TRY-AGAIN-B
                ($TEST (*WM GOAL TRY AGAIN)
                        (*WM STEP *X1 *X2)))
        =>
```

```
        (($REMOVE *WM (STEP *X1 *X2))
         ($BUILD *WM (GOAL STEP TRY-AGAIN-LAST)) ))
(P-STEP-TRY-AGAIN-1
        ($TEST (*WM GOAL TRY AGAIN)
               (*WM DEVICE *X1 ON)
               (*LTM ISA *X1 BUTTON) ))
=>
        ((OPERATE-CONTROL *X1 OFF)
         (WAIT-FOR-DEVICE)))
(P-STEP-TRY-AGAIN-2
        ($TEST (*WM GOAL STEP TRY-AGAIN-2)
               (*LTM INITIAL-STATE *X1 *X2)
               (*WM STEP *X1 NIL)
            (*LTM ISA *X1 *X3)
               (*LTM ISA *X3 CONTROL)))
=>
        (($REMOVE *WM (STEP *X1 NIL)(GOAL STEP TRY-AGAIN-2))
         (OPERATE-CONTROL *X1 *X2)
         (WAIT-FOR-DEVICE)
         ($BUILD *WM (GOAL STEP TRY-AGAIN-LAST)) ))
(P-STEP-TRY-AGAIN-3
        ($TEST (*WM GOAL STEP TRY-AGAIN-3)
            (*LTM INITIAL-STATE *X1 *X2)
            (*WM STEP *X1 NIL)
            (*LTM ISA *X1 SWITCH)))
=>
        (($REMOVE *WM (STEP *X1 NIL)(GOAL STEP TRY-AGAIN-3))
         (OPERATE-CONTROL *X1 *X2)
         (WAIT-FOR-DEVICE)
         ($BUILD *WM (GOAL STEP TRY-AGAIN-LAST)) ))
(P-STEP-TRY-AGAIN-3-SKIP
        ($TEST (*WM GOAL STEP TRY-AGAIN-3)
               (*LTM INITIAL-STATE *X1 *X2)
               (ABSENT *WM STEP *X1 NIL)
               (*LTM ISA *X1 SWITCH))
=>
        (($REMOVE *WM (GOAL STEP TRY-AGAIN-3))
          ($BUILD *WM (GOAL STEP TRY-AGAIN-LAST)) )
(P-STEP-TRY-AGAIN-LAST
        ($TEST (*WM GOAL STEP TRY-AGAIN-LAST)
            (*LTM OPERATE-GOAL-STATE *X1 *X2) ))
=>
        (($REMOVE *WM (GOAL TRY AGAIN)(GOAL STEP TRY-AGAIN-LAST))
         ($BUILD *WM (GOAL ENERGIZE *X1)(GOAL FIND PATH)(GOAL
PROPAGATE ENERGY)) ))
```

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