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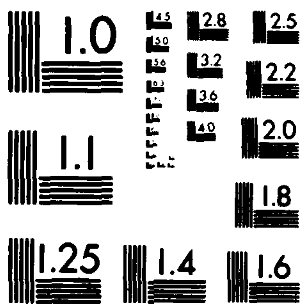

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AN INVESTIGATION OF MENTAL CODING MECHANISMS AND HEURISTICS USED IN ELECTRONICS TROUBLESHOOTING

MARK M. BURROUGHS, LT COL, USAF

APRIL 1980

FINAL REPORT - DISSERTATION

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This research is comprised of four separate but related efforts, which are: A Review of Troubleshooting Literature; An Outline of a Theoretical Description for a Process Model; A Mental Encoding Experiment Relating to Troubleshooting; and An Experiment on Heuristics Used in Troubleshooting. In all, some 33 publications pertaining to behavioral aspects of troubleshooting were reviewed, in addition to over 60 other papers dealing with mental encoding and with heuristics. A theoretical description of a process model problem space in

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) mathematical terms was developed and outlined quantitatively, using tensor analysis. Next, a heuristical process model, which is the qualitative counterpart of such a mathematical model was described. Finally, a discussion of the relative merits of each model, in view of man's cognitive limitations, was presented.

The mental encoding experiment was designed to study the coding mechanisms used by technicians of varying skill in working with circuit schematics. Employing Air Force technicians from different skill classifications, it was shown that variations in their encoding procedures could be identified and cataloged.

The heuristic experiment identified some of the heuristics used by skilled troubleshooters in the course of troubleshooting. A heuristic is a mental rule of thumb which may aid in finding a solution to a problem, but which does not guarantee a solution. The specific troubleshooting instance investigated in this experiment involved the repair of defective television receivers by professional electronics technicians.

AN INVESTIGATION OF MENTAL CODING MECHANISMS

AND HEURISTICS USED IN ELECTRONICS TROUBLESHOOTING

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF ENGINEERING

UNIVERSITY OF OKLAHOMA

April 1980

Lt Col Mark M. Burroughs
Department of Mathematical Sciences
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PREFACE

The research reported herein was conducted for the Air Force Institute of Technology under the sponsorship of the United States Air Force Academy. Of primary interest are the implications of the results with regard to training and evaluation methods currently used by Air Training Command in its technical training school curriculums.

ABSTRACT

This research is comprised of four separate but related efforts, which are:

(1) A Review of Troubleshooting Literature;

(2) An Outline of a Theoretical Description for a Process Model;

(3) A Mental Encoding Experiment Relating to Troubleshooting, and

(4) An Experiment on Heuristics Used in Troubleshooting.

In all, some 33 publications pertaining to behavioral aspects of troubleshooting were reviewed, in addition to over 60 other papers dealing with mental encoding and with heuristics.

A theoretical description of a process model problem space in mathematical terms was developed and outlined quantitatively, using tensor analysis. Next, a heuristical process model, which is the qualitative counterpart of such a mathematical model was described. Finally, a discussion of the relative merits of each model, in view of man's cognitive limitations, was presented.

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ACKNOWLEDGEMENTS

The United States Air Force has provided the means by which I was able to participate in graduate education programs, and I am appreciative of those opportunities.

My co-chairmen were particularly instrumental in seeing this effort completed. Dr. Alan L. Dorris introduced me to the precepts of decision theory and stood patiently by while I inched forward. Dr. LaVerne L. Hoag stepped in when it appeared that I might falter and provided the calm reassurance and skillful guidance which allowed me to continue the effort.

The remaining members of my committee, Dr. Robert A. Shapiro, Dr. Bobbie L. Foote and Dr. Larry K. Michaelsen also deserve praise and credit, as each contributed to my program in his own unique way.

Certain other individuals made contributions which deserve special acknowledgement. My father-in-law, John A. Bennett, Jr., aided me in the conceptual phase of this effort by providing insights from his extensive experience in the maintenance field. Lt. Col. Thomas Bohan provided the interface between myself and the 3rd Combat Communiciations Group, AFCS, Tinker AFB, Oklahoma, where the first experiment was conducted. Credit for the successful completion of that experiment must be given for the most part to Lt. Col. Phillip Lurie and to CMSgt. Lee Roy Henkes. The second experiment owes its success to two professional electronics technicians from the Colorado Springs, Colorado area, Mr. Dave Berry from AA TV Service, and Mr. Dave Hartzler from All American TV.

The support and understanding of my wife, Ann, and children, John, Scott and Cynthia, are also deserving of special mention. They, in fact, gave more to this effort than did I. My mother, Edna, deserves special recognition too, as she continually encouraged and supported me during my early educational endeavors.

Finally, I am indebted to Donna Weiss of the Frank J. Seiler Research Laboratory at the United States Air Force Academy for her skillful performance in typing this manuscript.

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CHAPTER I

INTRODUCTION AND CONCEPT OVERVIEW

In 1971, Slovic and Lichtenstein published an exhaustive review of the literature dealing with the modeling of human decision making (problem solving, choice, or judgment). Briefly, they concluded that:

> The evidence to date seems to indicate that subjects are processing information in ways fundamentally different ... (from those of traditional Bayesian and regression approaches) ... (and as a result) ... we will have to develop new models and different methods of experimentation.

They went on to suggest the technique of cognitive process modeling as a promising strategy for the development of a theory of human judgment.

With these comments in mind, the purpose of the research outlined below will be to employ a process model approach in order to investigate the mental coding mechanisms, as well as the heuristics, or mental rules of thumb, which are used in an applied problem setting, that of electronics troubleshooting. These coding mechanisms and heuristics are viewed as a means by which the troubleshooter can simplify the information relating to the problem under consideration, and thereby reduce that problem to one of cognitively manageable proportions. This study will therefore focus on mental coding patterns used by troubleshooters of varying skill. It will also focus on the use of groups of heuristics, or heuristical programs, by highly skilled troubleshooters during different phases or stages of the troubleshooting process.

In addition to the goals outlined above, there are two other goals of this study. The first of these latter goals is to summarize the past research relating to electronics troubleshooting. Unlike some of the more active fields, such as Bayesian decision theory, where frequent literature reviews are the rule, rather than the exception, there has not been a thorough survey of the literature on electronics troubleshooting for at least ten years. Therefore, a review of pertinent literature will be included in this study. The second of these latter goals will be to propose a mathematical model which will relate heuristics to earlier concepts of decision theorists. While the overall study will be process model oriented, rather than oriented toward a mathematical model, it nevertheless seems appropriate to speculate theoretically as to what general form such a mathematical model might take.

The setting for the majority of the study will be the electronics maintenance area of the 3rd Combat Communications Group, Air Force Communications Systems Command, Tinker Air Force Base, Oklahoma. This unit has approximately 450 electrical maintenance technicians assigned to it, of which about 375 directly participate in the care and repair of the electronic equipment for which the group has responsibility. The equipment spans the electronics spectrum from simple radio receivers to elaborate radar tracking and navigation devices.

The emphasis on the use of operational settings for this research was intentional. Numerous laboratory studies relating to electronics troubleshooting have been conducted in the past. These studies have typically characterized electronics troubleshooting as a complicated process, involving the collection, handling, and analysis of large amounts of information. To assist the informationally beleaguered troubleshooter, many such studies concluded by recommending the employment of various types of performance aids. Other alternatives were largely ignored. These studies helped to extend the frontiers of knowledge concerning the use of performance aids by minimally skilled technicians, but they did little to clarify the relevant information handling and processing differences between troubleshooters of varying skill. It is important that such differences be studied, as they likely will lead to a more definable understanding of what constitutes skill in troubleshooting. Also, the identification of essential differences can lead to better screening and training procedures for technician trainees.

Acquisition of troubleshooting skill typically takes anywhere from three to ten years of experience in electronics. This has resulted in a distribution of troubleshooting skill within most maintenance organizations that ranges from beginner, or entry level, troubleshooter to that of highly skilled troubleshooter. While there are many variables which relate to one's placement within such a distribution, only the two variables mentioned earlier, mental coding mechanisms and use of heuristics, will be emphasized in this study. These two aspects will be studied and analyzed in detail and the results are veiwed as the major contribution of this research. Details of the methodology to be used will be provided below in the appropriate chapter.

To summarize, the following are the objectives of this study:

Review and summarize the relevant literature on electronics troubleshooting.

Provide a theoretical mathematical model for a troubleshooting problem space, and relate it to earlier decision models and to a heuristic model.

Investigate the differences in mental coding abilities of electronics troubleshooters of varying skill levels.

Study the heuristic procedures used by highly skilled troubleshooters during various stages of the troubleshooting process.

The next chapter will relate to the first objective above and will present a review of pertinent literature.

CHAPTER II

REVIEW OF PAST RESEARCH

II.1 A Selective Review of Behavioral Decision Theory

The study of behavioral decision theory is a vast and expanding field. In the past few years, over a thousand books, articles and technical reports have been published, describing how people make decisions and how they can be helped to make better decisions (Slovic, Fischhoff & Lichtenstein, 1977). In what follows below, a selective review of the field, as it pertains to the study of mental processes used in troubleshooting, is presented.

The emphasis in this research will be on the descriptive, rather than on the normative, aspects of troubleshooting. With this in mind, the next step is to consider where such a study might be cataloged within the broad framework of behavioral decision theory. In the review article on behavioral decision theory by Slovic, Fischhoff and Lichtenstein cited above, five subcategories are proposed. These subcategories can then be further divided into their descriptive and normative aspects. The list includes probabilistic judgment models, such as with Bayesian decision making; regression approach models, such as with linear regression and ANOVA; risky choice models, such as with subjective expected utility; dynamic decision models, such as with dynamic programming; and general choice models, such as with process description and heuristics.

A thorough survey by Slovic and Lichtenstein (1971) reviewed past research in the Bayesian and Regression approaches and compared the two models. The Bayesian paradigm uses Bayes' theorem in studying how people perceive, process and evaluate the probabilities of uncertain events. The regression paradigm uses analysis of variance, as well as conjoint, measurement and multiple regression techniques to develop algebraic models that describe the method by which individuals weight and combine information. As is evident, the basic differences between the two approaches are that with the Bayesian approach, the decision process is formulated in the context of conditional probabilities and Bayes' theorem; while with the regression approach, the decision process is formulated in the context of the general linear hypothesis. No attempt will be made here to comment on the various results of Bayesian research. To illustrate the complexity and diversity of activity in this area, a more recent bibliography on Bayesian statistics and related behavioral work than the review article just cited, included 106 specialized books, 1322 journal articles, and about 800 other publications (Houle, 1975). While the material on regression models is equally voluminous and well summarized by the review aticle mentioned above, one additional reference deserves comment. An important and insightful article as to why linear models provide excellent fits was authored by Dawes and Corrigan (1974). They observed that linear models have typically been applied in situations in which the predictor variables are monotonically related to the criterion (or can easily be rescaled to be monotonic), and in which there is error in the independent and dependent variables. They demonstrated that these conditions insure good fits by linear models, regardless of whether the weights in such models are optimal. Hence, the linearity observed in judges' behaviors may be reflecting only a characteristic of linear models, and not a characteristic of human judgment. Neither the Bayesian nor the regression approaches will be pursued further in this research.

Risky choice models have enjoyed a wide following, due in part to the availability of a convenient research paradigm, choices among gambles; and in part due to a normative theory, the subjective expected utility (SEU) model, against which behavior could be compared. The SEU model is formulated on the assumption that people behave as though they maximized the sum of the products of utility and probability. The credit for formalization of the model is generally attributed to Savage (1954) and Edwards (1955). The former author identified a number of rules or axioms which should be satisfied before the model is applied to a given situation. It is frequently the case, however, that the axioms are not satisfied, and hence the SEU model should not be applied. Because of these problems with some of the theory's fundamental assumptions, as evidenced by recent data, even strong supporters have agreed that reevaluation of the theory is in order (MacCrimmon & Larsson, 1976). Risky choice models will not be utilized in the investigation of trouble-shooting.

Dynamic decision models apply to the study of tasks in which decisions are made sequentially in time; the task specifications may change over time, either independently or as the result of previous decisions; information available for later decisions may be contingent upon the outcomes of earlier decisions; and implications for any decision may reach into the future (Rapoport, 1975). With a few exceptions, this approach has not drawn much interest. There are several possible reasons for this. One is that models of this type are characterized by a high degree of mathematical sophistication, which might deter some researchers. Another is the significant on line computer and long start up times which are generally required. More importantly, however, is that these models are so complex and require so many assumptions that the interpretation of experimental results is typically ambiguous (Slovic, Fischhoff & Lichtenstein, 1976). As with the previous models summarized above, a dynamic programming decision making model will not be used in this research.

The study of general choice models is still in the foundational stages. In their introduction to two volumes on contemporary developments in the field of mathematical psychology, Krantz, et al. (1974) noted that accumulation of knowledge and establishment of laws of choice behavior have been slow to emerge. Other researchers have observed that this field is in a state of transition, moving away from the assumption that choice is expressible as a monotone function of scale values or utilities of the alternatives (Slovic, Fischhoff & Lichtenstein, 1976). Many present efforts are aimed at developing concepts which describe choice in terms of information processing phenomena. Slovic, Fischhoff and Lichtenstein go on to trace the recent attention being given to this area and to draw conclusions regarding the state of the field at the present time.

> In 1971 ... only a handful of studies ... looked at subjects' information processing heuristics. Since then, rather than simply comparing behavior with normative models, almost every descriptive study ... has attempted to determine how the underlying cognitive processes are molded by the interaction between the demands of the task and the limitations of the thinker.

> Researchers appear to be searching for heuristics or modes of processing information that are common to a wide domain of subjects and choice problems. However, they are finding that the nature of the task is a prime determinant of the observed behavior.

These comments are suggestive of the approach to be used in this research effort on electronics troubleshooting. Specifically, the heuristics which troubleshooters use to simplify the information environment in which they function will be identified, and the usage patterns of heuristics employed during various phases of the troubleshooting process will be studied. However, before initiating this study, the review and analysis of past research will be continued. The next portion of this review will focus on literature relating to mental coding.

II.2 A Review of Research Relating to Mental Coding

Human information processing involves keeping track of incoming stimuli and bringing such input into contact with already stored material. It has been suggsted that sensation, perception, memory, and thought can be considered to be along a continuum of cognitive activity (Haber, 1969). Mental coding is an operation which has been described as a sensory reception of a stimulus along with a perceptual process that involves the interaction of sensory functions and the cortex or memory (O'Keefe, 1976). Therefore, certain of these elements of the cognitive continuum will be discussed below in more detail.

Several researchers have suggested that far more information is transmitted to the brain by the sense organs than is actually perceived (Alpern, Lawrence & Wolsk, 1967; Welford & Houssidas, 1970). They report further that the information that is perceived is both grouped and ordered. What is involved is a selective filtering operation by the brain on the sensory inputs. At times, less than the full amount of stimulus information needed for ongoing activities is passed through by this operation. When this occurs, it can be manifested by such actions as pausing too long at a red light after it has turned from red to green, or missing a turn along a familiar route. The purpose of the selective filtering operation is to provide economy in handling the incoming information. Thus, attention is paid to some information, while the rest is ignored for the most part.

Due to the interdependence of sensation and perception, there are different viewpoints as to what is sensed and what is perceived. Berkeley (1910) advanced the view that visual sensations themselves do not give much knowledge about the world, but that they do give a basis to use in arriving at correct interpretations. He further made the point of distinguishing between perception and sensation, since what is perceived can be different from the physical stimulus. A more recent investigator has supported this distinction between perception and sensation (Rock, 1975). He found that they were not the same, but that they were still interdependent and were influenced by such factors as motivation, expectations, and previous experiences.

A perceptual process has been defined as all of those processes concerned with the translation of stimulus energy falling on a receptor surface into the reports of experience, responses to that stimulation, and memory persisting beyond the termination of that stimulation (Haber, 1969). Haber assumed that a perceptual response was not an immediate consequence of stimulation, but one which had gone through a number of stages or processes, each of which took time to pass through. He further suggested that this processing is limited by the capacities of the information handling channels, the information content of the stimulus, and the prior experiences and current condition of the perceiver. In addition, these perceptual processes cannot be studied or analyzed independently of the memory processes, since he believed recoding and preservation of information occur at all stages of information processing.

This viewpoint was supported by Norman (1969), who studied the information flow as it entered an individual and was processed by the nervous system. A simplified picture of this flow is as follows: The senses provide inputs as to the state of the world, and these sensory inputs are interpreted and their psychological content is extracted. In order to do this, the incoming signals must be processed and the interpretations made on the basis of past experience and accumulated knowledge. Thus, memory must play an active role here, since it can provide the necessary information about the past that is used in the interpretation process of sensory inputs. Further, it is necessary to have a temporary storage capability to store the incoming information while it is being interpreted. This temporary storage capability is what is known as short term memory.

As mentioned above, human information processing involves keeping track of incoming stimuli and associating this input with information which has already been stored. In general, short term memory (STM) refers to the storage capacity available to perform the comparison of incoming stimuli with already stored material. It has been observed that the term STM has been used to refer to three distinct features of such a memory system (Fitts & Posner, 1967). One sense in which STM has been used is as a relatively direct representation of a stimulus, as opposed to a memory system which involves symbolic recoding, like storing the name or description of the stimulus. This direct representation of information without verbal encoding is useful in explaining the learning and retention of many skills. It is commonly agreed that such representational storge exists, at least in the form of visual after images, for very short periods of time (Melton, 1963). Representational storage has generally been categorized as a very early stage in information processing, which decays within a second or two, unless coding takes place. This first type of definition of STM has been characterized as being a sensory one in which the stimuli may not reach the conscious level of the individual (Fitts & Posner, 1967). They have described this level as follows:

> At the neuro-physiological level, electrical phenomena associated with sensory stimulation of short duration, such as a click or a 1 millisecond flash, persist for at least several hundred milliseconds after the event.

The second sense in which STM has been used is as the concept of an operational memory (Hunter, 1964). This refers to information stored in long term memory which has been activated in order to solve a particular problem. An example would be the adding together of the digits of one's telephone number. Here, it would be necessary to keep available the stored digits of the phone number during the course of the summation operation.

The third sense in which STM has been used relates to the interval between presentation and recall. This has been defined as a system which loses information rapidly in the absence of sustained attention (Fitts & Posner, 1967). For example, to aid in retaining information, a person could say to himself aurally what the information is, whether it be vocally or subvocally.

For the purposes of this research, the second definition seems most applicable. That is, STM will be looked at as an operational concept, although elements of the first and third definitions also apply to some extent.

It is the view of some researchers today that there is a buffer store, a short term memory, and a long term memory, which form a three stage system (Broadbent, 1971). Other researchers have proposed a two stage system, consisting of a short term memory and a long term memory (Newell & Simon, 1972). In the latter's view, the buffer stage is part of the STM. Stimuli from items to be screened by the memory system are received from the sense organs and are continuously recirculated between the buffer storage area and the limited capacity STM storage area. A selection process then occurs which determines which of these elements are retained in STM and which elements are lost from buffer storage. Miller (1956) reported that information content is not a critical factor in this selection process, due to chunking and coding operations which take place. Broadbent (1971) referred to coding as a further process, and noted that if an item has been presented by the senses, it will enter buffer storage, but unless some further process takes place within a second or two, the item will be lost. For this research, the view of Newell and Simon will be adopted, and memory will be considered to be a two stage system, consisting of STM and LTM. STM will include the buffer stage suggested by Broadbent. The material which follows will concentrate on some specifics of STM, chunking and coding.

Newell and Simon (1972) proposed a human information processing model which makes use of the analogy between computer processing and human information processing. The authors of this model caution that the use of such an analogy does not imply that humans make decisions and solve problems like computers. Rather, their intent in presenting such a model is to provide a means of understanding how individuals process information in order to reach decisions and solve problems. The Newell-Simon model of human information processing is shown in Figure 2.1 below.

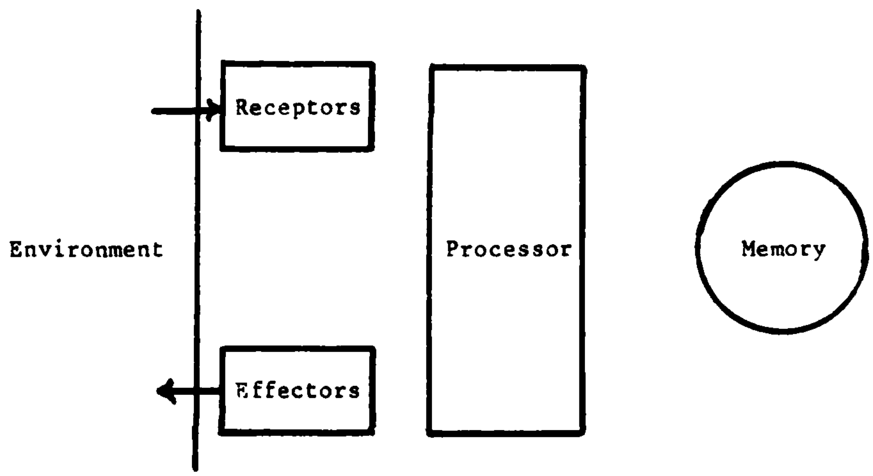

Figure 2.1 General structure of a human information processing system.

The detailed description of this model contained in the reference cited above has been summarized by Davis (1974). The human information processing system is considered to consist of receptors which receive input from the environment, a processor, memory, and motor output into the environment via the effectors. A receptor is a sense organ, a nerve ending which is specialized for the reception of stimuli. An effector is a muscle, gland, etc., which is capable of responding to the system's nerve impulses or other stimuli. Three different memories are involved. These are long term memory, short term memory, and external memory. The LTM is thought to have essentially an unlimited capacity. It requires only a few hundred milliseconds to recall information from the LTM. This is called read time. However, the time necessary to commit information to LTM, called write time, is much longer, and is on the order of 50 to 100 seconds, for example, to memorize a ten digit number. STM is thought to be a component of the processor. It is believed to be small with regard to capacity, and able to hold five to seven chunks of information. The process of committing information to STM and recalling information from STM appears to be relatively fast in comparison with LTM times. Further, although the capacity of STM appears to be about seven chunks of information, only two chunks can be retained in STM during a time period when some different task is being performed. This has suggested that STM is used for input and output processing. External memory consists of external media, such as books, paper or displays. The write (commit) time for external memory is frequently less than the time required to commit information to LTM, but the read (recall) time can be relatively slow.

The processor can perform only one task at a time, and therefore is serial in nature. It consists of three components: the elementary processor, the STM, and the interpreter. The elementary processor contains a set of elementary information processes or eip's. These can be thought of as extremely basic functions, such as the replacement of one value with another (e.g., x = 2.5). The STM, described above in some detail, holds the input and output symbol structures of the eip's. The interpreter determines the appropriate eip's to be executed as well as their sequence of execution, that is, the particular program to be used for the decision making or problem solving exercise at hand. The relationships between LTM, the processor, and the external memory in the

Newell-Simon model of human information processing are summarized in Figure 2.2 below. Simon and his colleagues have shown how computer programs based on such a model can be constructed which show how the simple mechanisms described above can be organized into complex thought processes (Lewin & Zwany, 1976).

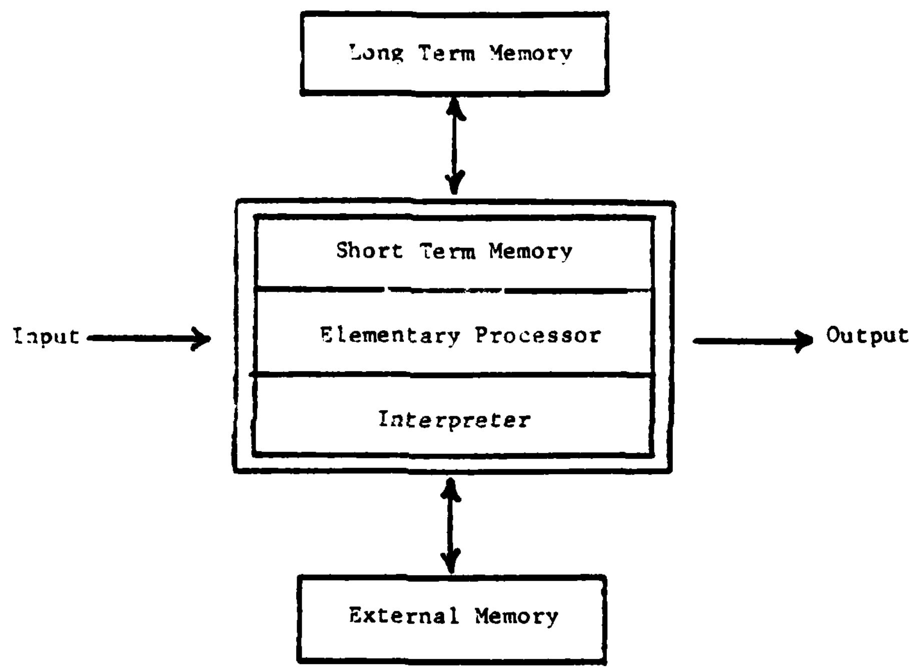

Figure 2.2 The three memories of the Newell-Simon model.

Within the context of the above model, chunking and then coding can be meaningfully discussed. Norman (1969) suggested that an individual's apparent memory span could be improved by recoding or chunking information. Chunking was a concept developed earlier by Miller (1956) as a result of his investigations of human memory capacity. Miller concluded that STM appeared to be limited by the number of items, rather than by the information content of these items. Thus, he suggested that the memory span could be increased by a more efficient grouping of items, in effect resulting in fewer things to be remembered. For example, it would be difficult to recall a random sequence of 12 binary digits which were presented for five seconds. However, the task would be considerably simplified if the digits were chunked into four successive single Arabic digits. Vernon (1952) held the view that individuals chunk or group unconsciously in an attempt to impart meaning. He offered the following observation:

> With any perception process there is a spontaneous tendency on the part of the observer to segregate the incoming sensory patterns into groups. The observer segregates the visual field into separate comprehensible parts.

As stated above, one of the purposes of this research will be to study some of the mental grouping patterns of skilled electronics trouble-shooters. Prior to concentrating on that task, however, some further comments on coding will be given below.

Haver (1969) suggested that the first stage in the memory process involves translating external stimulation into some sort of internal code. This encoding takes place prior to an item's entry into a conscious level. Norman (1969) discussed the process of encoding and offered the following observation:

> The differences between our ability to retain things in immediate memory result from differences in the types of information processing involved. When we try to make an absolute judgment, we are trying to encode information. That is, we are trying to categorize the stimulus input according to previously learned classifications.

Norman continued by writing that the encoded information is the material which is stored. He conjectured that the apparent memory span can be improved by recoding or chunking information, as defined by Miller and described above. Broadbent (1971) argued that the encoding process, labeled classification by him, occurs during perception of an item. Hence, how the item is perceived depends in part upon how it was coded.

These conclusions concerning mental encoding could account for frequent reports that, for skilled individuals, the appropriate object which they are seeking amidst a collection of homogeneous objects seems to pop out from the background (Hyman, 1976). In some experiments, for example, the background is composed of letters, while the target is one or more letters in abnormal orientation (mirror image, upside down, etc.). With some practice, the target letter seems to pop out almost instantly when presented with a test array. But when the target is a letter or unfamiliar object in normal orientation against a background of letters which are all in abnormal orientation, the task is enormously more difficult. It would appear that individuals notice the unusual or unfamiliar, so that should the background be composed of unfamiliar elements, one has great difficulty in disregarding it.

The above has relevance to extracting meaningful and important information from a larger body of information. Experiments have shown that such a task is more easily accomplished when the material to be abstracted is unfamiliar, but embedded in a familiar or coherent background (Hyman 1976). However, the task is more difficult when the material is familiar and coherent, but is embedded in a background which is unfamiliar or incoherent. These results suggest a possible explanation as to how successful individuals are able to selectively filter a large body of information and attend to only that part which is relevant to their task.

Other researchers have approached the issue of information encoding in a somewhat different manner. These generally involve comparing highly skilled individuals with those of lesser skill in the same task. Some of these experiments involved sight reading in music (Hyman, 1976) while others looked at chess grandmasters (DeGroot, 1966; Chase & Simon, 1973). It was found that the expert was able to work with chunks of larger size than the non-expert. Chase and Simon, for example, found that the master did not excel in the number of chunks he could handle simultaneously in STM. That is, the grandmaster and players of lesser skill have the same STM span of five to seven chunks. What makes the difference, however, is that the grandmaster utilizes chunks containing more information.

This can be illustrated by a simple experiment which DeGroot and others have conducted. A subject is presented with a pattern of pieces on a chessboard for a period of five seconds. If the pieces represent a position from an actual game, the grandmasters can generally reproduce the entire pattern without error (24 pieces placed correctly). Ordinary players can generally reproduce only about six pieces correctly. However, if the pattern is a random one, the grandmaster and the ordinary player perform equivalently, with each placing approximately six pieces correctly. The conclusion is that something about his knowledge and mastery of the game enables the grandmaster to operate with chunks comprised of four units each (four pieces embedded in each of six chunks equals 24 pieces), when the pattern is one from an actual chess game. With a random chess pattern, the grandmaster is no better than the ordinary player at encoding, and must use an entire chunk for each piece. Simon and others have sugggested that it is the encoding mechanisms which account for part of the grandmaster's superiority in the game of chess.

As stated previously, this research effort will study some of the encoding mechanisms utilized by electronics troubleshooters of varying skill levels. The research outlined above suggests that these coding mechanisms may account for part of an individual's success as a troubleshooter. An additional factor which might also account for part of this success is the employment of heuristics, or mental rules of thumb, which enable one to efficiently sift through complex information presentations and utilize only that which is relevant to the immediate problem. To lay the groundwork for the heuristical portion of the research, a literature review of this topic will be presented next.

II.3 A Review of Research Relating to Heuristics

In their current review of the literature on behavioral decision theory, Slovic, Fischhoff and Lichtenstein (1976) commented on the increased attention being paid to the role of heuristics in human information processing. They pointed out that much of the impetus for this change can be attributed to Tversky and Kahneman's endeavors with three judgmental heuristics, representativeness, availability and anchoring. While these are always efficient and sometimes valid, they can lead to biases that are large, well entrenched and important in their implications for decisionmaking.

These comments reflect a growing trend by reseachers to turn to the study of heuristics as a means of understanding how people deal with complex problems involving large amounts of information which must be processed during the solution period. The material below will outline some of the results of this research, and will lay the groundwork for the investigation of heuristics used by electronics troubleshooters.

Before continuing further, it might be helpful to define the term heuristic. Some authors have defined heuristic as a process that may solve a given problem, but offers no guarantee of doing so (Newell, Shaw & Simon, 1963). They go on to comment that as a noun, heuristic is rare and generally means the art of discovery. The adjective heuristic is defined by Webster as: serving to discover or find out. It is in this sense that it is used in the phrase heuristic process or heuristic method. For conciseness, the use of heuristic as a noun is synonymous with heuristic process. No other English word appears to have this meaning.

As a further means of clarifying the meaning of heuristic, it could be contrasted with an algorithm (Taylor, 1965). An algorithm is a process for solving a problem which guarantees a solution in a finite number of steps if the problem has a solution. An example of a very simple algorithm would be that for obtaining temperature on the Centigrade scale when the value for a Fahrenheit scale is known: Subtract 32 and multiply the result by 5/9. Another example would be finding the maximum of a function for which the equation is known: Take the first derivative, set it equal to zero, solve for x, and then continue with one of three alternate procedures (look at the derivative's slope, take the second derivative, or plug in trial values).

A heuristic, on the other hand, is a process for solving a problem which may aid in the solution of it, but offers no guarantee of doing so. One of the earliest examples of an application of a heuristic process was developed by the mathematician Polya (1945). He presented some heuristics useful in problem solving at the level of high school mathematics. One heuristic he described, for example, is that of working backwards:

Begin with the result you wish to obtain and work backwards step by step toward that which is given. This same heuristic was described earlier by Dunker (1945), who believed that it was generally useful in problem solving. More recent evidence, however, suggests that it will be an effective aid in the solution for certain classes of problems, but it may be detrimental if employed in attacking other problems (Newell, Shaw & Simon, 1962). A familiar and widely employed heuristic is the use of an analogy: Look for an analogy between the situation with which one is attempting to deal and some other situation with which one has successfully dealt in the past. This may aid one in attacking the new problem. In his two volume work, Polya (195') dealt at greater length with the role of heuristic procedures in mathematical problem solving.

For more varied kinds of problems, other heuristics have been devised. One example of a more generally useful heuristic is what is called the means-end analysis: One compares what one has with what one wishes to obtain; the difference between the two is identified; then an operation to reduce the difference is found and carried out; one repeats this procedure until the problem is solved. Another generally useful heuristic is the one called make a plan: Find a problem which is similar to that which one is attempting to solve, and which is also simpler; solve the simpler problem; use the procedures successful in solving the simpler problem as a plan for solving the more complex problem.

Heuristics applied to a specific activity, that of chess, were investigated by Simon and Simon (1962). This paper focused on the supposed insightful powers of discovery and proditious memories of chess masters and grandmasters. The researchers were able to demonstrate that much of the chess problem solving by these persons was done through the use of highly selective and powerful heuristic processes. These heuristic programs enabled the skilled player to bypass the enumerative process used by lesser players, and to concentrate on selective strategies. It was concluded in this study that expert chess players discover winning combinations because their cognitive processes incorporate these powerful and selective heuristics, not because they think faster or memorize better than other people. Since these findings are important to the present research, some further comments relating to them are appropriate.

As was mentioned, the principle finding of the Simon and Simon article was that, with regard to the game of chess, successful problem solving is based on highly selective heuristic programs, rather than on prodigies of memory and insight. Before considering such programs in detail, however, a few of the quantitative aspects of a typical chessboard situation will be described.

Looking at a chessboard, it is difficult to appreciate the total complexity of the game. There are only 64 squares on the board, and 32 pieces. Yet there are 10^{43} board positions possible and more than 10^{120} possible games. To put these numbers in perspective, consider that there are 10^{55} molecules comprising the entire earth (Kozdrowicki & Cooper, 1974). Or consider a computer which could analyze one million board positions in one second; then it would take this computer 3.17×10^{29} years to analyze all board positions. After one million years of constant computation, the computer would have completed less than one thousand-billion-billionth of one percent of the total problem.

In contrast to these figures, the human brain was described above as being quite limited in several important respects. It functions relatively slowly, operating in the range of hundredths of seconds. Also, its very small short term memory (STM), capable of storing about seven chunks of information at a time, acts as a relative handicap. However, the key factor which allows men to successfully compete with computers in the game of chess is the selectivity that the man employs. This lack of selectivity on the part of the computer accounts for the fact that the most successful computer chess program to date only plays at about the high amateur level (Senft, 1975). In any event, the typical chess position presents a player with a choice of about 30 possible moves. If the player considers the opponent's possible responses to each move, there are now about 900 possibilities to be explored. Since it is known that a grandmaster often looks five or six moves ahead, the consideration of all possibilities at this point would result in a total that was on the order of 5×10^{14} moves (Horowitz & Reinfeld, 1956). Yet it has also been shown that the same grandmaster who looks, say, six moves ahead only considers 50 to 100 possibilities at most (Newell, Shaw & Simon, 1958). Thus, through the mental filtering process mentioned earlier, heuristics, the skilled human player is able to significantly reduce the problem space on which he operates to a level which can be managed. An example of such a heuristic program for chess is described below.

The game of chess can be divided into phases, the opening game phase, the middle game phase and the end game phase. The central hypothesis advanced by Simon and Simon (1962) was that the behavior of a chess player in pursuing these various phases is governed by a program that determines which moves he will consider among the totality of moves which comprise the problem space. The authors used the term program in exactly the sense it is used in the digital computer field, to denote an organized sequence of instructions, executed serially in a well defined manner. Since the end game, or mating phase, is generally of most interest, a mating combinations program will be given as an illustration.

The basic idea of this program is that the space of possible moves is examined in a highly selective fashion, rather than exhaustively. Three principles govern selection of a move:

> The attacker only examines moves that are forceful. Since the attacker is seeking a line of play leading to checkmate, he is under no obligation to examine all legally available moves, but only those he thinks promising.
>
> All legal alternatives open to the opponent, when it is the opponent's turn to move, must be explored. The essence of a mating combination is that the opponent is unable to escape checkmate no matter what he does.
>
> If any move the attacker examines, no matter how forceful, allows the opponent numerous moves in reply, the attacking plan is abandoned as unpromising. This acts to both reduce the number of alternatives to be considered by the player and to restrict the freedom of action of the opponent.

With these principles in mind, the actual program of heuristics can be described. The program generates all checking moves for the player and lists them in priority order based on the following heuristics:

> Give highest priority to double checks (moves which attack the opponent's King with two or more pieces simultaneously) and discovered checks (moves that take another man out of a piece's line of attack on the opponent's King).
>
> Check with a more powerful in preference to a less powerful piece.
>
> Give priority to checks which leave the opponent with the fewest replies (don't consider the interposition of an undefended piece a reply).
>
> Give priority to a check that adds a new attacker to the list of active pieces.
>
> Give priority to a check which takes the opponent's King farthest from its base.

Experiments showed that the actual priority order didn't greatly affect the average performance of the program. Hence, the above heuristics may be considered in lexicographical order. That is, if two or more alternatives are tied as best on a criterion, one moves down to the next criterion (Einhorn, 1970).

A number of skilled chess players who have examined the program indicated above, agreed that it incorporated many of the heuristics they use in discovering mating combinations. They pointed out, however, that certain other heuristics which are well known to chess players were missing from the program. In particular, skilled chess players do not limit their search of the problem space entirely to checking moves. Rather, they also examine certain other forcing moves, for example, attacks that threaten mate in one move, as well as sacrificial moves which weaken the pawn protection of the opponent's King. As a consequence of this, the program outlined above probably underestimates the selectivity of a chess master's analysis, and likely exaggerates the amount of search required to discover and evaluate strong moves.

To assess the effectiveness of the heuristic mating program in a more quantitative fashion, 136 different chess positions were analyzed using the program. With each of these positions, the heuristics were applied to search for mate. The program described above was successful in 52 of these 136 situations, or in 38 percent of them. That is, application of the program heuristics, performed by hand rather than by computer, reached mate in 38 percent of the cases attempted. Furthermore, the addition of the one move mating threat produced ten more checkmate situations, which improved the success rate to 46 percent. So, from the level of complexity discussed earlier (one billion possibilities if an average position is analyzed three moves deep for all possible moves), a simple program consisting of six heuristics, executed by hand, was successful in almost one half of the 136 positions analyzed. The authors point out that the positions analyzed were not used in constructing the heuristic program, but rather were chosen from a chapter on mating attacks from a standard chess book (Fine, 1952).

More recent work in the area of judgmental heuristics has been conducted by Tversky and Kahneman. They investigated the heuristics of representativeness, availability and anchoring in the context of probabilistic judgments over a variety of tasks. An excellent summary of these heuristics appeared in the review article by Slovic, Fischhoff and Lichtenstein (1976).

For the probability that object A belongs to class B, or the probability that process A will generate event B, Kahneman and Tversky (1972) looked at the judgment by representativeness heuristics: People answer such questions by examining the essential features of A and of B and assessing the degree of similarity between them, that is, the degree to which B is representative of A. When B is similar to A, such as when an outcome is highly representative of the process from which it originates, then its probability is judged to be high.

Several lines of evidence support this hypothesis. One is a belief by subjects in the law of small numbers, which results in even small samples being viewed as highly representative of the populations from which they are drawn (Tversky & Kahneman, 1971). This action results in an underestimation of the error and unreliability inherhent in small samples of data. Also, both the subjective sampling distributions and posterior probability estimates were insensitive to sample size, a normatively important but psychologically non-representative factor. Another line of evidence to support the representativeness heuristic was the demonstration that people's intuitive predictions violate normative principles in ways that can be attributed to representativeness biases (Kahneman & Tversky, 1973). For one, representativeness causes prior probabilities to be neglected. For another, predictions tend not to be properly regressive, being insensitive to data reliability considerations.

The availability heuristic is described as follows: An event is judged likely or frequent if it is easy to imagine or recall relevant instances relating to it (Tversky & Kahneman, 1973). Generally, instances of frequent events are easier to recall than instances of less frequent events, and likely occurrences are usually easier to imagine than unlikely ones. Hence, availability can be a valid one for the assessment of frequency and probability. However, there are other factors that can affect availability which do not pertain to likelihood. Some of these factors which can result in systematic biases are familiarity, recency and emotional saliency.

The last of these three particular judgmental heuristics is that of anchoring and adjustment. With this process, a natural starting point or anchor is used as a first approximation to the judgment. As additional information is received, the anchor is adjusted to provide accommodation to it. It has been reported, however, that the adjustment process is imprecise and insufficient (Slovic, 1972). Tversky and Kahneman (1974) have shown how this heuristic could cause two undesirable biases. These were to arrive at overly narrow confidence intervals and a tendency to misjudge the probability of conjunctive and disjunctive events.

Of the three heuristics, representativeness has received the most attention to date. A discussion of work related to these three judgmental heuristics is contained in the previously cited review article (Slovic, Fischhoff & Lichtenstein, 1976).

Theories of choice have begun to incorporate heuristics. One major new theory is that of elimination by aspects (Tversky, 1972a; Tversky, 1972b). The elimination by aspects heuristic works as follows: Choice between alternatives is viewed as a covert sequential elimination process. Alternatives are viewed as sets of aspects. At each stage in the sequential process, an aspect is selected with probability proportional to its importance. Alternatives which are judged to be unsatisfactory on the selected aspect are eliminated. The process continues until all alternatives but one are eliminated.

An interesting study from the field of business concerned heuristics managers used under harassed conditions (Wright, 1974). The harassed heuristic was described as follows: Decisionmakers operating under either time pressure or distraction would tend to systematically place greater weight on negative evidence than would their counterparts under less stressful conditions. In other words, rather than look at all aspects of each alternative, the decisionmaker would selectively scan aspects for negative dimensions, and then eliminate the alternative on that basis alone.

The importance of heuristics in problem solving has, until recently, not been widely recognized. For those classes of problems for which simple algorithms are known, such procedures are, of course, preferred. They guarantee a solution if the problems have solutions. But for many important classes of problems for which algorithms are known, such procedures cannot be employed because of the enormous amount of time which would be required to carry them out. There is, for example, an algorithm for playing chess: Consider all possible continuations of the game from the existing position to termination and then select one move which will lead to checkmate of the opposing King. As described in detail earlier, this is not a realistic approach, given the information processing limitations of man. An estimate made by the mathematician Shannon (1950) indicated that if this procedure were employed, it is unlikely that a single game would be completed within a lifetime, even if the players worked at the speed of the fastest electronic computers. The use of the algorithm in playing chess is simply not feasible. Instead, those who are skilled at the game of chess employ heuristics, as discussed above.

II.4 A Review of Electronics Troubleshooting Research

In conducting the review of research relating to electronics troubleshooting, it was necessary to depart somewhat from the seasoned approach of utilizing various library abstracts and citation indices. The reason for this is that much of the research conducted in this area was done under Department of Defense (DOD) sponsorship and was of a specialized, military related nature, rather than of a general nature. Therefore, the bulk of the work and the results were published in the form of contractual technical reports and laboratory reports. Of these, many are still available from the Defense Documentation Center (DDC) in Alexandria, Virginia, or from the National Technical Information Service (NTIS) in Washington, DC. The nature of the source of the reports should not imply that they lack for experimental rigor. For example, a prominant researcher in this field from the University of Southern California, Rigney (1969), stated in his final contractual report to the Office of Naval Research (ONR) that during the eight year period from 1961 to 1969, 34 technical reports relating to various aspects of maintenance and troubleshooting had been submitted to ONR. These 34 reports, he went on to write, formed the basis for four chapters in books, seven publications in professional journals, and over one dozen papers presented at professional society meetings.

During the course of this review, the DOD affiliation of a research effort, rather than the professional journal affiliation, will be emphasized. The reason for this is that the DOD report is generally more detailed as to the physical characteristics of the experiment, the data collection process, the data itself and the experimental design. Where it is known that the DOD report was incorporated into a journal article, mention will be made of this fact in the reference section. For convenience, DDC code numbers (AD numbers) are included where appropriate. These range from five element (not counting the AD prefix) numerical codes, for example AD 12345; to six element numerical codes, for example AD 123456; to seven element alpha-numeric codes, for example AD A123456; depending on the age of the document. In order to obtain a five element coded document from DDC, one should specify "old document", otherwise it might be interpreted as an error.

The first step in this review of the literature on electronics troubleshooting will be to discuss what is meant by the term, troubleshooting. Troubleshooting occurs in a situation which has two prominant elements, a technician and a system which has malfunctioned. It is the task of the technician to fix the system. Attempts to find what is causing the malfunction are called troubleshooting behavior, which is a kind of problem solving activity.

Certain elements of the interaction between the technician and the system are common requirements of successful troubleshooting (Grings, et al., 1953). That is, the technician must have some knowledge of how the system functions normally; he must obtain information about the current state of the system; he must relate the information he gets to his conception of the normal system, to his past experience with malfunctions of this or similar systems, and to his theoretical knowledge of functional relationships embodied in the system; and he must formulate and test hypotheses as to the most likely cause or causes of the malfunction.

Electronic circuits have certain characteristics which give them a unique degree of troubleshooting difficulty. Most of the difficulty stems from the fact that the electron is invisible. Except at a few isolated spots in the circuit where information carried by it is translated into sensory terms by some type of output device, the flow of electrons in the equipment, and the complex functional interaction of its parts, are abstract. For example, a wire with a potential of 10,000 volts looks just like a wire with no voltage at all.

This attribute of functional invisibility places certain demands on the technician. He is required to know and to interrelate two different representations of a circuit, a theoretical conception made up of abstract concepts and based on a schematic, and its actual physical form comprised of a complicated arrangement of leads, tubes, capacitors, resistors, etc., which make up the system.

Interest in troubleshooting began in the early 1950's, with the proliferation of elaborate radar and communication systems. In his doctoral dissertation on electronic troubleshooting, Saupe (1954) noted that to his knowledge, there had been no published, definitive, experimental investigations of the processes involved in troubleshooting electronic equipment prior to that time. Saupe used technical school trainees who had received approximately six months training in electronics principles and maintenance procedures, as subjects. Their task was to locate one of eight contrived malfunctions in a radio receiver. The radio was not one of the standard units in operational use at the time, but rather it had been specially constructed for the experiment. A total of 40 trainees took part in this study.

Nine hypotheses relating to aspects of the troubleshooting process were investigated. To test these hypotheses, a variety of statistical approaches were employed, including analysis of variance, correlation, t tests and contingency tables. The first hypothesis concerned the relationship between mechanics' knowledge of basic electronic facts and principles and their troubleshooting ability. Here it was shown that knowledge of basic electronics fundamentals is a necessary, though not sufficient, condition for success in the solution of troubleshooting problems.

Hypotheses two through eight concerned the contribution or detraction which specific components of the troubleshooting process make to success in the troubleshooting task. Hypothesis two, relating to perception of a symptom, was not supported: Successful mechanics tend to perceive the symptoms of a malfunctioning piece of equipment completely and correctly; whereas, unsuccessful mechanics tend to perceive the symptom incompletely or incorrectly. Hypothesis three, relating to the tendency to perform general checks, was inconclusive: Successful mechanics tend to attempt to secure sufficient information before accepting a hypothesis concerning the specific area of the equipment in which the trouble resides; whereas, unsuccessful mechanics frequently accept a hypothesis without attempting to secure such information. Hypothesis four, concerning the first hypothesis accepted, was supported: The first hypothesis accepted by successful mechanics tends to be correct; whereas, for unsuccessful mechanics, it tends to be incorrect. Hypothesis five, relating to wrong hypothesis behavior, was supported: Unsuccessful mechanics tend to (a) entertain more incorrect hypotheses, and (b) pursue incorrect hypotheses for a longer period of time than successful mechanics. Hypothesis six, concerning use of obtained information, was supported: Successful mechanics, upon obtaining critical information in their checking procedures, tend to recognize and use it; whereas, unsuccessful mechanics do not. Hypothesis seven, errors in the use of test equipment, was not supported: Successful mechanics tend to make fewer errors in the use of test equipment than do unsuccessful mechanics. Hypothesis eight, duplication of checks, was inconclusive: Successful mechanics duplicate the same checks less frequently than do unsuccessful mechanics.

The final hypothesis of the study concerned characterizing mechanics on the basis of their overall patterns of response or methods of attack on troubleshooting problems. This hypothesis, which was supported, read as follows: It is possible to differentiate among mechanics on the basis of overall methods of attack employed. Furthermore, different methods of attack characterize mechanics at different levels of proficiency with the prototype troubleshooting process being characteristic of the most successful mechanics. The prototype troubleshooting process was a general description of different classes of activity which take place in the course of troubleshooting, such as orientation, concentration on a specific stage, search within a stage, and identification of the defective component.

Of the above hypotheses, the two which dealt most closely with the present study are hypothesis six, pertaining to the use of information by technicians, and hypothesis nine, pertaining to patterns of attacking troubleshooting problems. These will be addressed in greater detail in the sections on coding and heuristics, respectively.

In summarizing the effort described above, it was one of the first attempts at describing the behavior known as troubleshooting. As such, it provided a foundation upon which succeeding studies could build. Of particular interest was the human information processing approach which it used with regard to the ability of technicians to interpret and analyze their sensory inputs. The general conclusions of the study were as follows:

> The troubleshooting situation can realistically and profitably be viewed as a type of diagnostic problem solving task which requires (a) knowledge of fundamental electronic facts and principles as a base, and (b) on a specific problem, a course of action guided by an adequate orientation, and by succeedingly more restrictive hypotheses, formulated on the basis of careful observation and the logical elimination of possible alternative causes. The final and most specific hypothesis will eventually be shown to be correct.
>
> Strategic elements of the requirements for successful troubleshooting can be empirically identified and subjected to analytical investigation.

During the latter part of the 1950's and throughout the 1960's, the number and variety of troubleshooting studies increased. One of these studies which focused directly on aspects of the troubleshooting process was that conducted by Saltz and Moore (1953). This investigation looked at troubleshooting on three types of equipment: Q-24 radar, reciprocating engines, and remote control turrets. The first part of the study utilized analysis of variance techniques to test hypotheses concerning differences between good and poor troubleshooters with regard to four factors: knowledge of the equipment, previous experience, intelligence, and formation of abstract concepts. Five of the best and five of the poorest line troubleshooters, as rated by their supervisors, were used from each of the three equipment areas. The study concluded that:

> Good troubleshooters know more about the functioning of the equipment upon which they work than do poor troubleshooters.
>
> Good and poor troubleshooters differ in previous experience.
>
> Good and poor troubleshooters do not differ in intelligence.
>
> Good troubleshooters do not form abstract concepts more readily than poor troubleshooters.

Another aspect of the investigation consisted of interviews with troubleshooters to discover what they thought were important procedural aspects of the troubleshooting process. The categories of differences between good and poor troubleshooters which emerged referred to the following points:

> Logical analysis of thinking out the problem.
>
> Knowledge of the equipment.
>
> Past experience with the particular malfunction.
>
> Ability to use test equipment properly.

The last phase of the study consisted of actual observations of technicians performing troubleshooting on their respective types of equipment. The step by step procedure observed for each maintenance man was analyzed with the aid of specialists from each of the three maintenance areas. Eight kinds of behavior which hindered troubleshooting effectiveness were identified:

> Checking part of the system which is not in the flow of information from which the symptom arises, or ignoring part of the system because it was not noticed that the component was part of the flow of information relevant to the symptom.
>
> Avoidance of a difficult check.
>
> A difficult check was made when a simpler one would have sufficed.
>
> Checks were repeated needlessly.
>
> After isolating the trouble between two points, further checks were made beyond, rather than between, the two points; or a check was made between two points despite the fact that no trouble was found between them.
>
> A check was omitted in tracing the flow of information despite the fact that the check was one the men probably knew was relevant.
>
> The men failed to remember information correctly.
>
> Some piece of rote information (e.g., the particular voltage normally expected at a given point) was not readily available.

The above errors, plus the findings derived earlier, suggested an interpretation of troubleshooting behavior in terms of a hierarchy of responses, as follows:

> Components high in the response hierarchy but not relevant to the flow of information may be tested as a consequence of competition between responses for evocation.
>
> A response, because it is high in the response hierarchy may be repeated needlessly.
>
> Components high in the response hierarchy but difficult to access are ignored.
>
> Rote information is extremely liable to failure of accurate recall.

Methods for dealing with these restrictions on troubleshooting proficiency were suggested for further research. These were viewed as relating to the technicians' information processing abilities.

Information pertinent to isolating malfunctions - Critical information necessary to effective troubleshooting may be a thorough knowledge of the functional relationships between a system's components.

Methods of organizing and presenting this information - Discriminability between various information chains can perhaps be enhanced by their isolation on separate diagrams and emphasis of their interrelationships improved through use of color codes.

Methods by which the troubleshooter can select and organize information relevant to particular malfunctions - Training troubleshooters to pre-plan and verbalize their approach might furnish strong cues for successive responses, eliminate needless repetition, and help the troubleshooter to think out his problem; special test equipment might aid the troubleshooter in investigating hard to reach components; and technical manuals containing necessary rote information and circuit diagrams emphasizing important component interrelationships, in pocket size, might be an effective troubleshooting aid.

As the last point suggests, performance aids were being viewed by an increasing number of researchers as a means of extending the information processing capability of troubleshooters. This proved to be a popular approach, as contrasted with a more behaviorally oriented approach which focused on the actual human information processing mechanisms being used and means of improving them. Since the present effort will concentrate on the latter approach, the remaining papers which are reviewed will accordingly be restricted to representatives of that category.

A report by Miller, Folley and Smith (1953) contained a description of procedures for troubleshooting electronic equipment based upon rational and logical considerations. Two kinds of methods or procedures were discussed, troubleshooting from probability data and troubleshooting by logical elimination of malfunction sources.

The first method was used quite extensively during World War II in field practice. It is very effective when large numbers of identical or similar equipment are used for long periods of time, providing the equipment is not too complicated (Foley, 1964). It was the method used to repair many home radios during the 1930's.

Troubleshooting from probability data required an accurate historical record of equipment performance in terms of the various malfunction symptoms. It also required the attendant corrective actions which had been effective in the past for eliminating specific symptoms of equipment malfunctions. Another requirement for this method of troubleshooting was the skill involved in making routine checks, adjustments and replacements. The overall procedure entailed the use of probability tables of likely causes of malfunction paired with the associated symptoms of equipment error or malfunction. These tables were made up from the malfunction history of the equipment, and the success of this method depended on the reliability of the tables.

Further investigation of the method of troubleshooting from probability data has shown it to be a less desirable method than troubleshooting by logical elimination. This followed from the standpoints of operational effectiveness, data collection and tabulation, and practicality of training. In addition, it was not effective on new and more complex equipment for which no history had been developed, nor was it practical for locating unusual malfunctions.

Troubleshooting by logical elimination, on the other hand, required a functional block diagram of the equipment, some training in the elementary logic of eliminating alternatives, and the skills and knowledge involved in making checks, adjustments and replacements.

Logical elimination involves systematic checks which eliminate as causes, first the major and then the minor portions of the system, until the malfunction is narrowed down to the responsible component. The functional block diagram is used as the basis for tracing chains of electrical information flow throughout the interacting portions of the equipment. Areas of the equipment which indicate out of tolerance readings in the data chain during the course of the troubleshooting are then examined further in order to pinpoint specific components causing the malfunction symptom. The component is then adjusted, replaced, or repaired, depending upon the corrective action which will most effectively eliminate the malfunction in the time available for equipment servicing.

Two phases or aspects of the logical elimination procedure are discussed step by step. In the first phase, the technician performs systematic checks which isolate the data flow chain or chains which contain the malfunction. For isolating a specific malfunctioning component within a chain, the half split technique is of special relevance. In essence, the half split technique says to check the input and output of a given data chain. If the input is good and the output is out of tolerance, cut the chain in half and repeat the checks. Continue to split the part of the chain with the good input and out of tolerance output until a single component can be isolated as the problem. For example, a straight series chain with eight stages is shown in Figure 2.3 below.

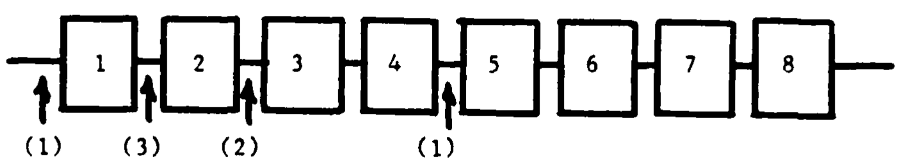

Figure 2.3 The half split technique.

The first test under the half split approach would be to check the data flow at point (1). If it were normal, then it may be assumed that any malfunction is in one of the last four stages. If the input reading were good and the output reading were abnormal, it may be assumed that the malfunction is in one of the first four stages. If the latter were the case, the next check would be made at point (2). If abnormal at this point, the next check, (3), would isolate the malfunction to a particular stage.

It can be seen that this approach is closely related to information theory, in that the number of steps required for problem isolation is $\log_2 N$, where N equals the number of units involved in the chain. In information theory, the above expression yields the number of bits of information required to select between one of a number of alternatives.

Evans and Smith (1953) studied measures of technician effectiveness for advanced students in some of the Navy's electronics technical training schools. Plans called for the development if suitable performance test measures with which to be able to distinguish among levels of troubleshooting ability. Unfortunately, only a preliminary investigation was accomplished before government funding was lost for the project. Some of the findings of this abbreviated study are summarized below.

The study consisted of observing troubleshooting behavior, as well as administering written test material to the technicians. The study began with the selection of 14 advanced students to act as behavioral subjects. This pool was later reduced to ten subjects by the researchers, as it was felt that by the time ten troubleshooting behavioral observations had been recorded, the most common troubleshooting tendencies would have been exhibited. The written test portion of the study utilized between 50 and 60 subjects.

The physical arrangement for the troubleshooting portion of the test consisted of a written statement of the problem; a series of questions about the problem, with answers covered by "tabs" of paper; and series of possible solutions to the problem, with "correct" and "incorrect" covered by tabs of paper. No actual equipment was used. Each subject was exposed to five common problems and five unique problems, as devised by an experienced Navy technician and members of the research staff. Since it was a well accepted maintenance concept that a high proportion of all failures in electronic equipment are tube failures, the majority of both the common and unique problems were tube related. Behaviors were observed and recorded by instructors from the technical school faculty.

The researchers reported that common troubleshooting behaviors were observed, however they declined to identify these trends further. The major reported finding indicated that a small percentage of the subjects exhibited marked symptoms of perseverance. They continued to make tests in stages of the equipment which could logically have been eliminated from consideration on the basis of information previously obtained. It appeared, further, that the stage in which they tended to continue to make unnecessary tests was the stage about which they knew the least.

The written tests were used to form a statistical composite of the qualifications of a troubleshooter, as deemed necessary by the trainee respondants. This composite indicated that if a person were not a good troubleshooter, then he would not be perceived as being a good technician. Thus, troubleshooting was viewed by the technicians themselves as the most critical aspect of their job. Aside from these conclusions, the funding problem cited earlier prevented a further exploration of behavioral troubleshooting.

Interest soon began to focus on the teaching of basic troubleshooting principles (Warren, et al., 1955). It was observed that regardless of the unique characteristics of a particular machine system, the process of troubleshooting by means of data flow analysis involved the application of certain basic procedures of a general and logical nature. Such procedures are abstract in the sense that they are independent of knowledge specific to the system, and may be applied in isolating a malfunction component in any logical system for which a schematic data flow chart is available. This was one of the earliest suggestions that the job of troubleshooting could be approached in terms of some generalized rules which would be applicable over a wide range of equipment. Previous views of troubleshooting had presumed that a vast and complex reservoir of electronics knowledge was needed by successful troubleshooters. In addition, it was noted that a particular attack which is efficient in one troubleshooting situation may not be so in other situations. This suggested that the generalized rules were lexicographic in nature.

Unfortunately, as with the earlier studies, the physical environment for the research was less than desirable. Due to equipment shortages, the troubleshooting task took the form of a verbal symptom report by one of the researchers, followed by a verbal troubleshooting reply by a subject. In this case, the subjects were experienced contractor field engineers. They were asked to describe in detail the steps they would take in isolating the malfunction. In addition to relating what checks would be made, they were to indicate how each check would be accomplished, why it would be made, what information could be obtained at each check point, and what this information would mean in terms of subsequent checks or decisions. The verbal interchange was tape recorded to permit an extensive study of the troubleshooting procedures to be made.

Comparison of the protocols of the three different equipment experts troubleshooting the same malfunctions revealed nearly identical logical considerations underlying the decisions which each made. However, differences did appear in the symptom checking techniques employed by different individuals. This was primarily reflected in the degree of sophistication of the test equipment selected for use.

Analysis of the troubleshooting protocols for 33 malfunctions was undertaken. These indicated a variety of steps or procedures which could be followed in troubleshooting the system. Many of these procedures were based on specific knowledge of characteristics of the system under consideration. Others were abstract processes of making logical eliminations which would be applicable to troubleshooting any system.

Examples of those procedures based on specific knowledge or characteristics of the system used in the experiment are shown below.

> Checking the power supply to a loop or chain of flow - This is a logical procedure intended to isolate the malfunction to a linear chain in cases where a separate power flow and signal flow exist.
>
> Visual inspection of a chain for obvious signs of a malfunctioning component - This procedure involves specific skills of recognizing a malfunction from the physical appearance of a component and/or a connecting component.
>
> Changing the modus operandi of the system in order to simplify the loop under investigation, e.g., such as changing frequency or changing the timing sequence - This

step would require considerable specific knowledge of the functional characteristics of the system.

Replacing components in a linear chain of flow on the basis of ease - This procedure also required some familiarity with the system, but was still somewhat a trial and error approach.

In addition to specific procedures such as those listed above, some protocols repeatedly involved abstract processes which would be applicable in logically isolating a malfunction in any complex data flow system. In essence, these abstract procedures represented acknowledged principles of logical inference as applied to a data flow network. Troubleshooting on the basis of these procedures was basically a process of making successive logical eliminations of loops, chains, and components until the malfunctioning component was isolated.

Examples of those procedures based on abstract and general characteristics of a system are shown below.

Trace the data flow backwards from the symptom indicator, thereby eliminating all loops and chains other than those which feed into the data flow to that indicator.

Trace the data flow back to a point where the signal is fed to another loop or chain (which can be called a point of divergence of flow), and check the output of the parallel flow. Depending on the results of the check, the malfunction may be isolated before or after the point of divergence.

When data flow is traced back to a point of converging input, check both chains just prior to their convergence in order to isolate the malfunction to one of the converging chains.

When data flow is traced back to a resolving component, check inputs of both converging chains. If both are normal, the malfunction is located in the resolver.

When data flow is traced back to a loop or chain, locate a point where a known signal can be inserted into the flow in order to isolate the malfunction in one section of the loop or chain.

The authors suggest that from the standpoint of the pure logic of troubleshooting by data flow analysis, all of the essential processes are embodied in the first three principles listed above. The last two procedures are less abstract in that they apply to systems containing resolving components and points where known signals can be inserted. Practically speaking, however, these two characteristics are sufficiently common in systems requiring trained troubleshooters, that they may be considered as necessary specifications of a generalized training course.

As can be seen, the effort summarized above continued on the same theme as that of Evans, et al. (1953) in searching for and identifying general processes or methods of troubleshooting. The major criticisms of both works are the narrow pool of subjects employed and the unrealistic test environment used in the studies.

The next major effort in the study of electronics troubleshooting from a behavioral viewpoint was that of Bryan, et al. (1956). This report made a detailed examination of the ways electronics technicians responded in troubleshooting situations. Data from four sources were examined in an attempt to develop a framework for a behavioral analysis of troubleshooting. The first source represented data from observations of electronics repairs attempted during cruises at sea. This data did not contriubte much to the analysis however, as it was used only in an illustrative, rather than supportive, role. A job sample troubleshooting test provided a second source of data. Here, troubles were introduced into equipment by substituting faulty parts for good ones, by misaligning stages, and by causing various kinds of concealed discontinuities. Data from this source formed the smallest portion of the total data collected from all sources. A third source of data was obtained under simulated troubleshooting conditions. This source comprised the largest share of the total data. The fourth source of data also was derived under simulated troubleshooting conditions, and used a special device to automatically record the troubleshooter's responses. In all, a total of over 1500 troubleshooting records were available for analysis.

An important outcome of the data reduction was the identification of progressive phases in the troubleshooting process. These consisted of the initial action, the initial action sequence, the initial localizing sequence, subsequent localizing sequences, the isolating sequence, and the component replacement. The paper examined the sequences in detail and reported on patterns within each of them, based on the observations described earlier. Two types of electronic equipment, a radio and a radar unit, were used in assessing the patterns. These types of equipment were chosen due to their wide use and importance throughout the military services.

In all, there were four general and 58 specific conclusions which resulted from this research. The general conclusions are listed below.

> Experienced technicians showed marked individual differences in their ability to locate defects in malfunctioning electronic equipment.
>
> The actions in a troubleshooting performance were seldom random, but were dependent on the circuitry, the problem conditions, and the subject's style of search.
>
> The typical troubleshooting attempt was made up of three qualitatively different kinds of behavior: generalized searching, localized searching, and component adjustment or replacement.
>
> If a man was a good radio troubleshooter, the chances were good that he was a good radar troubleshooter, granting some previous exposure to each type of equipment.

The first conclusion suggested that even among experienced technicians, there were differences in the efficiencies of their heuristical programs. Also, since these heuristical programs are assumed to be lexicographic in nature, this could explain differences in troubleshooting style and efficiency.

The second and third conclusions support the contention that technicians typically use a pattern of activities, or a heuristical program, in the course of troubleshooting. Such programs can vary somewhat depending on the circumstances of the problem. As described above, there are different kinds of behavior which can be identified, consisting of generalized searching, localized searching, and component adjustment or replacement. Within each of these kinds of behavior, there are phases, such as the initial action, the initial action sequence, etc. Each of these phases would be related to a heuristic program. As outlined earlier, one of the major goals of the present research is to identify the separate heuristics, which make up each of the heuristical programs.

The fourth and final general conclusion suggests that the heuristical programs are not necessarily unique for a given piece of equipment. Rather, with some exposure to differing types of equipment, the technician can use the heuristical programs to troubleshoot those types of equipment as well.

The remaining conclusions were specific in nature, but it is possible to summarize them in terms of the three types of behavior previously mentioned.

> With regard to getting started, approximately the first third of the average troubleshooting performance was devoted to generalized localizing activity. This extended from the first action to the point where the man began intensive isolating checks within a stage. Most of the activity

conu̲sted of signal injections and waveform checks, and several stages were usually involved.

As the technician started to get closer to the source of the problem, localized searching behavior within a restricted area of the equipment began. This often amounted to about a third of the average troubleshooting attempt. It usually reflected the technician's belief that he had narrowed the trouble area. The typical performance here contained three sequences of intensive checking within a stage. These intrastage sequences were short and consisted mainly of DC voltage and resistance measurements. Generally, two such sequences occurred before the first replacement was made.

The payoff, or the replacement of a suspect component, was a feature of nearly every performance, and as many as two to four replacements were not uncommon. Most initial replacements took place after a series of generalized and localized seearch activities, at about the middle of a typical performance. In a sense, a replacement represented an integration of the man's previous searching behavior and served as a check on his interpretation of the problem data.

Redundant activity was found to be a part of almost every troubleshooting effort. A redundant action was one which furnished no new information, that is, one which if omitted would have left the performance essentially complete. The proportion of redundant actions ranged as high as 75 percent, but generally 30 to 50 percent was the case.

Since all of the problems used were contrived, a time limit of from ten to 30 minutes was imposed. The technician's tempo, or working rate, changed with the problem situation, but the average tempo was found to be between two and three actions per minute.

The research study described above laid important groundwork for the present effort. Much of it will be helpful in seeking out and elaborating on the fundamental units and categories for coding electronics troubleshooting behavior.

In a paper assessing the necessity for an extensive basic electronics training program for Air Force maintenance trainees, Brown (1957) noted that from a practical viewpoint such training was undesirable. He based this on two reasons. First, he believed that it was unlikely that many of the trainees would be capable of assimilating much in the way of basic training of this kind. Second, he felt that there were ways of increasing the information handling capacities of the trainees, which were not incorporated in any of the training programs in use at that time.

The reasons given for these assertions are important to this current research effort. In his first argument, Brown addressed the concept of information overload. He believed that the form in which the material was presented caused the trainees' cognitive facilities to become saturated, and made the retention of the material difficult. In making his second point, Brown suggested that the form in which the material was presented did not lend itself to efficient mental coding by the trainees.

Brown went on to recommend that the teaching of basic principles and relations should be such that the maintenance person was provided with a kind of content free framework to which a wide variety of specific situations could be fit. This was likened to the acquisition of skill in the manipulation of algebraic or other mathematical symbols according to the rules embodied in mathematical logic. Once these essentially content free skills have been learned, it then becomes possible to solve a wide variety of problems by substituting real quantities for the alphabetical symbols in the formulas. For example, suppose that a student learns a relationship of the form: If A is greater than B and B is greater than C, then A will be greater than C. This is essentially a content free symbolic relationship, since in the actual learning of that relationship, it was unnecessary to specify what A, B and C were, nor the dimension or property with respect to which the relationship held. Because of the tremendous generality of the relationship, it can be applied to an unlimited number of specific situations.

This, then, gave further clarification to the form of the heuristics used in electronics troubleshooting. Each heuristic should consist of a content free framework, to which specific troubleshooting situations could be fit. Further, the technicians' coding mechanisms should be such that information from the system being troubleshot could easily and effectively interface with this framework.

Czech (1957) surveyed various electronics troubleshooting methods and reported that they appeared to have several characteristics in common. For example, all assumed that the troubleshooter possessed certain supportive skills such as vision, olfaction, tactual sensitivity, and the ability to use test equipment and to make adjustments and minor repairs. These skills are used first in order to obtain as complete a symptom picture as possible. In troubleshooting to the malfunctioning chassis, the system block diagram was consulted next so as to determine points at which checks and adjustments might be made so that each action eliminated as many chassis from consideration as possible. Czech referred to this approach as the crux of all the methods of troubleshooting. In each case, the system block diagram was traced backwards, from outputs to inputs, to points of data flow divergence, convergence, feedback, and so forth. The ability to recognize parallel but qualitatively different outputs of chains to an indicator was essential and often gave important cues as to the location of a malfunction. Half split checking procedures (going from general checks to progressively more specific checks) were recommended wherever series chains of chassis were involved. Use was made of probability data whenever available, and of such procedures as writing down check results, switching identical chassis, and comparing readings obtained on test equipment against lists of required readings. These rules all represent different heuristics, and taken together, they would form a heuristical program for between stage troubleshooting.

Many of the characteristics of between stage troubleshooting, or troubleshooting to chassis, seemed to be characteristics of troubleshooting to parts within chassis, or within stage troubleshooting. For example, the use of test equipment was required for both. Backtracking on the chassis block diagrams and schematics was necessary. The person troubleshooting needed to be alert for strange sounds, smells, and other indications from the equipment. A possible point of difference was that the within stage troubleshooting required a greater knowledge of basic electronics than did between stage troubleshooting.

Another in the series of publications on the theme of teaching efficient troubleshooting techniques was the work of Bryan and Schuster (1959). Here, the authors were concerned with the teaching of effective troubleshooting methods to technician trainees. Sixty troubleshooting problems were developed for use during the training sessions, based upon studies of actual equipment malfunctions on a navigational radar unit.

The purpose of the subsequent training effort was to teach the application of a set of logical principles which would be appropriate under a wide variety of problem conditions. For each step in the troubleshooting process, the use of such principles would assist in answering two basic questions: Where should one check and what type of check should be made.

With regard to the first question, where to check, a number of rules were proposed. One should inspect the various indicators (oscilloscope, meters or speaker) for the unit and identify the symptoms of trouble that they represent. Were there signals? Were the sweeps normal? Keeping these symptoms in mind, the overall diagram for the unit should be consulted. The signal flow paths or circuitry leading up to the indicators where trouble had been detected should be investigated carefully, while the stages whose outputs were normal should be ignored for the moment. Such activities correspond to the between stage troubleshooting heuristical program mentioned earlier, called bracketing. That is, indicators which showed signs of trouble were located. The signals from these indicators were then traced back to a point where the circuit was known to be operating normally. The extreme points of the circuitry which resulted defined or bracketed the trouble area.

The bracketed area should get smaller with each new check, if the check is selected properly. If an irrelevant check is made, i.e., one that picked up information at some point outside of the trouble bracket, then the trouble bracket would remain the same as before the check was made. As each move is made, the information gained should be interpreted with regard to this relevance toward narrowing the trouble brackets. Then, the next move should be planned so as to give additional information about the reduced trouble brackets.

Once the trouble brackets have been established, the signal flow paths within them should be analyzed. The first step in this process would be to determine the type of data flow involved: linear, divergent, convergent, delay, feedback, switching, or a combination of these. Different troubleshooting rules or heuristics would apply to these different types of signal flow. These are summarized below.

A linear path is a simple chain of elements, whose main feature is that there are no branching inputs or outputs anywhere along the line. A case of this sort is shown in Figure 2.4 below.

Figure 2.4 An example of a linear flow.

The half split rule of heuristic mentioned earlier (Miller, Folley & Smith, 1953) covered troubleshooting with this type of signal flow: Succeeding measurements are made at or just before the midpoint of the trouble brackets. In the case shown, normal output at the power amplifier with no output at the speaker would indicate a defective speaker.

A divergent signal flow is where two or more outputs are fed from one common feedpoint (Warren, et al., 1955). An example would be the power transformer in a TV set, such as shown in Figure 2.5 below.

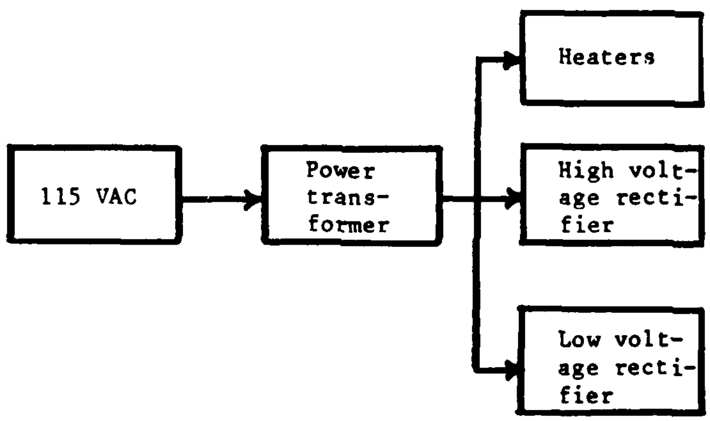

Figure 2.5 An example of a divergent flow.

The heuristic which applies to this circuit is as follows: If any output is normal, then the stage at the point of divergence (in this case the power transformer) has to be normal. Furthermore, the other outputs of this stage are presumed to be normal up to the following stage inputs. In this case, one could simply observe that the heaters in the tubes were lit, and the operation of the circuitry up to the point of divergent flow would be verified. No other checks would be needed.

A stage which combines two or more inputs is called a point of convergence (Warren, et al., 1955). The numer of outputs is immaterial in defining a convergence point. An example of a convergent stage is the mixer in a superheterodyne radio receiver, shown below.

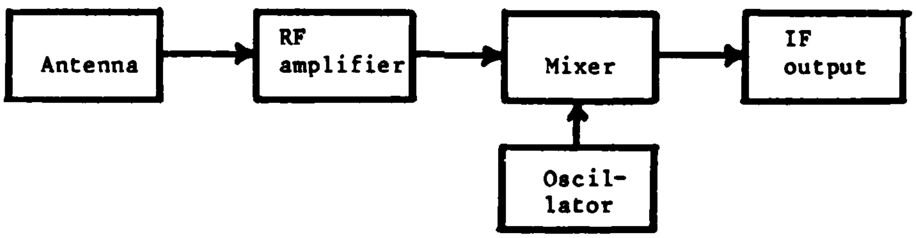

Figure 2.6 An example of a summative convergent flow.

There are two general types of convergence circuits, depending upon the input requirement to produce an output:

> Summative - All inputs are required to produce an output. This corresponds to an "and" operator in the terminology of logic.
>
> Alternative - Any input is sufficient to produce an output. This corresponds to an "or" operator in the terminology of logic.

The only way to distinguish between these two types in practice is to know the circuit function, i.e., what the circuit is supposed to do, and how it does it. The mixer shown above is an example of a summative point of convergence, in that both inputs are required for an output. The heuristic for this type of circuit is as follows: Check each input plus the convergent stage itself to pinpoint the trouble. Only if all inputs are normal and the output abnormal, can the trouble be localized to the convergent stage itself.

An example of an alternative point of convergence is a ghost monophonic channel to combine sound signals from two separate inputs in a stereo amplifier. This case is shown in Figure 2.7 below. The common ghost channel will provide an output for either an A or B input or both.

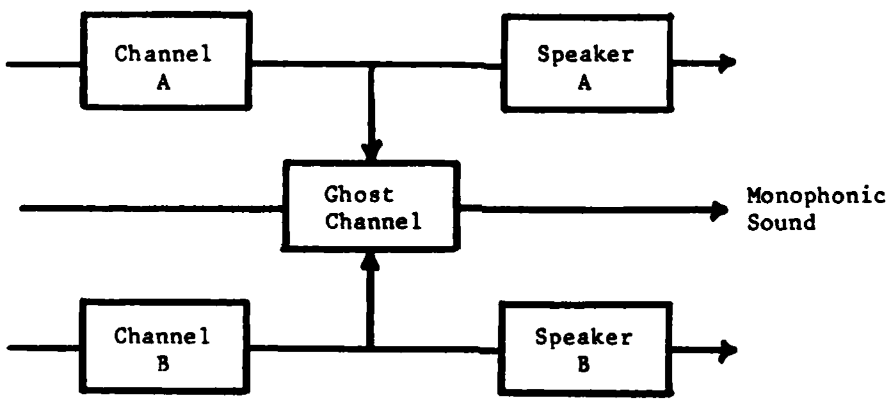

Figure 2.7 An example of an alternative convergent flow.

The heuristic for this type of circuit is as follows: Check one input; if it is normal and the output abnormal, the trouble is in the convergent stage itself. If one input is abnormal, see what is the matter with it, and leave the convergent stage alone.

It should be noted that in a signal flow sense, controls (knobs, switches, and adjustments) make the controlled stage a point of convergence. A tuned RF amplifier is an example of this and is shown in Figure 2.8 below.

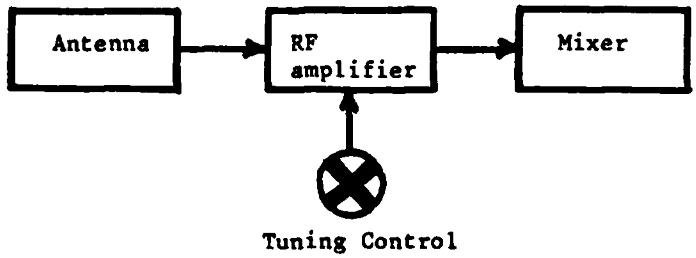

Figure 2.8 An example of convergent flow with a control.

A feedback circuit is one where part of the output of a stage is fed back circularly into its input. This is shown diagramatically in Figure 2.9. The feedback path may be around just one stage, as within a delay multivibrator, or around several stages, as in a stereo system with overall feedback from the speakers to the amplifier input.

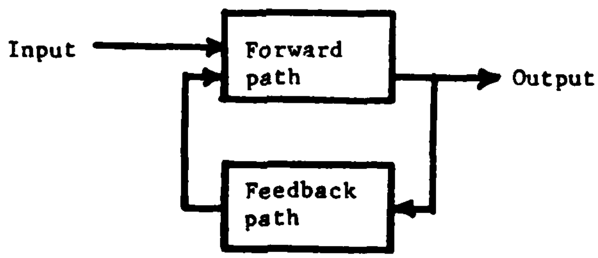

Figure 2.9 An example of a feedback loop.

The troubleshooting heuristic here is the following: Change, by either opening or shorting, the feedback part of the loop and note the effect on the output. If the output can be modified by changing the feedback, then the entire circuit, forward path and feedback path is functioning normally. If the output is not effected by the feedback path modification, then the feedback path is not functioning properly.

Switching circuits may have aspects of linear, divergent and convergent signal paths. However, they have a unique logical property which makes them highly important in troubleshooting. The troubleshooting heuristic is as follows: Move the switch to another position. Then if the trouble disappears, the problem is in the signal path now switched out. However, if the trouble persists, then the problem is in the signal path common to both switch positions.

An example of an application of this heuristic is shown in Figure 2.10 below.

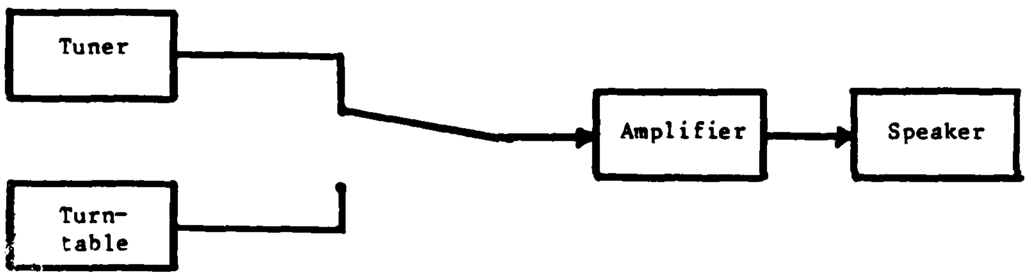

Figure 2.10 An example of a switching circuit.

Suppose that there is no output when the set is in the tuner position. Switch to turntable. Now, if an output is present, the trouble is in the tuner section. If there is still no output, the trouble likely lies in the amplifier or speaker. Other possibilities would include either the switch itself or the common power supply.

Other heuristics for systematic identification of problems in separate components have been suggested. These generally involve checking the component from the point of signal entry to the point of signal exit.

For example, with a tube, the heuristic is as follows: Check the control grid first, then the plate, cathode and other secondary grids. This order follows, since a signal comes in on the control grid, goes out on the plate, and the cathode and secondary grids are common to both of these elements.

For a transformer, a similar heuristic follows: Check the primary first, and the secondary next. Again, this order is derived from the fact that a signal enters a transformer on the primary winding and leaves on the secondary winding.

With regard to individual components, it is generally the case that the highest probability of failure is associated with tubes, followed by resistors, capacitors and transformers. The much higher failure rate of tubes explains the fact that they are generally socketed, rather than hardwired, into a chassis.

The second question, that of what type of check to make, was also addressed. It will be assumed that the first question, where to check, has already been answered. One must then decide between such options as varying controls, taking waveforms, or replacing one or more parts. Whatever the type of check which is made, it will address only a certain number of trouble possibilities. A front panel check, such as manipulating a control, is a highly generalized check as to the possible area of trouble. That is, it covers a wide range of trouble possibilities, and therefore is not very precise. The other extreme is that of replacing a component part. This is a highly precise check, and as such it covers only one possible source of trouble. Between these two are intermediate types of checks, such as adjustments, waveform checks, voltage measurements, and resistance checks.

An efficient approach is one of making the type of check which is most appropriate to the size of the trouble bracket at a given time.

A heuristic covering the span of checks from general to intermediate to specific would be the following: As one progresses in locating a malfunction, vary the type of measurements made in a specified order. Start with front panel checks, then make adjustments, take waveforms, measure voltages, measure resistances, and finally, replace a part.

Using such a sequence results in wide initial coverage but low initial precision. Gradually, as localization proceeds, the coverage narrows while the precision increases. Such a sequence can be likened to an information funnel. At each stage of checking, all possible relevant checks should be made prior to continuing on to a more precise series of checks. Similarly, checks outside of the trouble brackets, as well as redundant checks, should be avoided, as they contribute nothing to localizing the trouble.

The next electronics troubleshooting research effort that is pertinent to the present study was conducted for the Navy by McKendry, Grant & Corso (1960). This study was of a normative nature in that 52 design engineers and field engineers were questioned about system and equipment troubleshooting procedures. Most of this study dealt with 13 specific, representative circuits and included such aspects as test point and component location, parameters important in troubleshooting, and test equipment needed to check those parameters. The information was collected from written responses to questionnaires. No equipment was utilized in the study. The responses were analyzed and frequency plots were constructed for each circuit, indicating the important parameters to check, the required test equipment and the use of test points.

The 13 circuits were divided into classes, depending on their function. These classes included amplifier circuits, oscillator and modulator circuits, timing circuits, and special (other) types of circuits. Using the first class, amplifier circuits, as an example, it was found that the most important troubleshooting parameters to check on low frequency amplifiers were the output waveforms. For higher frequency amplifiers, the most important circuit parameters to check were the pin voltages. For the former, it was found that the oscilloscope was the piece of test equipment most frequently recommended, while for the latter case, a vacuum tube voltmeter was cited most often. Corresponding findings were detailed for the remaining classes of circuits.

It was also mentioned that the selection of a particular approach or piece of test equipment was not clear cut. For example, in troubleshooting the IR amplifier, there were four parameters receiving between 14 percent and 21 percent of the total vote as the first choice to check. In troubleshooting the RF amplifier, the top three pieces of test equipment received 31 percent, 29 percent and 20 percent of the vote, respectively, as the first choice of the respondees to the questionnaire. This pattern is indicative of a lexicographic strategy, since there often is a grouping of closely ranked choices, from which one must be selected. If there is a tie as to which choice is best, one would simply go to the next lowest choice and operate using it.

In general, it is important to keep in mind that such tabulations are summaries of opinions, and therefore might disagree with any one engineer's idea of the correct way to proceed. However, there were no significant differences between the impressions of the design engineers and those of the field service engineers.

In addition to considering specific circuits, the study also dealt with procedures for troubleshooting on the system level. The same pool of 52 design and field service engineers that participated in the circuit study, participated in this study. The replies of the engineers to the system questionnaire relating to the selection of system parameters to check is given in Figure 2.11 below. The entries are in terms of the percentage of the total respondents choosing the troubleshooting parameter first, second, etc. Because of the rounding error, the columns do not always total to 100 percent.

The replies indicate that the following procedure would be used in checking the system parameters. The first parameters checked would be either: (1) the waveforms of all signal outputs, or (2) the waveforms of all signal inputs. These would be followed by checks of: (3) the plate signal voltage, (4) waveforms of all inputs to subassemblies, (5) waveforms of all outputs to subassemblies, (6) filament voltages, (7) bias supply voltages, (8) grid and plate waveforms of all tubes, and (9) all internally generated waveforms. The heavy dependence on waveforms in system troubleshooting is apparent in this study, which was based on inputs from practicing engineers. Such emphasis would tend to place a high value on an oscilloscope as a troubleshooting instrument. Some of the earlier studies which were summarized above (see for example Bryan & Schuster, 1959, or Miller, Foley & Smith, 1953) did not agree with this finding. It was perhaps a consequence of their training that engineers attached a high preference to the use of an oscilloscope over simpler options such as a volt-ohm meter.

Parameter	Order of Choice 1	2	3	4	5	6	7	8	9
Waveforms of all Signal Outputs	32	14	2	16	6	4	15	3	3
Waveforms of all Signal Inputs	23	19	17	7	8	2	5	3	0
Plate Supply Voltages	18	12	19	4	13	9	2	5	7
Waveforms of all Inputs to Subassemblies	2	16	19	18	11	11	5	3	7
Waveforms of all Outputs to Subassemblies	3	14	15	25	2	13	12	3	3
Filament Voltage	17	6	6	5	8	2	10	5	3
Bias Supply Voltge	4	12	9	7	9	13	7	11	7
All Internally Generated Waveforms	0	0	4	2	9	11	19	14	10
Grid Waveforms of all Tubes and Plate Waveforms of all Tubes	0	0	11	4	9	6	5	30	13
Grid Waveforms of all Tubes	0	0	0	4	4	13	10	14	7
Plate Waveforms of all Tubes	0	2	0	0	13	6	12	5	10
Plate Supply Current	0	0	0	2	0	4	10	5	13
Cathode Waveforms of all Tubes	2	0	0	4	2	0	0	0	7
Filament Current	0	2	0	2	4	2	0	3	7
Bias Supply Current	0	2	0	2	2	4	0	0	3

Figure 2.11 Responses of 52 design engineers and field engineers to the system questionnaire.

As stated earlier with regard to the circuit parameters, the pattern of responses for the system parameters was suggestive of a lexicographic strategy for choosing between the various heuristics comprising the overall heuristical program for troubleshooting system parameters. Such a program began with general input-output checks and power supply (plate voltages and filament voltages) checks. A technician might vary the order of those checks, depending on the test equipment available, accessability of the test points, and general convenience. Once those general checks were performed, the technician should concentrate on more specific areas of the system, but as Figure 2.11 indicates, the pattern was still one of input-output and power supply tests. After a defective area of the system was localized, the specific circuit checks outlined earlier applied.

At this point, the review of the literature has suggested that the technician might employ different heuristical programs for different phases of the troubleshooting process. For example, it was mentioned earlier that technicians displayed a pattern of initial actions in starting the troubleshooting process. These actions, the overt manifestations of their heuristics, included such behavior as varying the control settings and changing modes of operation. From the information thus obtained, the technician then employed system and circuit heuristical troubleshooting programs, such as those just described, to identify the defective circuit element. The replacement or repair of the suspect element either solved the problem or resulted in a re-initiation of the heuristical troubleshooting sequence.

The studies summarized above represent a sufficient foundation from which the present study could be continued. It will be recalled that the present study is concentrating on identifying the electronics troubleshooting heuristics being employed by highly skilled technicians in actual troubleshooting situations. The earlier studies had a similar goal, but they relied on contrived troubleshooting situations and utilized subject pools comprised of technician trainees or of practicing engineers to make inferences about the behavioral heuristics of technicians in the field, working under operational conditions. By directly concerning itself with operational technicians, the present study fills an important void which was not addressed by earlier researchers.

The remaining research efforts pertaining to electronics troubleshooting which are reviewed below do not shed much additional light on troubleshooting behavior. In some instances, these studies were supportive of earlier works, while in other cases they considered aspects of troubleshooting which were not directly related to the present study, such as modeling troubleshooting as a stochastic decisionmaking process. All studies pertaining either directly or indirectly to the present study, however, are included for completeness.

From 1953 to 1969, the University of Southern California Department of Psychology, under a contract with the Navy, investigated a number of aspects relating to personnel engaged in electronics troubleshooting. The work performed during this interval was concerned with four major research areas: maintenance and maintainability of electronic equipment, multidimensional scaling, computer personnel selection, and technician training. In general, the reports called attention to the number and complexity of tasks required to fulfill maintenance requirements for even relatively simple equipment, such as a radio transceiver or a search radar. Also, it was noted that the technician's job continues to be made unnecessarily difficult by equipment that simply was not designed for ease of maintenance and by cumbersome technical manuals which seem almost to be deliberately organized to prevent the technician from finding the information needed. The specific studies from this series which are relevant to the current research are summarized below.

Grings, et al. (1953) conducted a study of the problems inherent in the measurement of troubleshooting skill. They noted that conventional paper and pencil tests might be ill suited for that purpose. Such tests were most useful for measuring knowledge which was presumably related to or necessary for the performance of troubleshooting tasks. However, the format of those tests generally was too inflexible for eliciting meaningful samples of a performance. Also, paper and pencil tests were inadequate for presenting realistic troubleshooting problems to a subject. They tended to rigidly structure the technician's path from beginning to end by supplying a very limited number of standard alternatives, choice points, and samples of problem information. Further, they gave away information by listing alternatives and crucial cues.

Conventional job sample tests, on the other hand, evoke performance which was generally assumed to be representative of that on the job by the use of actual equipment. The drawbacks to such an approach were the administrative inconvenience, the expense of the equipment required, and the inherent difficulty of scoring the tests.

Some important guidelines for those engaged in the study of troubleshooting were detailed in the study. Analysis showed, for example, that the troubleshooting task was composed of heterogeneous subtasks, each requiring certain activities which were determinants of the success or failure of the troubleshooting effort.

It was emphasized that the technicians had to structure the problem for himself. He started with a certain number of givens in the situation, such as front panel indications, output symptoms, operator reports, supplementary reference material, and his own experience. Between this start and the end of the problem lay a solution route which he determined. The route might have numerous byways, or it might proceed by the shortest path from start to successful completion of the problem. The important point was that the solution path is the result of the interaction between the situation and the individual. No two technicians will solve the problem in exactly the same way. There were no fixed alleys in the maze which they transversed. Each individual selected his own test points in the circuit and was faced with his own choice points in his decisionmaking process.

Such a view of troubleshooting behavior rejected the idea that the technician's successive responses were rigidly determined by his preceding responses. Analysis of detailed response records has shown that even the successful troubleshooter made both fruitful and unfruitful moves. He might indulge in repetitive behavior, making the same measurement over and over at a test point. Or, he might skip about in the circuit with no apparent relationship among his responses. The view that the first response determined what the second response would be, and that one and two determined the nature of the third, presented too rigid a picture of the troubleshooting process.

The researchers suggested that the ideal format for the measure of troubleshooting behavior would start the subject with a standard minimum of information about a problem, and then force each subject to structure his own presolution behavior. In essence, he would be provided with a pool of information relating to the problem, from which he could sample according to his own inclinations. The setting and equipment used by the subjects should be the same as that found in their usual troubleshooting environment. These two points, an unstructured response format and a realistic environment, are the two most frequently violated concepts by researchers engaged in the study of troubleshooting.

The next report in the University of Southern California (USC) series considered those factors influencing troubleshooting difficulty (Rigney & Hoffman, 1961). The factors were identified by using paper and pencil tests administered to technician trainees. The factors considered in the study were the type of diagram used to represent the system (block versus detailed), the degree of failure of the defective stage (partial versus complete) and the problem category (feedback versus non-feedback).

It was found that the stimulus clutter in the detailed diagram will not have any appreciable effect in making those problems harder than their block diagram counterparts. Problems involving a feedback loop were correctly solved less often than those which did not. Also, partial failures were more difficult to solve than were complete failures. In general, it was found that any condition which complicated the simple, direct interpretation of symptom information made the problem harder to solve.

The next report in the USC series which pertained to the present effort considered human factors research in electronics maintenance (Rigney & Hoffman, 1962). Among the many points addressed by this survey article was the fact that little research had been conducted on maintenance variables. By this, it was meant that there had been no attempt to break down the maintenance task in terms of understanding its basic psychological elements. It was suggested that increased effort be undertaken toward achieving such an understanding. Other than drawing attention to the problem, and the lack of research on it, this report did not address any other areas relevant to the present study.

A later report looked at the problem solving aspects of corrective maintenance (Rigney, et al., 1965). These were represented in terms of the criterion tasks of system state recognition, fault localization, circuit isolation, and component isolation tasks. Four performance tests incorporating these criterion tasks were developed for an operational radio transceiver and administered to a sample of 54 shipboard Navy technicians who were responsible for the maintenance on the device aboard their ships.

The test results showed that very few of the technicians in the sample could successfully perform the criterion tasks of system state recognition and fault localization. The technicians were somewhat better on the criterion tasks of circuit and component isolation, although this was highly dependent upon the nature of the malfunction. Other technician weaknesses uncovered by the tests were in equipment operation, in symptom recognition, and in test equipment use.

While not many of the details were given on the backgrounds of the subjects, the results would suggest that they were not highly experienced. This was partially evidenced by the finding that they scored low in equipment operation and in test equipment use. A possible cause might have been that newly assigned technicians were used for the test, rather than a cross section of technicians with varying levels of experience. In any event, the study was somewhat unique in that shipboard equipment was used and that the test was conducted in an operational setting.

Following this effort, the next few reports from the USC group dealt with an Experimental Fault Locator (XFL) (Rigney, et al., 1965a; Rigney, et al., 1965b). This device served as a performance aid for technicians engaged in troubleshooting tasks. Generally, each type of equipment had its own unique performance aid. The principle problems with performance aids were that they didn't encourage development of troubleshooting skills, and that they couldn't generally cope with unusual malfunctions as well as could a thinking, experienced troubleshooter.

Later reports went on to deal with computer programs for assessing corrective maintenance times for different types of equipment (Rigney, et al., 1966a; Rigney, et al., 1966b). The purpose here was to identify troublesome parts of a system, requiring inordinately high man-hours to repair. Once identified, these subsystems were analyzed further to see if they could be re-engineered and simplified. The general findings were that trends were not readily apparent, and even if detected, corrective action was not easily accomplished.

A Bayesian model approach was also used in studying troubleshooting behavior (Rigney, et al., 1966c). A symptom-malfunction (S-M) matrix was constructed as a basis for matching the electronics technician's troubleshooting capabilities to the hardware requirements. S-M matrices show interrelationships between possible malfunctions and the set of symptoms which each malfunction can cause, in the sense that certain symptoms are more compatible with certain malfunctions than they are with other troubles. The resulting S-M model was called the Bayesian Electronics Trouble Shooting (BETS) model. This model was used as a criterion measure of troubleshooting ability. Using the model, the uncertainty remaining in the S-M matrix was computed after each symptom sampling step. The BETS troubleshooting strategy was to select each successive test step on the basis of its potential uncertainty reduction in an information theory sense. BETS could be used at each step in the troubleshooting sequence to select that combination of test and test point which had the greatest potential uncertainty reduction.

Thirty-nine technician trainees assigned to a Naval technical training facility were given both a S-M completion test and a troubleshooting performance test based on the same circuit. Data collected from each subject were number and location of errors in the S-M matrix completion test, test points at which symptoms were sampled, the sequence of sampling steps taken in the performance test, interstep times, number of malfunctions isolated out of a total of six, and total time to isolate each malfunction.

Analysis of the data revealed that these technicians were only about one-third as efficient as the BETS computer program in troubleshooting a given circuit. There was a moderate positive correlation between the quality of a technician's subjective S-M matrix, as determined by the completion test, and the quality of his troubleshooting performance. The subjects' subjective matrices were used in conjunction with a Bayesian algorithm to identify those technicians who acted like Bayesian processors while troubleshooting. The criteria of Bayesianism were terminal malfunction probability values computed by applying the technician's own sequence of steps, recorded during the performance tests, to his subjective matrix using the Bayesian algorithm. About one-half of the technicians qualified as resembling Bayesian processors.

As a simulator of ideal troubleshooting performance, the BETS model, with the associated S-M matrix, had potential applications in several areas. It could be viewed as a normative, optimal heuristic for troubleshooting. It could also serve as a criterion measure of troubleshooting ability at the process level. Finally, since it could be used to troubleshoot a piece of electronic equipment, once its S-M matrix representation had been constructed, it offered a useful design tool with which to adjust the cognitive aspects of the troubleshooting requirements of a proposed system to the measured capabilities of a population of technicians. This latter application of BETS could be done early in the design cycle so as to make the cost of changes relatively inexpensive.

A follow-up study with BETS was made using more advanced trainees (Rigney, et al., 1967). Thirty-six advanced technician trainees were given a S-M matrix completion test on a blocking oscillator circuit. Next, via card simulation format, each technician attempted to solve six troubleshooting problems in the same circuit. Records were kept of each voltage and resistance reading made and of each component replacement choice. After the troubleshooting session, the subjects took a retest on the S-M matrix completion test. Using the technician's S-M matrix values as a starting point and his series of checks as information cues, a Bayesian computation was carried out for each performance. This computation yielded Bayesian likelihoods for each replaceable component in the circuit.

The advanced trainees demonstrated superior performance to the earlier sample of technician trainees, described above. Improvement occurred in the areas of troubleshooting time, steps to solution, and the number of correct solutions. The retest indicated that as a technician worked on search problems in the oscillator, he improved on his original S-M matrix for that circuit. This pointed to the conclusion that learning of S-M relationships occurred as a result of troubleshooting activity.

As in the earlier experiment, only a little more than one-half of the subjects were appreciably Bayesian in making component replacement choices. It was also found that an improved S-M matrix was related to several troubleshooting competence indicators.

The two efforts discussed above attempted to formulate a normative standard, based on Bayesian decision theory, against which individual troubleshooting performances could be compared. The Bayesian Electronics Trouble Shooting (BETS) model, a troubleshooting heuristic implemented by a computer program, was developed to compute the uncertainty remaining in the S-M matrix after each symptom-sampling step in the troubleshooting process. This attempt, while of interest from a theoretical point of view, did not result in much in the way of practical benefits. Aside from the fact that technician trainees were again being used to make inferences about experienced technicians in the field, the use of a Bayesian model failed on other grounds. One reason was that the Bayesian model was too insensitive to important differences in information processing skills. This was illustrated by the lack of a significant difference between the two samples with regard to Bayesian behavior, when there were clearly defined and demonstrable differences in the trouble-shooting skill levels of the two test groups. Also, it appeared that the Bayesian model was too inflexible to accommodate the dynamic changes which occurred during the troubleshooting process. That is, the Bayesian model did not yet approach the reasoning ability of the human mind. It did not take into account the constraints and mechanisms of short term memory, for example. Further evidence cited earlier suggested that individuals seek to limit the problem, through the use of heuristics. The Bayesian model, on the other hand, supposed conception and aggregation capabilities on the part of individuals, which were unrealistic. In short, since it was generally accepted that individuals do not reason and think in a statistical, much less a Bayesian, manner, such models will not be considered further in the present descriptive study of electronics troubleshooting. The principle contribution of the studies outlined above were the XFL and the BETS concepts. XFL was devised to compensate for a troubleshooter's weaknesses in working with and applying technical and symptom information. BETS was developed to provide an ideal standard against which troubleshooting performance could be measured, and to aid in designing maintenance efficiency into new systems.

A descriptive analysis of the structure of maintenance work was the next area of study pursued by the USC group which was relevant to the current effort (Rigney, et al., 1968a). All of the maintenance oriented toward restoring the equipment to operationally ready status was conceived as a hierarchy of serial activities, defined in descending order as corrective maintenance requirements (CMR's), tasks, and actions. This is illustrated schematically in Figure 2.12 below.

$$\underbrace{\left[\underbrace{\left\{\begin{matrix}\text{Task 1} & \text{Task 2}\\ (a_1,a_2), & (a_3,a_4,a_5)\end{matrix}\right\}}_{\text{CMR 1}}\ ,\ldots,\ \underbrace{\left\{\begin{matrix} & \text{Task m}\\ (a_{15},a_{16}),\ldots, & (a_{n-1},a_n)\end{matrix}\right\}}_{\text{CMR k}}\right]}_{\text{MTC}}$$

Figure 2.12 Decomposition of a MTC into CMR's, tasks and actions.

Some of these subgoals or CMR's occurred so frequently that they were named. These included system state recognition, fault localization, circuit isolation, component isolation, and component replacement. These CMR's corresponded closely to the action sequences of troubleshooting which were identified earlier by Bryan and Schuster (1959).

All activities, whether observable or nonobservable, which were performed in achieving the ultimate goal of returning the unit to service are collectively termed the maintenance task cycle (MTC). A MTC goal required certain CMR's, a CMR goal determined a set of required tasks, which in turn had goals which required the performance of certain actions. General methods of identifying goal sets were described by which the technician could work toward the ultimate goal through first attaining intermediate goals. Three work structuring processes, adapted from the problem solving literature, were described. These were goal decomposition, goal set transformation, and feature extraction. The first process involved breaking the ultimate maintenance goal, which was usually not immediately attainable, down into smaller, more attainable goals. Achievement of these smaller goals allowed achievement of the ultimate goal, which was to return the system to an operationally ready status. In the context of Figure 2.12, the CMR's represented attainable subgoals. The second process involved the decomposition of task goal sets into appropriate action goal sets, and vice versa. For example, in order to complete the task goal of power supply check out, certain actions, such as turn on, adjustment, test probe placement, etc., had to be accomplished. Similarly, the performance of one or more actions could fulfill part or all of several task goal sets. An instance of this would be where the turn-on, adjustment, and test probe placement action sequence would be in more than one task goal sequence. The net result would be that sets of possible goals were successively transformed into smaller sets until the set was empty. The final process, feature extraction, related to the selection of alternative subgoals from the set of all subgoals of a problem. That is, certain features interpreted by the technician were determinants of subgoal selection and ensuing activity. Examples of some features which might affect whether a particular task goal was selected included the technician's estimate of the value of attaining the task goal, the expected time required to attain the task goal, and the confidence on the part of the technician that the task goal could be attained at all. In effect, this process guided the selection of one alternative from several alternative tasks or sequences of tasks to be performed.

In the performance of the MTC, the technician was characterized as working at a maintenance interface. He utilized interface input elements to change the state of the equipment and output elements to interpret those changes and to gauge progress toward the achievement of the subgoals and the ultimate goal.

This paper made several important contributions which will figure prominantly in the current study. First, the authors reinforced the concept introduced earlier by Bryan and Schuster of a descriptive process model of troubleshooting behavior. Where Bryan and Schuster used the term action sequences, Rigney, et al., used CMR's. Both papers also agreed on the essential point that troubleshooting consisted of a series of actions which might be functionally and logically grouped together. There remains, however, a key difference between what was done by Rigney and his co-workers and what is proposed by the present study. The former recognized the interchange between incoming information to the technician and his resultant actions, but no attempt was made to discuss the specific processes at work. Accordingly, the present paper will describe the heuristical programs used in filtering the incoming information and the actions which follow. In terms of Figure 2.12, a heuristical program will be described for each CMR, and this program will be directly relatable to the actions which result.

The final report in the USC series which was applicable to the current study dealt with the topic of corrective maintenance performance (Rigney, et al., 1968b). This paper concerned itself with the specific CMR's discussed above, system state recognition, fault localization, circuit isolation, component isolation, maintenance adjustments, and repair. These were actual performance tests designed to identify errors committed in the course of troubleshooting, as well as sources of poor performance. With regard to strong and weak points in troubleshooting technique, the tests showed the technicians were good in performing designated front panel checks and in making go no-go judgments. They were moderately weak in selecting additional checks for symptom elaboration and they were poor in using standard test equipment, in performing system level checks, and in accurately reducing fault areas. As with some of the earlier studies by this group, details were lacking as to the experience levels of the subjects. It is likely, judging from the results, that the experience levels were low. This illustrates another key difference between the Rigney series of studies and the present study. The latter specifically concentrates on the study of heuristical methods used by experienced technicians while operating in a maintenance environment.

During the same time period as the early Rigney studies, the Institute of Radio Engineers' Human Factors in Electronics Group published a special issue relating to electronics systems maintenance. That issue, as well as one earlier study by the same group, were both pertinent to the current investigation into heuristics and coding mechanisms used in electronics troubleshooting.

The latter study investigated the coding of electronic equipment in order to facilitate maintenance (Ely, Hall & Van Albert, 1960). The aim of the study was to improve maintenance of electronic equipment by determining what information to place on the equipment and developing techniques for its display. Detailed data were collected from various maintenance installations, showing that there were marked variations between observed test point readings in normally functioning systems and those called for in the maintenance manuals. This resulted in confusion on the part of technicians assigned to maintain the system and a distrust of the technical manuals. To overcome these problems, recommendations were developed concerning information to be displayed on system equipment. These included the designation of functional groupings, identification of signal paths, identification of and sequence for each test point, and presentation of historical information. These recommendations were incorporated on an oscilloscope, and a comparison of average troubleshooting time was made with an identical uncoded scope. The comparison indicated that the troubleshooting time for the coded scope was reduced on the average of one-half of that required for the uncoded scope.

An important finding which emerged from this study was that the coding process appeared to only help the inexperienced technicians, particularly in locating and identifying difficult malfunctions. It did not help experienced technicians to appreciably improve on their troubleshooting times, nor did it aid significantly in the identification of easy malfunctions. This implied that experienced technicians were already employing mental coding procedures to a large degree, while the inexperienced technicians who had not yet cognitively formulated such procedures, were greatly aided by their presence in coded form on the chassis.

The IRE's special issue on electronics maintenance included an overview of pertinent human factors considerations (Manheimer & Kelly, 1960). Among these was the observation that many maintenance studies reflected too little knowledge of the maintenance man in the maintenance environment. Statistics about the man who performs maintenance in the services abound, it was noted, but intensive studies of the man in maintenance environment by those with a clear idea of what electronics maintenance entailed were sadly lacking. Studies performed at that time reflected for the most part a mechanistic view of man, rather than a behavioral one. In this light, the British psychologist, Sir Frederic Bartlett (1953), commented that many of those who do human factors research tended to view man in the much used phrase "man-machine relationship" as another machine of a somewhat different type.

The comments above, while critical of some past research, are supportive of the goals of the present study. A specific intent of the current study is to emphasize behavioral, rather than mechanical, aspects of troubleshooting. In addition, troubleshooters of varying levels of experience will be observed within their normal maintenance environment.

The next relevant study in the IRE series was a two part analysis of the fault location behavior of technicians servicing electronic equipment (Rigney, et al., 1961b; see also Bryan & Schuster, 1959). In the first part, some 422 records of troubleshooting behavior were reviewed. It was found that technicians frequently accumulated sufficient symptom information from test points to isolate a malfunctioning stage or to identify a faulty component, before they were aware that they had done so. Typically, they either continued to make redundant or irrelevant checks before entering the correct stage or replacing the correct component, or they never did use the information and thus they failed to solve the problem. Also, 71 percent of the first replacements were found to be incorrect. These results suggested that the search for symptom information and the interpretation of that information were not closely coordinated processes.

The second part of the study considered the differential effects of practice in applying troubleshooting strategy. Two groups of technicians were used. One was experienced in the circuitry involved while the other was inexperienced. After practicing troubleshooting techniques applicable to the circuitry, the two groups were tested. It was found that the experienced group made a higher proportion of efficient moves relative to the inexperienced group. It was concluded that the former group improved primarily in terms of using more sophisticated troubleshooting techniques, while the latter group gained chiefly by obtaining a better understanding of gross circuit relationships. One problem with this study was that written records of technicians working on simulated system components were used, rather than direct observations of technicians at work on actual equipment.

From these two analyses, it appeared that neither understanding alone nor technique alone sufficed for troubleshooting proficiency. Both

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AN INVESTIGATION OF MENTAL CODING MECHANISMS AND HEURISTICS USE--ETC(U)

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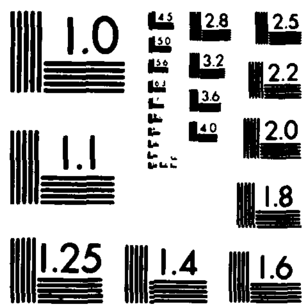

MICROCOPY RESOLUTION TEST CHART
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were necessary. Also, it was shown that even the relatively experienced technician benefited from learning to apply a sound, general strategy.

The final study from the IRE series which pertained to the current research dealt with how to design more maintainable circuits (McKendry, Corso & Grant, 1961). This paper was an abbreviated version of an earlier technical report by the same authors, reviewed previously (McKendry, Grant & Corso, 1960). Briefly, questionnaires were distributed to 210 design and field service engineers to obtain information on the primary factors affecting fault location time. Results showed that certain parameters yielded more troubleshooting information on all circuits, and that these parameters remained approximately the same for the frequency range studied. For example, patterns (heuristics) were suggested from the data, such as: check tubes first, then resistors, then capacitors, etc.; or check input waveforms first, then output waveforms, then power supply voltages, etc.

One finding from this study, which pointed out a potential problem with using one class of subjects to make inferences about another class, was that the engineers listed the oscilloscope as the most useful piece of test equipment. This was contradictory with results from studies of technician practices, which indicated that technicians actually preferred a volt-ohm meter to an oscilloscope.

The next study that touched on the more behavioral aspects of electronics troubleshooting considered the effects of ambiguous test results on troubleshooting performance (Pieper & Folley, 1967). The principal thrust of this paper was to assess the effects of varying levels of ambiguity on two groups of subjects (high school students) who used different troubleshooting approaches. One group of subjects was composed of those with high electronic aptitudes, while the other group had those with medium aptitudes. Ambiguous test results were simulated by the statement "unknown", as opposed to "good" or "bad" to represent unambiguous test results.

Since these subjects all had medium to high electronics aptitude, but no training or actual experience, the method used to impart trouble-shooting training is of great interest here. This method amounted to the teaching of certain rules or heuristics, some of which were discussed above. Actual classroom and laboratory training time consisted of 11 hours, after which the subjects were able to successfully troubleshoot various circuits of moderate complexity.

The overall troubleshooting process was depicted for the subjects as shown below in Figure 2.13.

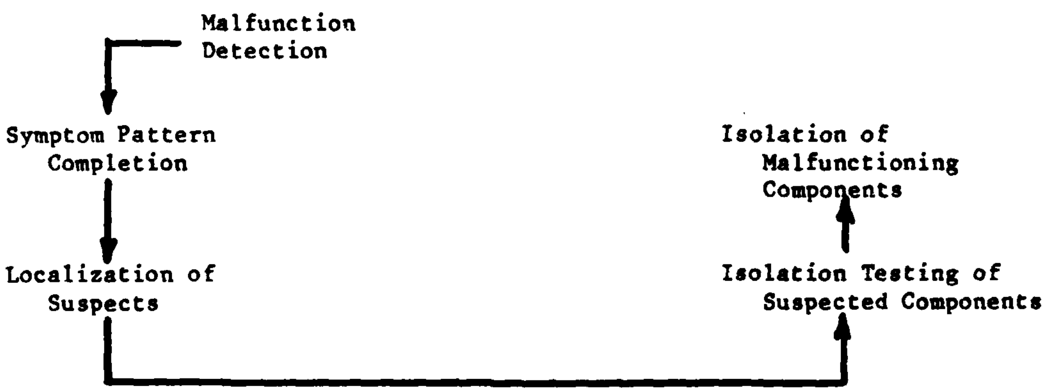

Figure 2.13 The troubleshooting process.

For each of the four parts of the troubleshooting process shown in Figure 2.13, rules or heuristics were taught during the training sessions which enabled the subjects to progress toward isolation of the malfunctioning component. Some of these rules are shown below.

> The Symptom Pattern Completion part included the checking of all panel and control settings and a determination of the condition of all system outputs.
>
> Localization had a variety of applicable rules, depending upon the nature of the suspected circuitry. For example, with an out of tolerance output, the following rule applied: The suspect components are those which feed only the out of tolerance output.
>
> Isolation also featured a list of rules, depending on whether the test results were unambiguous or ambiguous. For unambiguous test results, the half split strategy was recommended. For ambiguous test results, another test point, as near as possible to the original point, should be tested, until an unambiguous reading could be obtained.

The above procedures were vague and general, when compared with some of the more specific rules and strategies discussed earlier. However, the overall concept was supportive of the idea that troubleshooting can be viewed as an information processing operation, which utilizes simple mental rules or heuristics with which to selectively filter the mass of available information down to that which is essential to resolving the malfunction. Since the purpose of the Pieper-Folley paper was to study the effects of ambiguity on troubleshooting, they apparently chose to utilize heuristics in their training in order to save time, and in order to achieve a troubleshooting facility for their subjects which would have required much longer to impart using conventional methods.

The next development in troubleshooting theory which will be considered was that of proceduralized troubleshooting (Elliott, 1967). The term proceduralized troubleshooting has been used to refer to a wide variety of task designs, the object of which has been to eliminate the necessity for the technician to decide, select, remember, deduce, identify, etc., any or all of a number of facts required for performance of his task. The term was usually applied when the decision about where in the system the technician was to check next was made for him by a performance aid. Proceduralized methods could also provide other advantages. The same performance aid presentation which told the technician where to look next could also display expected normal readings and tolerances, test point locations, test equipment and test selection, parts identifications, and additional instructions of various sorts. For example, the likelihood of error in resistance measurements could be reduced by specifying the position of the meter selector switch and the scale value. Under those circumstances the technician would not have to decide where to place the switch, based on the expected reading, or to convert the scale value to ohms as a function of the multiplier.

Since the approach of the current behavioral research is completely opposite to a proceduralized approach using performance aids, it is appropriate that some contrasts be drawn between the two. To begin, the behavioral approach attempts to capture the heuristics and mental coding mechanisms which are actually being employed by technicians in the field. The proceduralized approach specifies steps to be taken, usually in the form of a go-no go decision tree process. Elliott himself noted that a frequent criticism of the proceduralized approach was that it provided the wrong answers to the easy problems and gave no help at all on the hard problems. The reason for this shortcoming was that no performance aid was capable of matching the cognitive flexibility of a trained and experienced individual. This was illustrated in the earlier discussion of the complexity of even an orderly problem, such as a game of chess. A related problem was that proceduralized methods generally didn't allow for the possibility of ambiguous readings. With conventional methods, or with heuristical methods of troubleshooting, there is more flexibility in surmounting such a problem.

Another contrast was, of course, in the amount of supporting material necessary for the two techniques. With the proceduralized approach, the technician employing the performance aids was viewed as technically naive. Therefore, the aids necessarily had to account for every possible malfunction in each area of the system. Those first had to be developed, packaged and then indexed for easy use. With the heuristical approach, the technician relies upon a set of mental rules developed through experience, and consults the technical data only for specifics unique to a given system.

The contrast between the two methods with regard to correctness of the information supplied is also worthy of mention. With the proceduralized approach, it was assumed that the performance aid contained the information needed at the appropriate point and that the information was correct. The technician proceeded on this assumption because it was his only alternative, since neither his training nor his performance aid provided any other line of approach. If the information was absent or in error, failure to identify the defective component generally resulted. When that occurred, the technician's only recourse was to repeat the procedure based on the assumption that he must have made an error. With a heuristical approach, the technician is conditioned by experience to try alternative approaches in seeking out the malfunctioning component. If a first approach results in an unsuccessful choice, a different approach can be tried until success is achieved.

A follow-on study was conducted using service technicians in competition with high school students (Elliott & Joyce, 1968). The service technicians, all with field experience, used the same troubleshooting techniques they ordinarily used on their jobs. The high school students used specially developed performance aids. A set of 13 troubleshooting and repair problems on seven solid state circuit modules which contained up to five stages each, comprised the test for each group. It was found that the work speed and the frequency of repairs for each group were not significantly different.

In reviewing the details of the experiment and the narrative, it was unclear as to whether the malfunctions were induced by the same persons who devised the performance aids. A review of the performance aids and the induced malfunctions showed them to be quite similar. For example, the seven page performance aid dealing with Module 300, the Variable Frequency-Variable Amplitude Sinusoidal Oscillator, concentrated on the waveforms for the five transistors and gave much less information on the unit's other 23 electrical components. The discussion of the circuit which comprised the first page of the aid was highly technical, employing such terms as feedback, decoupling network, emitter follower, leakage and gain, and other terms. It seems unlikely that many of those terms were meaningful to a group of high school students having only 11 hours of electronics training. Also, no mention was made regarding intermittent malfunctions or unusual malfunctions. The performance aid implied that all readings were of a stable and discernable nature. In summary, it seems unlikely that such aids could successfully meet the challenge of day to day maintenance on operational equipment.

By the late 1960's, much of the interest and funding support for research into electronic troubleshooting had diminished. This trend has continued through the present time. However, a recent exception was the publication by a group of Danish researchers of a paper dealing with mental procedures used in electronics troubleshooting (Rasmussen & Jensen, 1973). The technicians involved in the test were all experienced, and the test was conducted in their normal working area. As a technician worked through various problems in troubleshooting, his verbalized, introspective comments were tape recorded. Written summaries were then prepared from the recordings and were subsequently reviewed by the technicians for accuracy and completeness. A total of 45 cases were recorded and summarized, comprising six individuals performing fault finding on eight different types of equipment. From these, routines were identified and extracted, and their frequencies of occurrence tabulated.

While the overall paper was characterized by a lack of specificity from the descriptive point of view, it did serve to reinforce several important ideas. For one, the paper supported the statement by Bainbridge, et al. (1968) that a very formalized analysis in which the procedure of the man is compared with a model covering all possible strategies is an impractical and unrealistic approach. Rather, man is selective in extracting pertinent information from the total pool of available information, hence a model of such a process should be structured accordingly. The study also made the point that different technicians could have different mental models of the same system, depending on their backgrounds, experience and other factors. For example, the mental model of a car would likely be different for a consumer, a mechanic and a car salesman. Thus, the way in which information is encoded and heuristically processed will be affected by how the system is modeled. Another important point was that one's training and background strongly influence the troubleshooting approach employed. A design engineer might approach a fault localization problem by utilizing detailed observations of the faulty response and consideration of the internal anatomy and functioning of the system. A technician, on the other hand, might choose to scan through the suspect part of the circuitry, making a rapid series of go-no go checks, comparing parameters with those of a similar nature in other parts of the unit known to be working satisfactorily. Both of these procedures have proven to be effective in fault localization, however, the latter approach is more cognitively manageable. Finally, the authors pointed out that the body of knowledge resulting from experiments in clear cut laboratory conditions, dealing with well defined and supposedly isolated aspects of human behavior, should be supplemented by studies conducted of the mental procedures used by operational personnel in real life working conditions. The results of such studies are important for the design of data displays to support system operation, for the establishment of the physical layout of a system, and for the detailing of the maintenance procedures and manuals in order to facilitate system repair.

As noted above, the actual findings of this study were general in nature. They confirmed earlier findings that troubleshooting typically proceeds from the system to the subsystem to the component level. Also, techniques employed within each of these levels may either be of a functional or of a topological (location) nature. The study found that in the making of judgments about where to check or whether the reading was good or bad, the general electronic experience of the technician involved was the most often cited basis used where normative data was not available. Related to the questions of where to look and what to look for, was the finding that 80 percent of such decisions were made based upon a single observation and upon general experience. Only 20 percent of such decisions were based upon careful reasoning and consideration of the internal functioning of the specific system. Again, this implies a process of selective filtering of the available information. Another significant point was that the troubleshooter's search through the system seemed to be governed by the results of the previous step, rather than by an overall, predetermined plan of attack. This, of course, would be supportive of the idea of keeping cognitive strain to a minimum. In general, it was concluded that the complete troubleshooting procedure used in a specific case depended strongly on the type of equipment, the actual malfunction, and the operator. This gave further support to the notion that there is no one general troubleshooting approach which would be applicable to all systems.

The final work surveyed in this review of troubleshooting literature related to evaluating maintenance performance (Shriver & Foley, 1974). While this paper primarily dealt with performance aids, it also reiterated a point of consequence to the present study. It asserted that paper and pencil tests of job knowledge and electronic theory were poor indicants of troubleshooting skill. Einhorn (1971) earlier had pinpointed the problem with such measures, when he wrote that the practice of presenting cues to the judge in a decomposed form not only imposed the experimenter's own judgment as to what the relevant cues actually were, but more importantly, it did a considerable part of the cognitive work for the judge. The Shriver-Foley study further pointed out that little work was underway to develop adequate troubleshooting measures. The authors particularly criticized the idea of relating a single written test score to troubleshooting ability. In order to adequately study and assess electronics troubleshooting, they wrote, one must employ practicing technicians in a maintenance setting, who are working on actual operational equipment.

II.5 Summary of the Review of the Literature

Because of the diversity of the works reviewed in the preceding sections, a summary is provided below. The same order as that used previously--behavioral decision theory, mental coding, heuristics, and electronics troubleshooting--is retained in the summary material.

With regard to behavioral decision theory, it was observed that the present study falls into the category known as descriptive process modeling. This means that emphasis is on how the decisionmaker actually makes decisions, as opposed to a normative approach which would indicate how one should make decisions, given the same circumstances. A process model approach is non-mathematical in nature, and describes decision-making in terms of heuristics, or mental rules of thumb, rather than in terms of a mathematical approach, such as Bayes' theorem. As noted by Slovic, Fischhoff and Lichtenstein, the process model approach is being used with increasing frequency by researchers in applied decisionmaking settings.

Other behavioral decisionmaking approaches were reviewed and summarized. These included probabilistic judgment models, such as Bayesian decision making; regression approach models, such as with linear regression and ANOVA; risky choice models, such as with subjective expected utility; and dynamic decision models, such as with dynamic programming. Contrasts between the models were discussed, along with their relevance to the current study.

The next area which was reviewed pertained to mental coding. Mental coding is an operation which has been described as a sensory reception of a stimulus, along with a perceptual process that involves the interaction of sensory functions and the memory. An important distinction was made between sensation and perception. Sensation is provided by the senses, which give inputs as to the state of the environment. Perception occurs when these inputs are interpreted and their psychological content is extracted. The role of the selective filtering process in determining which of the sensory inputs should be perceptually attended to was discussed. The memory provides a facility for accumulating and storing the knowledge thus obtained. This facility is broken down further into a two stage system (Newell-Simon model), consisting of short term memory (STM) and long term memory (LTM).

This model, and its relationship with the overall human information processing system model, also proposed by Newell and Simon, was summarized in the context of how mental coding is accomplished. Memory can be improved by a recoding process called chunking. Since STM is limited by the number of items, rather than the amount of information it contains, one's capacity to remember can be increased by a more efficient grouping of those items. The encoded, or chunked, information is what is actually stored in memory.

Experimental results from the game of chess have shown that experts are able to work with chunks of larger size than are non-experts. However, experts are limited to the same number of chunks, five to seven of them, as are non-experts. Thus, it is in the coding process that a clear differentiation between highly skilled and lesser skilled individuals has emerged. That is, while members of both classifications utilized the same number of chunks, those chunks associated with members of the highly skilled category are richer in information, due to greater coding efficiency on the part of those individuals.

A related feature is the use of powerful and selective heuristics which enable one to efficiently sift through complex information presentations and utilize only that which is relevant to the problem. As with the mental coding mechanisms, the use of heuristics is a cognitive process which has been necessitated and molded by the interaction between the demands of the task and the limitations of the decisionmaker.

In terms of defining what is meant by the word heuristic, it can be contrasted with an algorithm. An algorithm is a process for solving a problem which guarantees a solution in a finite number of steps if the problem has a solution. An example of a simple algorithm would be the one to convert temperature on the Fahrenheit scale to its equivalent on the Centigrade scale. A heuristic, however, is a process for solving a problem which may aid in its solution, but offers no guarantee of doing so. An example of a problem solving heuristic is to use an analogy. That is, look for an analogy between the situation with which one is attempting to deal and some other similar situation with which one has successfully dealt in the past.

Heuristics have been applied to various activities, including the game of chess. Studies have shown that expert chess players discover winning combinations because their cognitive processes incorporate specialized heuristics and not because they think faster or memorize better than other players. The degree of complexity of a typical game of chess, and the various heuristical programs which can be applied to different phases of the game were discussed.

A recent series of studies centered on three heuristics used in the context of probabilistic judgments made in a variety of task situations. These three heuristics were representativeness, availability, and anchoring and adjustment. The heuristic of representativeness applied at times in judgments of the probability that object B belonged to class A. When B was similar to A, that is, representative of it, then the probability was judged to be high. The availability heuristic applied in instances whereby an event was judged likely or frequent if it was easy to imagine or recall relevant instances, that is, when such recollections were readily available. With anchoring and adjustment, a neutral starting point or anchor was used as a first approximation to a probability judgment. This anchor was then adjusted to accommodate the implications of additional information.

The task of choosing between alternatives was viewed in terms of an elimination by aspects heuristic. Here, alternatives were viewed as sets of aspects. At each stage of a sequential choice process, an aspect was selected with probability proportional to its importance. Alternatives judged to be unsatisfactory on the selected aspect were eliminated, and the process continued until only one alternative remained.

A somewhat different heuristic has been applied in decision situations involving time pressures or distractions. Here, instead of considering all aspects of each alternative, managers simply scanned aspects for negative dimensions, and then eliminated alternatives on that basis alone. This was an example of a noncompensatory strategy, since the favorable aspects could not overcome the unfavorable aspects of a given alternative.

The examples above are a few of the heuristically oriented studies which have recently been conducted. As late as 1971, when Slovic and Lichtenstein surveyed literature on decision theory, they found only a handful of studies that looked at subjects' information processing heuristics. However, in their 1976 review of the literature, they assert that almost every descriptive study is now incorporating the study of heuristics as a means of obtaining a better understanding of man's cognitive processes.

In conducting the review of literature relating to electronics troubleshooting, it was found that most of the sources were in the form of government contract reports. A number of these had been published in professional journals, but in general, the government documents were more detailed. Therefore, the government reports were used more extensively than were the corresponding journal articles.

The functional invisibility of the electron was discussed along with the unique troubleshooting problems which this causes. Also influencing the troubleshooting process was the disparity between the schematic representation of a circuit and its actual form.

Prior to the 1950's, electronic equipment had not come into wide enough use to justify much research interest in either electronics maintenance or electronics troubleshooting. However, with the advent of elaborate communications and surveillance systems in the military, along with commercial television and computational systems, a great deal of interest was generated in the care and repair of these systems.

A doctoral study conducted by Saupe at the University of Illinois investigated nine hypotheses relating to the troubleshooting process. It was found, for example, that knowledge of basic electronics was a necessary, but not a sufficient, condition for success in solving troubleshooting problems. Other hypotheses were concerned with some of the specific elements of the troubleshooting task. It was found that good and bad technicians perceive symptoms with about the same degree of completeness and correctness. It was not clear that better technicians tended to secure sufficient information before accepting a hypothesis, to any greater degree than did poorer technicians. It was found, however, that the first hypothesis accepted by better technicians tended to be correct more often than did the first hypothesis accepted by poorer technicians. Also, it was found that poorer technicians entertain more incorrect hypotheses. Successful technicians, upon obtaining critical information in their checking procedures, tend to recognize and act upon it better than do poorer technicians. With regard to errors in the use of test equipment, no difference was found between good and poor technicians. Also, concerning the number of redundant checks made, there appeared to be no difference. Finally, it was found that it is possible to differentiate among technicians with regard to the approach, while poorer technicians were less systematic. A criticism of this study was that it used technician trainees, rather than practicing technicians, as subjects. Many subsequent studies also used trainees, rather than experienced technicians, as subjects.

Saltz and Moore looked at differences between good and poor troubleshooters. They found that good troubleshooters knew more about the functioning of equipment upon which they worked than did poor troubleshooters, that good and poor troubleshooters differed in previous experience, that good and poor troubleshooters didn't differ in intelligence, and that good troubleshooters didn't form abstract concepts more quickly than poor troubleshooters. Troubleshooters themselves were interviewed for their opinions as to what they believed were important procedural factors in troubleshooting. Those which emerged were logical analysis, or thinking out the problem, knowledge of the equipment, past experience with a particular malfunction, and ability to use test equipment properly. In addition to these, a hierarchy of behavioral responses was proposed, along with comments pertaining to technicians' information processing abilities.

A report by Miller, Folley and Smith described two procedures for troubleshooting electronic equipment. One was based on probability data, while the other was based on logical elimination of malfunction sources. Troubleshooting using probability data necessitated considerable historical data regarding past malfunctions, as well as a record of what steps had been taken to solve these prior malfunctions. These must be indexed and personnel trained in their use must be available. On the other hand, troubleshooting by logical elimination required a functional block diagram and some training in the elementary logic of eliminating alternatives. Systematic checks are then employed in this method to narrow the possible malfunction sources.

Evans and Smith did a study of troubleshooting techniques used by technician trainees in paper and pencil exercises. The data from these were then summarized to form a statistical composite of a troubleshooter. However, the subjects and the test environment limited the generality of the results. The most important finding was that the technicians viewed troubleshooting as the most critical aspect of their job.

Warren, et al., focused their interest on the teaching of basic troubleshooting principles. They noted that troubleshooting by data flow analysis primarily involved the application of certain basic procedures of a general and logical nature. To obtain these, they used inputs from experienced field engineers. The engineers were asked to describe in detail the steps they would take in isolating various malfunctions. Actual equipment was not used. Instead, a researcher supplied verbal symptom information to the subjects. Comparisons of the protocols of three such experts troubleshooting the same malfunctions revealed nearly identical logical considerations underlying the steps which each took. Examples of procedures relating to specific systems, as well as procedures applicable to a wide range of systems, were summarized. This study represented another in a series designed to identify general processes or methods of troubleshooting.

Bryan, et al., considered troubleshooting from a behavioral viewpoint. This was the first study to detect and classify progressive phases in the troubleshooting process. These phases consisted of the initial action, the initial action sequence, the initial localizing sequence, subsequent localizing sequences, the isolating sequence, and the component replacement. The paper examined the different phases in detail. The outcome of the study included four general conclusions and 58 specific conclusions. The implications of those conclusions to a heuristical troubleshooting approach were examined. In general, they were found to be supportive of such an approach.

The comments of Brown in a report on Air Force training requirements were also supportive of the approach envisioned by the current research. He advocated that the teaching of basic principles and relations should be such that the maintenance person was provided with a kind of content free framework to which a wide variety of specific situations could be fit. Such an approach would be dissimilar to the one used in technical training courses at that time, in which large amounts of loosely structured information were presented to the trainees. This resulted in their cognitive facilities being saturated and made retention difficult. The implication for the present study was that the heuristical programs for the different troubleshooting phases should represent a content free framework, to which specific troubleshooting situations could be fit.

Following Brown's study, Czeh surveyed various electronics troubleshooting methods and reported that they appeared to have several characteristics in common. The most important of these was that all of them were devised with the intent of eliminating as many chassis from consideration as possible with each step. He further noted that within stage troubleshooting and between stage troubleshooting employed similar protocols, however, the former required a greater understanding of basic electronics.

Bryan and Schuster, like Warren, et al., were interested in how more efficient troubleshooting techniques could be taught. To accomplish this, they devised a set of logical principles which would be appropriate to use under a wide variety of problem conditions. At each step of the troubleshooting process, these principles would aid in deciding where to check and what type of check to make.

Using front panel indications and other symptom information, the trouble area was bracketed. Then various logic techniques were applied, depending on the type of circuitry involved. These logic techniques were applicable to linear flow, divergent flow, convergent flow, feedback and switching circuits.

The next study of importance to the present research was conducted for the Navy by McKendry, Grant and Corso. This study was normative in nature, in that design engineers and field engineers were questioned regarding system and equipment troubleshooting procedures for units with which they were associated. The responses were collected using a written questionnaire. From these, frequency plots were constructed for each of 13 circuits, as well as for groupings of similar circuits. The results showed that selection of a particular approach or of a particular piece of test equipment was not clear cut. Rather, it was dependent on the type of equipment, its frequency range, its function and other factors. Also, the engineers indicated a heavy reliance on the oscilloscope for making many of their checks. Other studies have suggested that technicians, because of convenience and their less formal training, would prefer to use a simpler instrument such as a volt-ohm meter. It was further observed that the system level troubleshooting heuristics were indicative of a lexicographic strategy. That is, the checks are ordered in importance with lower level tests being employed only in the case that there is uncertainty as to which higher level test should be used. This was an intuitively simple approach, and while lexicographic models are difficult to model mathematically, they fit well with the process model approach envisioned in the current research.

The next series of papers on electronics troubleshooting were all published under the auspices of the University of Southern California Department of Psychology, under various Navy contracts. This research effort lasted from 1953 until 1969. It paralleled the general trend in troubleshooting resarch of rapid development in the mid 1950's to mid

1960's, followed by a gradual and continuing decline in interest and funding support.

Grings, et al., conducted a study of the problems inherent in the measurement of troubleshooting skill. He detailed the drawbacks of conventional paper and pencil tests and recommended, instead, that job sample tests be used. With these, the technician structured the problem for himself and received no outside cues as to how to proceed or what choices to make. Equally important, they believed, was a realistic troubleshooting environment. The researchers also concurred with Bryan, et al., in viewing the troubleshooting task as being composed of heterogeneous subtasks (phases). In addition, they rejected the notion that a technician's successive responses should be rigidly determined by his preceding responses. It was shown that even successful troubleshooters make unfruitful moves.

Next, Rigney and Hoffman looked at factors influencing troubleshooting difficulty. This study was somewhat restrictive in that only three factors were considered. It was found that schematics were no more difficult to use than were block diagrams, that problems involving feedback loops were more difficult to solve, and that partial or intermittent malfunctions were more difficult to solve than complete failures.

A series of reports by Rigney and his associates followed, which looked at such topics as the problem solving aspects of corrective maintenance, an experimental fault locator, computer aided diagnosis and a Bayesian model approach to troubleshooting. Arguments for and against these various approaches were advanced. In general, it was concluded that they would be difficult to implement in an operational environment.

Following these studies, Rigney and his associates turned to a descriptive study of the structure of maintenance work. While the approach they used employed new terminology, the troubleshooting behavior structure which resulted was similar to that identified earlier by Bryan, et al., and Grings, et al. The Rigney group broke each troubleshooting task, called a maintenance task cycle or MTC, down into corrective maintenance requirements, or CMR's. These CMR's were then further divided into tasks, and the tasks divided into the actions required. The CMR's represented the phases of troubleshooting which were discussed earlier. In performing the MTC, the technician was characterized as working at a maintenance interface. He used interface input elements to change the state of the equipment and output elements to interpret those changes and to gauge progress. The strong point of this paper was the development of a troubleshooting structure. However, no attempt was made to describe the specific processes at work in the various parts of that structure.

The final paper in this series by Rigney and his associates which was relevant to the current study dealt with corrective maintenance performance. It used the MTC framework developed earlier and considered specific CMR's, such as system state recognition, fault localization, circuit isolation, component isolation, maintenance adjustments, and repair. Performance tests conducted to identify strong and weak points in troubleshooting technique revealed technicians to be good in performing front panel checks and in making go-no go judgments. They were moderately weak in selecting additional checks for symptom elaboration and they were poor in using test equipment, in performing system level checks, and in accurately reducing fault areas. Like many of the other Rigney studies, the subject pool for this study was likely made up primarily of recent technical school graduates. This would explain the lack of facility with test equipment on the part of the subjects.

During the same time period as the early Rigney studies, the Institute of Radio Engineers (IRE) published a special issue relating to the maintenance of electronic systems. In addition, other issues of this publication periodically contained articles addressing electronics troubleshooting.

One such IRE study by Ely, et al., investigated the coding of electronic equipment in order to facilitate maintenance. The coding consisted of designating functional groupings, identifying signal paths, highlighting test points, and the inclusion of historical data. It was found that the coding only helped the inexperienced technicians, particularly in locating and identifying the more difficult malfunctions. Experienced technicians were not appreciably aided by it.

Next, Manheimer and Kelly made a study of pertinent human factors considerations in electronics maintenance. They observed that many maintenance studies reflect too little knowledge on the part of the investigator of the maintenance man in the maintenance environment. Statistics about the individuals who perform maintenance abound, but intensive studies of the man in the maintenance environment by those with a clear idea of what maintenance entails, were described as being sadly lacking.

Following this study, Rigney and his associates looked at the fault location behavior of technicians servicing electronic equipment. Among the findings were that technicians frequently accumulated sufficient information with which to solve the problem before they were aware that they had done so, and that about 70 percent of first replacements were found to be incorrect. Also considered were the effects of teaching improved troubleshooting methods to maintenance personnel with high and low levels of experience. It was found that both groups improved on their techniques, however, the experienced group improved in a more sophisticated sense.

The final applicable study from the IRE series was by McKendry, et al., and was an abbreviated version of a previously cited technical report. This paper concerned itself with the use of questionnaires, which were distributed to design engineers and to field engineers to elicit normative troubleshooting information. The findings from this paper were summarized above.

Pieper and Folley studied the effect of varying levels of ambiguity on troubleshooting performance. A group of technically naive high school students were trained in troubleshooting techniques over an 11 hour period. They were then able to successfully compete with experienced technicians in troubleshooting circuits of moderate complexity. Since 11 hours of training hardly compares with the experience levels of the technicians, the content of the training course must have been characterized by a highly efficient transfer of pertinent troubleshooting information. The overall troubleshooting process was divided into phases, similar to those discussed earlier. These phases included malfunction detection, symptom pattern completion, localization of suspects, isolation testing of suspected components, and isolation of the malfunctioning component. For each of these phases, rules or heuristics were taught during the training session, which enabled the high school students to satisfactorily carry out troubleshooting operations.

Proceduralized troubleshooting, using performance aids, was discussed by Elliott and Elliott and Joyce. The purpose of reviewing these two articles was to contrast the performance aid approach with that of using heuristics. In general, proceduralized methods of troubleshooting have not achieved wide acclaim due to the extensive research and tabulation necessary to support them. Elliott himself recognized this deficiency when he cited the frequent criticism of proceduralized troubleshooting, which is that it provides the wrong answers to the easy problems and gives no help at all on the hard problems. Recent improvements in the proceduralized approach have only succeeded in refuting part of this criticism.

Two Danish researchers, Rasmussen and Jensen, made a study of mental procedures in electronics troubleshooting. Unlike many of the studies reported on above, the subjects in this case were all experienced technicians. During the course of the experiment, the verbal introspective comments of the subjects were recorded, and then these were analyzed in an effort to identify the underlying mental processes being employed. A number of conclusions of importance to the present study emerged. First, a formalized analysis in which a subject's behavior is compared to a model containing all possible strategies is impractical in a real life setting. Also, different technicians will likely have different models of the same system, depending upon their background, training and experience. Thus, the way in which information is coded and heuristically processed will be affected by the model being employed. A design engineer might choose to make detailed observations of a faulty system response and then reconcile these with his understanding of the internal anatomy and functioning of the system. A technician, on the other hand, might choose to make a rapid series of simple go-no go checks through a suspect part of the circuitry, comparing measured parameters with those in other parts of the system known to be functioning normally. In making another point, the authors stressed that the body of knowledge resulting from experiments in clear cut laboratory conditions, dealing with well defined and supposedly isolated aspects of human behavior, should be supplemented by studies conducted in real life working conditions of the mental procedures used by operational personnel. Finally, the authors concluded that it was unlikely that a completely general troubleshooting model, applicable to all systems, exists. Rather, models of trouble-shooting behavior are likely to be dependent upon the type of equipment, the actual malfunction, and the operator.

The final work surveyed relating to troubleshooting was that of Shriver and Foley. While this paper primarily addressed the area of performance aids, it also reiterated two important points. One was that paper and pencil tests, typically generating a single numerical score, are unsatisfactory as indicants of troubleshooting ability. The other point was that in order to adequately study and assess electronics troubleshooting, one must employ practicing technicians in a maintenance setting who are working on actual operational equipment.

This summary completes the survey of the literature. The next chapter will address a theoretical model in order to show a connection between conventional decision models and the process model approach. Following this, the two experiments relating to mental coding mechanisms and heuristics applicable to electronics troubleshooting will be described.

CHAPTER III

OUTLINE OF A THEORETICAL DESCRIPTION FOR A PROCESS MODEL

III.1 Introduction

The theory and empirical research of cognitive processes can be traced to Newell, Shaw and Simon (1958), later to Newell and Simon (1972), and more recently to Lewin and Zwany (1976). The theory assumes that such processes as thought, verbal behavior, and problem solving behavior are performed as sequences or phases of simple information processing steps. These steps are referred to as elementary information processes or elementary processes, and they consist of such operations as storing information in symbolic form, retrieving it, moving it, generating transformed data, comparing two symbols for equality, and associating two symbols. In short, elementary processes are simple logic manipulations of data. In a manner similar to the way a computer program evolves from the combination of many simple operations, these elementary processes can be organized into complicated thought structures. The framework for each sequential thought structure, or phase of thought, is a cognitive problem space, which incorporates the results of the various elementary processes along the appropriate problem dimension or dimensional combination. The problem spaces are, therefore, the psychological representations of the problem environment (Lewin & Zwany, 1976). The problem space available to an individual is determined by his intelligence and by the information available to him from his memory and from the objective task environment.

III.2 Model of an Individual's Problem Space

A structural image of an individual's problem space is suggested in the figures below. The region on the left represents a general problem space, whose dimensions are all of the various individual predictors or attributes relevant to the problem. From this all encompassing space, the decisionmaker cognitively selects the dimensions which will be used to construct his initial model subspace of the problem. The bringing together of these dimensions to form the initial model subspace is shown schematically as node 1 in Figure 3.1.

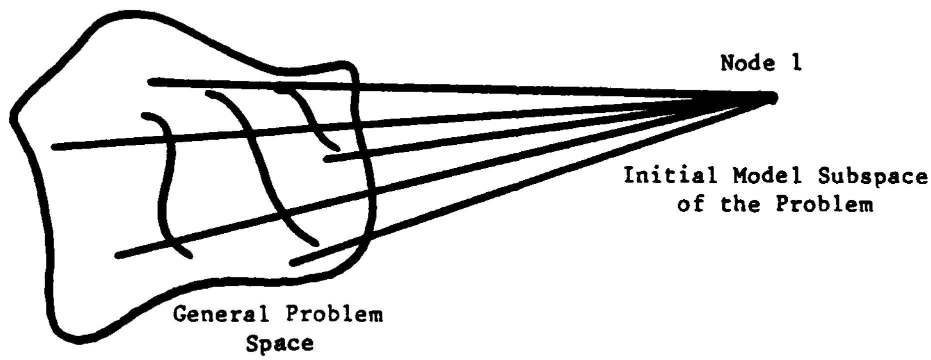

Figure 3.1 Formation of a problem's initial model subspace.

The term subspace is used to emphasize that in constructing problem models, the individual is cognitively limited, and can therefore consider only a few of the many relevant dimensions of the problem. For generality, these dimensions are assumed to be non-linear and non-orthogonal. Points of preference along the various dimensions, as well as other preference points within the subspace, are derived using the problem solver's elementary processes. These points comprise a hypersurface within the subspace which represents the individual's psychological model of the problem. For example, when planning to purchase a car, a person might have a mental picture of an ideal car. Such a car might be defined along the dimensions of color, seating capacity, engine size, mileage rating and available options. In addition, there might be certain combinations of two or more dimensions which would be preferable to other combinations. The preferred points along each dimension, together with the points indicating preferred combinations of dimensions, would make up the hypersurface representing that person's ideal model for the car purchase problem.

The initial model may be sufficient to allow the problem solving, decisionmaking or choice process (hereafter referred to simply as problem solving) to be completed, or it may be insufficient. In this latter case, a second node is created, as shown in Figure 3.2. This second problem subspace is comprised of some or all of the dimensions making up the initial model of the problem, as well as other dimensions from the general problem space.

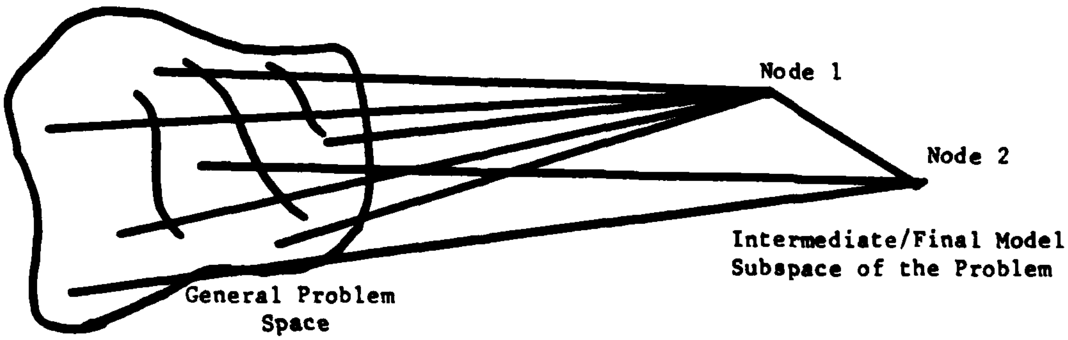

Figure 3.2 Formation of a problem's intermediate/final model subspace.

Again, the preferred points along the new dimensions, as well as other preferred combinations of dimensions within the subspace, collectively form the hypersurface which represents the individual's new model. The procedure continues until a model encompassing the right dimensional characteristics is achieved, at which time a decision, judgment, or choice is made (problem solution) and the process terminates.

In summary, dimensions are selected by the problem solver from a general problem space of all dimensions of relevance to the problem under consideration. Points of preference along these dimensions, as well as points indicating preferred dimensional combinations are derived using elementary processes to form a cognitive model for the decisionmaker. The model is sequentially varied by including new dimensions and discarding others until the right combination is achieved, at which time a decision is made.

One point in the above discussion merits further comment. This relates to the number of dimensions considered at each node in the sequence. As reported earlier, Miller, as well as Newell and Simon, concluded that individuals can store no more than five to seven symbols in short term memory. Lewin and Zwany (1976) regard this as evidence that no more than five to seven dimensions would be considered at any one node or stage of the problem. It has been reported that, in actuality, individuals usually consider fewer than five aspects or dimensions of a problem, with abstractions from reality characteristically involving perhaps two symbolic representations at any given time (Newell & Simon, 1972). Therefore, it seems reasonable to suggest that at each node or stage of problem solving, five dimensions will typically be used to form the cognitive model. These dimensions will not always be the same for everyone, but considerations such as culture and demography would suggest the existence of similarities for a given problem. For example, in buying a house, some of the common dimensions comprising the initial and later models might be price, area and number of bedrooms.

III.3 Outline of a Mathematical Model Development

It is useful, from a theoretical standpoint, to consider how those problem subspaces might be described in mathematical terms. The following is not meant to be a rigorous development of the mathematical foundations of such subspaces, but rather to be an outline as to how such a development might proceed. If a subspace comprised of five non-orthogonal, non-linear dimensions is typically used by individuals in problem solving, then any mathematical model that is advanced for such a process should be geometrically compatible with those notions. A mathematical modeling tool known as tensor analysis incorporates those requirements and has been utilized extensively by researchers in the areas of electro-magnetic field theory, theoretical mechanics, and relativity physics.

Tensors are simply the generalized case of scalars and vectors. A tensor is usually classified by order, according to the number of components associated with it in n dimensional space. A useful formula in working with tensors is given below.

$$N = n^T \tag{3.3.1}$$

where

N = Number of components of the tensor in the problem space

n = Dimensionality of the problem space

T = Order of the tensor in the problem space

For example, a scalar has one component, magnitude, regardless of the dimensionality of the space in which it is being described. A scalar, then, is a tensor of zero order, since

$$N = n^T \tag{3.3.1}$$

and

$$1 = n^o, \text{ all } n < \infty. \tag{3.3.2}$$

Similarly, the number of components of a vector is numerically equal to the dimensionality of the space involved. Hence, a vector must be a tensor of order one (first order tensor), since

$$N = n^T \tag{3.3.1}$$

and

$$N = n^1, \text{ all } n. \tag{3.3.3}$$

In summary, scalars are zero order tensors and vectors are first order tensors.

With a three dimensional subspace, then, a zero order tensor (a scalar) representation would provide only one component to which cognitively meaningful information could be assigned. Such a model would not even account for the main effects along each dimension. With a first order (a vector) representation, three components would be provided, one for the main effect along each dimension. Still with the same subspace, a second order tensor, having $3^2 = 9$ components, would account for main effects as well as interactive effects. The component representations of zero, first and second order tensors are shown below.

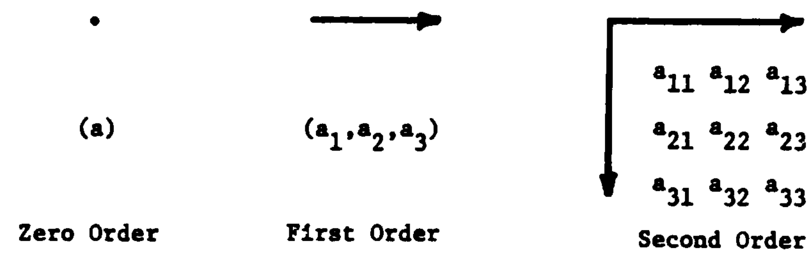

Figure 3.3 Component representations of zero, first and second order tensors in three space.

It is more convenient to deal with the components of tensors of order two or higher, rather than the tensor itself. For example, while a third order tensor in 3 space is geometrically complicated and difficult to visualize, the components of such a tensor may be thought of as an array of its 27 components formed in a three dimensional matrix cube, shown below.

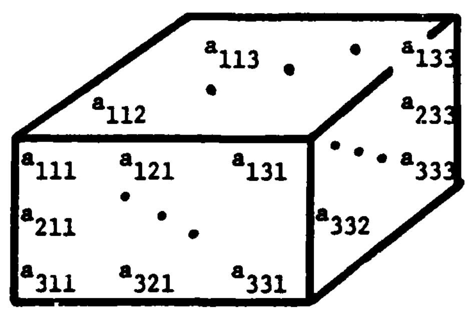

Figure 3.4 Component representation of a third order tensor in three space.

As is indicated by the arrows in the above two figures, the numerical order of the tensor corresponds to the number of dimensions necessary to describe its components. Higher order tensor component arrays may be thought of as hypercubes.

Using the tensor concept, a mathematical model can be constructed of the problem subspaces at each stage of the decision process. Unlike vector representations of decision spaces, these subspaces are unrestricted with regard to linearity, orthogonality and the number of components.

The mathematical approach described above provides a means by which a heuristical model can be related to earlier mathematical decision models. For example, with the weighted sum or expected value model, a first order tensor (vector) was used, and weights were assigned to its various components along each dimension. These components were then summed and a decision rule, such as choose the alternative with the largest component sum, was applied. A criticism of this decision tool was that only main effects were included. As noted above, second order and higher tensors are not limited to only including the main effects.

Similarly, correlation is also definable in terms of tensors and tensor operations. For example, take two first order tensors (vectors), $\underline{X}$ and $\underline{Y}$, representing sample data, where both are n x 1. Put them in mean deviate form (mdf) by subtracting the respective means, $\overline{X}$ and $\overline{Y}$, from each X_i component and Y_i component. Make the resultant tensors unit tensors by dividing each by the square root of the sum of the squares of the components. The correlation, r(X,Y) is then defined as the tensor inner product (vector dot product) of the two unitized, mean deviate form first order data tensors. This is summarized symbolically below.

$$\underline{X} = \begin{bmatrix} X_1 \\ X_2 \\ \\ X_n \end{bmatrix} \rightarrow \underline{X}_{mdf} = \begin{bmatrix} X_1 - \overline{X} \\ X_2 - \overline{X} \\ \\ X_n - \overline{X} \end{bmatrix} = \underline{X}. \rightarrow |\underline{X}.| = \sqrt{\underline{X}.' \cdot \underline{X}.} \rightarrow \underline{X}_* = \frac{\underline{X}.}{|\underline{X}.|} \quad (3.3.4)$$

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \\ Y_n \end{bmatrix} \rightarrow \underline{Y}_{mdf} = \begin{bmatrix} Y_1 - \overline{Y} \\ Y_2 - \overline{Y} \\ \\ Y_n - \overline{Y} \end{bmatrix} = \underline{Y}. \rightarrow |\underline{Y}.| = \sqrt{\underline{Y}.' \cdot \underline{Y}.} \rightarrow \underline{Y}_* = \frac{\underline{Y}.}{|\underline{Y}.|} \quad (3.3.5)$$

Then,

$$\underline{X}_* \cdot \underline{Y}_* = \frac{\underline{X}. \cdot \underline{Y}.}{\sqrt{\underline{X}.' \cdot \underline{X}.}\ \sqrt{\underline{Y}.' \cdot \underline{Y}.}} = \frac{(1/n)\underline{X}. \cdot \underline{Y}.}{\sqrt{(1/n)\underline{X}.' \cdot \underline{X}.}\ \sqrt{(1/n)\underline{Y}.' \cdot \underline{Y}.}}$$

$$= \frac{\dfrac{\sum_{i=1}^{n} (X_i - X)(Y_i - Y)}{n}}{\sqrt{\dfrac{\sum_{i=1}^{n} (X_i - X)^2}{n}}\ \sqrt{\dfrac{\sum_{i=1}^{n} (Y_i - Y)^2}{n}}} = \frac{\sigma XY}{\sigma X\ \sigma Y} \quad (3.3.6)$$

where the expression on the right is the definition of the correlation between X and Y, r(X,Y). Therefore,

$$r(X,Y) = \underline{X}_* \cdot \underline{Y}_* \quad (3.3.7)$$

where $\underline{X}_*$ and $\underline{Y}_*$ are unitized, mean deviate form, first order data tensors.

The sum of squares terms used in the above development are also prominently embedded in the analysis of variance (ANOVA), another decision tool. Since regression, ANOVA, and related techniques are definable in terms of the components of first and second order tensors (vectors and matrices), it seems reasonable to suggest that extensions of these techniques into more elaborate problem spaces might be possible. Such extensions could serve to provide more satisfactory mathematical models of decision processes than can presently be obtained. Since the present research effort is aimed at the development of a process model, rather than a mathematical model, of human problem solving behavior, such extensions will not be pursued further here.

III.4 Relationship Between the Mathematical Model and the Process Model

The remainder of this research will concentrate on the more qualitative aspects of decision behavior. Decisions will be assumed to take place in problem subspaces in a sequential fashion as described earlier. The sequential approach was dictated by the finding that most problem solvers could only consider five dimensions at a time. Therefore, at each stage of the problem solving sequence, a hypersurface within that stage's five dimensional subspace comprises the psychological model used by the problem solver. In evaluating the model at each of these stages, the problem solver uses a series of mental rules of thumb, or heuristics. Heuristics were described earlier. The effect of their use is to allow a series of rapid go-no go checks to be performed, with a minimum of cognitive strain. Whereas the hypersurface and the problem subspace discussed above relate quantitatively to the dimensions of the problem being considered at each stage, the heuristics used at each stage relate qualitatively to those same dimensions. Rather than working with a mathematical equation in order to structure and solve the problem, the problem solver instead applies a set of simple mental rules in dealing with the problem and determining the next course of action. The information thus derived is either used at the next stage, along with fresh inputs from the general space relating to the problem under consideration, or it is used to solve the problem and thereby terminate the process.

This descriptive view of problem solving incorporates several important features, which are summarized below.

> The approach builds upon the Newell-Simon model, as well as on the work of Miller, as to the descriptive nature of individual problem solving.
>
> The cognitive limitations of the individual in dealing with the general problem space are recognized and incorported in this model. A sequential approach, amounting to a series of simple go-no go decisions at each stage, is suggested. Such decisions are made based on a set of heuristics applicable to that stage of the problem.
>
> A basis for constructing a mathematical model of the problem solving process is outlined. An approach using tensors is suggested, as it is more general than other models. There are no restrictions on orthogonality, linearity, dimensionality, or the number of components associated with each dimension.
>
> The heuristical program used at each stage of the problem solving process is the psychological counterpart of the hypersurface and problem subspace used at each stage in the mathematical model. Thus, the results of this research will lay the groundwork for future studies of a more normative and mathematical nature.

The purpose of this chapter, then, is to provide some theoretical speculation as to how a more realistic mathematical model of human problem solving than is presently available might be structured. In addition, this chapter serves as an interface between earlier mathematical methods used to describe problem solving behavior and the heuristical process model approach of behavior proposed by this research.

CHAPTER IV

PERCEPTION, MEMORY, AND IMPRESSION IN ELECTRONICS TROUBLESHOOTING

IV.1 Introduction

The purpose of this experiment was to study the encoding mechanisms used by troubleshooters of varying skill levels. Such mechanisms are viewed as the means by which technicians cognitively combine and summarize information essential to their problem solving, or electronics troubleshooting, responsibilities. Prior to dealing directly with the details of the experiment, a few preliminary comments on the relationship of these encoding mechanisms to problem solving and troubleshooting will be presented.

Rigney and his associates (1961a and 1962) have stated that there is no clear way to separate problem solving behavior and troubleshooting behavior so that one may point to a particular instance and say that it is troubleshooting but not problem solving. Rigney, et al., contended that these were but two of the labels attached to a broad spectrum of similar behaviors.

In problem solving, the individual starts with given conditions and utilizes a solution route to work toward a goal. It is characteristic of the problem solving situation that of these three elements, the least visible and most difficult to study is the solution route. This first experiment, therefore. considered one of the important aspects of the solution process, that of how information relating to the problem is perceptually structured for introduction into that process. With regard to the problem spaces and hypersurfaces discussed previously, the encoding mechanisms represent part of the information interface between the general problem space containing all relevant information relating to the problem and the particular problem subspace and hypersurface combination in use at a given moment. The encoding mechanisms serve to separate problem information into components along the various dimensions of the subspace. In terms of the associated psychological model of the problem, the encoding mechanisms serve to standardize information from the problem environment into a form which is compatible with heuristics and other cognitive operations used to analyze and solve the problem.

The actual means by which this standardized, or encoded, information is transformed in the problem solving solution route process are not well understood. Earlier, it was suggested that elementary processes are arranged in a series of steps, similar to a computer program (Newell & Simon, 1972, and Fischhoff, 1975). Each grouping of the elementary processes, or program, represents a separate thought structure. Different thought structures can then be combined to form a solution route for a given problem. During the problem solving process, information in standardized form is input into the problem solver's cognitive facilities, where it is operated on by these thought structures.

In electronics troubleshooting, the technician primarily uses visual inputs in gathering information, although inputs from touch, smell and hearing are also employed. Visual inputs come from the observation of control settings, dial readings, signal paths and circuit components.

Some of these inputs can be perceptually difficult to interpret, due to the characteristics of electricity described earlier. The perceptual structures seen by the technician represent the information inputs used by him in constructing his psychological model of the troubleshooting problem. Those perceptual structures are made up of information which has been encoded or chunked into various standardized formats. Such structures are then compatible with the cognitive operations used later in the troubleshooting process.

As reported previously, researchers have studied the encoding mechanisms used by chess players (Chase & Simon, 1973) and sight readers of music (Reicher, 1975). In general, it has been found that highly skilled individuals employ chunks which are larger and structurally different than those of lesser skilled persons. All, however, are limited to a short term memory span of about five to seven chunks. For example, in chess a grandmaster can operate with five chunks, each having a magnitude of five chess pieces, for a total of 25 pieces. Ordinary players operate with the same number of chunks, but each has a magnitude of only one piece, for a total of five chess pieces. Thus, in formulating strategy and evaluating potential moves, a grandmaster would enjoy a five to one advantage over an ordinary player. Further arguments and experiments have affirmed that it is in the chunking process that much of the superiority of the skilled individual lies (Reicher, 1975).

Since the degree of chunking or encoding sophistication has been found to be a determinant of skill rating in the two areas reported on above, this first experiment proposes to investigate the encoding mechanisms employed by electronics troubleshooters of varying skill. The potential results of such a study are threefold. First, the actual encoding mechanisms used by technicians engaged in electronics troubleshooting would be identified and cataloged. This information is not available at present. It would be useful in the design of training and refresher courses for persons engaged in the maintenance of commercial, industrial and defense systems. Secondly, the feasibility of rating troubleshooting skill based on encoding ability could be evaluated. Presently, troubleshooting skill is a concept which is difficult to define and evaluate. A third consideration is that this would be one of the first studies of coding mechanisms used by individuals in their primary occupation. The previous studies included persons whose occupation for the most part were not directly related to the nature of those experiments.

Several approaches were considered for studying the encoding mechanisms used by technicians. Comments relating to some of these are given below.

Previous studies have suggested that a problem solver's perceptual processing is very rapid and probably unavailable to conscious introspection. As to whether introspective methods can be trusted, two researchers recently argued that people lack awareness of the factors that affect their judgments. After documenting their claim with the results of six experiments, they concluded that investigators who are inclined to place themselves at the mercy of introspective analyses would be better advised to remain in the armchair (Nisbett & Wilson, 1976). While this may be overstated, it does cast doubt as to whether an accurate and detailed verbal description of the solution process can be obtained from the subject. On the other hand, it has also been suggested that introspective analysis is still the best means available for understanding problem solving processes, so long as its limitations are recognized and understood (Simon, 1978).

Eye movements have also been used to record what aspects of a problem are being attended to by subjects. However, such records are imprecise, particularly with regard to inputs from peripheral vision. Also, data from eye movements doesn't indicate what information is being abstracted from a display.

A method for isolating and studying perceptual structures was outlined by Chase and Simon (1973). It was used in their study of perception in chess, and a variation of it will be employed in this study of perception in electronics troubleshooting. This method avoids some of the problems of introspection and eye movement analysis.

IV.2 Scope

The objectives of this experiment are to isolate and define the coded patterns or chunks into which information is being grouped by technicians of varying skill levels as they are reading and interpreting electrical schematic diagrams. In particular, the similarities and differences in the chunks used by technicians in the three skill categories will be investigated and analyzed. Chunk boundaries will be defined and relations which hold among the components of a chunk will be described. Chunks from the perception and memory tasks will be compared with regard to size and content in order to assess their degree of similarity. Finally, other statistical measures will be applied in order to gain added insight into the cognitive processes employed in the reading of schematic diagrams.

Within stage troubleshooting will be emphasized since the typical circuits involved are common to a wide range of electrical equipment. Accordingly, a selection of representative circuits from various sources, such as handbooks and design manuals, will be used.

Three tasks will make up the body of the experiment. In the perception task, technicians will reconstruct a circuit diagram while it remains visually accessible. The technician's successive glances at the reference circuit diagram will be used as an index of chunking. The assumption here is that under the conditions of the experiment, the technician will encode only one chunk per glance, while reconstructing the diagram (Chase & Simon, 1973). This task will be helpful in learning how technicians of varying skill levels typically encode information from a schematic diagram. That is, in practice the technician generally has the schematic close at hand to refer to as he is pursuing his troubleshooting routine. Hence, there is no need to commit the diagram to memory. Rather, he can simply refer back to it as often as is necessary. Accordingly, the results of this task should yield a fairly realistic appraisal of the structural complexity of chunks characteristically employed by technicians of differing skill levels.

In the memory task, the technicians will be asked to reconstruct a circuit diagram from memory after a brief exposure to it. The timing or clustering in recall will be used to segment the output into chunks. This task will be useful in establishing a measure of chunking capacity. Here, the technicians will be obliged to encode as much information from the schematic as they can accommodate in one 12 second visual exposure to it. From these trials, a distribution of the number of chunks employed can be obtained. Chunking complexity, as well as capacity, might also be considered here, but the atypical nature of the task - memorizing, rather than frequent glances back at the schematic - suggests that a more valid measure of chunking complexity can be acquired from the perception experiment. Chunking capacity, on the other hand, cannot be validly obtained from the first task, since the technician is not obligated to encode more than one chunk or even one element per glance.

The impression tasks will be a subset of both the perception and memory tasks, in that the technician's initial element, chunked or otherwise, in both of these tasks will be of interest. Impression is defined here to be the most cognitively dominant aspects of the visual display. Thus, it constitutes the subject's initial description of a visual stimulus (Hyman, 1977). Hence, the first element encoded from each of these tasks will be analyzed in an effort to identify cognitively outstanding features for each circuit. The details of the methodology for this experiment are described below.

IV.3 Methodology

Fifteen technicians, equally divided with regard to the three level (lowest rating), five level and seven level (highest rating) Air Force skill ratings were used as subjects. Ten circuit diagrams from technical manuals and design handbooks were used to generate the stimuli. Such circuits are employed in a broad cross section of electrical and electronic equipment.

Schematic diagrams were used in the experiment rather than the actual circuitry, since schematics are the common mode of presentation for circuit information, and they are routinely used and depended upon by technicians engaged in troubleshooting work. Moreover, the analysis and reasoning processes in troubleshooting are more apt to be done using a schematic than using the actual circuitry.

The subjects reconstructed all circuit schematics using only a sheet of paper and a felt tip pen. The paper and pen approach was chosen in order to prevent the introduction of unwanted cues into the tasks previously described. Timing to one second for each circuit schematic reconstruction was maintained, and all reconstruction performances were videotaped. The details for the tasks follow below.

In each trial for the perception task, two sheets of paper, 8 1/2" x 11", were used, along with a felt tip pen and a brown manila folder. The schematic to be used for a given trial was drawn on one of the sheets of paper and taped to the inside of the manila folder. The other sheet of paper, which was blank, was taped to the front of the folder. The technician was instructed that when the signal was given, he was to open the folder, look at the schematic, close the folder and redraw as much of the schematic as could be remembered onto the blank sheet of paper, as quickly and as accurately as possible. He was advised that he could glance at the reference schematic as often as was required to complete the task. The folder remained flat on the work surfacce at all times, and the technician simply flipped back and forth between the two sheets of paper. In this way, only one sheet of paper was visible at any given time, thereby requiring the subject to mentally encode the relevant circuit information.

The procedure used in the memory task was similar to that used in the perception task. Here, however, the technician was able to view the reference schematic for only twelve seconds. The technician then redrew as much of the reference circuit as could be remembered on the blank sheet of paper in front of him, taking as much time as necessary.

For the impression task, the initial element encoded in each of the above two tasks was recorded and compared across all of the trials. These comparisons were made in order to highlight the most prominant encoding features of the schematic diagrams. The initial element aspects which were considered were the element itself, whether or not it was chunked, if the element was part of a branch or part of a loop, if it was an internal or an external element, if it was active or passive, its spatial location and the degree of the relationship between it and the next element.

In order to minimize subject fatigue, six sessions of thirty minutes duration were scheduled over a two week period for each technician. During a session, a subject would arrive and seat himself at the work area. Instructions for that session's particular task were read and a practice trial was completed. The practice trial consisted of redrawing various circuit elements which were similar to those he would encounter in the actual trials. The conditions for the practice trial and the experimental trials for that particular session were always identical. Following the practice trial at the beginning of each session, the experimental trials were carried out. Most subjects completed a given session in less than twenty minutes. The order that the schematics were presented to a subject was randomized. Half of the subjects completed the memory task before doing the perception task, and half of the subjects did them in the opposite order. Appendix A lists the order for all subjects, shows the instructions for each task and presents some environmental data.

IV.4 Data

IV.4.1 Introduction

A videotape of the perception and memory tasks was made in order to record the sequence used by the technicians to redraw each of the circuit schematics. Times were recorded to the nearest second throughout the duration of the tasks. In this way, the time between the drawing of successive circuit components and groups of components could be measured. These measured time intervals were used to differentiate between inter- and intra-chunk boundaries, with long intervals (greater than or equal to two seconds) corresponding to boundaries between successive chunks, and short intervals (less than two seconds) corresponding to divisions between elements belonging to the same chunk.

IV.4.2 Successive Circuit Element Relationships

The nature of the circuit relationships between successive elements separated by long and short pauses, respectively, was then analyzed for information which indicated how circuit elements were being chunked. Five circuit relationships between successively drawn elements were predicted to occur, and these are described below.

> Coupled Elements - Elements are arranged in a fashion such that one element is electrically linked with another element by a field or by a short circuit connection. An example of a coupled circuit would be a tuned indictive-capacitive filter.
>
> Proximity Elements - Each element is located immediately adjacent to one or more additional elements. An example would be a resistor-capacitor parallel combination. For this experiment, proximity or nearness was defined to have occurred when the center of an element was within 42 millimeters of the center of the reference element. A short discussion concerning the rational for selecting this value is provided below.

Same Type Elements - Both elements are the same type. Examples would be two resistors or two capacitors.

Active Elements - Elements which act as sources of electrical energy. Examples would be power terminals, tubes and transistors.

Passive Elements - Elements which act to store energy or to dissipate energy. Examples would be inductors, capacitors and resistors.

With regard to the selection of the criterion for proximity or closeness, the literature was helpful, but vague. Woodson and Conover (1973) addressed the visual field which the human eye perceives. They reported that based on an angle of plus or minus 30 degrees with the visual axis, and a viewing distance of 14 inches to 18 inches, the field of view would be circular with a radius of from 8.1 inches to 10.4 inches. This seemed unrealistically large for a task such as reading a schematic. Indeed, it was noted during the pilot study that the subject seemed to be moving his head and eyes about as he was viewing the schematics, rather than taking in the entire 8 1/2 x 11 inch schematic in a single glance.

Poulton (1960) conducted a survey of the literature and reported that the length of a line of print was variously recommended to be 3.5 to 5.5 inches (Burt), 3 inches (Tinker and Patterson), or greater than 2 inches (Luckiesh and Moss). He concluded that most experiments didn't yield statistically reliable differences.

Poulton, Warren and Bond (1970) reported on the criteria used in the selection of spatial dimensions for line lengths and figures in the journal Applied Ergonomics. They stated that in the absence of experimental results, the decision was based on the qualities of being ergonomically efficient and pleasing. The lengths used typically vary between 50 and 89 millimeters.

Finally, Chase and Simon (1973) used the criterion of adjacent squares in their chess study. This worked out to a field of from 41 to 54 millimeters on each side of the piece of interest, assuming the pieces to be centered on each square.

Based on the above results, a circular viewing field of diameter 88 millimeters (about 3.5 inches) was used. When the center of the circular field was placed on the midpoint of an element, any element whose midpoint was within the 88 millimeter diameter circle was judged to be proximate.

The five circuit relationships between successively drawn circuit elements (Coupled, Proximate, Same, Active and Passive) result in 32 possible combinations which are shown in Figure 4.1. For convenience, the relationships are abbreviated as C, N, S, A, and P, respectively. The first combination listed, for example, is -. This symbol implies that there was no relationship between two successively drawn elements. The elements were not coupled (directly connected to each other), they were not proximate (the centers of the two elements were more than 44 millimeters apart), they were not both active or both passive (instead, one element was active and one was passive), and they were not the same (did not belong to the same family, e.g., they were both not vacuum tubes). The twenty-eighth combination listed, for another example, is CNSP. This symbol means that the relationship between two successively drawn circuit elements was that they were coupled (directly connected to each other), proximate (the centers of the two elements were a distance less than or equal to 44 millimeters apart), the same (the elements belonged to the same family, e.g., they were both resistors), and passive (the elements either dissipated or stored energy).

1.	-	x12.	NA	23.	SPC
2.	C	13.	NP	*24.	SAP
3.	N	14.	SA	*25.	APC
* 4.	S	15.	SP	*26.	APN
x 5.	A	*16.	AP	x27.	CNSA
6.	P	*17.	CNS	28.	CNSP
7.	CN	x18.	CNA	*29.	NSAP
* 8.	CS	19.	CNP	*30.	SAPC
x 9.	CA	x20.	NSA	*31.	APCN
10.	CP	21.	NSP	*32.	CNSAP
*11.	NS	x22.	SAC		

Key: - = No Relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive

Figure 4.1 Possible circuit element relationships.

Not all of the 32 combinations which are possible are physically realizable. For example, combination 16, AP, implies that an element may be both active and passive, a contradiction. Similarly, combination 4, S, is not realizable by itself, since if two elements are the same, they will be either both active or both passive. There are a total of twelve combinations (preceded by an asterisk) which are not realizable. Further, not all of the remaining 20 realizable combinations actually occur in the operational circuits employed in the experiment. These combinations total seven and are preceded by an x. The remaining 13 circuit relationships which may actually occur between successive circuit elements are shown in Figure 4.2. As a final example, combination ten, CNP, may be considered. This symbol infers that the relationship between two successively drawn circuit elements was that they were coupled (directly connected to each other), proximate (the centers of the two elements were a distance less than or equal to 44 millimeters apart), and passive (the elements either dissipated or stored energy). The two successive elements were not, however, the same (they were not members of the same family, e.g., they were both not capacitors).

1. -	5. CN	10. CNP
2. C	6. CP	11. NSP
3. N	7. NP	12. SCP
4. P	8. SA	13. CNSP
	9. SP	

Key: - = No Relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive

Figure 4.2 Actual circuit element relationships.

IV.4.3 The Nature of Data Sets

It is appropriate at this point to comment on the nature of data sets in general, and on the data set for this experiment in particular. The first question to be addressed with regard to a data set pertains to the level of measurement of the variables in such a set. Once the level has been determined, appropriate statistical tests may then be used to analyze the data.

The traditional classification of levels of measurement was developed by S. S. Stevens (1946). He identified four levels: nominal, ordinal, interval and ratio.

The nominal level of measurement is the lowest of the four levels. It makes no assumptions about the values being assigned to the data. Each value is a distinct category, and the value itself merely serves as a label or name for the category. An example of nominal classification would be the wearing of different numbered uniforms by members of a baseball team. The properties of the real number system (addition, multiplication, etc.) cannot be transferred to these numerically coded categories. Hence, statistics which assume ordering or meaningful numerical distances between such categories may not be used.

When it is possible to rank order all of the categories according to some criterion, then the ordinal level of measurement has been realized. An example would be the ranking of college football teams by various groups during the fall season. Each ranked team or category has a unique position relative to all other teams, lower than some and higher than others. Knowing that a team ranked fifth is ranked higher than a team ranked sixth and that a team ranked sixth is higher than a team ranked seventh automatically conveys the fact that the team ranked fifth is higher than the team ranked seventh. It is not clear, however, how much better the fifth ranked team is than the sixth ranked team. All that is known is that one is lower, but the distance between them is not defined. The characteristics of ordering is the only mathematical property of this level of measurement, and the use of numeric values as symbols for category names does not imply that any other properties of the real number system are applicable.

With interval level measurement, the distances between categories are defined in terms of fixed and equal units. For example, a thermometer records temperatures in terms of degrees, and a single degree implies the same amount of heat, whether the temperature is at the low end or at the high end of the scale. The difference, therefore, between 16° and 18° is the same as the difference between 97° and 99°C. A further point is that the interval scale does not have an inherently determined zero point, but merely one that is agreed upon as a matter of convention.

For this reason, interval level measurement allows the study of the differences between categories but not of the proportionate magnitudes. That is, it would be incorrect to assert that $60^{o}F$ is twice as hot as $30^{o}F$.

The ratio level of measurement has the same properties as does the interval level of measurement, with the additional property that the zero point is defined by the measurement scheme. For example, when physical distances are investigated, the zero distance is naturally defined as being the absence of any distance between two points. The result of having a fixed and given zero point defined means that ratio comparisons may be made, along with distance comparisons. An example might be the assertion that a yard stick (three feet) is three times as long as a ruler (one foot). Ratio level measurements satisfy all the properties of the real number system. Therefore, any mathematical manipulations appropriate for real numbers may also be applied to ratio level measures.

IV.4.4 Data for Experiment I

With regard to the data for this first experiment, the degree of the relationships was measured on the ordinal scale. That is, it was possible to rank order the encoding variables (categories) based on the degree of complexity (or simply "degree") of the composite relationship between two successive circuit elements. The range in this experiment was from zero, or no relationship between two successive circuit elements, up through a total of four relationships discernible between two successive circuit elements.

Within each of the categories pertaining to level of complexity are embedded the codes themselves. For example, within the third level of complexity, the encoding relationships are CNP, NSP and CSP. These are nominal scale designations, in that each is a distinct category of approximately equal encoding complexity.

The comparison between the degree of the relationships and the relationships themselves highlights the fundamental difference between the nominal and ordinal scales. The ordinal scale incorporates the greater than relation (>), along with the equal relation (=), whereas the nominal scale incorporates only the equal relation.

The appropriate distributional measures are therefore the mode and frequency for the nominal level categories, and the median and percentile for the ordinal level categories. These values are easily determined from the tabled information shown in Tables 4.1A through 4.1D. For example, in the first data grouping (Perception-Within: Seven Skill Levels), the mode for the nominal categories would be category 12, CNP, which has a frequency of occurrence of 51.11%. Similarly, the median value for the ordered data would be degree = 3, with the percentages for each degree category as shown. While percentages are used throughout, the total number of elements in each data set is also provided below the grouping pertaining to that set.

Tables 4.1A through 4.1D, then, show the frequencies for the different composite relationships and for the various degree levels of complexity of these relationships, for each of the three skill levels in the perception and memory tasks described previously. The purpose of this table is to display the patterns of utilization of the various encoding alternatives, as well as to show the chance distribution which would result if random selection of successive components were in effect.

Table 4.1A Percentage data indicating the usage of the composite relationships, by relationship designation and by the degree of the relationship, for technicians in the three different skill categories, as well as the usage predicted based on chance (random circuit element selection) alone, for encoding two successive circuit elements within the same chunk during the perception task (PERCEPTION-WITHIN).

Composite Relationships	Degree of Relationships	Observed Percentages for Each Technical Skill Level						Theoretical Percentages Based on Chance Alone	
		Seven Level		Five Level		Three Level			
1. -	0	.44	.44	.72	.72	.36	.36	7.49	7.49
2. C		1.56		3.97		2.50		1.40	
3. N	1	0	6.45	0	14.26	.18	8.76	.31	56.75
4. P		4.89		10.29		6.08		55.04	
5. CN		.44		2.89		3.22		1.03	
6. CP		7.11		7.58		7.69		1.50	
7. NP	2	2.67	13.11	6.50	21.12	4.65	20.03	5.27	24.03
8. SA		1.11		.18		1.07		.21	
9. SP		1.78		3.97		3.40		16.02	
10. CNP		51.11		38.09		44.90		7.49	
11. NSP	3	3.33	62.22	3.07	47.84	2.86	54.20	1.65	9.81
12. SCP		7.78		6.68		6.44		.67	
13. CNSP	4	17.78	17.78	16.06	16.06	16.64	16.64	1.86	1.86
		Total = 450		Total = 554		Total = 559		Total = 1935	

Key: - = No relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive

Table 4.1B Percentage data indicating the usage of the composite relationships, by relationship designation and by the degree of the relationship, for technicians in the three different skill categories, as well as the usage predicted based on chance (random circuit element selection) alone, for encoding two successive circuit elements in a time span of less than two seconds during the memory task (MEMORY-LESS THAN).

Composite Relationships	Degree of Relationships	Observed Percentages for Each Technical Skill Level						Theoretical Percentages Based on Chance Alone	
		Seven Level		Five Level		Three Level			
1. -	0	1.78	1.78	.90	.90	1.60	1.60	7.49	7.49
2. C		5.62		10.48		7.35		1.40	
3. N	1	0	13.31	.30	17.97	0	15.34	.31	56.75
4. P		7.69		7.19		7.99		55.04	
5. CN		5.03		5.99		5.11		1.03	
6. CP		7.10		6.29		3.51		1.50	
7. NP	2	4.14	19.53	4.19	20.96	4.15	14.69	5.27	24.03
8. SA		1.48		.30		.32		.21	
9. SP		1.78		4.19		1.60		16.02	
10. CNP		42.01		36.83		44.41		7.49	
11. NSP	3	2.37	50.00	2.40	43.72	3.51	53.99	1.65	9.81
12. SCP		5.62		4.49		6.07		.67	
13. CNSP	4	15.38	15.38	16.47	16.47	14.38	14.38	1.86	1.86
		Total = 338		Total = 334		Total = 313		Total = 1935	

Key: - = No relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive

Table 4.1C Percentage data indicating the usage of the composite relationships, by relationship designation and by the degree of the relationship, for technicians in the three different skill categories, as well as the usage predicted based on chance (random circuit element selection) alone, for encoding two successive circuit elements which were not part of the same chunk during the perception task (PERCEPTION-BETWEEN).

Composite Relationships	Degree of Relationships	Observed Percentages for Each Technical Skill Level						Theoretical Percentages Based on Chance Alone	
		Seven Level		Five Level		Three Level			
1. -	0	4.58	4.58	3.31	3.31	6.23	6.23	7.49	7.49
2. C		5.72		6.95		7.87		1.40	
3. N	1	0	37.76	0	41.72	0	39.02	.31	56.75
4. P		32.04		34.77		31.15		55.04	
5. CN		5.49		4.97		3.93		1.03	
6. CP		5.72		4.97		9.84		1.50	
7. NP	2	9.84	28.83	6.29	25.50	6.23	27.21	5.27	24.03
8. SA		0		0		0		.21	
9. SP		7.78		9.27		7.21		16.02	
10. CNP		20.82		23.51		20.98		7.49	
11. NSP	3	1.14	25.39	1.32	25.82	1.64	25.90	1.65	9.81
12. SCP		3.43		.99		3.28		.67	
13. CNSP	4	3.43	3.43	3.64	3.64	1.64	1.64	1.86	1.86
		Total = 437		Total = 302		Total = 305		Total = 1935	

Key: - = No relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive

Table 4.1D Percentage data indicating the usage of the composite relationships, by relationship designation and by the degree of the relationship, for technicians in the three different skill categories, as well as the usage predicted based on chance (random circuit element selection) alone, for encoding two successive circuit elements in a time span of greater than or equal to two seconds during the memory task (MEMORY-GREATER EQUAL).

Composite Relationships	Degree of Relationships	Observed Percentages for Each Technical Skill Level: Seven Level		Five Level		Three Level		Theoretical Percentages Based on Chance Alone	
1. -	0	7.19	7.19	9.68	9.68	9.90	9.90	7.49	7.49
2. C		7.19		8.60		10.89		1.40	
3. N	1	0	53.23	0	55.91	.99	38.61	.31	56.75
4. P		46.04		47.31		26.73		55.04	
5. CN		6.47		4.30		10.89		1.03	
6. CP		2.16		3.23		5.94		1.50	
7. NP	2	3.60	24.46	3.23	19.36	.99	27.72	5.27	24.03
8. SA		.72		0		.99		.21	
9. SP		11.51		8.60		8.91		16.02	
10. CNP		13.67		11.83		11.88		7.49	
11. NSP	3	.72	14.39	0	11.83	2.97	16.83	1.65	9.81
12. SCP		0		0		1.98		.67	
13. CNSP	4	.72	.72	3.23	3.23	6.93	6.93	1.86	1.86
		Total = 139		Total = 93		Total = 101		Total = 1935	

Key: - = No relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive

The patterns of utilization which are shown were obtained from videotape recordings of the perception and memory sessions described above. The Perception-Within data was obtained by counting the number of inter element intervals within a chunk. The boundaries of a chunk were identified by flips of the manila folder (when the technician elected to refer back to the schematic). These intervals were typically on the order of tenths of a second to less than two seconds in duration. The Perception-Between data resulted from timing the duration of the glance times when the technician referred back (flipped back) to the reference schematic he was redrawing. These intervals typically varied from two seconds to ten seconds. The Memory-Less Than and the Memory-Greater Equal data came from timing the actual inter element intervals. If an interval was less than two seconds, it was coded under the Memory-Less Than category; while if it was two seconds or longer in duration, it was coded under the Memory-Greater Equal category. The relationship between any two successive elements was determined by using the criteria described earlier. A videotape playback machine, a TV monitor and a stop watch were employed in gathering this data.

It should be noted that on the redrawn memory schematics, one error was allowed before analysis was terminated. The one error criteria seemed reasonable, in that in the memory task, an occasional error often preceded a sequence of correctly drawn elements. Two or more errors, however, generally signaled the initiation of a guessing phase, in which numerous additional errors occurred. The allowable first error was graded as if it had been correctly draw. This criteria was actually used in less than ten percent of the redrawn memory schematics.

The chance distribution was developed by first recording all of the various relationships between every possible pair of elements in each of the circuit diagrams. The totals for each of the 13 possible relationships, as well as the total number of relationships for a given circuit diagram, were then summed with the respective totals from the other circuit diagrams. Using the summed figures, the chance probability for a given relationship was developed as the total number of occurrences for that particular relationship, divided by the total number of possible relationships.

Table 4.2 shows the distribution of times between successively drawn elements for the perception and memory tasks. These intervals encompass the total effort of the different skill levels under the two task conditions.

As with the previous table, times were obtained by playing back the video tapes and timing each pause between elements, or inter element interval, to the nearest second using a stop watch. In cases which were difficult to call, the tape was replayed two additional times in order to obtain a consensus reading. An interval was defined to have begun when the pen was lifted from the paper, and defined to have ended when the pen touched the paper. In a few cases where the technician exhibited pauses without lifting his pen, the criteria of cessation of motion and continuance of motion were used.

The use of one second increments and rounding to the nearest second seemed both reasonable and attainable. Several schemes were tried in an effort to use increments of tenths of a second, but it was found that consensus was difficult to achieve using this fine a measurement.

Table 4.2 Time interval data for two successively drawn circuit elements for each of the skill level categories in both the perception task and the memory task, indicating the distribution of elapsed times between the point where the drawing of the first element was completed and the point where the drawing of the second element was initiated.

	PERCEPTION TASK			MEMORY TASK		
Elapsed	Technician Skill Level			Technician Skill Level		
Time Interval	3 Level	5 Level	7 Level	3 Level	5 Level	7 Level
Less than 2 seconds	562	559	448	305	335	330
2 seconds	75	59	124	25	26	41
3 seconds	77	60	148	21	20	26
4 seconds	41	53	71	10	11	23
5 seconds	31	29	35	16	11	12
6 seconds	28	24	21	10	6	7
7 seconds	17	23	14	10	6	9
8 seconds	14	10	7	1	6	5
9 seconds	5	11	8	1	2	3
10 seconds	7	10	5	1	4	3
Greater than 10 seconds	14	17	7	9	1	9
TOTALS	871	855	888	409	428	468

NOTE: The term "skill level", as used above and throughout this study, is an Air Force designation. It is used to denote a degree of technical competence, based on Air Force criteria. A three skill level (or three level) is the lowest technical rating, a five skill level (or five level) is a middle technical rating, and a seven skill level (or seven level) is the highest (for purposes or this study) skill rating.

In contrast to the data in Tables 4.1A through 4.1D, which was of nominal and ordinal level of measurement, the data for the times between elements will be treated as interval level data. It was felt that the interval level was more appropriate than the ratio level, since rounding was used.

Tables 4.3A and 4.3B illustrate how each schematic was chunked by the different technicians. For example, in the memory task, technician number 3-1 (three skill level-first subject) employed two chunks (2), encoded five elements (5), and the total degree of his two chunks was five (5). Symbolically, this is represented by 2/5/5 (number of chunks/ number of elements/total degree).

The number of chunks and the number of elements in those chunks were obtained by simply totaling the results for each redrawn schematic. The total degree of the encoding relationships used in the chunking process was computed based on the degree criteria described earlier. An example is presented in Figure 4.3. This example is from the memory task, involved technician 5-4, and dealt with schematic number 2. The subject redrew a total of nine elements. There were two chunks (circuit elements 1-2-3 and circuit elements 4-5-6-7). The total number of elements in these chunks was seven (elements 1 through 7). The degree of the first chunk was four and the degree of the second chunk was six for a total degree of ten. The degree of four for the first chunk was computed by summing 1 (for the degree of the relationship C) and 3 (for the degree of the relationship CSP). The degree of six for the second chunk was computed by summing 1 (for the degree of the relationship P), 3 (for the degree of the relationship CNP) and 2 (for the relationship NP). Elements 8 and 9 were not encoded in a chunk, as the elapsed time between

Table 4.3A Memory task chunking data, indicating for each of the five technicians in the three skill categories, the number of chunks employed to encode each of the ten electrical schematic diagrams, the number of elements chunked for each of the schematics, and the total degree of the codes employed in the chunking process for each schematic.

Skill Level-Tech. Code	MEMORY TASK Schematic Number 1	2	3	4	5	6	7	8	9	10
3-1	2/ 5/ 5	2/11/30	1/ 3/ 6	2/12/28	1/13/28	1/ 9/21	3/11/22	1/ 3/ 7	2/16/37	3/13/29
3-2	2/ 4/ 5	2/ 7/12	2/ 4/ 3	2/ 7/16	2/ 5/ 7	1/13/33	1/ 5/ 9	3/13/24	2/10/22	1/ 3/ 7
3-3	3/12/21	2/ 5/ 6	2/ 8/12	1/ 6/14	2/ 5/11	3/13/28	1/ 4/ 8	3/11/20	2/ 9/22	1/ 6/12
3-4	4/ 8/11	2/ 9/19	1/ 2/ 1	3/11/25	1/ 3/ 5	3/11/21	4/14/23	1/ 8/21	2/14/31	3/ 9/18
3-5	2/ 9/18	1/ 5/13	1/ 3/ 3	1/ 7/19	1/ 2/ 1	2/10/22	1/ 5/ 9	1/ 8/18	2/ 7/16	1/ 5/10
5-1	1/ 4/ 8	1/ 3/ 2	2/10/18	0/ 0/ 0	2/ 5/ 8	1/ 4/ 7	4/10/12	1/ 4/11	1/ 5/10	4/11/21
5-2	1/ 4/ 5	1/ 5/11	3/10/20	0/ 0/ 0	3/ 9/17	3/ 9/16	1/ 5/ 6	1/ 8/22	1/13/36	2/ 5/ 7
5-3	4/10/12	1/ 3/ 4	2/ 8/15	3/15/40	2/ 6/10	3/13/27	2/ 6/ 8	2/ 6/11	2/16/40	2/ 7/14
5-4	3/ 8/13	2/ 7/10	2/ 8/14	0/ 0/ 0	4/18/42	2/ 8/17	3/ 9/11	4/13/24	2/13/24	3/16/32
5-5	3/12/21	1/ 8/16	2/11/19	1/ 9/27	5/19/40	2/15/33	3/ 7/ 8	4/17/35	2/16/38	2/10/20
7-1	1/ 5/10	3/14/27	2/10/21	1/ 5/12	5/18/32	2/ 8/12	1/ 2/ 1	1/ 4/11	2/15/34	1/11/26
7-2	1/ 8/16	4/13/29	2/ 9/19	2/10/27	2/ 5/ 8	3/10/20	4/12/21	4/14/27	3/13/28	5/14/25
7-3	2/ 4/ 4	2/ 9/17	2/ 7/12	1/ 4/10	2/ 7/12	2/ 6/11	3/ 9/16	1/ 6/15	1/ 5/12	1/ 2/ 4
7-4	3/ 7/11	2/ 8/14	3/10/18	2/ 9/20	4/ 9/14	4/14/31	1/ 9/18	2/ 7/14	3/16/35	2/ 8/13
7-5	1/ 3/ 2	2/ 9/16	2/ 5/ 6	4/12/23	2/ 5/ 8	2/ 6/ 8	4/11/16	1/ 4/10	3/13/29	3/16/34

Key: Number of Chunks/Number of Elements Chunked/Total Degree Chunked

Table 4.3B Perception task chunking data, indicating for each of the five technicians in the three skill categories, the number of chunks employed to encode each of the ten electrical schematic diagrams, the number of elements chunked for each of the schematics, and the total degree of the codes employed in the chunking process for each schematic.

Skill Level-Tech. Code	PERCEPTION TASK Schematic Number 1	2	3	4	5	6	7	8	9	10
3-1	6/15/26	3/10/19	2/ 4/ 6	7/21/45	10/24/39	4/15/34	4/15/27	5/17/35	2/ 4/ 6	5/16/29
3-2	4/10/17	2/ 8/20	2/ 7/10	5/13/27	8/29/52	4/21/49	4/14/25	3/12/26	3/10/21	3/15/33
3-3	4/16/30	6/16/28	3/10/19	7/24/47	9/30/56	5/14/27	5/13/23	7/20/37	3/15/32	3/16/33
3-4	5/13/23	4/15/31	3/ 7/12	5/17/43	7/28/58	5/18/35	6/14/21	6/20/37	2/15/36	4/11/22
3-5	4/14/23	5/19/37	3/11/20	5/22/54	10/30/58	6/20/40	4/14/23	5/20/39	4/16/34	3/13/29
5-1	5/12/19	4/17/34	4/10/14	7/18/31	8/30/55	4/18/36	6/15/17	6/19/29	5/16/33	4/16/29
5-2	5/16/29	5/16/34	4/11/18	5/23/52	9/28/52	6/19/35	6/16/22	7/17/28	4/15/30	4/14/26
5-3	7/15/21	5/14/26	2/ 4/ 3	6/18/42	9/24/40	6/16/31	5/11/18	7/20/34	5/15/33	4/16/33
5-4	6/15/26	6/14/25	3/ 9/14	7/19/38	4/27/50	6/17/31	3/10/17	4/16/35	4/16/38	6/15/25
5-5	5/18/27	3/20/37	2/10/12	2/15/38	6/27/54	4/21/42	4/16/21	1/ 7/16	1/16/38	1/15/34
7-1	6/14/23	5/17/36	2/ 9/18	7/21/40	7/20/35	6/15/26	5/13/23	6/17/33	4/16/39	4/14/29
7-2	4/12/24	4/13/30	4/10/15	5/16/34	7/14/22	4/14/33	4/12/23	6/15/27	5/15/32	5/14/27
7-3	4/ 8/12	5/14/25	2/ 4/ 6	8/19/35	9/19/30	4/11/22	5/11/16	6/15/27	6/12/19	5/12/22
7-4	6/13/19	4/10/21	1/ 2/ 2	7/15/24	8/21/37	3/ 9/18	5/12/20	3/ 6/10	5/12/23	5/12/20
7-5	5/15/26	5/16/32	3/ 8/15	6/21/44	7/29/59	5/21/42	5/15/22	6/18/32	5/15/28	4/15/29

Key: Number of Chunks/Number of Elements Chunked/Total Degree Chunked the drawing of these elements and elements adjacent to them was greater than or equal to two seconds. Hence, the entry in Table 4.3 reads 2/7/10. The dashed lines, then, separate successive circuit elements which were not chunked together. These are elements 3 and 4, elements 7 and 8, and elements 8 and 9. The relationships between these successive, non-chunked elements are to the right of the dashed lines which represent the boundaries between neighboring chunks, between individual elements which were not chunked, or between an unchunked element and a chunk. The numbers in parentheses indicate the time duration in seconds between the two elements which flank such boundaries. No time duration specified between the chunked elements indicates that the duration was less than two seconds.

The next group of data relates to the impression portion of this experiment. It is shown in Tables 4.4A and 4.4B. The format of this table is similar to that of Tables 4.3A and 4.3B. The schematic numbers are shown along the top margin, while the technician numbers are listed along the left hand margin. As in the previous table, the impression data from the memory task is given first, followed by the data from the perception task.

Within these tables the following arrangement is employed. The first entry is a number which indicates the code number of the first circuit element drawn by the technician. The second entry is either a C or a $\overline{C}$. The symbol C indicates that the first element was part of a chunk, while the symbol $\overline{C}$ indicates that the first element was not part of a chunk. The third entry is either an L or a B. The L signifies that the first element was part of a loop, while the B indicates that it was part of a branch. The fourth entry is either an E or an I. The E

```
1
 C
2
 CSP
3
---- CNP (4 second interval)
4
 P
5
 CNP
6
 NP
7
---- P (8 second interval)
8
---- CNP (3 second interval)
9
```

Key: The numbers on the left (1 through 9) indicate that nine elements were redrawn by the technician.

The codes between the numbers show the relationships between the successive circuit elements. - = No Relationship, C = Connected, N = Proximate, S = Same, A = Active, P = Passive.

The dashed lines signify boundaries between chunks or between individual elements which were not chunked (grouped) with any other element.

The numbers in parentheses represent the elapsed time interval between adjacent chunks, between an adjacent chunk and a single element which was not part of a chunk, or between two elements, neither of which was part of a chunk.

Figure 4.3 Chunking example from the memory task, indicating the number of circuit elements encoded, the encoding relationships between successive circuit elements, the boundaries between chunks and individual elements which were not part of a chunk, and the elapsed time intervals between successive elements which were not part of the same chunk.

Table 4.4A Impression data from the memory task, indicating for each of the five technicians in the three skill categories, the code number of the first circuit element drawn, whether that first element was part of a chunk, if it was located in a loop or on a branch within the circuit, whether it was an interior or an exterior element, if it was an active element or a passive element, the quadrant in which it was located on the page, and the degree of the relationship between it and the second element drawn.

Skill Level-Tech. Code	MEMORY TASK Schematic Number 1	2	3	4	5	6	7	8	9	10
3-1	1CBEP1-2	5$\bar{C}$LEA1-1	1$\bar{C}$BEP1-1	12CBEP3-3	1CBEP1-1	10CLEP1-3	2CBEP2-4	1CBEP1-3	1CBEP1-4	1CBEP1-4
3-2	1CBEP1-2	1CBEP1-1	5CLEA1-1	16$\bar{C}$LEA4-0	1CBEP1-1	1CLEP1-3	7CLIA1-2	4CBEP1-3	1CBEP1-4	1CBEP1-4
3-3	1CBEP1-2	1$\bar{C}$BEP1-1	1CBEP1-1	1CBEP1-3	2$\bar{C}$BEA2-1	1CLEP1-3	3CBEP2-3	1CBEP1-3	1$\bar{C}$BEP1-4	7CBEP4-3
3-4	6CLIA1-2	5CLEA1-1	1CBEP1-1	7CBEP2-3	2CBEA2-2	3CLEP1-3	2CBEP2-2	1CBEP1-3	1$\bar{C}$BEP1-4	5$\bar{C}$BEA3-1
3-5	17CBEP3-3	20CBEP3-4	10CBEP3-2	1CBEP1-3	1CBEP1-1	1CLEP1-3	2CBEP2-3	1CBEP1-3	1CBEP1-4	5CBEA3-2
5-1	6CLIA1-2	1CBEP1-1	1CBEP1-1	1CBEP1-0	1CBEP1-1	1CLEP1-3	2CBEP2-2	1CBEP1-3	1CBEP1-4	1CBEP1-4
5-2	6CLIA1-0	5$\bar{C}$LEA1-1	5CLEA1-1	16$\bar{C}$LEA4-0	2CBEA2-2	15CLEA3-2	7CLIA1-1	11CLEA1-2	1CBEP1-4	1CBEP1-4
5-3	6CLIA1-2	5CLEA1-1	5$\bar{C}$LEA1-1	1CBEP1-3	1CBEP1-1	1CLEP1-3	7CLIA1-1	4CBEP1-4	1CBEP1-4	1CBEP1-4
5-4	1CBEP1-2	5CLEA1-1	1CBEP1-1	1$\bar{C}$BEP1-0	1CBEP1-1	1CLEP1-3	2CBEP2-2	1$\bar{C}$BEP1-3	1CBEP1-4	1CBEP1-4
5-5	1CBEP1-2	1CBEP1-1	1CBEP1-1	1CBEP1-3	1CBEP1-1	1CLEP1-3	7CLIA1-1	1CBEP1-3	1CBEP1-4	1CBEP1-4
7-1	6$\bar{C}$LIA1-2	5CLEA1-1	5CLEA1-1	16$\bar{C}$LEA4-2	2CBEA2-2	1CLEP1-3	7CLIA1-1	11$\bar{C}$LEA1-0	1CBEP1-4	1CBEP1-4
7-2	6CLIA1-2	5$\bar{C}$LEA1-1	5CLEA1-1	16$\bar{C}$LEA4-0	2CBEA2-2	1CLEP1-3	7CLIA1-1	2CBEP2-1	1CBEP1-4	1CBEP1-4
7-3	1CBEP1-2	1CBEP1-1	1CBEP1-1	1$\bar{C}$BEP1-3	1CBEP1-1	1CLEP1-3	8CLEP3-3	1CBEP1-3	1CBEP1-4	1CBEP1-4
7-4	6CLIA1-2	19CBEP3-3	5CLEA1-2	24CBEP3-3	1CBEP1-1	20CBEP3-3	7CLIA1-2	11CLEA1-2	1CBEP1-4	15CBEP3-3
7-5	6CLIA1-2	5CLEA1-1	5CLEA1-1	12CBEP3-3	1$\bar{C}$BEP1-1	15$\bar{C}$LEA3-2	7$\bar{C}$LIA1-1	1CBEP1-3	1CBEP1-4	1CBEP1-4

Key: For an explanation of the codes, refer to page 144.

Table 4.4B Impression data from the perception task, indicating for each of the five technicians in the three skill categories, the code number of the first circuit element drawn, whether that first element was part of a chunk, if it was located in a loop or on a branch within the circuit, whether it was an interior or an exterior element, if it was an active element or a passive element, the quadrant in which it was located on the page, and the degree of the relationship between it and the second element drawn.

Skill Level-Tech. Code	PERCEPTION TASK Schematic Number 1	2	3	4	5	6	7	8	9	10
3-1	1CBEP1-2	5$\overline{\text{C}}$LEA1-1	5$\overline{\text{C}}$LEA1-1	1$\overline{\text{C}}$BEP1-3	1CBEP1-1	1CLEP1-3	3CBEP2-3	1CBEP1-3	1$\overline{\text{C}}$BEP1-4	1CBEP1-4
3-2	6CLIA1-2	3$\overline{\text{C}}$BEP1-3	1CBEP1-1	1CBEP1-3	4CBEP2-3	7CLEP1-3	3CBEP2-2	2$\overline{\text{C}}$BEP2-1	7CBIP3-4	1CBEP1-4
3-3	2CLIP1-3	1CBEP1-1	1CBEP1-1	16CLEA4-0	1CBEP1-1	1CLEP1-3	7CLIA1-2	1CBEP1-3	14CBEP3-4	6CLEP4-3
3-4	6CLIA1-2	5CLEA1-1	5$\overline{\text{C}}$LEA1-1	7CBEP2-3	2CBEA2-2	3CLEP1-3	3CBEP2-3	1CBEP1-3	1CBEP1-4	1CBEP1-4
3-5	1CBEP1-3	20CBEP3-4	10CBEP3-3	1CBEP1-3	1CBEP1-1	7CLEP1-3	1CLEP1-2	1CBEP1-3	1CBEP1-4	1CBEP1-4
5-1	2CLEP1-3	5$\overline{\text{C}}$LEA1-1	1CBEP1-1	1CBEP1-3	1CBEP1-1	1CLEP1-3	1CLEP1-2	4CBEP1-3	1CBEP1-4	5CBEA3-1
5-2	6CLIA1-2	5$\overline{\text{C}}$LEA1-1	5CLEA1-2	16CLEA4-2	2CBEA2-2	15CLEA3-2	7$\overline{\text{C}}$LIA1-1	11$\overline{\text{C}}$LEA1-1	1CBEP1-4	5CBEA3-1
5-3	6CLIA1-2	5$\overline{\text{C}}$LEA1-1	5$\overline{\text{C}}$LEA1-2	12CBEP3-3	2CBEA2-2	15CLEA3-2	8CLEP3-3	1CBEP1-3	1CBEP1-4	1CBEP1-4
5-4	1CBEP1-2	1$\overline{\text{C}}$BEP1-1	1$\overline{\text{C}}$BEP1-1	1$\overline{\text{C}}$BEP1-3	1CBEP1-1	7CLEP1-3	1CLEP1-2	1CBEP1-3	1CBEP1-4	1CBEP1-4
5-5	1CBEP1-2	1CBEP1-1	1CBEP1-1	14$\overline{\text{C}}$LIP3-3	2CBEA2-1	1CLEP1-3	7CLIA1-1	1CBEP1-3	1CBEP1-4	1CBEP1-4
7-1	6CLIA1-2	5$\overline{\text{C}}$LEA1-1	5$\overline{\text{C}}$LEA1-1	16$\overline{\text{C}}$LEA4-1	1CBEP1-1	15$\overline{\text{C}}$LEA3-2	7CLIA1-2	11$\overline{\text{C}}$LEA1-0	1CBEP1-4	5$\overline{\text{C}}$BEA3-0
7-2	6CLIA1-2	5$\overline{\text{C}}$LEA1-1	5CLEA1-1	16$\overline{\text{C}}$LEA4-3	2$\overline{\text{C}}$BEA2-2	1CLEP1-3	7$\overline{\text{C}}$LIA1-2	2$\overline{\text{C}}$BEP2-1	1CBEP1-4	1CBEP1-4
7-3	1$\overline{\text{C}}$BEP1-2	1$\overline{\text{C}}$BEP1-3	1$\overline{\text{C}}$BEP1-1	1$\overline{\text{C}}$BEP1-3	1$\overline{\text{C}}$BEP1-1	1CLEP1-3	1CLEP1-2	1CBEP1-3	1CBEP1-4	1CBEP1-4
7-4	1$\overline{\text{C}}$BEP1-3	1$\overline{\text{C}}$BEP1-3	1$\overline{\text{C}}$BEP1-1	1$\overline{\text{C}}$BEP1-3	1CBEP1-1	7CLEP1-3	17CBEP3-3	3$\overline{\text{C}}$BEP2-2	1$\overline{\text{C}}$BEP1-4	1$\overline{\text{C}}$BEP1-0
7-5	6CLIA1-2	5$\overline{\text{C}}$LEP1-1	5CLEA1-1	16CLEA4-0	1CBEP1-1	15CLEA3-2	7$\overline{\text{C}}$LIA1-1	1CBEP1-3	1CBEP1-4	1CBEP1-4

Key: For an explanation of the codes, refer to page 144.

indicates that the element was an exterior element, while an I indicates that the element was an interior element. An exterior element is one which has no element between it and the perimeter of the schematic. An interior element is one which is not an exterior element. The fifth entry is an A if the first element was an active element, and it is a P if the first element was a passive element. Active and passive elements were defined previously. The sixth entry is a number which identifies the quadrant in which the first element was located in the schematic. The seventh entry, following the dash, indicates the degree of the encoding relationship between the first element and the second element. An example of how this scheme is applied can be explained using Figure 4.4.

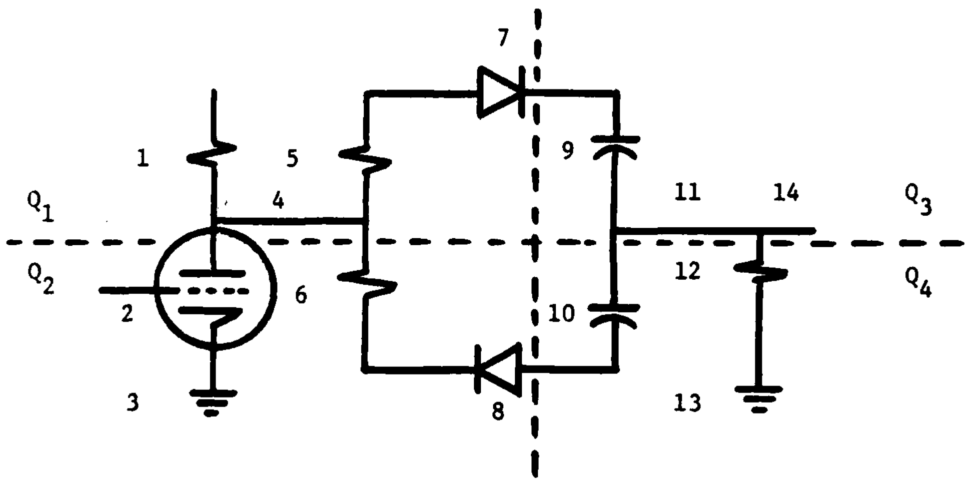

Figure 4.4 Impression coding example.

Assume, for instance, that circuit element 2 was the first element drawn and that it was part of a chunk, with a relationship of degree 1 with the second element. The appropriate entry in Table 3.4 would be 2CBEA2-1. It is the element labeled 2, it is part of a chunk, it is located on a branch, it is an exterior element, it is an active element, it is in the second quadrant (the dashed lines separate the quadrants), and the degree of the relationship between it and the second element is 1.

If circuit element 7 had been drawn first and it was not part of a chunk, but had a relationship of degree 2 with the second element, its entry would be 7$\overline{C}$LEP1-2. It is the element labeled 7, it was not chunked, it is located on a loop, it is an exterior element (the only interior elements are those labeled 4, 5, 6 and 10), it is passive, it is in the first quadrant and the degree of the relationship between it and the next element is 2.

Table 4.4 completes the data of interest in this experiment. The next two sections will present analyses of this data and discuss the conclusions which result.

IV.5 Analysis of the Data

IV.5.1 Analysis of Chunking Capacity and Chunking Sophistication Data

The first step in the analysis will be to consider differences in the nature of the two tasks. With the memory task, the technicians' short term memories were being evaluated as to their chunking capacity. That is, they were asked to reproduce as much as they could recall from a brief, one time exposure to the schematic. With the perception task, on the other hand, the chunking sophistication of the different skill levels was of principal interest. Here, the technicians had free access to the schematic, and they could encode it as they saw fit, knowing that it was readily available to them.

The data presented in Table 4.3 provides a means of analyzing both chunking capacity and chunking sophistication by skill level. The memory data from Table 4.3 will be used to analyze chunking capacity, while the perception data from Table 4.3 will be used to analyze chunking sophistication.

IV.5.1.1 Analysis of Chunking Capacity

Table 4.5 below shows the number of chunks per schematic by skill level for the memory task. This data is considered to be a more relevant measure of chunking capacity than is the corresponding data for the perception task, since in the perception task, the technician was free to encode as little as one chunk or one element per glance.

Table 4.5 Chunking capacity data by skill level for the memory task, where the table entries indicate the distribution of the number of chunks used by the five technicians in the three different skill categories to encode circuit information from each of the ten schematic diagrams.

Skill Level	Chunks Per Schematic - Memory Task						
	0	1	2	3	4	5	6 or more
3	0	20	19	9	2	0	0
5	3	13	17	10	6	1	0
7	0	13	19	9	7	2	0

For the three skill level technicians, the mean chunking capacity was 1.86 chunks per schematic, with a standard deviation of 0.86 chunks per schematic. The corresponding statistics for the five skill levels were 2.12 and 1.17, while those for the seven skill levels were 2.32 and 1.13. These were based on a sample size of 50 for each skill category.

The difference in mean chunking capacity by skill level can be analyzed using the usual test for paired observations with a sample size greater than thirty.

This test assumes that the population distributions of the criterion measures are approximately normal in form, and that the samples are large ($n > 30$). It makes no assumption about the equality of the population variances. Under these conditions, the sampling distribution of Z is approximated by $N(0,1)$.

The null hypothesis under this test is that the mean chunking capacity is the same for two given skill level groups. Application of the test to the three possible combinatorial groups yields the following results.

Table 4.6 Statistical analysis results of mean chunking capacity by skill level, under the null hypothesis that the mean chunking capacity is the same for two given skill groups.

Skill Groups	z Value	$P(Z > z; H_o)$
3 vs 5	1.27	0.102
5 vs 7	0.87	0.192
3 vs 7	2.29	0.011

The analysis of chunking capacity by skill level is informative about the differences along this dimension for the three groups. First of all, the mean chunking capacity increases with skill rating. The three level technicians are relatively tightly grouped about an average capacity figure of less than two chunks, while the five level and seven level technicians are more dispersed about an average chunking capacity of over two chunks. The chunking capacity variances are markedly similar for the five and seven levels, while the distribution for the three level technicians differs from that of the five and seven levels with regard to both location and dispersion. A statistical analysis of the hypothesis that there is no significant difference between the chunking capacities of the three skill groups was undertaken. It indicated that, at best, there is less than one chance out of five that these samples came from populations having the same mean chunking capacities. While this figure differs from the more traditional values such as 0.05 or 0.01, the total data picture supports the alternative hypothesis that chunking capacity increases with skill level rating.

IV.5.1.2 Analysis of Chunking Sophistication

Chunking sophistication will be gauged by considering the average degree of the relationships between successive elements within chunks employed by members of the various skill level groups in the perception task. Perception data is considered to be a more relevant measure of chunking sophistication than is the corresponding data for the memory task, since the perception mode is most commonly used in troubleshooting. That is, the technician typically has the schematic readily available, and he makes frequent reference to it during the troubleshooting activity, rather than attempting to memorize it.

The degree of the relationship between two successively chunked elements was defined in section IV.4.4. It was pointed out there that the degree data was measured on the ordered, rather than the interval, scale. It has been suggested by contemporary researchers (Abelson and Tukey, 1959) that it is both meaningful and reasonable in certain cases to define intervals for ordered data. Labovitz (1970) goes further by advocating the use of interval statistics to any ordinal level variable, in all but the most extreme situations. He states that, "Although some small error may accompany the treatment of ordinal variables as interval, this is offset by the use of more powerful, more sensitive, better developed, and more clearly interpretable statistics with known sampling error." In the present situation, the interval of degree will be taken as one unit. That is, it will be assumed that the difference between a first degree and a second degree relationship is the same as the difference between a third degree and a fourth degree relationship. Such an interval unit seems appropriate, since the concept of degree was defined as a simple enumeration of the number of relationships between two successive elements.

Table 4.7 summarizes the perception chunking sophistication data from Table 4.3 by skill level. As with the chunking capacity data, there are a total of 50 cases for each of the three different skill categories. The different cases correspond to the average degree of the relationships between successive elements which were chunked during a particular trial. Since there were ten schematics and five subjects in each skill category, there are a total of fifty trials for each of the skill groupings.

The average degree of the relationships between successive elements within a chunk may be calculated for each trial as follows. The numerator for such a figure is simply the total degree. The denominator is the total number of successive elements minus the total number of chunks, or simply the total number of successively paired elements. For technician 3-1 and schematic 1, the entry in Table 4.3 (perception) is 6/15/26. The average degree of the relationship for this trial is therefore 26/(15-6) or 2.889. Averages for the other trials can be calculated in a similar manner, and from these a mean and standard deviation (in degree units) for all fifty trials within a skill category can be obtained. The mean and standard deviation for the three levels were, respectively, 2.801 and 0.2835, for the five levels they were 2.612 and 0.4184, and for the seven levels they were 2.918 and 0.2785.

The difference in mean chunking sophistication by skill level can be analyzed using the usual test for paired observations with a sample size greater than thirty. The null hypothesis under this test is that the mean chunking sophistication is the same for two given skill groups. Application of the test to the three possible combinatorial groups yields the following results.

Table 4.7 Statistical analysis results of mean chunking sophistication by skill level, under the null hypothesis that the mean chunking sophistication is the same for two given skill groups.

Skill Groups	z Value	$P(Z > z;\ H_0)$
3 vs 5	-2.65	0.004*
5 vs 7	4.29	0.000
3 vs 7	2.07	0.019

*$P(Z < z;\ H_0)$

The analysis of chunking sophistication by skill level provides insight about the differences along this dimension for the three groups. Mean chunking sophistication does not increase from three levels to five levels, but rather decreases. However, it increases both from five to seven levels and from three to seven levels. Also, the variance of the five levels is over twice as large as the variances of the other two groups. A statistical analysis of the hypothesis that there is no significant difference between the chunking sophistication of the three skill levels was accomplished. The results indicated that, at best, there are less than two chances out of one hundred that these samples came from populations having the same mean chunking sophistication.

Therefore, the total data picture supports the alternative hypothesis that chunking sophistication varies with skill rating, with the highest degree of sophistication being employed by seven level technicians.

IV.5.2 <u>Analysis of Time Interval Data</u>

Table 4.2 presented the distribution of times between successively drawn elements for the perception and memory tasks. This data was collected for the purpose of identifying parallels between the perception and the memory tasks.

It will be noted that the totals differ for the two tasks. The perception totals are all in the 800 to 900 range, while the memory totals fall between 400 and 500. This is not unexpected, since the perception task allowed free access to the schematic, and hence resulted in more elements being drawn, while the memory task limited the technicians to a single glance. The result was that technicians recorded roughly twice as many successive element intervals under the perception task as under the memory task.

The six distributions, corresponding to each of the three skill levels under the two task conditions, appear to be similar with regard to position, dispersion, symmetry and kurtosis. They are, however, markedly non-normal. In order to measure the degree of association between these six sets of interval level data, therefore, a correlation analysis was performed. The resulting Pearson correlation coefficients are shown in Table 4.8. The null hypothesis here is that there is no relationship between the six distributions. The significance figure in all cases was 0.001. The significance figure measures the probability that the observed relationship could have happened by chance.

Table 4.8 Pearson correlation analysis of time interval data, indicating the degree of association among the distributions of the time intervals between successively drawn elements for technicians in the three different skill categories during the perception and memory tasks.

	PERCEPTION TASK			MEMORY TASK		
	Three Level	Five Level	Seven Level	Three Level	Five Level	Seven Level
Three Level	1.0000					
Five Level	0.9985	1.0000				
Seven Level	0.9713	0.9615	1.0000			
Three Level	0.9936	0.9980	0.9498	1.0000		
Five Level	0.9965	0.9981	0.9497	0.9991	1.0000	
Seven Level	0.9981	0.9990	0.9602	0.9980	0.9984	1.0000

The results of the correlation analysis indicate that the smallest r value is on the order of 0.95. This value is indicative of a strong linear relationship between the time interval distributions exhibited by the various skill levels in the two tasks. The goodness of fit of a bivariate linear regression line applied to this data is close to perfect ($r = 1.0$) for all of the combinations. Further, the relationship is direct, rather than inverse, for all of the cases, as the sign of r is uniformly positive.

When the statistic r^2 is considered, the strength of the relationship is further quantified. This follows from the fact that r^2 is a measure of the proportion of variance in one variable which is explained by the other variable. For the time interval data, the smallest r^2 value is on the order of 0.90, indicating that bivariate linear regression lines would account for at least ninety percent of the total variance. Hence, the amount of total time interval variance which could not be explained by using a linear regression line as a prediction device would be on the order of less than ten percent.

Based on the above, the hypothesis that there is no relationship between the six time interval distributions is rejected. The alternative hypothesis is accepted, and based on the correlation results, a strong linear relationship between the time interval data sets is statistically verified.

IV.5.3 Analysis of Encoding Data

The next dimension or characteristic to be considered will be the encoding relationship between successive elements, chunked or otherwise. The data pertaining to encoding relationships was presented in Table 4.1. As discussed previously, this data is partly nominal and partly ordered in level of measurement.

The frequencies displayed in Table 4.1 for the different skill categories show a greater deviation from the chance frequencies under the perception-within and memory-less than conditions, than do the conditions of perception-between and memory-greater equal. Furthermore, within each of the four experimental conditions (perception-within, memory-less than, etc.) there are similarities across the skill levels with regard to the encoding relationships employed.

IV.5.3.1 Nonparametric Correlation Analysis of Encoding Data

In order to measure the degree of association across skill levels with regard to the encoding relationships employed, for each of the four experimental conditions, a matrix of correlation coefficients was developed. Because of the nature of the data, a Spearman correlation analysis was used. Of the two principal methods of nonparametric correlation analysis, Spearman's r_s and Kendall's tau, tau is more typically used when a fairly large number of cases are classified into a relatively small number of categories. The r_s is used when the ratio of cases to categories is smaller (Nie, Hull, et al., 1975). Table 4.9 gives the Spearman correlation coefficients for the categories of interest. The significance figure in all cases was 0.001.

Table 4.9 Nonparametric correlation analysis of encoding relationships across skill levels for the four experimental conditions, indicating the degree of association among the distributions of the encoding relationships employed by technicians in the three different skill categories during the perception and memory tasks.

Experimental Condition	Skill Groups	R_s Coefficient
Perception-Within	3 vs 5	0.9641
	5 vs 7	0.9514
	3 vs 7	0.9479
Memory-Less Than	3 vs 5	0.9460
	5 vs 7	0.9640
	3 vs 7	0.9549
Perception-Between	3 vs 5	0.9316
	5 vs 7	0.9727
	3 vs 7	0.9516
Memory-Greater Equal	3 vs 5	0.8934
	5 vs 7	0.9514
	3 vs 7	0.8690

Based on the above, the null hypothesis that there is no association or relationship between the four experimental condition distributions is rejected. Instead, the alternative hypothesis, that there is a strong linear relationship across skills with regard to encoding relationship employed, is accepted. It will be further noted that the percentage of explained variance is as small as 76 percent for only the last condition, while the percentage figures for explained variance for the other three conditions are all on the order of 90 percent or greater.

IV.5.3.2 Z Score Analysis of Encoding Data

Because of the high correlations across skill levels for the various experimental conditions, it is reasonable to group the encoding data for the different skills in each of the four conditions (Chase & Simon, 1973). Then, since the same kinds and degrees of relatedness between successive elements hold for technicians of differing skill, the grouped data can be analyzed to identify encoding patterns.

The analysis will be accomplished in the following manner. The observed number of times that the thirteen different composite relationships were used by each of the skill groups under the four different conditions in Table 4.1 will be totaled. The total number of times each composite relationship was used will then be divided by the grand total for all composite relationships to obtain an observed probability for each relationship. The observed probability (P_O) will then be compared with the expected, or chance, probability (P_E), along each of the composite relationships (- to CNSP). This comparison will be made using the Z score expression shown below (Parl, 1967).

$$Z = \frac{P_O - P_E}{SE_{P_O - P_E}} \qquad (4.5.3.2.1)$$

where

$$SE_{P_O - P_E} = \sqrt{\sigma P_O^{\,2} + \sigma P_E^{\,2}} \qquad (4.5.3.2.2)$$

and

$$\sigma P_O = \sqrt{\frac{P_O(1-P_O)}{n-1}}, \qquad \sigma P_E = \sqrt{\frac{P_E(1-P_E)}{n-1}} \qquad (4.5.3.2.3/4)$$

NOTE: The chance probabilities (P_E) were calculated by first recording, for each position, all combinatoric relationships that exist between every possible pair of elements. P_E is then simply the total number of occurrences of a relationship divided by the total number of possible pairs.

The deviation of the Z score (the observed probability minus the expected probability, divided by the standard error), assuming the normal approximation to the binomial, is that deviation which would result under the null hypothesis that the observed probabilities came from a distribution identical to that of the chance distribution.

The observed and expected frequencies can be obtained from Table 4.1. They are summarized by experimental condition in Table 4.10. Note that the basis of comparison has been changed from 100.00 percent to 1.0000. The resultant Z score value is included for each composite encoding relationship.

The Z score values provide insight as to how the encoding relationships compare with that which would be expected from chance considerations alone. A small score, for example, suggests that chance factors are influencing the mental operations which determine the nature of the circuit relationships which are encoded. A large positive score suggests that the associated encoding relationship is favored by the cognitive encoding processes. Conversely, a large negative score suggests that the associated encoding relationship is being tuned out or not utilized by the cognitive encoding processes.

For the purposes of this analysis, a small score will be defined as any Z value lying between +3 and -3. The choice of these values results in a confidence level of 0.998 in rejecting the null hypothesis that chance considerations alone motivated the selection of encoding relationships. Z values greater than +3 indicate those relationships which were used more extensively than chance considerations alone would warrant. Z values of less than -3 indicate those encoding relationships which were utilized less than chance would suggest.

Table 4.10 Z score analysis of encoding data, indicating the number of standard errors by which the observed probabilities of usage of the composite encoding relationships differed from the expected (chance) probabilities of usage of the composite encoding relationships, under the null hypothesis that the observed probabilities came from a distribution identical to that of the chance distribution.

PERCEPTION-WITHIN

Composite Encoding Relationship	Observed Probability	Expected Probability	Z Score Value Under the Null Hypothesis
-	0.005	0.075	-11.17
C	0.028	0.014	2.80
N	0.001	0.003	- 1.39
P	0.072	0.550	-36.67
CN	0.023	0.010	2.87
CP	0.075	0.015	8.26
NP	0.047	0.053	- 0.81
SA	0.008	0.002	2.39
SP	0.031	0.161	-13.71
CNP	0.443	0.075	26.37
NSP	0.031	0.017	2.66
SCP	0.069	0.007	9.29
CNSP	0.168	0.019	14.91

MEMORY-LESS THAN

Composite Encoding Relationship	Observed Probability	Expected Probability	Z Score Value Under the Null Hypothesis
-	0.014	0.075	- 8.71
C	0.078	0.014	7.19
N	0.001	0.003	- 1.25
P	0.076	0.550	-33.62
CN	0.054	0.010	5.79
CP	0.057	0.015	5.32
NP	0.042	0.053	- 1.34
SA	0.007	0.002	1.72
SP	0.025	0.161	-13.88
CNP	0.410	0.075	11.85
NSP	0.027	0.017	1.67
SCP	0.054	0.007	6.35
CNSP	0.154	0.019	11.34

PERCEPTION-BETWEEN

Composite Encoding Relationship	Observed Probability	Expected Probability	Z Score Value Under the Null Hypothesis
-	0.047	0.075	- 0.42
C	0.067	0.014	6.46
N	0.000	0.003	- 2.50
P	0.326	0.550	-12.17
CN	0.049	0.010	5.49
CP	0.067	0.015	6.34
NP	0.078	0.053	2.58
SA	0.000	0.002	- 2.00
SP	0.080	0.161	- 6.81
CNP	0.216	0.075	10.07
NSP	0.013	0.017	- 0.89
SCP	0.027	0.007	3.77
CNSP	0.030	0.019	1.80

MEMORY-GREATER EQUAL

Composite Encoding Relationship	Observed Probability	Expected Probability	Z Score Value Under the Null Hypothesis
-	0.087	0.075	0.72
C	0.087	0.014	4.65
N	0.003	0.003	0.00
P	0.405	0.550	- 4.97
CN	0.072	0.010	4.31
CP	0.036	0.015	1.98
NP	0.027	0.053	- 2.52
SA	0.006	0.002	0.93
SP	0.099	0.161	- 3.37
CNP	0.126	0.075	2.66
NSP	0.012	0.017	- 0.75
SCP	0.006	0.007	- 0.22
CNSP	0.033	0.019	1.36

IV.5.4 Analysis of Impression Data

The final effort associated with this first experiment will be to utilize data collected in the perception and memory tasks to identify the most impressionable aspects of the schematic presentations. The data used in this analysis is summarized in Table 4.4. The dimensions of interest here are the first element drawn, whether the element was chunked or not chunked, if the element was part of a loop or part of a branch, if the element was in the interior or along the exterior of a circuit, the spatial location of the element on the page and the degree of the relationship between the element and the next one drawn. Each of these characteristics will be analyzed separately below. Because of the high correlations evidenced on the encoding relationship data across skill levels, the skill data will again be grouped together under the two tasks, memory and perception. The only exception to this grouping will be in the analysis of initial encoding relationships.

IV.5.4.1 Analysis of First Element Preferences

First element preferences for each of the ten schematics were determined by tabulating the frequencies with which different circuit elements appeared first in the redrawn circuits. The numbers may be cross referenced to the components they represent by referring to the circuit schematics in Appendix B. First element preferences are summarized in Table 4.11. The numbers used to identify different circuit components were assigned after the experiment was completed, and they were not available to the technicians during any phase of the memory or perception tasks.

Table 4.11 First element preferences by schematic number.

MEMORY TASK

Schematic Number	First Elements (Number in parentheses indicates the number of times a particular element was picked first)	Total Number of Circuit Elements
1	6 (8), 1 (6), 17 (1)	18
2	5 (8), 1 (5), 20 (1), 19 (1)	20
3	1 (7), 5 (7), 10 (1)	11
4	1 (7), 16 (4), 12 (2), 7 (1), 24 (1)	24
5	1 (10), 2 (5)	31
6	1 (10), 15 (2), 3 (1), 10 (1), 20 (1)	21
7	7 (8), 2 (5), 3 (1), 8 (1)	17
8	1 (9), 11 (3), 4 (2), 2 (1)	21
9	1 (15)	16
10	1 (11), 5 (2), 7 (1), 15 (1)	16

PERCEPTION TASK

Schematic Number	First Elements (Number in parenthesis indicates the number of times a particular element was picked first)	Total Number of Circuit Elements
1	6 (7), 1 (6), 2 (2)	18
2	5 (8), 1 (5), 20 (1), 3 (1)	20
3	1 (8), 5 (7)	11
4	1 (7), 16 (5), 12 (1), 7 (1), 14 (1)	24
5	1 (9), 2 (5), 4 (1)	31
6	1 (6), 15 (4), 7 (4), 3 (1)	21
7	7 (6), 1 (4), 3 (3), 8 (1), 17 (1)	17
8	1 (9), 11 (2), 4 (1), 2 (1), 3 (1)	21
9	1 (13), 7 (1), 14 (1)	16
10	1 (11), 5 (3), 6 (1)	16

The first point to be noted from Table 4.11 is that there was perfect agreement between the memory and perception tasks with regard to the element most often redrawn first. Indeed, on the second most preferred initial element, there was agreement on eight of the ten schematics, with the only differences being on schematic seven and schematic nine. The remaining choices are, for the most part, one time selections.

While it is apparent that other than chance considerations are at work in the selection of the first element, it is informative to consider a typical case. For example, in schematic number 3, the element labeled 1 was selected as the first element 7 times out of 15 trials in the memory task, and 8 times out of 15 trials in the perception task. Under the null hypothesis that all elements enjoy an equal probability of being selected first, the binomial distribution can be used to find the probability of 7 selections of element 1 in 15 trials. Here, p is equal to 1/11 or 0.0909, since there are a total of 11 elements in schematic number 3. From the usual tables for binomial probabilities, the probability of seven selections of the same element out of fifteen trials is 0.0001. Hence, the null hypothesis can be rejected with 0.9999 confidence in favor of the alternative hypothesis that patterned selection, rather than chance or random selection, is being employed with regard to first element preference in both the memory and perception tasks.

IV.5.4.2 Analysis of First Element Chunking

Table 4.4 provides information about first element chunking, which can be used to make inferences about the behavior of technicians on this dimension. It will be recalled that the symbol C implies that the first element was chunked, while the symbol $\overline{C}$ indicates that the first element stood alone and was not part of a chunk. The information on first element chunking is summarized below for the memory and perception tasks.

The data below reflect a clear disposition on the part of the technicians to initially absorb information in chunks, rather than element by element separately. Hypothesizing a 4 to 1 chunking ratio for first elements, one can perform a goodness of fit test. The 4 to 1

Table 4.12 First element chunking, indicating the extent to which the initial elements were chunked by technicians during the memory and perception tasks.

MEMORY TASK

Number of First Elements Chunked	127
Number of First Elements Not Chunked	23
Total Number of First Elements	150

PERCEPTION TASK

Number of First Elements Chunked	107
Number of First Elements Not Chunked	43
Total Number of First Elements	150

chunking ratio implies that 4 out of every 5 first elements are chunked. These values were the only integer values which appeared to reasonably agree with the data. Under the null hypothesis, the chi square value for the perception task is 7.04. For one degree of freedom, this corresponds to $P = 0.008$. For the memory task, the chi square value is 0.82. For one degree of freedom, this corresponds to $P = 0.393$. Hence, for the perception task, there is question whether the hypothesized chunking ratio applies, while for the memory task, the null hypothesis cannot be rejected with any significant degree of confidence.

Of the two tasks, there is more inclination on the part of the technician to chunk information in the memory task than in the perception task, as discussed earlier. With perception, he had free access to the schematic, and therefore he could encode as little as one element per glance. This difference between the two tasks very likely accounts for the discrepancy between the observed and the hypothesized chunking ratio in the perception task.

IV.5.4.3 Analysis of Branch Versus Loop First Elements

This portion of the impression analysis concerns itself with whether an element was located within a closed circuit loop or on an open circuit branch. In courses on circuit theory, there are two principal methods of circuit analysis which are taught. One method applies to closed loops and is called loop analysis, while the other method applies primarily to branches and is called node analysis. Therefore, the circuit geometry applicable to a particular element determines how that element would be viewed from a circuit analysis standpoint.

The ten schematics used in the study contained a total of 195 elements. Of these, 91 were branch elements and 104 were loop elements. Since there were only a total of 150 first elements in each of the tasks, the actual numbers of both types of elements will be changed from a base of 195 to a base of 150 for purposes of analysis. These new expected values, along with the observed values, are shown in Table 4.13 below.

Employing a chi square goodness of fit test under the null hypothesis that chance factors alone dictate whether a loop element or a branch element will be chosen first, the memory chi square value is found to be 27.80, while the perception chi square value is computed as 18.35. These correspond to P values which are both less than 0.005 (chi square: 7.88, 1). Based on these results, the null hypothesis is rejected with greater than 0.995 confidence in favor of the alternative hypothesis that patterned selection influences whether the first element selected will be a loop element or a branch element.

Table 4.13 Branch versus loop first elements, indicating the extent to which branch or loop initial elements were selected by technicians during the memory and perception tasks.

MEMORY TASK

Observed/Expected Loop Elements	53/85
Observed/Expected Branch Elements	97/65

PERCEPTION TASK

Observed/Expected Loop Elements	59/85
Observed/Expected Branch Elements	91/65

The observed frequencies suggest that for the circuits employed in this study, branch elements are preferred or selected first on a 2 to 1 ratio over loop elements. Employing a goodness of fit test under this hypothesis results in a memory chi square value of 0.27 and a perception of chi square value of 2.43. Hence the null hypothesis cannot be rejected with any significant degree of confidence.

IV.5.4.4 Analysis of Interior Versus Exterior First Elements

The impression analysis along this dimension is similar to that just undertaken with regard to branch and loop elements. Exterior elements are those which are located on the perimeter of a circuit, while interior elements are those which are not exterior elements. The observed and expected frequencies are shown in Table 4.14. As in the previous section, the expected frequencies have been based on a total of 150 elements.

Table 4.14 Interior versus exterior first elements, indicating the extent to which exterior or interior initial elements were selected by technicians during the memory and perception tasks.

MEMORY TASK

Observed/Expected Interior Elements	16/ 36
Observed/Expected Exterior Elements	134/114

PERCEPTION TASK

Observed/Expected Interior Elements	16/ 36
Observed/Expected Exterior Elements	134/114

Under the null hypothesis that chance factors alone determine whether an interior or an exterior element is selected first, the memory chi value value is 14.62, as is the perception chi square value. For one degree of freedom, the null hypothesis may be rejected with greater than 0.995 confidence.

The observed frequencies suggest that for the circuits employed in this study, exterior elements are selected first on an 8 to 1 ratio over interior elements. Employing a goodness of fit test under this hypothesis results in a memory and a perception chi square value of 0.03. Hence the null hypothesis cannot be rejected with any significant degree of confidence.

IV.5.4.5 Analysis of Active Versus Passive First Elements

First element preference with regard to active versus passive elements was considered next. Active elements contribute energy to a circuit, while passive elements either store or dissipate circuit energy.

The observed and expected frequencies for these two categories are shown in Table 4.15. As in the previous two sections, the expected frequencies have been based on a total of 150 elements.

Table 4.15 Active versus passive first elements, indicating the extent to which active or passive initial elements were selected by technicians during the memory and perception tasks.

MEMORY TASK	
Observed/Expected Active Elements	47/ 8
Observed/Expected Passive Elements	103/142
PERCEPTION TASK	
Observed/Expected Active Elements	46/ 8
Observed/Expected Passive Elements	104/142

Under the null hypothesis that chance factors alone determine whether an active or a passive element is selected first, the memory chi square is 200.84 and the perception chi square is 190.67. For one degree of freedom, the null hypothesis may be rejected with greater than 0.995 confidence.

The observed frequencies suggest that for the circuits employed in this study, passive elements are selected first over active elements at about a 2 to 1 ratio. Employing a goodness of fit test under this hypothesis results in a memory chi square value of 0.27 and a perception chi square value of 0.48. Hence the null hypothesis cannot be rejected with any significant degree of confidence.

IV.5.4.6 Analysis of First Element Spatial Locations

In addition to the characteristics considered above, it is also reasonable to address the question of whether an element's location on the paper, as opposed to its location in the circuit, has any influence on its selection as a first element. For the purpose of identifying an element's spatial location, the pages on which the schematics were presented to the technicians were divided up into four quadrants. The identification of the quadrants was accomplished using the numbering system shown in Figure 4.5 below.

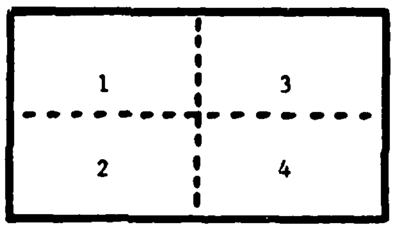

Figure 4.5 Quadrant numbering system.

Equivalent quadrants are indicated by dashed lines on the schematics shown in Appendix B. These quadrant designations were not available to the technicians during the experiment.

The data pertaining to spatial preference is shown in Table 4.16.

Table 4.16 Spatial locations of first elements, indicating the quadrant in which initial elements selected by technicians were located.

	Quadrant			
	1	2	3	4
MEMORY TASK	118	13	14	5
PERCEPTION TASK	116	13	15	6

Under the null hypothesis that each quadrant has an equally likely chance of having a first element in it, the expected frequency for each quadrant would be 37.5. Employing a goodness of fit test under that hypothesis, the memory chi square would be 231.72 and the perception chi square value would be 220.27. For three degrees of freedom, the null hypothesis may be rejected with greater than 0.995 confidence.

The actual number of elements in each of the quadrants is shown in Table 4.17. Since the total number of elements is 195 for the ten schematics, a conversion has been made to a base of 150 for the purpose of analyzing the data.

Table 4.17 Actual number of elements per quadrant.

	Quadrant			
	1	2	3	4
Actual Number (Base of 195)	41	49	71	34
Analysis Number (Base of 150)	31	38	55	26

Under the null hypothesis that chance alone determines the likelihood of a first element coming from a given quadrant, the memory chi square value is 315.91 and the perception chi square value is 301.66. For three degrees of freedom, the null hypothesis may be rejected with greater than 0.995 confidence.

The observed frequencies suggest that for the circuits employed in this study, first elements are selected from the first quadrant over the other three quadrants at about a 4 to 1 ratio. Employing a goodness of fit test under this hypothesis results in a memory chi square value of 0.16 and a perception chi square value of 0.66. Hence, the null hypothesis cannot be rejected with any significant degree of confidence.

IV.5.4.7 Analysis of Initial Encoding Relationships

The last question to be addressed with regard to the impression data concerns itself with encoding relationships between initial elements and second elements which were part of a chunk. It was earlier illustrated that chunking sophistication, as measured by the average degree of the relationships between successive elements within a chunk, differed by skill level. Whether such a difference exists for the chunked initial encoding relationships will now be considered.

Table 4.17 indicates the average degree and the standard deviation of the encoding relationships for the different skill levels. These were developed in an earlier section of this chapter. It also shows the average degree and the standard deviation of the chunked initial encoding relationships for the perception portion of the impression data.

Table 4.18 Chunking sophistication, indicating the average degree and standard deviation of the chunked initial encoding relationships.

Chunking Sophistication-Perception Data/All Chunked Elements

Seven Level	2.918 (0.2785)
Five Level	2.612 (0.4184)
Three Level	2.801 (0.2835)

Chunking Sophistication-Impression Data/All Chunked Elements

Seven Level	2.651 (1.0665)
Five Level	2.450 (1.0610)
Three Level	2.583 (1.2129)

Key: First number indicates the mean, while the second number (in parentheses) indicates the standard deviation.

The data suggest that one of the trends noted earlier is continued with the impression data. Chunking sophistication is highest for seven levels and lowest for five levels. On the other hand, the standard deviations suggest that there is greater variability in the impression task than in the perception task overall.

The difference in mean chunking sophistication by skill level in the impression task can be analyzed using the Winer test described earlier for paired observations with a sample size greater than thirty. The null hypothesis under this test is that the mean chunking sophistication is the same for two given skill groups. Application of the test to the three combinatorial groups yields the following results. Therefore, the null hypothesis cannot be rejected with any degree of confidence.

Table 4.19 Statistical analysis results of mean chunking sophistication by skill level for the impression task, under the null hypothesis that the mean chunking sophistication is the same for two given skill groups.

Skill Groups	z Value	$P(Z > z; H_0)$
3 vs 5	-0.53	0.298
5 vs 7	0.73	0.233
3 vs 7	0.24	0.405

In addition to comparing chunking sophistication within a given task, comparisons may also be made across two tasks. The data from Table 4.17 may be used to analyze the difference between the impression and perception tasks with regard to this dimension. The null hypothesis here is that the mean chunking sophistication is the same for a given skill group in both tasks. Application of the test yields the following results.

Table 4.20 Statistical analysis results of mean chunking sophistication by skill level for the impression task versus the perception task, under the null hypothesis that the mean chunking sophistication is the same for a given skill group during both tasks.

Skill Group	z Value	$P(Z > z; H_0)$
3 Levels	1.15	0.130
5 Levels	0.91	0.180
7 Levels	1.21	0.110

The results indicate that, at best, there is about one chance out of six that these samples came from populations having the same mean chunking capacities. These figures differ from traditional values such as 0.05 and 0.01, but together they indicate that mean chunking sophistication differs across the two tasks for a given skill group.

IV.6 Discussion and Conclusions

IV.6.1 Chunking Capacity

The experimental data support the contention that chunking capacity differs with skill level rating. This difference is less defined between three and five levels and five and seven levels, but it is clearly defined between three levels and seven levels. The capacity of the three levels was something less than two chunks per schematic, while the capacity of the five levels and the seven levels was above the two chunk boundary.

The variance and skewness of the respective distributions also provide information with regard to chunking capacities. The three levels were relatively tightly grouped around one and two chunks per schematic. The five levels exhibited the most variation, but they were clearly grouped around two chunks per schematic, with about an equal number of cases above and below that value. The seven levels also were grouped around two chunks per schematic, but it was a tighter grouping than that of the five levels. Also, there was a more pronounced tendency toward a higher capacity than a lower chunking capacity, with regard to the two chunks value. Finally, only in two instances did three levels employ 4 or more chunks per schematic. On the other hand, there were seven instances for five levels in this category and nine instances for seven levels.

Overall then, chunking capacity is less developed for three levels on virtually every count. Five levels show an improved capacity, but they tend to vary back toward that of three levels. Seven levels show a marked tendency toward higher chunking capacity on every aspect.

From an intuitive standpoint, these results were reassuring. The seven level, by virtue of his training and experience advantages, should be expected to excel on this dimension. The three level technician has had only about six months of training to call upon and virtually no experience. The five levels are at various points along the training and experience trails, and their performance substantiates this in between status.

With regard to earlier research, the findings of Miller and of Chase and Simon, cited previously, are substantiated. Miller's magical number of 7 plus or minus 2 is operative in the encoding of schematic diagrams. Indeed, his re-evaluation of several earlier studies suggested that there was more magic in the 7 minus 2 rather than in the 7 plus 2. This is clearly the case in this study. Chase and Simon demonstrated that the chess grand master partially achieved his superior performance by recalling more chunks. In other words, they asserted, the number of

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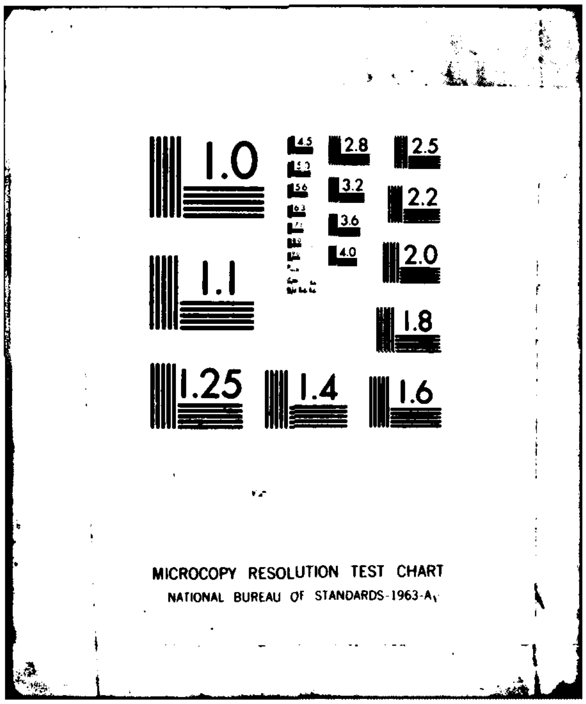
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chunks is related to chess skill. This is also the case here with regard to the encoding of schematic diagrams. Higher skill rating and higher chunking capacity are closely related.

IV.6.2 Chunking Sophistication

Chunking sophistication was assessed by comparing the average degree of the relationships between successive elements within a chunk. Chunking sophistication did clearly vary with skill level, but with an unexpected progression. Rather than the seven to five to three which might be supposed, the five levels were below the three levels on this dimension. The seven levels, as might be expected, strongly exhibited the highest degree of sophistication.

Aside from the inversion of the three and five levels, the five levels once again displayed the largest variation and the seven levels the smallest variation. This again suggests that the five skill rating is a transition status between two fairly well defined states on each end. The performance of five levels on this dimension, as on the previous one, fluctuates between the entry level state and the highly skilled state.

The inversion between the three levels and the five levels is deserving of comment. One possible explanation is related to the grasp of electronics fundamentals which each group enjoys. The three level group is comprised of recent high school graduates who have just completed a technical training school of about six months duration. The school environment is one of fairly intense concentration on electronics fundamentals. By virtue of a number of factors, such as subject interest, lack of diversions and encouragement from above, there is a tendency to concentrate on the material and master it to a high degree. Upon arriving at their duty stations, three levels participate in an equipment familiarization course of one type or another, which emphasizes the fundamentals of the given unit's equipment. Therefore, the three level is in a peaked state with regard to knowledge of fundamentals. The five level, on the other hand, has typically been removed from the technical school environment by at least a year or more. Factors such as increased diversions, concentration on one system, reassessment of career goals and others may act to decrease his proficiency with regard to electronics fundamentals. It is likely, therefore, that his state of knowledge of fundamentals is below that of the just out of school three level. The seven levels, by contrast, have made their career choices, passed a rigorous proficiency examination on electronics and systems fundamentals, and have accumulated experience in the profession. They too, then, enjoy a peaked state with regard to knowledge of electronics fundamentals.

From an intuitive standpoint, chunking sophistication seems to be related to knowledge of fundamentals, rather than to experience. Chunking capacity, on the other hand, seemed to be related to experience, to the extent that experience and skill are related.

With regard to earlier research, there is no clear parallel to chunking sophistication. Chase and Simon considered chunk size, or the number of chess pieces per chunk, but the relationships between those pieces were considered separately. In general, they found that grandmasters partially achieve superior performance by recalling larger chunks. The present results suggest that skilled troubleshooters achieve superior results by recalling more sophisticated chunks. Since a more sophisticated encoding capability suggests that more components could be encoded per chunk, the present results are in agreement with earlier findings.

IV.6.3 Time Intervals

The data related to time intervals was used to assess the degree of association between the memory and perception tasks by skill level rating with regard to time intervals between successively drawn elements. The results indicated that there was a strong linear relationship present, or that a linear model would adequately predict the time interval distribution for a selected group in one task, given the results of any other group in either task.

The results infer that the time durations for the cognitive operations at work in each of the two tasks, memory and perception, across the three skill groups are related. Thus, the time interval between successively redrawn pieces represents the first dimension along which there is agreement between different skill levels.

From an intuitive viewpoint, this suggests that the same time spans of thought between successive elements were used in the perception task as were used in the memory task. Furthermore, each skill group used about the same amounts of thinking time between successive elements. Similar timing distributions, then, suggest that similar encoding mechanisms are likely being utilized.

IV.6.4 Encoding Mechanisms

Analysis revealed that the same kinds and degrees of encoding relationships were being used by technicians in the different skill groups. In performing this analysis, the two second standard used by

Chase and Simon in their chess studies was adopted. Pauses which were two seconds or more were interpreted as indicating chunk boundaries, while pauses of shorter duration were assumed to be within chunk pauses.

The grouped data was then analyzed for each of the two tasks to evaluate the utilization of encoding relationships, by comparing what was observed to what would be expected from chance factors alone. Large deviations from chance indicated that some patterned encoding process was in use, while small deviations indicated that random encoding was likely being employed.

Before considering the Z values themselves, it is informative to note the similarity of the patterns of those values for different pairs of experimental conditions. The patterns for perception-within and memory-less than agree very closely on 11 of the 13 categories with regard to both magnitude and direction of encoding relationship utilization. Also, while the agreement is less pronounced for the perception-between and memory-greater equal conditions, there is agreement on 10 out of the 13 relationships as to which are motivated by chance and which are motivated by factors different from chance. The relationships for which there is disagreement are C and CN in the first instance and CP, CNP and SCP in the second.

In the first instance (perception-within and memory-less than), it will be noticed that the strongest (largest Z score) relationship is CNP. The Z values differ between the two conditions, however, being 26.37 and 11.85 respectively. This suggests that in the memory-less than task, subjects are using the somewhat simpler encoding mechanisms, C and CN, to supplement the more elaborate CNP mechanism used almost exclusively, relative to the other two, in the perception-within condition.

In the second instance (perception-between and memory-greater equal), there does not appear to be any directly traceable simplifying strategy of the type just described. Rather, the tendency seems to be one of operating closer to chance on all of the memory-greater equal relationships, relative to the perception-between relationships. For example, the largest deviation in the former case is 4.97 magnitude units, while in the latter case, six relationships have magnitude deviations greater than five units. Viewed another way, in the memory-greater equal condition, there are only four relationships which deviate from chance (C, P, CN and SP); while in the perception-between condition, seven relationships deviate from chance (C, P, CN, CP, SP, CNP and SCP). This again suggests that in the memory-greater equal condition, subjects are being more random and less patterned, relative to the perception-between condition, in choosing successive elements.

The Z score values indicate that for the within-chunk conditions (perception-within and memory-less than), the two most utilized encoding relationships are CNP and CNSP. Because of the simplifying strategy mentioned above for the memory-less than condition, there is disagreement as to whether SCP or C is next most utilized. The relationship CP is the only other relationship to have greater than chance utilization under both conditions. Relationships which are tuned out or avoided for these two conditions are, in order of least utilization, P, SP and - (no relationship). There is perfect agreement between the two conditions as to which relationships are not utilized and their order of non-preference. For the within-chunk encoding relationships, then, there is a predisposition to use more elaborate encoding relationships (CNP and CNSP) and avoid using simpler relationships (P, SP and -).

For the between-chunk conditions (perception-between and memory-greater equal), the Z scores suggest that there is near agreement here. Perception-between has four relationships which have greater than chance utilization. These are, in order, CNP, C, CP and CN. For memory-greater equal, the corresponding relationships are C and CN. Those which are avoided under both conditions are, in order of most avoidance, P and SP. Except for the relationships CNP and CP, used in the perception-between condition, then, there is perfect agreement as to which encoding relationships are and are not utilized to any degree different from chance. As discussed above, the tendency toward chance utilization in the cognitively more difficult memory-between condition probably accounts for the discrepancy. Finally, there is a predisposition, with the exception of the CNP relationship, to use simpler encoding relationships, as well as to generally deviate less from chance, in between-chunk encoding.

With regard to earlier research, the above results are highly supportive of the assertions of Chase and Simon that similar cognitive operations are evidenced in the perception-within and memory-less than conditions and in the perception-between and memory-greater equal conditions, in the encoding of chess positions. Also, their findings that chess piece encoding relationships deviate further from chance under the perception-within and memory-less than conditions and that the relationships are closer to chance for the perception-between and memory-greater equal conditions appear to be applicable with regard to the encoding of electrical circuit relationships. This simply implies that within-chunk encoding is more patterned and less random than is between-chunk encoding.

As a final comment with regard to the analysis of this data, the results of the memory-greater equal experimental condition were very close to that which would have been expected from an intuitive standpoint. It was noted earlier that the memory task was more difficult from a cognitive standpoint than was the perception task. Technicians typically do not work under the memory condition. Rather, they will generally have the schematic close at hand, where they can make frequent referrals to it. Also, they do not operate under a time constraint, such as was imposed on them in the memory task. As a result, one would expect the memory-greater equal encoding relationships to be closer to chance than were those of any of the other experimental conditions. Indeed, as was pointed out, only four of the thirteen relationships deviated from the chance distribution. It would also be expected that simpler relationships would be employed more often than would be complex relationships. This was the case, with only first degree and second degree relationships being employed which differed from what was expected from chance considerations alone. The results further indicate that the most dominant encoding characteristics (largest Z scores) are related to elements which are either connected or connected and near. Thus, under the most cognitively demanding task, the only non-chance encoding mechanisms which seemed to be operative were to choose the next element if it was connected to the present element, or to choose it if it was connected and near the present element. Elements which had only the relationship of being both passive or both the same and passive were tuned out, apparently because of the cognitive strain of choosing between so many possibilities.

IV.6.5 First Element Preferences

Technicians indicated a clear disposition to begin the redrawing process with certain elements on each of the schematics and under both task conditions. Moreover, there was perfect agreement between the two tasks as to which element was the most preferred, and near perfect agreement as to which was the next most preferred element. Given that there were certain elements which made a greater cognitive impression than others, characteristics of the elements were investigated separately.

IV.6.6 <u>First Element Chunking</u>

Technicians showed a marked tendency to encode the first element within a chunk. The data suggested that four out of every five first elements were encoded as part of a chunk, for the circuits used in this experiment. There was no support for the hypothesis that first element chunking was a random phenomenon. This suggests that technicians have a strong predisposition to chunk information when they start to read a schematic diagram.

IV.6.7 <u>Branch Versus Loop First Elements</u>

Branch elements were preferred or selected first over loop elements. The data indicated that two branch elements were selected for every loop element. Apparently, technicians found it simpler to start with an element isolated on a branch, rather than enter a closed loop and select one of its elements as the initial element. Chance considerations would have resulted in four loop elements being selected for each branch element.

IV.6.8 <u>Interior Versus Exterior First Elements</u>

Technicians exhibited a high degree of preference for exterior elements as first elements. The data suggested that eight out of every nine first elements was an exterior element. Technicians are apparently scanning the perifery of a circuit to obtain their initial element, rather than getting it from the interior of a circuit. Chance considerations would have resulted in three exterior elements being selected for each interior element.

IV.6.9 Active Versus Passive First Elements

Passive elements were typically selected first over active elements. The data indicated that two out of every three first elements was a passive element. Active elements were selected first, however, in much greater numbers than random selection would predict, based on the ratio of passive to active elements of eighteen to one. This implies that technicians key on active elements to a greater extent than passive elements in selecting an initial element. Passive elements, however, because of their relatively greater numbers, are still typically chosen over active elements. In general, if a passive element also happens to be an exterior branch element in the upper left part of the schematic, it will likely be chosen over nearby passive elements as the initial element.

IV.6.10 Spatial Locations of First Elements

Besides circuit considerations, another factor which influenced first element selection was the location of the elements on the paper. Technicians selected as their first elements, elements which were in the upper left hand quadrant of the paper over elements in all other quadrants combined at a four to one ratio. There was no support for the hypothesis that quadrant selection was a random phenomenon.

The tendency to begin with a first quadrant element is likely related to two factors. First, in reading text we are conditioned to begin in the upper left of the page and work across and down. Second, it has become somewhat of a schematic convention to show a circuit's input in the upper left hand portion of the circuit. The technicians apparently find it simpler to work on an input to output basis.

IV.6.11 Initial Encoding Relationships

Chunking sophistication, with regard to the initial element and the second element encoded, tends to follow the same trend noted earlier for all elements, with two exceptions. First of all, the relative differences between the different skill groups along this dimension is less pronounced. This suggests that seven levels do not gain any advantage in the early going, but rather establish their advantage over the long haul. Second, the variation is much greater for initial chunking sophistication than it is for overall chunking sophistication. Again, this indicates that there is no well patterned surge by technicians in any of the groups when they begin encoding information. Rather, their initial encoding is more random than is their encoding overall.

A tendency which was discussed earlier is evident here. That is that five levels exhibit the weakest encoding sophistication of the three skill groups. Possible reasons for this inversion between the three and five levels were given in a previous section.

Chunking sophistication comparisons by skill group were made between the impression and the perception tasks. Since the perception task includes the data used in the impression task, it is not surprising that the P values obtained make it difficult to show evidence of a clear difference between the two tasks. The fact that the values were as small as they are, therefore, suggests that post-initial encoding sophistication does indeed differ in the direction of greater sophistication from initial encoding sophistication. Again, this implies that the level of encoding sophistication builds as the encoding process progresses, rather than starting high and tailing off.

Previous research by Chase and Simon reported that chunk size is related to chess skill only for the first few chunks. Then, there was a gradual drop in chunk size. This seems to somewhat contradict the present results. During an earlier discussion here in this paper, however, it was observed that chunk size and chunking sophistication are not the same. Also, it was noted that chess is a much more structured situation than is the reading of electrical schematic diagrams. Perhaps the difference can be explained by recognizing that the chess grandmaster, because of the structured nature of the game, approaches it in a more premeditated manner. The skilled technician, on the other hand, may approach the schematic in a more open minded manner, since, unlike the beginning game structure of chess, there is no guarantee that he will instantly recognize and identify the electrical relationship portrayed by the schematic diagram. Also, the technician enjoys a static problem, while the grandmaster faces one which is dynamic. Hence, the technician may employ a leisurely approach, in contrast to the grandmaster who, from the opening move on, is under time and competitive pressure.

IV.6.12 Impression

The previous seven sections suggest that it is possible to categorize a technician's initial impression of an electrical schematic diagram. For a given schematic, there is general agreement as to which element will receive his attention first. Occasionally, either of two elements will serve as the consensus initial focal point for a given circuit. Technicians have a tendency to group or chunk other circuit information with the initial element, rather than isolating on it alone. The initial element will typically be a branch element along the exterior of the circuit. Also, the first element picked will generally be in the top left quadrant of the drawing. While the first element is almost always a passive element, technicians choose active elements more often than their numbers would predict. Technicians apparently find it relevant to focus initially on active elements if they are also exterior branch elements in the upper left part of the schematic. Finally, the initial encoding employed by the technicians is somewht less sophisticated and varies more than does their overall encoding. The skilled technician exhibits no marked advantage over technicians of lesser skill in the initial encoding process. Rather, it is over the duration of the encoding exercise that the skilled technician builds his advantage over his lesser skilled contemporaries.

CHAPTER V

HEURISTICS USED IN ELECTRONICS TROUBLESHOOTING

V.1 Introduction

This experiment was conducted in order to identify and characterize some of the heuristics employed by skilled electronics troubleshooters in a specific operational setting, during various stages of the troubleshooting process. The term heuristic will be used in the same way as described earlier in the review of the literature. That is, in contrast to an algorithm which guarantees a solution, a heuristic simply aids in the solution to a problem. The central hypothesis of this experiment is that the behavior of technicians engaged in troubleshooting is strongly influenced by such heuristics, which are used as a means of selectively filtering the mass of available information down to that which is essential to resolving the problem.

An earlier section of this paper (see Section II.4) summarized a number of heuristical procedures applicable to electronics troubleshooting which had been documented by previous researchers. In general, these earlier studies utilized either technician trainees or engineers as subjects to infer how troubleshooting could be efficiently and logically accomplished. For whatever reasons, there have been very few studies involving those individuals who are the acknowledged experts in their field, the experienced, professional electronics technician. The purpose of this experiment, therefore, is to study the processes which are typically employed by such individuals.

V.2 Scope

V.2.1 The Complexity of the Problem

Earlier, in the review of the literature, the complexity of the game of chess was addressed, based on the number of possible combinations of pieces and chessboard squares. Chess is used as an example here, since its structure is sufficiently ordered as to permit a careful mathematical analysis of its complexity to be made. It was pointed out that with 32 pieces and 64 squares, there are 10^{43} two dimensional board positions possible and in excess of 10^{120} games. For purposes of perspective, there are about 10^{55} molecules comprising the entire earth. These figures are cited to illustrate the potential complexity of troubleshooting electronic circuits, sybsystems and systems. While the disarray of such entities makes a careful mathematical analysis of these structures infeasible, it is still possible to make comparisons between them and the situations which prevail in chess. Consider, for instance, a simple electrical circuit having 30 components. It can be argued, without a great deal of further elaboration, that an order of magnitude at least approaching the corresponding figure for possible chessboard positions applies with regard to the number of possible troubleshooting approach combinations for such a circuit. The exact number would depend upon the physical arrangement of the components. Since most practical circuits are three dimensional in their construction and appreciably non-geometric with regard to the interconnection of the various components, this magnitude estimate seems reasonable. Of course, when several simple circuits are electrically integrated in order to form a functional subsystem or system, the number of possible troubleshooting approach combinations appreciably increases.

The cognitive load suggested by these numbers is difficult to reconcile with the evidence cited in the first experiment regarding the limited memory capacity and information processing ability of individuals. Again however, an analogy with the game of chess provides a means of resolving the apparent disparity. This is best illustrated by noting that, due to memory and processor limitations, the largest and most sophisticated computers could, until recently, only play chess at about the level of a strong amateur. Yet the memory and processor units associated with these computers were vastly superior, with regard to capacity and speed, to the human mind. Since chess playing computers were typically programmed to perform exhaustive searches, the conclusion has been drawn that individuals employ mental rules or heuristics which permit them to conduct more selective searches. This selectivity results in a problem space which is reduced in magnitude to the point where it is compatible with the memory and processing limitations of man. An example of such a heuristic chess program was described earlier in the review of the literature. Indeed, chess playing computers are now competitive at the master level, by virtue of the fact that they incorporate heuristics which allow for smaller, more effective patterns of search.

In a corresponding sense, the experiment which follows below will seek to uncover some of the heuristics used by technicians in electronics troubleshooting. Certain fundamental differences between the two tasks raise doubt, however, as to whether the precision and simplicity of the chess heuristics described previously will apply to troubleshooting.

Relatively speaking, chess is clearly the more structured of the two situations. Chess is a two dimensional concept and is limited to a fixed number of pieces and board positions. The interaction between the pieces and the positions takes place in accordance with a clearly defined set of rules. In contrast, circuit elements are typically more numerous, they are arrayed three dimensionally, and they interact in a variety of patterns.

V.2.2 The Troubleshooting Process

Because of its complexity, several researchers have concluded that there exists no general troubleshooting approach. Instead, the troubleshooting procedure used depends strongly on the type of equipment, the actual problem and the problem solver himself. On the other hand, there is theoretical support for the notion that troubleshooting consists of subsets of clearly defined and closely related activities. Examples of these were given earlier under a variety of labels (phases, stages, cycles, etc.). The term stage will be adopted here to describe these different divisional concepts.

Stages, then, represent natural groupings of similar types of troubleshooting behavior. The nomenclature for these stages which follows has been widely used in the troubleshooting literature and has become fairly standardized. It is both descriptive of the type of behavior which is being displayed by the technician, as well as being functionally indicative of the extent to which the troubleshooting has progressed.

The first stage of troubleshooting will be called the Symptom Accumulation Stage. It relates to the technician's behavior in determining the status of the various system outputs. During this stage, the technician operates the different controls and exercises the different modes of the system in an effort to learn more about the malfunction. The activities associated with this stage are generally those which can be routinely accomplished using exterior controls and adjustments. The intended result of this stage is to identify subsystems (sound, power supply, etc.) in which to search further for the trouble.

The second stage of troubleshooting will be termed the Fault Localization Stage. A distinguishing characteristic of this stage is that technicians begin to make internal checks and measurements of the system's performance. The purpose of this stage is to narrow the list of potentially defective subsystems. This stage continues until a candidate subsystem is identified for more concentrated study.

The third stage of troubleshooting will be known as the Fault Isolation Stage. This stage commences when all activity becomes focused on a single, particular subsystem. The purpose of this stage is to trace the source of the malfunction to a particular circuit or component within the subsystem.

The fourth and final stage of troubleshooting will be labeled the Component Replacement Stage. This is the payoff for the technician, in that he learns whether or not he has been successful in restoring the system to operational readiness. If the component replacement or repair is the one needed to clear the malfunction, then the troubleshooting process terminates. If the component replacement was incorrect or only partly correct, then the third stage of troubleshooting, Fault Isolation, would be reinitiated. In some circumstances it might be necessary to return to one of the earlier two stages, and then work forward again toward a new component replacement action.

The heuristics assumed to apply to each of the stages of troubleshooting are listed below. These were developed in part based upon a consensus of what the literature on troubleshooting proposed, and in part based upon discussions with experienced technicians in the Air Force maintenance system. The following general guidelines also figured in the final selection of the heuristics.

> They should have the characteristic of being essentially content free, in the sense of Brown (1957).
>
> They should be able to deal adaptively with the unexpected as well as with ill-structured problems (Rigney, 1962).
>
> They will not be universally applicable, but will instead be influenced by the type of equipment, the actual malfunction and the technician (Rasmussen and Jensen, 1973).

In general, the approach is one of beginning with heuristics which give wide coverage but low precision and ending with those which give narrow coverage but high precision.

Heuristics Associated with the Symptom Accumulation Stage

> Check power input interface and line power - Confirms that power is available and being supplied to the system.
>
> Check and adjust front panel controls and indicators - This may be useful in ascertaining the status of some of the subsystems.
>
> Try different system modes - This may show whether the problem is system wide or unique only to one or more subsystems.
>
> Check and adjust other external controls and indicators - This may be helpful in determining the status of the various subsystems.
>
> Use the different senses to check for unusual system patterns - Symptoms such as excessive noise and heat or the presence of smoke may aid in locating the trouble area.

Heuristics Associated with the Fault Localization Stage

Check system using half split method - The first check is made in the middle of the system, the second check is made in the middle of the defective half, the third check is made in the middle of the defective quarter, and so on.

Check system using middle to trouble - The first check is made in the middle of the system, and succeeding ones are made in short progressive steps in the defective half.

Check system using output to input - The first check is made at the output of the system, followed by short progressive checks made toward the system input.

Check system using input to output - The first check is made at the input of the system, followed by short progressive checks made toward the system output.

Heuristics Associated with the Fault Isolation Stage

Check signal/pulse paths - Continuity is checked, the presence or absence of appropriate signals or pulses are verified, and their dynamic characteristics are noted.

Check D.C. voltages - The presence or absence of these voltages are verified. Of particular interest would be the B+, pin, filament and bias voltages. This includes voltage checks of similar elements known to be good and comparison with readings across suspect elements.

Check resistances - The measured resistances are compared with the values specified.

Check A.C. voltages - The presence or absence of these voltages are verified.

Other checks - These would include solder joints, leads, posts and other items of a general nature.

Heuristics Associated with the Component Replacement Stage

Replace a tube.

Replace a resistor.

Replace a capacitor.

Replace a connector.

Replace a coil.

In the experiment which follows, the above stages and the associated heuristics will form a hypothetical starting point that will be used in focusing on the observed actions of the technicians. The hypothetical model will be modified based on these observations. This approach is one of using a process model, rather than a mathematical model. A process has been defined as a systematic series of actions directed to some end (Stein, 1975). The heuristics employed within each stage are assumed to motivate the actions of the technicians. These actions of the technicians, along with their verbalized comments, are the only external indicators of the cognitive processes which are controlling the troubleshooting procedure. The actions themselves are directed to the end of completing the objective of that particular stage, be it symptom accumulation, fault localization, etc. When all of the stages have been accomplished, then the activity known as electronics troubleshooting has taken place.

V.2.3 The Experimental Task

This experiment will confine itself to a specific type of electronics troubleshooting, that of repairing television receivers (television sets). Several reasons motivated the selection of television receivers over other alternative systems.

Initially, it was intended that the experiment would focus on a system in use in the Air Force inventory. It was found, however, that current procedures for such systems were strongly oriented toward scheduled preventive maintenance and periodic inspection, rather than toward unscheduled maintenance. The scheduled procedures followed a fixed format and did not in any way approach the ideal format proposed by

Grings, et al. (1953), of having the technician start with a minimum of information and then structure his own solution behavior.

Equipment serviced by regional repair centers was the next option to be explored. These centers are operated by large companies such as General Electric, Panasonic and others. The problem with facilities such as these was that they are typically module oriented, rather than component oriented. Also, they rely a great deal on computer aided diagnostic programs.

Television receivers represented an ideal choice for several reasons. The sets are composed of components which operate at frequencies ranging from audio to UHF levels, they employ both sound and video circuits, and they are predominantly electrical in nature, with very few mechanical subsystems. Furthermore, the operational environment (the repair facility) in which the troubleshooting takes place is both convenient to access and is functionally representative of the typical troubleshooting setting. Finally, the chassis are physically large enough that over the shoulder discrimination between different subsystems and components is possible. These factors combined suggested that television receivers would be appropriate for use in this study.

Besides limiting the experimental task equipment exclusively to television receivers, the skill levels of the subjects were also controlled. That is, only highly skilled technicians were involved as experimental subjects, rather than using a cross section of subjects, as was done in the previous experiment. The credentials of the subjects will be discussed in a later section. The philosophy of using only one skill class was based on several reasons. The troubleshooting literature reported on earlier made extensive use of technician trainees and new technicians. Very few studies used highly skilled technicians as subjects. In contrast, skilled individuals were favored here, as they have had sufficient time and experience to hone their techniques, and as a result, likely employ established patterns of troubleshooting. The patterns of lesser skilled technicians are probably subject to greater change and fluctuation. Finally, the skilled technician represents a bench mark against which others are judged. Therefore, it is appropriate to concentrate on the heuristical techniques of the group which sets the standard.

In summary, the intent of this experiment is to address the heuristics used by technicians who are representative of a specific skill group, while they are engaged in troubleshooting a particular type of electrical equipment within an operational environment. The use of heuristics will be evidenced by the type of actions taken by the technicians as they are engaged in various stages of the troubleshooting process. The experimental activities will be centered around two closely related objectives. The first will be that of enlarging the data base with regard to the problem solving techniques utilized by representatives of a skill group which has received only minimal attention in the literature. The second will be to document the prevailing heuristics employed by members of that skill group.

V.3 Methodology

V.3.1 The Subjects

Two subjects were used in this experiment, with each subject participating in twenty trials. Subject A was a Certified Electronics Technician in the state of Colorado. This certification was supervised by an agency of the state government and required the passing of a written test on electronics fundamentals and theory. In addition, this individual was a member and former president of the Colorado Professional Electronics Association, a society for electronics technicians. The purpose of the society was to set technical and performance standards for those engaged in the profession. Subject A had six years of Air Force electronics maintenance experience, one year of commercial electronics experience, three years of general systems maintenance experience and for the past seven years had owned and operated an electronics (televi- sion, radio, stereo, C.B., etc.) repair facility. Subject B was also a Certified Electronics Technician and a member of the Colorado Profes- sional Electronics Association. In addition to pursuing electronics as a hobby, he was a trade school graduate and had five years of experience in the electronics field. He was also the owner and operator of an elec- tronics repair facility.

Subject A was generally regarded by his fellow technicians as one of the best, if not the best, in the area, particularly in the area of color television repair and servicing. Subject B did not have the estab- lished reputation enjoyed by subject A, but he nonetheless was a skilled and practiced technician.

Several reasons supported the approach of using two technicians and observing them over a large number of trials, versus the alternate approach of using many technicians over fewer trials. For one, using fewer technicians over many trials increases the chance of accurately capturing their troubleshooting approach. With fewer trials, there was the possibility of getting a distorted or a contrived picture. For another, the two subjects who participated in the test were provided with a steady flow of television sets requiring repair. These sets were partly supplied by a separate company, which advertised a policy of no charge estimates. The company's technicians made the house calls and either tried to repair the set in the home or repaired it in the company shop, if the problem was obvious (broken or frayed power cord, disconnected antenna, blacked out or cracked tubes, etc.). If company technicians were unable to effect a quick fix, then the set was sent to technician (subject) A if it was a color set, or to technician (subject) B if it was a black and white set. In addition, both technicians had sets to repair which were brought in by regular customers. The result was that the two technicians experienced a high exposure to broken television sets, which was on the order of two to six sets per day.

V.3.2 The Settings

Data collection for both sets of trials took place in the respective shops of the two subjects. These facilities consisted of a customer reception area, a repair area and a storge area for sets which had been fixed or were waiting to be fixed. Both subjects used their own tools and equipment and worked at their own pace. Their troubleshooting activities were infrequently interrupted by customers and by telephone calls. These averaged out to be one customer arrival per hour and two telephone calls per hour. These figures referred to morning hours only, since that is when most of the data collection took place.

V.3.3 The Data Collection Procedure

With both subjects, an initial contact was made and it was explained to them that a maintenance study was being conducted to determine how skilled technicians troubleshoot electronics equipment, specifically, television receivers. Following their agreement to participate, observations were begun on subsequent mornings. Afternoon observations were not convenient for either of them, as that was when they scheduled their house calls.

All observation data were recorded on a worksheet similar to that shown in Figure 5.1. As indicated by the worksheet, the variables of interest were the different actions that were taken by the technician while engaged in a troubleshooting trial. During a trial, the observed actions were written down sequentially along the right hand side of the sheet and check marks were also made on the appropriate lines. It was not anticipated that every applicable heuristic could be identified by simply analyzing the troubleshooting actions. Therefore, the observed actions were supplemented with the technician's verbal comments in some instances. These comments were recorded on the data sheets at or near the time the action was underway. Such comments were used to clarify the actions so that they could be described as accurately as possible. A sample trial is shown in Figure 5.2 and explained below.

For convenience in interpreting the example, a block diagram showing the various subsystems of a television receiver is provided in Figure 5.3. In this diagram, the radio fraquency (RF) signal from the television transmitting facility is received by the television receiver antenna and conducted to the RF Subsystem where it is amplified. It next goes to the Mixer/Oscillator Subsystem where the signal is modified to an intermediate frequency (IF). Upon entering the IF/AGC/Detector Subsystem, it is amplified again, its level is controlled and the video and sound modulating signals are removed from their respective carriers. The sound signal is conducted to the Sound Subsystem and subsequently is

MAINTENANCE STUDY - II

Date____________________ Time____________________

Equipment____________________ Specialist____________________

S.A.S.

________________ Power Input Interface/Line Power
________________ Front Panel Controls/Indicators
________________ Different System Modes
________________ Other External Controls/Indicators
________________ Use of Senses
________________ Other

Observed Actions

F.L.S.

________________ Half Split
________________ Middle to Trouble
________________ Output to Input
________________ Input to Output
________________ Other

F.I.S.

________________ Signal/Pulse Paths
________________ D.C. Voltages
________________ Resistances
________________ A.C. Voltages
________________ Other

C.R.S.

________________ Tube
________________ Resistor
________________ Capacitor
________________ Connector
________________ Coil
________________ Other

Figure 5.1 Data collection sheet for experiment 2.

MAINTENANCE STUDY - II

Date 19 April 1979 Time 0845 / 10 Minutes

Equipment Sharp Color TV 17" Specialist B-1

S.A.S.

X	Power Input Interface/Line Power
	Front Panel Controls/Indicators
	Different System Modes
	Other External Controls/Indicators
XX	Use of Senses (Listen/Filaments)
	Other

F.L.S.

	Half Split
	Middle to Trouble
	Output to Input
	Input to Output
	Other

F.I.S.

	Signal/Pulse Paths
X	D.C. Voltages
X	Resistances
	A.C. Voltages
XX	Other

C.R.S.

	Tube
	Resistor
	Capacitor
	Connector
	Coil
X	Other (Transistors)

Observed Actions

1. Felt Speaker Connections - OK
2. Listen for Click of Shorted Output Tube - OK
3. Measured Audio Amp Voltage Output - Low Collector Voltage
4. Check for Base to Emitter Short - Shorted
5. Replace Transistor - FIXED

Figure 5.2 Example data sheet from experimental trial number 21.

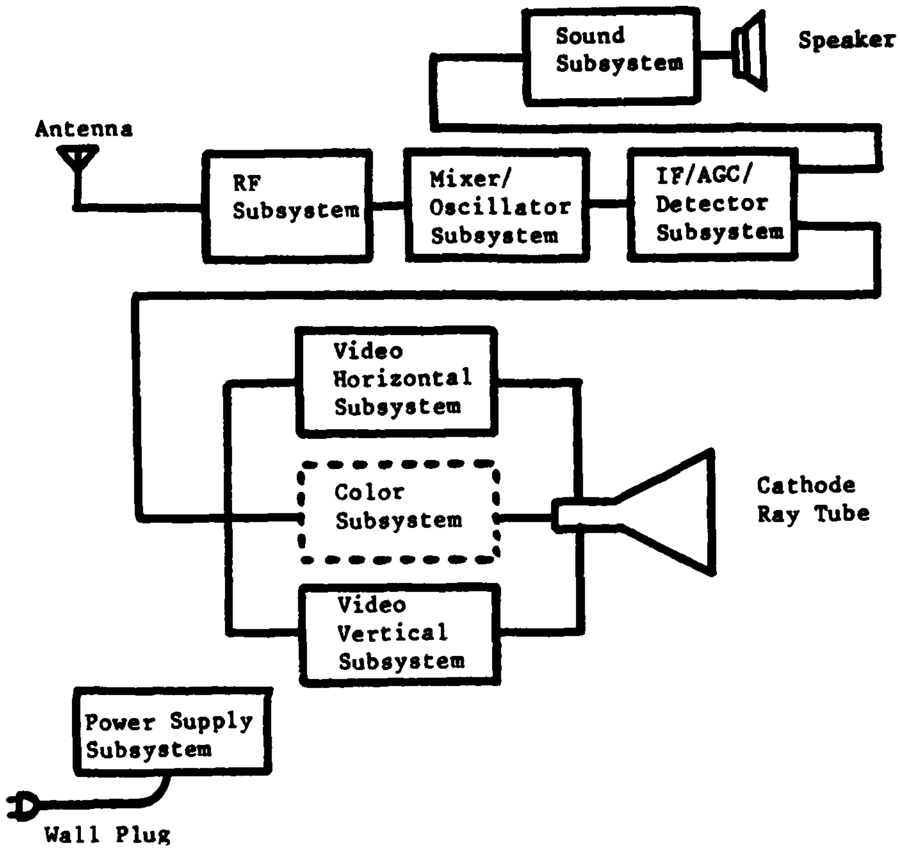

Figure 5.3 Television receiver block diagram.

heard through the speaker. The video signal separates between the Video Horizontal Subsystem, the Video Vertical Subsystem, the Color Subsystem (if applicable), and the cathode ray (picture) tube, with the net result being an image which is seen on the face of the picture tube. In addition, there is a Power Supply Subsystem which interfaces with the above subsystems.

In Figure 5.2 the data in the top four spaces is self-explanatory. The technician in this case was technician B, and this was the first trial for that subject. The symptom, either reported by the customer or observed by the technician, was listed next. Here, the symptom was "No Sound". Under the Symptom Accumulation Stage (SAS), the technician verified that there was power to the set by turning it on and visually noting that the filaments in the tubes were lit and that the screen was displaying a picture. He also verified the symptom of no sound by adjusting the volume control. In all trials, the On-Off Volume control was considered to be part of the Power Input Interface/Line Power action. Next he checked the connections to the speaker. To accomplish the speaker check, the technician was obliged to direct his attention to the internal chassis, and away from the external controls. This constituted a clear visual indication to the observer that the Symptom Accumulation Stage had ended and that a new stage of troubleshooting had commenced. Normally, the next stage would be the Fault Localization Stage (FLS), where the technician attempts to narrow the problem down to one subsystem. In this example, either of four subsystems could have caused the problem, the RF subsystem, the power supply subsystem, the mixer/oscillator subsystem or the sound subsystem. The technician elected to go directly to the sound subsystem, rather than performing checks on any of the other subsystems. By concentrating on one subsystem, he signified by his actions that he had entered the Fault Isolation Stage (FIS). As an aside, during the post trial debriefing session, the technician stated that he didn't have to check the other subsystems because he believed them to be operating satisfactorily. He explained that since the filaments in the power tubes were lit, the low voltage part of the power supply was good. Also, a picture was evident on the screen, so the high voltage portion of the power supply was good. Finally, the presence of the picture showed that the RF subsystem and the IF/AGC/detector subsystem were functioning properly. He therefore concentrated his efforts solely on the sound subsystem. Having checked the speaker connections, he next shorted the audio output tube and heard a click in the speaker. This signified that there was no problem within the speaker itself. He then went to the next component in the string which was the audio output transistor and measured its output voltage. This was lower than expected, suggesting that either the transistor was bad or that the input to it was below specifications. Upon measuring the resistances across the transistor, he found a short circuit between the base and the emitter of the device. This indicated that the transistor was bad. The identification of a faulty component signified that the Component Replacement Stage (CRS) was about to be initiated. The technician replaced the transistor, which restored the operation of the sound subsystem. Once the set was verified as being repaired, the trial was terminated.

This example of a troubleshooting trial illustrates several points about the data collection procedure. For one, the experiment is action oriented, rather than using some other variable, such as time. These actions, along with his verbalized comments, are the only external indicators of the factors which are motivating his troubleshooting procedure. Also, the technician's actions present clear indications as to the stage of the troubleshooting trial and as to what heuristic within that stage is being applied. Finally, the technician controls the pace and the direction of the trials.

Instructions were given to the technicians on only one occasion, at the initial meeting. They were informed that there was an interest in observing them as they repaired television sets, that twenty trials were desirable, and that the purpose was to compare their methods with techniques used by Air Force technicians. They were told that the observer would interfere as little as possible, but that occasional questions would be asked. Finally, it was suggested to them that it would be helpful if they would verbalize their actions to the extent that it was natural and convenient for them to do so.

The presence of an observer did not appear to significantly affect either of the technicians. In order to keep interference at a minimum, the observer was positioned about four feet from the work area and to one side of the technician. From this vantage point, it was possible to see the location in the chassis where the technician was working and the tools and equipment he was using. The observer generally could not read the actual measurements on the test equipment.

As the technician moved about the chassis and made various tests, he quite often verbalized his procedure. This verbalization seemed natural to him, occurred without any prompting on the part of the observer, and did not appear to interfere with the troubleshooting operation. Occasionally, the observer would have to ask what the result of a test was or why a certain action was performed. If it appeared that the technician was involved with a step, questions were delayed until a pause in the action or until the trial was over. Usually, the involved periods took place in the latter part of the Fault Isolation Stage, just prior to the defective component being located. Often times, when a defective part had been located, the technician would pause on his own and announce what component had failed and why it had failed.

An attempt was made to keep all sessions under three hours, based on what the technicians had reported to be their usual schedule, that of working on sets in the shop during the morning and making house calls in the afternoon. In a few instances when the technician indicated that he felt like working beyond the three hours, observations were continued. For the most part, then, the subjects were in control of what they did and when they did it.

V.4 Data

The data for the forty experimental trials is shown in Table 5.1 as an action matrix. The format for the matrix is similar to that used for the data collection except that it is somewhat more expanded. The four stages and the associated heuristics which were hypothesized for the troubleshooting procedure are listed, along with an indication as to whether or not a particular action was observed. In general, an "X" indicates that the action was observed, while a blank indicates that it was not observed. Additional letters are used to provide a more precise breakdown of the "Other" category. It will be noticed that the action labeled "Other" under the Fault Localization Stage and Fault Isolation Stage has been further broken down to "Senses" and "Other". The action, Senses, implies that the technician employed his senses (sight, touch,

TRIAL NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
S.A.S.																																								
Power	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Front	X	X		X	X		X			X			X		X					X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X
Modes		X		X									X		X							X	X	X		X			X			X	X	X			X		X	
External	X												X		X					X			X	X		X		X			X			X	X	X	X	X	X	
Senses	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Other																											A			B										
F.L.S.																																								
Half Split																																								
Middle To																																								
Out To In																																								
In To Out																											X													
Senses															X		X		X								X													
Other									E	D					D		F	D	E								C			H		E			D					
F.I.S.																																								
Signal/Pulse																	X															X		X		X	X		X	
DC Volts			X		X	X		X	X			X					X	X	X	X	X			X				X		X		X		X	X	X	X		X	X
Resistances												X				X		X	X		X			X	X			X		X		X		X		X			X	X
AC Volts																								X	X															
Senses		X	X			X		X	X			X	X		X	X	X		X	X	X				X				X	X		X				X		X	X	X
Other		G	O	H	G	G	K	R	K	G	H		H		R	G	G	N	O				L				H		G		M	G		P		O	P	P	P	R
C.R.S.																																								
Tube		X		X	X	X		X		X					X				X	X		X				X									X					
Resistor	X																								X	X										X			X	X
Capacitor																							X			X		X						X		X				
Connector		X	X				X	X					X				X		X								X		X	X								X		
Coil												X																												
Transistor									X									X			X		X									X					X			
Other		W				W					Y			W	S	T		Y						V	V				Z		T		U			V				

Table 5.1 Action matrix, indicating the usage patterns of the different heuristics within the various stages of troubleshooting over the forty experimental trials.

smell, etc.) while engaged in that stage of troubleshooting to detect or check on some aspect of the problem. It is assumed that his senses were in use throughout the troubleshooting procedure, but unless there was some overt evidence of their use, such as varying the volume control, studying the picture, or verbally stating that he noticed a component that looked suspicious, the action, Senses, was not checked. If the use of the senses was done in an indirect fashion, such as reading a meter, it was not recorded as a Sense Action. Instead, it was recorded as an action corresponding to whatever the meter was measuring (voltage, resistance, etc.). Also, under the Component Replacement Stage, the action labeled "Other" has been subdivided into "Transistor" and "Other."

In considering each trial, secondary problems were ignored. For example, the technician might discover that a solder joint showed signs of beginning to crystalize or that a tube was giving a marginally satisfactory reading. These actions were recorded on the work sheets, but they are not shown on the action matrix. Also, actions taken to tune the various circuits were not included in the data matrix. Examples of these would be where the technician adjusted the tint of the picture or where he spray cleaned the channel tuner. Generally, these secondary actions occurred after the Component Replacement Stage was completed. If, in the opinion of the technician, the secondary problem did affect the primary malfunction, then it was included in the action matrix.

Four of the actions which were common to almost every one of the troubleshooting trials have been omitted from the action matrix. Three of these were in the nature of preparatory steps and they did not differ appreciably for the majority of the trials. The first action was to remove the rear panel of the set and install a power cord known to be good. This cord bypassed the interlock on the back of the set. The second action was to hook up a shop antenna whose reception characteristics were known. Action number three was to turn the set on and verify the reported symptom. The order of the first two actions varied, but typically the antenna hook up followed the power hook up. The result of these two actions was to allow the technician to begin the troubleshooting procedure from familiar and known power and signal reference points. The fourth action occurred at the end of the troubleshooting procedure and involved a power on check of all modes or channels of the unit. This insured that the set was fully operational prior to it being returned to the customer.

The symbols used in Table 5.1 are listed below.

X - This symbol indicates that an action was observed on one or more occasions. Typically, most actions were not repeated, but if a repeat occurred, it generally did not exceed three repetitions. A blank space means that the action was not observed.

A - Information supplied by the customer, other than just a general statment of the symptom, figured prominantly in the troubleshooting procedure. The technicians reported that most customer information was not sufficiently detailed or precise to be of much use to them.

B - The technician removed and examined the fuse as part of his accumulation of symptom information.

C - Schematic diagrams and associated information published by the Howard W. Sams Comany were used. This company has a wide following in the electronics repair industry because of the detail, accuracy and applicability of their products.

D - Anchoring and adjustment were used, whereby the technician centered his activity on a suspect subsystem and then proceeded to check first it and then the adjacent subsystems until he had localized the problem.

E - Schematic diagrams were used, along with anchoring and adjustment.

F - Schematic diagrams and anchoring and adjustment were employed, along with the substitution of components known to be good.

G - Components known to be working correctly were substituted into the chassis or tubes were removed and their performance was verified on a tube checker.

H - Components were tapped, hit or wiggled to insure that they were not intermittently failing due to structural problems.

I - Components were heated or cooled in an effort to see if their operating characteristics were affected.

J - A combination of tapping, temperature modification and substitution were applied to one or more of the components.

K - A combination of tapping and temperature modification actions were applied to one or more components.

L - Schematic diagrams were used and a combination of tapping, temperature modification and adjustment were applied to one or more components.

M - Schematic diagrams were used, and a combination of temperature modification and substitution actions were applied to one or more components.

N - Schematic diagrams were used, and a combination of temperature modification, tapping and substitution actions were applied to one or more of the components.

O - Schematic diagrams were used, and substitution actions were applied to one or more of the components.

P - Schematic diagrams were used, and a combination of substitution and tapping actions were applied to one or more of the components.

Q - Tapping, temperature modification and before/after comparison actions were applied to one or more of the components.

R - Tapping and substitution actions were applied to one or more of the components.

S - The channel tuner was cleaned to correct a primary malfunction.

T - A diode was replaced in order to correct a primary malfunction.

U - A switch was replaced in order to correct a primary malfunction.

V - A fusistor or a fuse was replaced in order to correct a primary malfunction.

W - A flyback transformer or a focus divider was replaced in order to correct a primary malfunction.

Y - A circuit breaker was replaced in order to correct a primary malfunction.

Z - An alignment was performed in order to correct a primary malfunction.

V.5 Analysis of the Data

V.5.1 Introduction

The variables of interest here are the different actions employed by the technicians within each stage of troubleshooting. These actions are viewed as indicators of the heuristics which are being utilized. The actions for the forty experimental trials are summarized in Table 5.2. This summary reflects the number of trials in which a given type of action occurred, rather than tabulating the total number of times an action was evidenced. By approaching the data in this manner, each complete trial, or troubleshooting procedure, serves as the major point of emphasis, rather than the individual actions themselves. For example, the action, DC Voltage, was checked under the Fault Isolation Stage for trial number 3. This means that DC voltage measurements were taken at least once and possibly several times within the Fault Localization Stage during that particular trial. Checking the action, DC Voltage, conveys the fact that such a measurement figured in the troubleshooting procedure, while avoiding the slippery problem of trying to discern exactly how many times it was used. For instance, in one case the technician might first refer to a schematic and then make a series of DC voltage measurements, in another case he might be holding the probes in place while glancing back at the schematic to evaluate his reading, and in still another case he might be alternating probe placement and the reading of the schematic as he worked through a stage. In all of these cases, then, the relevant actions were the use of schematic diagrams and the measurement of DC voltages. The order and the frequency of these actions, while of interest, cannot be determined with any degree of objectivity. Further, such information would likely not provide any added insight beyond that already evident from the current approach.

Table 5.2 Action matrix summary, indicating the number of experimental trials in which the different heuristics within the various stages of troubleshooting were used.

STAGE / ACTION	TOTAL
S.A.S.	
Power	38
Front	26
Modes	14
External	15
Senses	40
Customer (A)	1
Fuse (B)	1
F.L.S.	
Half Split	0
Middle To	0
Out To In	0
In To Out	1
Senses	4
Schematics (C)	5
Anchor & Adjust (D)	8
Substitution (G)	1
Tap/Wiggle (H)	1
F.I.S.	
Signal/Pulse	6
DC Volts	21
Resistances	14
AC Volts	2
Senses	21
Schematics (C)	10
Substitution (G)	20
Tap/Wiggle (H)	15
Temperature (I)	5
C.R.S.	
Tube	12
Resistor	6
Capacitor	5
Connector	11
Coil	1
Transistor	6
Clean Tuner (S)	1
Diode (T)	2
Switch (U)	1
Fuse (V)	3
Transformer (W)	3
Breaker (Y)	2
Alignment (Z)	1

Table 5.2 also provides a finer breakdown than does Table 5.1. The latter shows combined actions for a particular trial, such as code K, the application of tapping and temperature modification actions to one or more components. The former separates out the individual actions for each trial and then shows the composite results over the forty trials. The result is that the actions labeled "Other" in the four stages are more precisely accounted for on an individual action basis. The codes shown next to some of the actions correspond to those used earlier with Table 5.1. Actions without codes next to them were defined previously.

As suggested by the nature of the data, the most appropriate method of analysis is to use frequency distributions to indicate the extent to which the various actions were observed within a given stage. The frequency of occurrence will be viewed as indicative of the strength of the different heuristics which motivate the observed actions. The strength of a heuristic will be defined as a predisposition to use it during a troubleshooting trial.

V.5.2 Analysis of the Symptom Accumulation Stage Data

The Symptom Accumulation Stage occurs when the technician takes action to determine the status of the various system outputs. The purpose of this stage is to provide him with information which will enable him to narrow down the problem to a subset of the various subsystems. Table 5.3 indicates the number of trials in which the various actions were evidenced. The order of the actions has been changed from that shown in Table 5.2 in order to reflect the frequency of occurrence for each action.

Table 5.3 Observed symptom accumulation stage actions.

ACTION	NUMBER OF TRIALS	PERCENT OF TRIALS
Use of Senses	40	100
Power to Chassis	38	95
Adjust Front Controls	26	65
Adjust Other Controls	15	38
Change Modes (Channels)	14	35
Use Customer Information	1	3
Check Fuse	1	3

V.5.2.1 Use of the Senses

The use of senses appeared in every one of the experimental trials. In all of these trials, there was clear evidence that the senses were being used in a purposeful manner. In a typical trial, the technicians would first visually scan the tubes as their filaments were lighting up. He was alert for tubes which didn't light up, suggesting an open filament if it was a single tube, a broken connection if it was several tubes, or a bad low voltge power supply if it was all of the tubes. He also watched for power tubes that glowed excessively, which indicated either an overvoltage condition or a short within the tube.

He next studied the picture. A horizontal line or a rolling picture isolated the problem to the vertical subsystem. A picture which was slanted to one side or the other indicated that the horizontal subsystem was at fault. If the picture was pulled in from the edges, or if no picture was present, the high voltage portion of the power supply subsystem was likely at fault. A picture which lacked sharpness and clarity pointed to the RF subsystem. When neither the picture nor the sound could be obtained, the mixer/oscillator subsystem was suspect, particularly if these symptoms were accompanied by a high pitched, audio oscillation and the screen displayed a pattern of rapidly moving lines.

Finally, the technician often checked components for evidence of discoloration, which would indicate that an overheated condition had occurred from excessive current being passed through them.

The technician also employed sound in accumulating symptom information. He listened for a crackling sound which indicated that high voltage was being applied to the picture tube. The technicians sometimes referred to this as the sound of bacon frying, since the sounds are very similar. If this sound were present, then high voltage on the order of 25,000 volts DC was being properly applied to the picture tube from the power supply subsystem. He also listened to insure that a normal sounding tone was present from the mixer/oscillator subsystem. If no sound was present, or if the tone was too high, then that subsystem was suspect. Arcing and sparking sounds also were helpful in pinpointing problem areas. One approach used was for the technician to disconnect the top cap on the high voltage tube and separate it from the anode slightly. He then applied power to the set and observed the arc. A strong arc indicated that the components feeding power to that tube were operating satisfactorily.

Smell was used to detect the presence of smoke from components which were overheating. While the overheating preceded the actual failure of the component, it often would cause the operating characteristics to change from those specified by the manufacturer.

Finally, touch was employed to gather information about the system. If components, particularly tubes, were cool to the touch, then it was apparent to the technician that they were not operating, in spite of the presence of filaments. He could then localize his efforts around that component. Touch was also used to identify defective fly back transformers in the high voltage subsystem. The technician would allow the set to run for a few minutes to get all components warmed to their operating temperatures. He would then disconnect the power and feel around the donut shaped transformer. The presence of hot spots on its surface indicated that internal arcing was taking place, resulting in a diminished output from the device.

From the comments of the technicians and from their actions, the use of senses was heavily relied upon in the accumulation of symptom information. While the same information could be obtained by using test equipment, they reported that it was easier, quicker and just as reliable to employ their senses to the fullest extent possible. Further, while the use of senses provided wide coverage of the system, it also gave high precision in a number of instances. These characteristics combined probably accounted for the frequency with which such actions were used.

V.5.2.2 Power Input Interface and Line Power

This action was used in all but two of the forty trials. One exception occurred when the technician visually noted a burned focus divider in the high voltage subsystem, just as he was about to plug in the power cord. The other exception occurred when the technician relied on the customer's description to isolate the problem to a defective connector. The customer had reported that the set, which was all solid state, worked fine for about fifteen minutes and then slowly faded out.

The intent of this action appeared to be one of insuring that power was being supplied to and distributed through the set. It was used in conjunction with the senses actions previously described, and it allowed the technician to be confident that he was using a known and reliable power source. This action gave wide coverage but very low precision.

V.5.2.3 Check and Adjust Front Panel Controls

These actions were used to build on the information obtained from the senses actions. This was particularly true if the problem appeared to be in the horizontal or vertical subsystems, as evidenced by the picture. The technician would note this and then generally vary the controls to see if any improvement or difference could be obtained. If the control varied the display, then the problem probably was in the chassis circuitry, while if the control had no effect, then it was suspect. As a result, such actions had a more narrow coverage, but they offered greater precision.

V.5.2.4 Try Different Modes

In the context of television receivers, this meant to try different channels. As with the previous action, this action was dependent on the information obtained through the senses actions. If the problem appeared to be related to the RF subsystem, the mixer/oscillator subsystem or the IF/AGC/detector subsystem, then this action was used. If, on the other hand, the problem appeared to lay in one of the other subsystems, this action would probably be bypassed. Since the television channel band is separated into a low band (channels 2 through 7) and a high band (channels 8 through 13), the technician could narrow the problem somewhat by contrasting the tuner's performance on the different bands. The result was again that of diminishing the coverage but increasing the precision.

V.5.2.5 Other Symptom Accumulation Stage Actions

The remaining two actions involved using the information supplied by the customer, and making a check of a specific component. Both of these were atypical of this stage. The technicians reported that customer information was generally too vague and ambiguous to be of much use to them. They preferred instead to view the set display themselves and draw their own conclusions. The check of a specific component (a fuse) was motivated by the technician's observation that no filament voltages were present. Each action occurred only once during the forty trials.

V.5.3 Analysis of the Fault Localization Stage Data

The Fault Localization Stage begins when the technician first starts to make internal checks and measurements of the system's performance at the chassis level. The purpose of this stage is to identify a specific subsystem upon which to concentrate the remainder of his efforts. It terminates when a single suspect subsystem has been identified.

The data indicated that the skilled technicians in this experimental setting almost totally bypassed the localizing stage. In fact, only ten of the forty trials contained actions which could be interpreted as localizing actions. The specifics of these ten trials are shown in Table 5.4.

Several reasons might account for the lack of observed actions which meet the definition of localizing actions. For one, past experience plays a key role in allowing the technician to quickly isolate on a particular subsystem. In certain cases, he reported that he remembered

Table 5.4 Observed fault localizing stage actions.

ACTIONS	NUMBER OF TRIALS	PERCENT OF TRIALS
Anchoring & Adjustment	8	20
Use of Schematics	5	13
Use of Senses	4	10
Input to Output	1	3
Tap/Wiggle	1	3
Substitution	1	3

a similar instance where the symptoms were similar, and suggested that a specific subsystem was at fault. An example would be a defective power supply subsystem which caused the picture to shrink or pull in from the edges. Closely related to this use of past experience is the diagnostic strength of the cues which affect the senses. Indeed, the technicians reported that most of the important information relative to resolving the problem was contained in the picture itself. By using the picture display, they saved both time and troubleshooting effort. In addition to viewing the picture, their senses also isolated many other problems down to the subsystem and component levels. When questioned, it was difficult for the technicians to attribute their localizing performance to one or the other of these two factors, prior experience or use of senses. They, instead, generally characterized it as a combination of the two. Since use of senses was the overt action displayed, it was used as the label for this combined action. The important point here, however, is that in three-fourths of the trials, use of the senses figured prominantly in permitting the technician to progress directly to a specific subsystem, rather than having to collect information and choose between two or more subsystems. The localizing actions which were used to decide between competing subsystems in the remaining one-fourth of the trials will be conridered next. In each of these trials, the technician verbally confirmed that he was attempting to pin the problem down from several choices to a specific subsystem.

In eight of the ten trials where localizing actions took place, anchoring and adjustment would most accurately describe the actions. The technician would initially focus on a single subsystem as an anchor. He then proceeded to first check it and then the electrically adjacent subsystems until he was satisfied that he had localized the problem. The technicians reported that they used different criteria for choosing their anchors. Some of these were hunches, accessibility, signal flow and random selection. Additional information which motivated their adjustments from the anchor point came from studying schematics, electrical measurements, use of the senses and their mental reasoning processes.

Schematic diagrams were used as localizing aids in five of the trials. Four of these five trials involved the combined use of schematics with anchoring and adjustment. In the fifth trial, only the schematic diagram was utilized, along with the technician's mental processes, to localize on a specific subsystem.

The next most frequently observed localizing action was the use of senses. These involved careful visual inspections in two of the trials, a combination of looking and listening in one trial, and the sense of smell in the fourth trial. These actions all took place after the Symptom Accumulation Stage had terminated and they were clearly confined to a subset of the total system.

The remaining actions were substitution of components, an input to output analysis, and tapping components. These were all one trial occurrences.

In general, when the localization stage was used, it was characterized by a lack of overt actions and an apparent high level of mental activity. During such periods, the technician volunteered very little insight into his reasoning processes, and interruptions by the observer seemed inappropriate.

V.5.4 Analysis of the Fault Isolation Stage Data

The Fault Isolation Stage begins when the technician has identified a single subsystem upon which to concentrate his actions for the remainder of the trial. The purpose of this stage is to identify the defective component or components. This stage terminates when the defective component has been identified. The observed actions which were used to isolate defective components are summarized in Table 5.5

Table 5.5 Observed fault isolating stage actions.

ACTION	NUMBER OF TRIALS	PERCENT OF TRIALS
Use of Senses	21	53
DC Voltage Measurements	21	53
Substitution/Tube Checks	20	50
Tap/Wiggle Components	15	38
Resistance Measurements	14	35
Use of Schematics	10	25
Signal/Pulse Measurements	6	15
Temperature Modification	5	13
AC Voltage Measurements	2	5

The use of senses figured in over half of the trials as a factor in isolating a defective component. Their use in direct diagnosis was discussed earlier, whereby a defective component was spotted in the Symptom Accumulation Stage (burned resistor, loose wire, etc.). If the technician reacted to these sensory cues from the Symptom Accumulation

Stage by immediately replacing the defective component, then those cues were not counted again under the Fault Isolation Stage. If, instead, he made additional checks in the subsystem in which the defective component that was generating the sensory cues was located, then those cues were counted in both the Symptom Accumulation Stage and the Fault Localization Stage.

Types of actions related to the senses which were observed in this stage included feeling components for the presence or absence of heat, listening for the sound of high voltage being fed to the picture tube or for the sound of the oscillator, and visually scanning the circuitry for components which were broken, burned or otherwise suspicious.

DC voltage measurements also figured in slighly over one-half of the trials. Several reasons might account for the apparent reliance on this type of measurement. The meters which are used to measure DC voltages are battery powered and require no external power source. Hence, they are convenient to use. Oscilloscopes and AC voltage meters both require external power sources and their mobility is limited. DC voltage measurements tend to be more stable and are typically closer to nominal values. Other measuring devices tend to have more inherent drift and are affected more by stray signals. Finally, the majority of the voltages within the set are rectified voltages. It is therefore possible to evaluate the performance of most components in a subsystem by checking such voltages exclusively.

Substitution of components known to be good and checking tube performance on a tube tester both accomplished the same end, that of eliminating a particular component from suspicion. This action was evidenced most often with plug in components (tubes, some transistors, module boards, etc.). It generally was not applied to hard wired components, except for capacitors. Since most manufacturers will socket those devices which are the weak links of the system, concentrating on such components is a prudent isolating approach. The order in which components were substituted or checked, other factors being about equal, was to start with devices that carried the most power and work toward those which carried the least power. Substitution and tube tests were very convenient from the standpoint of ease and speed.

The next most frequent type of action was that of tapping or wiggling components. The result was twofold. First, the electrical connection of the device with the rest of the system was verified. Second, the internal structure of the device was tested, without having to disassemble it. Components to which this type of action could apply are solder connections, tubes, wire bundles and circuit breakers. This type of action was also one which could be quickly and easily accomplished.

Resistance measurements were used to check resistors, capacitors, diodes and transistors. For the most part, these checks could be accomplished without removing the device from the circuit. Also, schematics provided by the Sams company, mentioned earlier, made it possible to trace resistance drops through a chassis, allowing one to isolate a short circuit. As with the previous actions, resistance measurements had the desirable characteristics of speed and ease.

Schematic diagrams were used in this stage as a means of checking parameter values and identifying probable defective components. These were usually employed after some or all of the above actions had failed to isolate the problem. Their relatively lower trial use percentage reflects the fact that they had to be retrieved from a file and that their use generally required a proportionally greater expenditure of time and effort than did the tests just discussed.

Signal and pulse measurements were obtained using an oscilloscope. Some of the drawbacks of this device were mentioned previously. Technicians typically resorted to it when working on circuit configurations with which they were unfamiliar. Once they understood the general behavior of such circuits, they often reverted back to one of the isolating actions described earlier.

Temperature modification was confined mostly to resistors and transistors. The effect of such action was to duplicate turn-on conditions (by cooling) after the set had been running for awhile, or to duplicate the operating temperature conditions of the enclosed cabinet (by heating) when the chassis was outside of the cabinet. This action was not generally resorted to early in the isolating process, since it was difficult to precisely control the amount of temperature variation. As most electrical components are temperature sensitive, a false conclusion could be drawn from the results of such actions.

AC voltage measurements were usually avoided. The drawbacks of this type of procedure were discussed above. Only two trials employed this type of isolating action.

In general, actions in this stage of troubleshooting were characterized by narrowing coverage and increasing precision. Those actions which were convenient from the standpoint of ease and speed were most heavily relied upon.

V.5.5 Analysis of Component Replacement Stage Data

The component replacement stage occurs after a defective component has been isolated and identified. This action, once it has been verified as solving the problem, terminates the troubleshooting procedure. The frequency of each replacement action is shown in Table 5.6. The totals there do not include components which were substituted for or checked on a tube checker and found to be good during the isolating stage. The totals do include those components which were discovered as being defective by substitution in the isolating stage, if they contributed to the primary problem. This approach avoids counting marginally satisfactory devices which were replaced as a preventive maintenance measure, as component replacement actions. Since most trials had multiple component failures, the percentages do not total to one hundred percent.

Table 5.6 Observed component replacement stage actions.

	NUMBER OF TRIALS	PERCENT OF TRIALS
Tube	12	30
Connector	11	28
Resistor	6	15
Transistor	6	15
Capacitor	5	13
Fuse/Fusistor	3	8
Transformer	3	8
Diode	2	5
Circuit Breaker	2	5
Coil	1	3
Switch	1	3
Clean Tuner	1	3
Alignment	1	3

The data shows that tubes led all components in replacement frequency. Tubes are socketed devices by virtue of their operating life characteristics, so that their standing relative to the other replaced components is not unexpected. Had it not been for the screening of sets by the company which estimated repairs, it is likely that more tube replacements would have been recorded. Also, do-it-yourself tube testers are widely available, which allows some degree of customer screening for tube malfunctions before the set is brought in for repair by the technician. These two factors likely held down the percentage of tube replacements.

With regard to the rest of the component replacement actions, connectors accounted for the next highest frequency of replacement. Connectors include both leads and solder joints. The remaining replacement frequencies do not appear to merit further discussion except for the last two. In these two trials, the components (channel tuner and oscillator) were returned to service by an action other than replacement. They were, however, the cause of the primary malfunction.

V.6 Discussion and Conclusions

V.6.1 The Troubleshooting Procedure

The results of this experiment confirm the staged nature of troubleshooting. These stages may be easily differentiated by keying on the actions of the technicians. Many researchers have hypothesized that such divisions exist, but little in the way of evidence of their usage, particularly by highly skilled technicians, has been cited.

An unexpected outcome was the usefulness of the information obtained from the Symptom Accumulation Stage. Because of this, the technician was able to immediately proceed to a specific subsystem in three out of every four trials. The problem insight obtained from the initial stage is most directly related to the action labeled use of the senses.

Earlier studies failed to identify such actions as a major contributor to the accumulation of symptom information. More than likely, this was due to the backgrounds of the majority of the subjects (technical school trainees) which were used. Experience, of course, plays a major role in knowing how one should use his senses, and the skilled technician combines these two dimensions in a highly effective manner. Simon has observed that the skilled chess player seems to see the right move. In the case of troubleshooting, the skilled technician seems to be able to sense the essence of the problem in a large number of cases.

The Fault Localization Stage, when observed, was difficult to analyze. This was probably because the technician himself was in a somewhat uncertain state as to what to do next. The most applicable description of his actions was that of anchoring and adjustment. He would focus on one of several competing subsystems, based on a hunch, signal flow, convenience or even random selection. He would then consider information from such sources as schematic diagrams, his senses, electrical measurements and his recollection of similar situations to adjust to the electrically adjacent subsystems. In this manner, he was able to localize to a single subsystem. Kahneman and Tversky suggested that anchoring and adjustment is a means by which humans ease the strain of integrating information, and indeed it describes the type of behavior which was most often observed during the localizing stage.

The more traditional approaches to localization (half split, input to output, etc.) were almost totally ignored by technicians in favor of anchoring and adjustment. Reasons for this probably relate to the origins of these more deliberate methods. In general, they were developed to train technicians in a technique of troubleshooting that left little to chance and which required very little background. The skilled technician appears to favor a less structured approach and to rely more on his experience and intuition.

The Fault Isolation Stage demonstrated that most of the isolating techniques used were accomplished with power applied to the chassis, and all components in place. An opposite extreme to this approach would be to completely disassemble the chassis and separately verify the performance of each component. The highest percentage of trials involving power off checks were associated with the action, resistance measurements, which was observed in about one-third of the trials. Even in these cases, many of the measurements were made with the components still wired into the chassis.

The isolating stage actions emphasized that the skilled technician favors actions which can be accomplished quickly and with ease. These are in the nature of use of the senses, component substitutions (if no soldering is involved), DC voltage checks, tapping or moving components, and resistance measurement actions. The technician seems to pattern his actions so as to glide smoothly through the isolation process, rather than getting bogged down at any one point. When he resorts to schematic diagrams, the oscilloscope or the AC volt meter, it is a signal that an interruption in this smooth process has occurred.

The Component Replacement Stage results were not unexpected. Tubes, which are high power, socketed devices, led all other relatively lower powered, hard wired components. Connectors were a close second to tubes. The technicians reported that certain chassis were known to have connector problems, due to the batch process and the design employed by that manufacturer. Also, there are considerably more connectors in the chassis than there are any of the other components, so the potential for connector failure is greater. The next three components (resistors, transistors and capacitors) all operate under power stress conditions, so it is anticipated that failures involving these would appear. None of the replacement actions for the remaining components were evidenced in more than ten percent of the trials.

In summary, the actions which were observed generally met the guidelines which were set forth earlier. They had the characteristics of being content free, as evidenced by the fact that schematic diagrams were used in only thirteen percent of the trials, with regard to localizing actions, and in only twenty-five percent of the trials, with regard to isolating actions. This suggests that the technician already was aware of most of the information he needed for the majority of his actions, rather than having to depend on external information sources. The actions dealt adaptively with all of the trial problems, the unexpected and the unstructured, in that they enabled the technicians to progress to a solution using a fairly set and standardized approach within each stage. In the accumulation stage, three of the actions were common to about two-thirds of the trials, the localization stage was bypassed in three-fourths of the trials, while in the isolation stage, three actions were common to over one-half of the trials. The actions were not universally applicable and the order in which they were used was dependent upon the problem, the equipment and the technician. Finally, the general trend was one of beginning with wide coverage and low precision and progressively narrowing the coverage and increasing the precision as each stage was completed.

V.6.2 Troubleshooting Heuristics

From the results of the trials, the heuristics which motivated the observed actions can be summarized. These heuristics are considered to apply primarily to the situation encountered in the experiment. Their order will be based on the frequencies which were tabulated earlier. The list will be truncated at the twenty percent level, as it seems clear that something which is used in less than one out of five trials is not much of an aid to the solution process.

Heuristics Associated with the Symptom Accumulation Stage

Use the senses - The senses of sight, hearing, touch and smell should be utilized to the maximum extent possible to detect unusual features about the components and circuitry.

Check power input interface and line power - Confirms that power is available and being supplied to the system.

Check and adjust front panel controls and indicators - This may be useful in ascertaining the status of some of the subsystems and of the controls themselves.

Check and adjust other external controls and indicators - This may be helpful in determining the status of the various subsystems and of the controls themselves.

Try different system modes - This may show whether the problem is system wide or unique only to one or more subsystems.

Heuristics Associated with the Fault Localization Stage

Anchoring and adjustment - A suspect subsystem is selected as an anchor point and then it and the electrically adjacent subsystems are checked until the problem is localized.

(Often the information obtained in the first stage will result in an immediate localization to a single subsystem.)

Heuristics Associated with the Fault Isolation Stage

Use the senses - The senses of sight, hearing, touch and smell should be utilized to the maximum extent possible to detect unusual features about the components and circuitry.

Check DC voltages - The presence or absence of these voltages are verified. Of particular interest would be the B+, pin, filament and bias voltages. This includes voltage checks of similar elements known to be good and comparison with readings across suspect elements.

Substitution of components and tube checks - Components known to be good are substituted for suspect components, or tubes are checked on a tube checker to verify their status.

Tap, wiggle or hit components - The internal mechanical structure of components is evaluated by these actions. Care should be exercised so as not to damage the components.

Check resistances - The measured resistances are compared with the values specified. The presence of short circuits may also be detected using this action.

Use schematic diagrams - Schematic diagrams are used to obtain parameters and signal flow information about the circuit.

Heuristics Associated with the Component Replacement Stage

Replace a tube.

Replace or resolder a connector.

As noted previously, there is no guarantee that these heuristics will result in a solution, but they will likely (in at least twenty percent of the trials) aid in finding a solution to a maintenance problem involving a television receiver.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

VI.1 Introduction

In this chapter a summary of the research performed during the course of this troubleshooting study is presented. Recommendations for future research are included to assist in identifying topics which would extend the current research effort.

VI.2 Summary

The general theme of this research is individual problem solving. The specific instance of problem solving studied was that of electronics troubleshooting. The research is comprised of four related areas, which are outlined below.

The first area consisted of a review and summarization of the relevant literature on individual problem solving, mental coding, heuristics and electronics troubleshooting. The results of this review indicated general agreement on the part of earlier researchers as to the staged nature of electronics troubleshooting, as well as some of the general characteristics of such stages.

The second area outlined a theoretical description for a problem solving process model. Such a model serves as a link between mathematical models which employ a scalar or vector approach and process models, which are action centered. The mathematical tool used was tensor analysis, which does not require dimensional linearity or orthogonality, yet still provides a means of modeling decision surfaces in n-space.

The third area involved an experiment designed to investigate a specific aspect of electronics troubleshooting, that of mentally encoding information from a schematic diagram of an electrical circuit, under two experimental conditions. One of the experimental conditions was that of perception, in which the technician could refer back to the schematic diagram he was encoding as often as he wished. The other experimental condition was that of memory, in which the technician was allowed only a twelve second view of the schematic for encoding purposes. The encoding abilities of technicians from three different skill groups were analyzed, using ten representative schematics, and assuming thirteen possible composite relationships between successively coded circuit elements. The results showed that it is possible to differentiate between highly skilled and lesser skilled technicians using the following criteria.

Chunking Capacity - The number of chunks encoded. A chunk is a group of two or more elements which are mentally encoded, where the time interval between the reconstruction of any two successive elements in the group is less than two seconds. In general, highly skilled technicians have a higher chunking capacity than do lesser skilled technicians.

Chunking Sophistication - The complexity of the composite encoding relationship between two successive elements in a chunk. It was demonstrated that highly skilled technicians utilize more elaborate composite encoding relationships, on the average, than do lesser skilled technicians.

Composite Relationship Preferences - This analysis indicated the extent to which the thirteen possible composite encoding relationships were being utilized by the technicians, as compared with the utilization based on chance alone (random selection of successive elements). The composite relationships which were favored and those which were avoided were identified.

Impression - This was defined as the first element preferences exhibited by technicians in the course of encoding the schematics. There was general agreement on which elements of the different circuits were initially keyed upon during the trials. Of particular interest were the findings that, for the circuits used in this study, most first elements were encoded as part of a chunk, most were branch rather than loop elements, most were exterior rather than interior elements, most were passive rather than active elements (although active elements were chosen as initial elements more often than chance alone would suggest), and from a spatial standpoint, most first elements were located in the top left quadrant of the paper upon which the schematic was drawn. Finally, a comparison of chunking sophistication for initial elements versus all elements suggested that skilled technicians establish their superiority along this dimension over the long run, rather than initially, during the process of encoding circuit schematic information.

The forth and final area was an experiment which identified the heuristics, as evidenced by the actions of the technicians, which figured most prominantly in the specific troubleshooting situation under investigation, that of repairing defective television receivers. A heuristic is a mental rule of thumb which may aid in solving a problem, but which doesn't guarantee a solution, as would an algorithm. An action oriented approach was used for this experiment, rather than an introspective one, so as to minimize interference with the technicians during the troubleshooting process. A four stage model of troubleshooting, as suggested by the literature, was assumed. The four stages, the Symptom Accumulation Stage, the Fault Localization Stage, the Fault Isolation Stage, and the Component Replacement Stage, each contain heuristics appropriate to that particular stage. Two professional electronics technicians participated in twenty troubleshooting trials each. Their actions during the course of these trials were summarized as an action matrix. This matrix indicated composite usage patterns of the different heuristics. The composite patterns were then broken down into individual heuristics within each stage. Each stage was then analyzed separately. The Symptom Accumulation Stage was characterized by highly insightful information cues which were gathered primarily through the senses. The Fault Localization Stage was bypassed in almost three-fourths of the trials, because the information from the Symptom Accumulation Stage had already facilitated an isolation to a particular module or component. In instances where fault localization was employed, normative approaches (half split, input to output, etc.) were avoided in favor of an approach characterized by anchoring and adjustment. The Fault Isolation Stage was characterized by quick, simple checks involving either D.C. voltage or resistance measurements. For the most part, checks which could be made with the components still wired into the circuit were preferred over checks which necessitated removal of a component. The Component Replacement Stage involved the replacement of defective tubes and connectors for the most part, and resistors, transistors and capacitors to a lesser extent. Based on these findings, a program was developed for the four stages, outlining the most utilized heuristics in each stage.

From a macroscopic viewpoint, the review of the literature in Chapter II laid the foundation for viewing electronics troubleshooting as a succession of stages which focus progressively on symptom accumulation, fault localization, fault isolation, and component replacement. Within each of these four stages, heuristics aid the technician in determining that information, from the total amount available, which is relevant to finding a solution to the troubleshooting problem at hand.

The mathematical approach outlined in Chapter III provided a means of describing each stage of troubleshooting as a problem model subspace of the general problem space. Here, node 1 would correspond to the Symptom Accumulation Stage, node 2 to the Fault Localization Stage, node 3 to the Fault Isolation Stage, and node 4 to the Component Replacement Stage. The dimensions at each problem model subspace node relate to the different heuristics within each of the troubleshooting stages. Such a model is adaptable to subspace dimensions which are characterized by non-linearity and non-orthogonality, as well as those which are linear and orthogonal.

The encoding of information from schematic diagrams of electrical circuits was considered in detail in Chapter IV. Prior experience and previously accumulated knowledge contribute significantly to enabling the experienced technician to solve typical or routine problems without resorting to the use of technical reference materials, such as schematic diagrams. In these cases, it is assumed that the necessary and relevant problem information has previously been mentally coded and is available to the reasoning processes of the technician. When, however, additional information is required from technical reference materials, as is often the case with atypical or difficult problems, the technician must encode such information using a standardized format. Once the information is in a format which is compatible with his thought and reasoning processes, it may then be used in structuring and evaluating the different dimensions (heuristics) of the problem model subspace.

Finally, the heuristics used by skilled technicians in each of the troubleshooting stages were examined in Chapter V. The relationship of the stages and the heuristics to the nodes and dimensions of the problem model subspaces has been discussed.

The heuristics were identified by an analysis of the actions displayed by the technicians, rather than by introspective analysis. The principal result of this experiment was a summary, based on frequency of occurrence, of the heuristics employed by skilled, professional electronics technicians while working in an operational troubleshooting situation.

VI.3 Recommended Future Research

A number of areas for further study are clearly available. They are:

1. Single out the few exceptional troubleshooters from within the highest skill group and analyze their coding techniques. At the seven skill level, some technicians begin to branch toward maintenance management, while others continue to specialize exclusively in maintenance. No attempt was made to separate maintenance managers from maintenance specialists in Experiment I.

2. Experiment I could be replicated using only graduates of civilian electronics technical schools, as opposed to the military electronics technical school graduates which were used in Experiment I. Perhaps the type of school influences the coding mechanisms which are developed by the technicians.

3. Problem solving stages and heuristics used in other occupations could be investigated. Two areas where some work has been accomplished are those of financial analyst and manager of a functional area.

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APPENDIX A

EXPERIMENT I SUBJECT ORDER, INSTRUCTIONS AND ENVIRONMENTAL DATA

A.1 Subject Order for Experiment I

Complete information as to the order of task and schematic diagram presentations to subjects by session number is indicated by the chart on page 243.

A.2 Instructions for Experiment I

Instructions provided to each subject prior to them performing the perception and memory tasks are shown on page 244. The practice schematic used by the technicians is shown on page 245.

A.3 Environmental Data for Experiment I

The environmental conditions under which this experiment took place are summarized below.

Temperature: Ranged from 64°F. in the mornings to 74°F. in the afternoons.

Lighting: Varied from 500 foot condles to 600 foot candles in order to provide sufficient illumination for video tape recording.

Background Noise: Typical values were between 53 and 68 decibels on the various scales (A Linear Fast, A, B, and C).

Figure A.1

Order of Task/Schematic
Presentations to Subjects by Session

Skill Level-Tech. Code	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6
3-1	P(3,6,8,5)	M(3,6,1)	M(8,5,4)	P(9,7,2)	M(2,9,10,7)	P(4,1,10)
3-2	P(3,8,1,2,4)	M(9,7,4,2,8)	M(3,1)	P(7,5,6)	M(10,5,6)	P(10,9)
3-3	M(2,8,7,1)	M(3,5,9,4)	P(5,2,3,6)	P(9,7,4)	M(6,10)	P(10,8,1)
3-4	M(10,9,3,8)	P(5,2)	P(8,9,4,1)	M(1,5,6)	M(7,4,8,2)	P(6,7,10,3)
3-5	M(2,4,8,3)	P(3,2,1,8)	M(10,1,5)	M(6,9,7)	P(10,6)	P(9,4,5,7)
5-1	M(9,10)	P(10,2,6,9,7)	M(6,4,5,2,8)	P(3)	P(8,5,4,1)	M(1,7,3)
5-2	M(4,10)	P(2,9,8)	P(4,10,3)	M(3,2,1,6)	P(6,1,7,5)	M(5,7,9,8)
5-3	P(7,4,6,3,2)	P(8,1,5)	M(9,7,1,10)	M(4,5,8)	P(9,10)	M(3,6,2)
5-4	P(5,2)	P(8,10,9,1,3)	M(8,5,4)	M(1,10,3,7)	P(6,7,4)	M(6,2,9)
5-5	P(5,3,9)	M(5,7,1,8)	M(2,9)	P(7,4,1)	P(2,8,6,10)	M(3,10,6,4)
7-1	P(7,1)	M(3,8,4,1)	P(6,8,10,2,3)	P(9,4,5)	M(6,7,10)	M(5,9,2)
7-2	P(9,1,4,5)	M(1,3,7,8)	P(6,2,7)	M(6,10)	M(9,4,5,2)	P(8,3,10)
7-3	P(5,10,3,1)	M(6,8)	P(6,2)	M(3,1,4,2,5)	M(9,10,7)	P(9,8,4,7)
7-4	M(8,10)	M(6,4,9,1)	P(1,10)	P(4,7,5)	M(3,2,7,5)	P(6,8,3,2,9)
7-5	M(6,3,5)	M(4,1,2,7)	P(2,9,8,5)	P(1,4,3,10)	M(8,9,10)	P(6,7)

Key: Left hand column refers to skill level of the technician followed by the particular technician's code.
In the body of the table, the P refers to the Perception Task, while the M refers to the Memory Task.
The numbers in parentheses refer to the schematics, by schematic code number (see Appendix B), which were redrawn during the indicated session.
As an example, using the upper left entry for technician 3-1 during session 1, the entry reads P(3,6,8,5). This states that technician 3-1 redrew schematics number 3,6,8 and 5 under the conditions of the Perception Task during session 1.

INSTRUCTIONS

Do you wear glasses? Are you right handed or left handed? Please have a seat.

This is a maintenance study dealing with schematic diagrams. In this session you will be asked to look at a series of schematics. For each one, you will be asked to redraw it as accurately and as quickly as possible. In order to collect the data for this study, we will be videotaping the redrawing process.

I want to emphasize two important points. First, please work at a pace which will allow you to complete the drawings accurately, while taking no more time than is necessary. Second, once you begin to redraw a schematic, please complete it before asking any questions. Do you have any questions at this time?

This first folder will be a practice run to familarize you with the procedure. Please redraw the page in the folder on the plain sheet of paper which is provided. We ask that you leave the sheets attached to the folder as they are, and simply flip the cover back and forth to refer to one or the other.

PERCEPTION

In this task, you may refer back to the schematic which you are trying to redraw as often as you wish. To refer back, simply flip back the top cover. At my signal you may begin. Continue working until you are finished. Again, you may flip the cover as often as you wish.

MEMORY

In this task, you will be asked to redraw the schematic after viewing it for a period of 12 seconds. At my signal, open the flip top and look at the schematic. At my next signal, close the cover and redraw as much of the schematic as you can remember. Again, do not open the folder once the viewing period is over.

When you are finished, lay your pencil down on top of the folder.

Please don't discuss any of the details of this session with your coworkers. Thank you.

Figure A.2

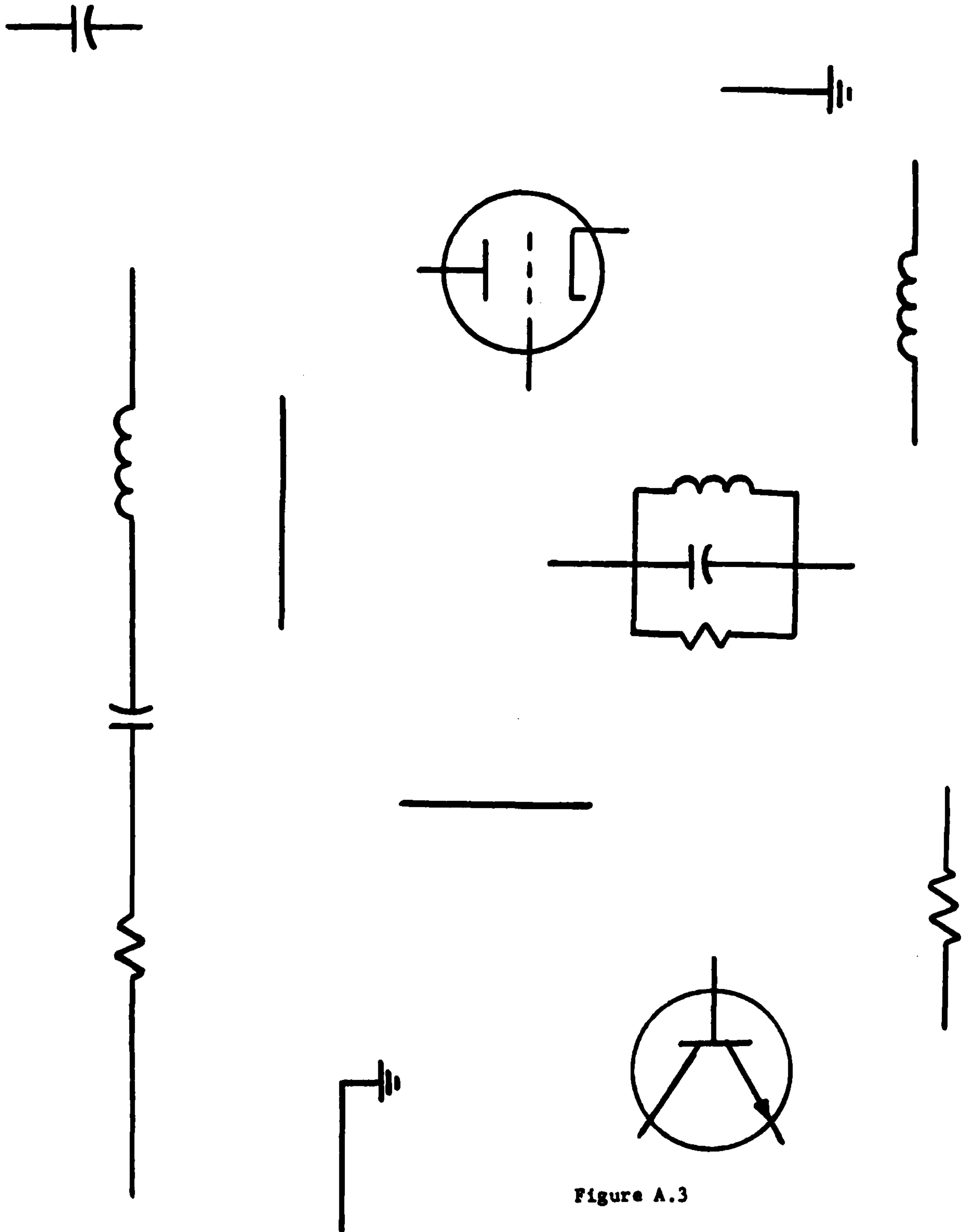

Figure A.3

Experiment I Practice Schematic

APPENDIX B

CIRCUIT SCHEMATIC DIAGRAMS

The following pages depict the circuit schematics used in Experiment I. During the perception, memory and impression tasks, only the diagram was viewed by the technicians. In the figures which follow, however, additional information is provided for the convenience of the reader, as to the nature of the circuit, the source of the diagram, the circuit element code numbers and the page quadrant numbers.

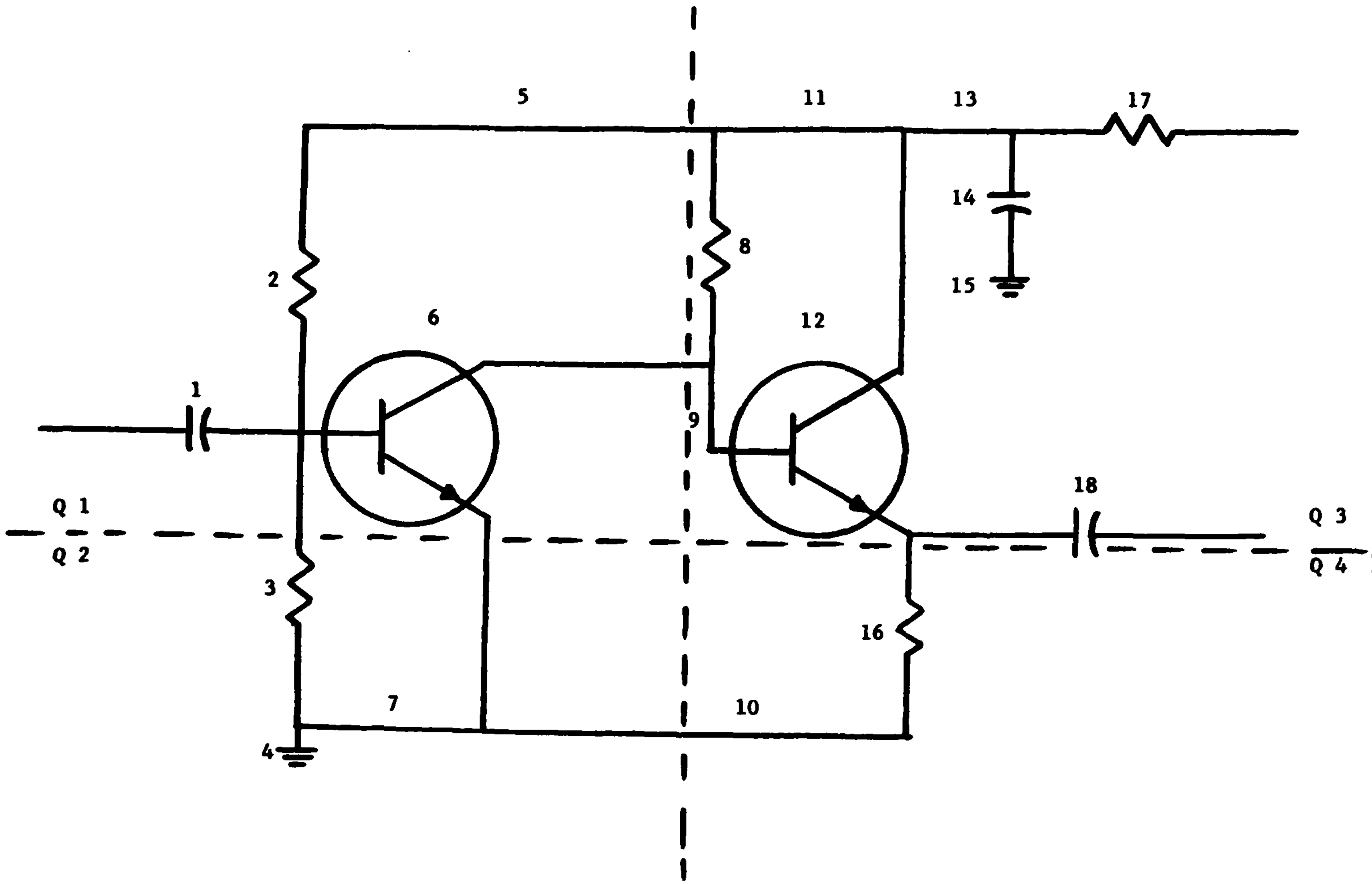

Figure B.1 **Hi gain, broad band amplifier.** **N = 18 Total Elements**

Source: **<u>Circuits, Devices, and Systems</u>**
Ralph J. Smith, 1966.

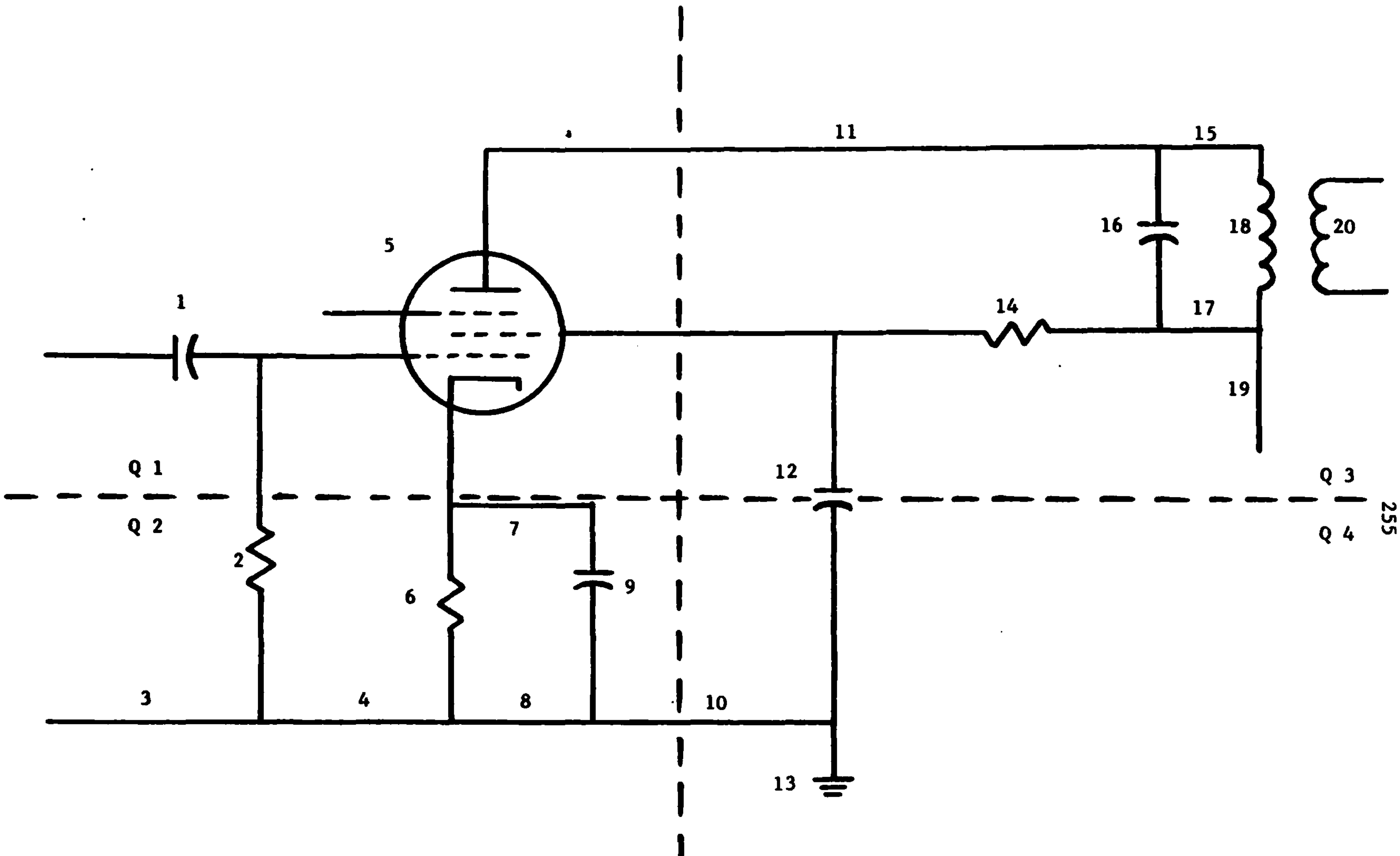

Figure B.2 Audio power amplifier. N = 20 Total Elements

Source: Handbook of Preferred Circuits
National Bureau of Standards, 1955.

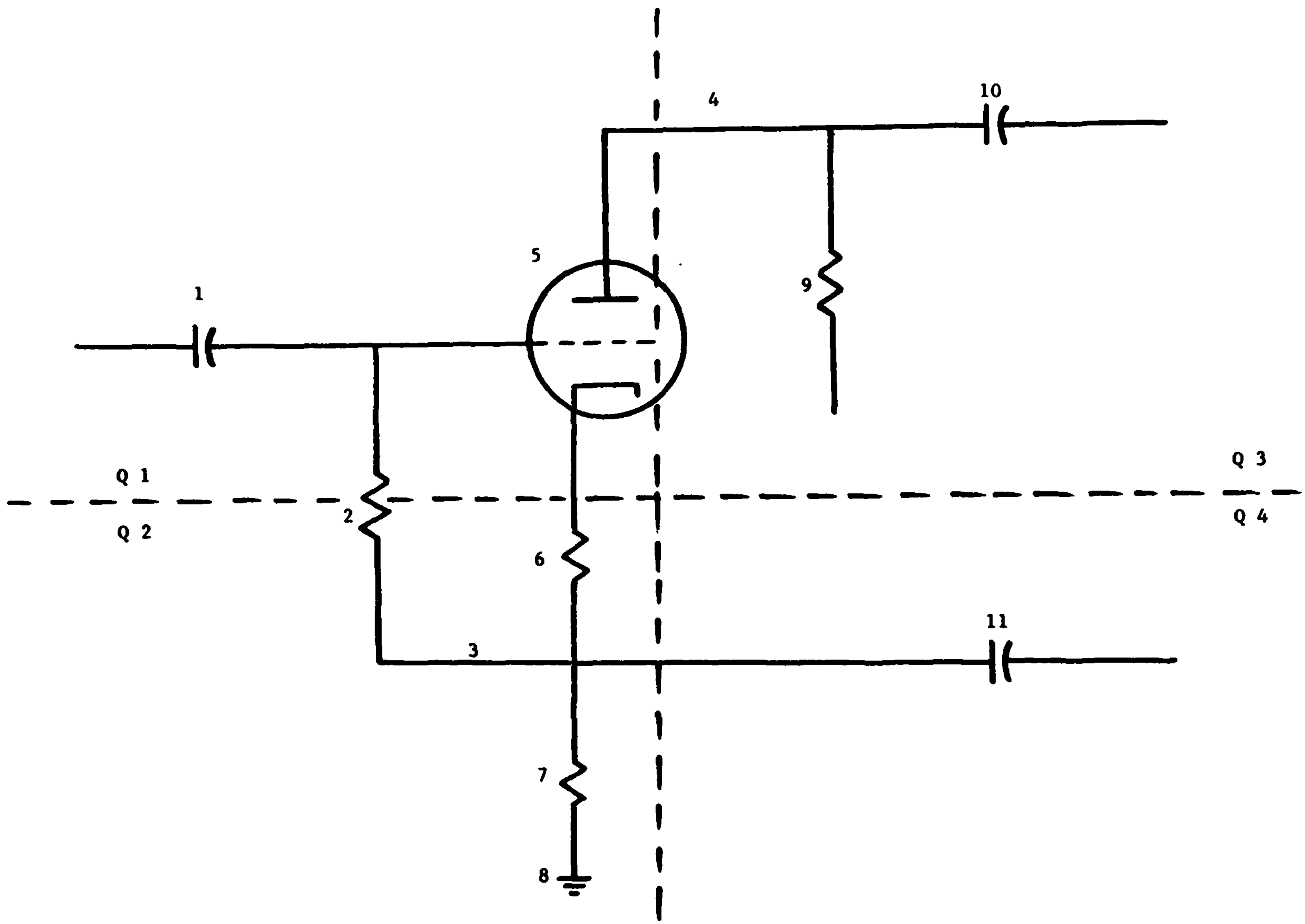

Figure B.3 Para-phase amplifier. N = 11 Total Elements

Source: <u>Handbook of Electronic Circuits</u>
Howard W. Sams Co., 1968.

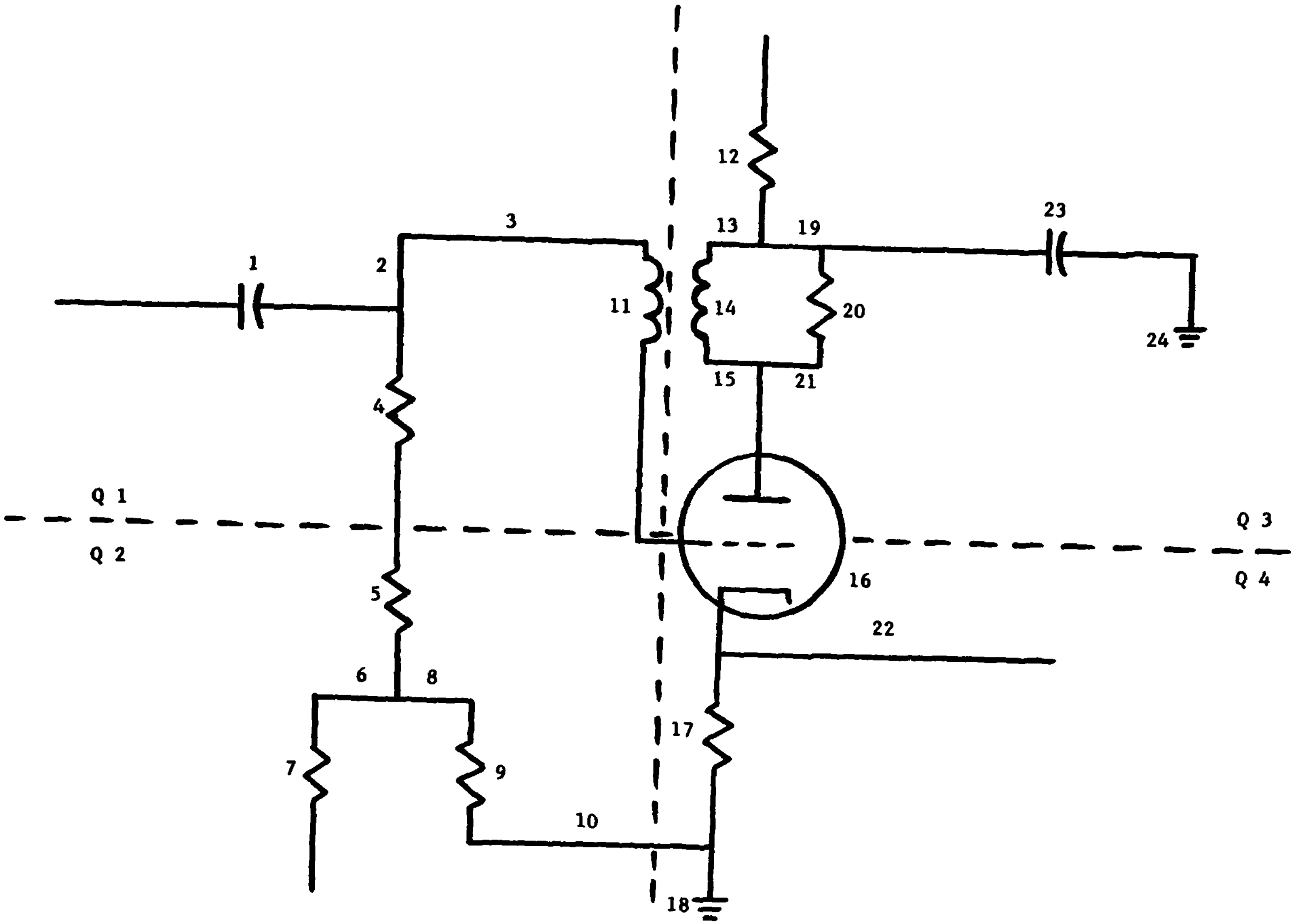

Figure B.4 Blocking oscillator.

N = 24 Total Elements

Source: Handbook of Preferred Circuits
National Bureau of Standards, 1955.

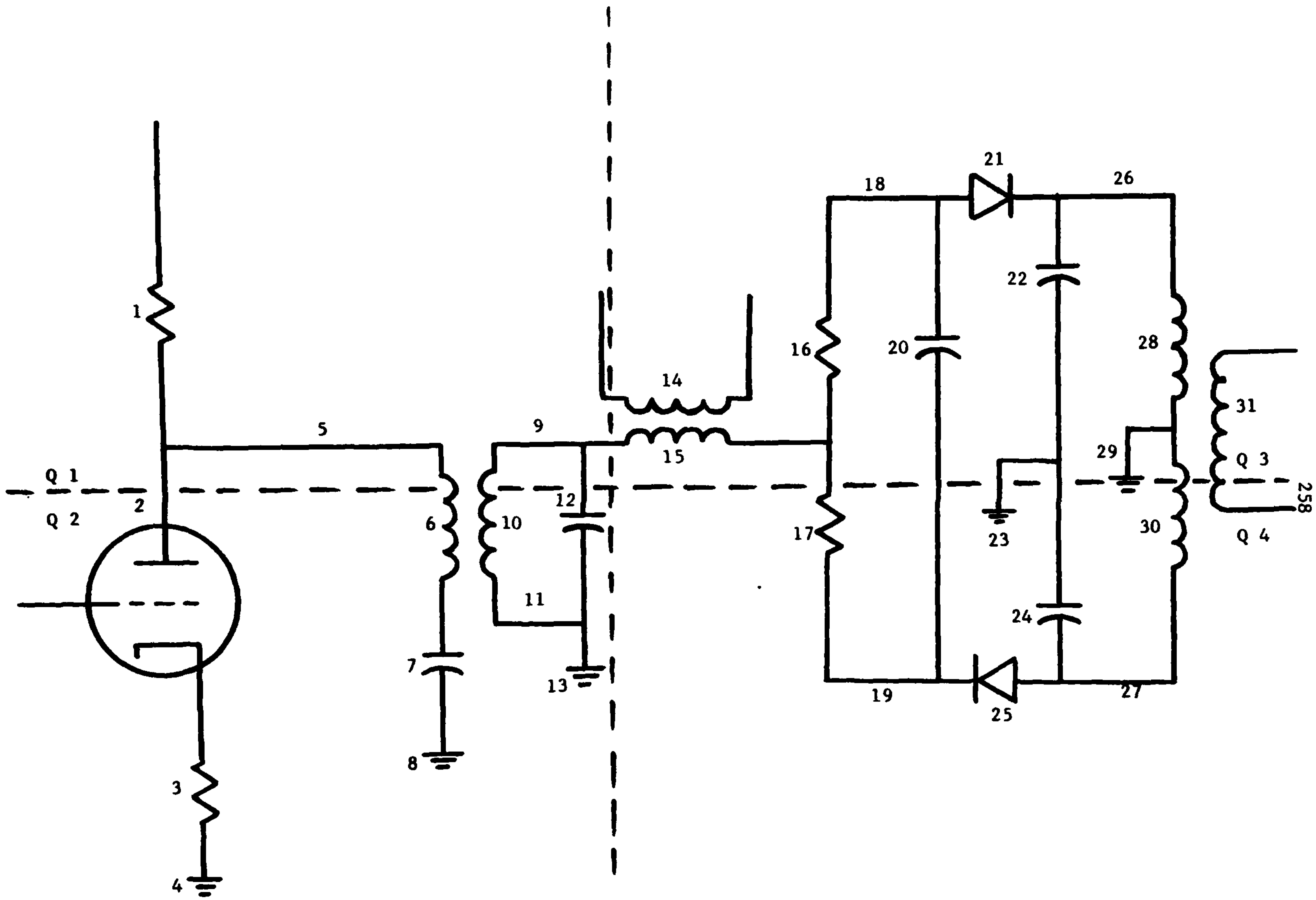

Figure B.5 Balanced modulator.

N = 31 Total Elements

Source: <u>ARRL Handbook</u>
American Radio Relay League, 1958.

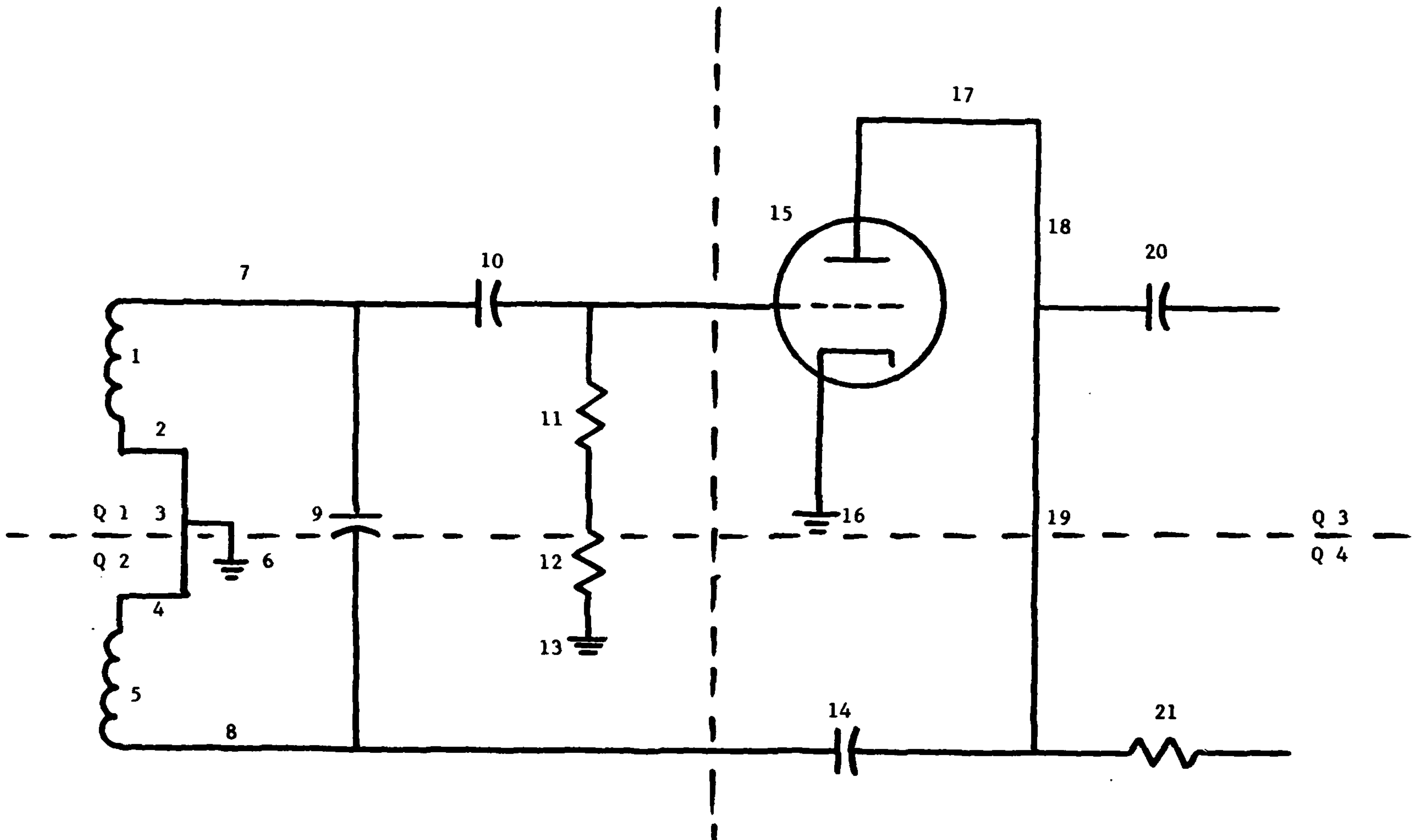

Figure B.6 Blocking oscillator.

N = 21 Total Elements

Source: <u>Handbook of Electronic Circuits</u>
Howard W. Sams Co., 1968.

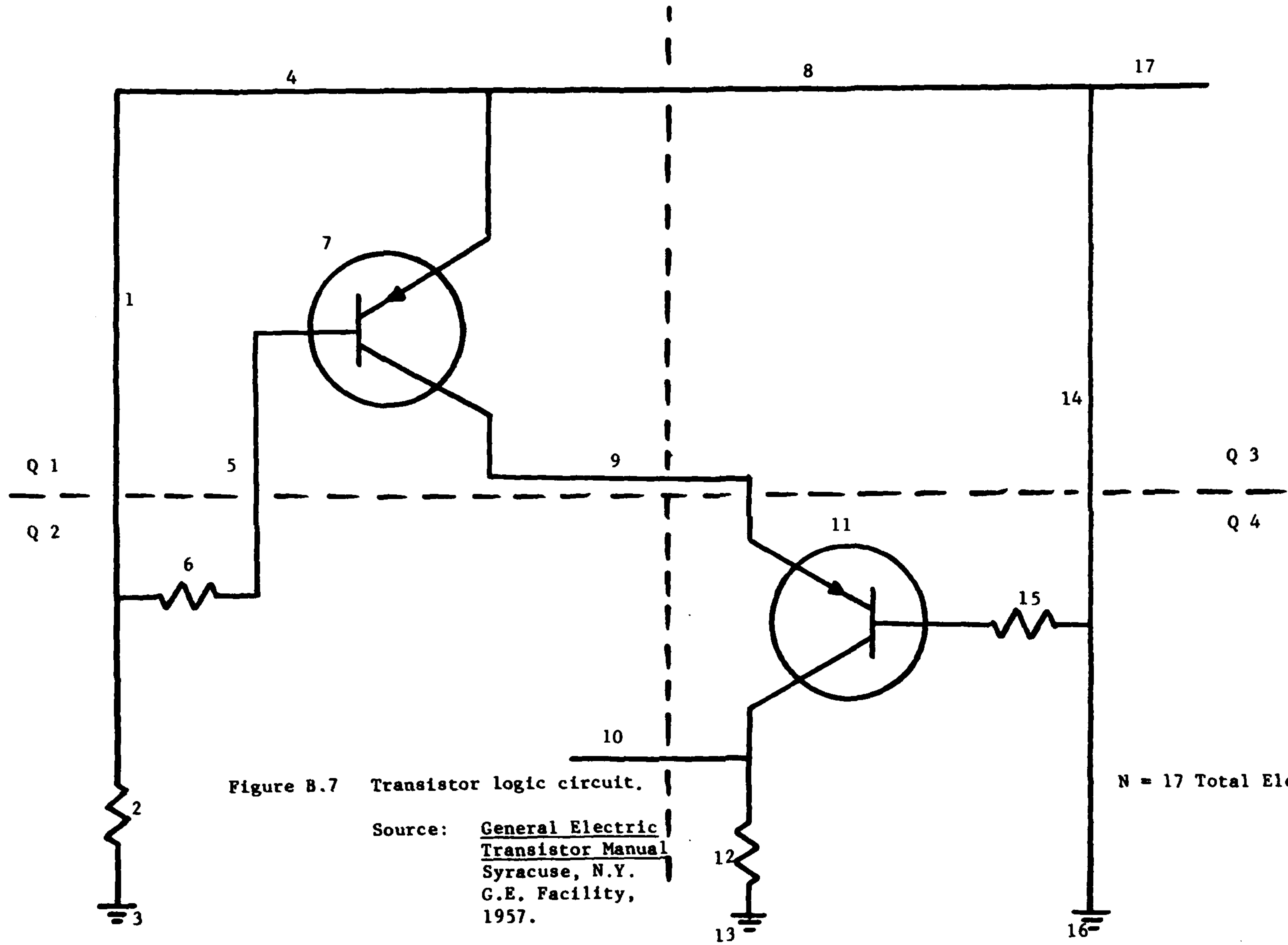

Figure B.7 Transistor logic circuit.

Source: <u>General Electric Transistor Manual</u>
Syracuse, N.Y.
G.E. Facility,
1957.

N = 17 Total Elements

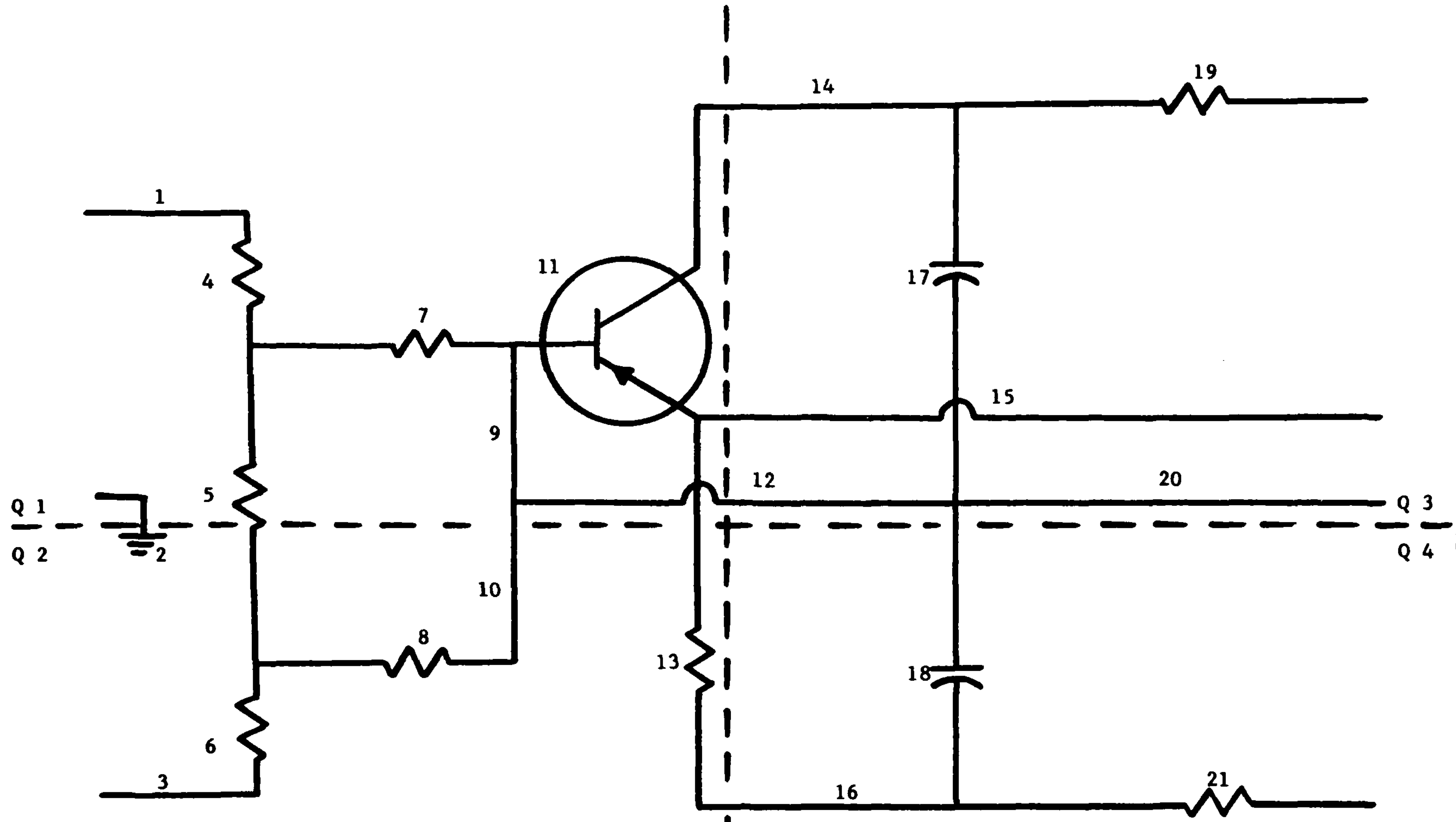

Figure B.8 Adder network.

N = 21 Total Elements

Source: <u>Circuits</u>
Applied Science Handbook, 1966.

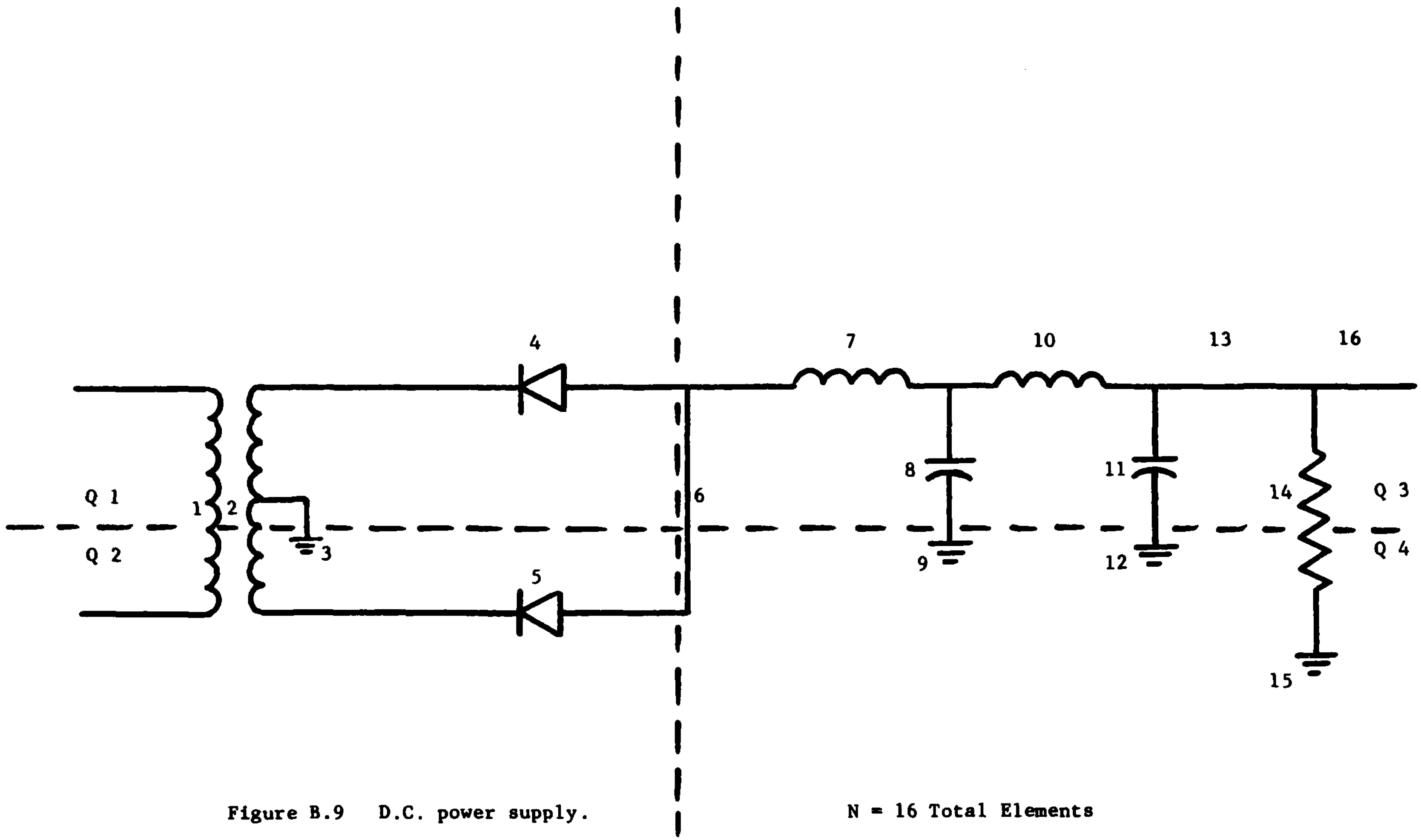

Figure B.9 D.C. power supply.

N = 16 Total Elements

Source: <u>Circuits, Devices, and Systems</u>
Ralph J. Smith, 1966.

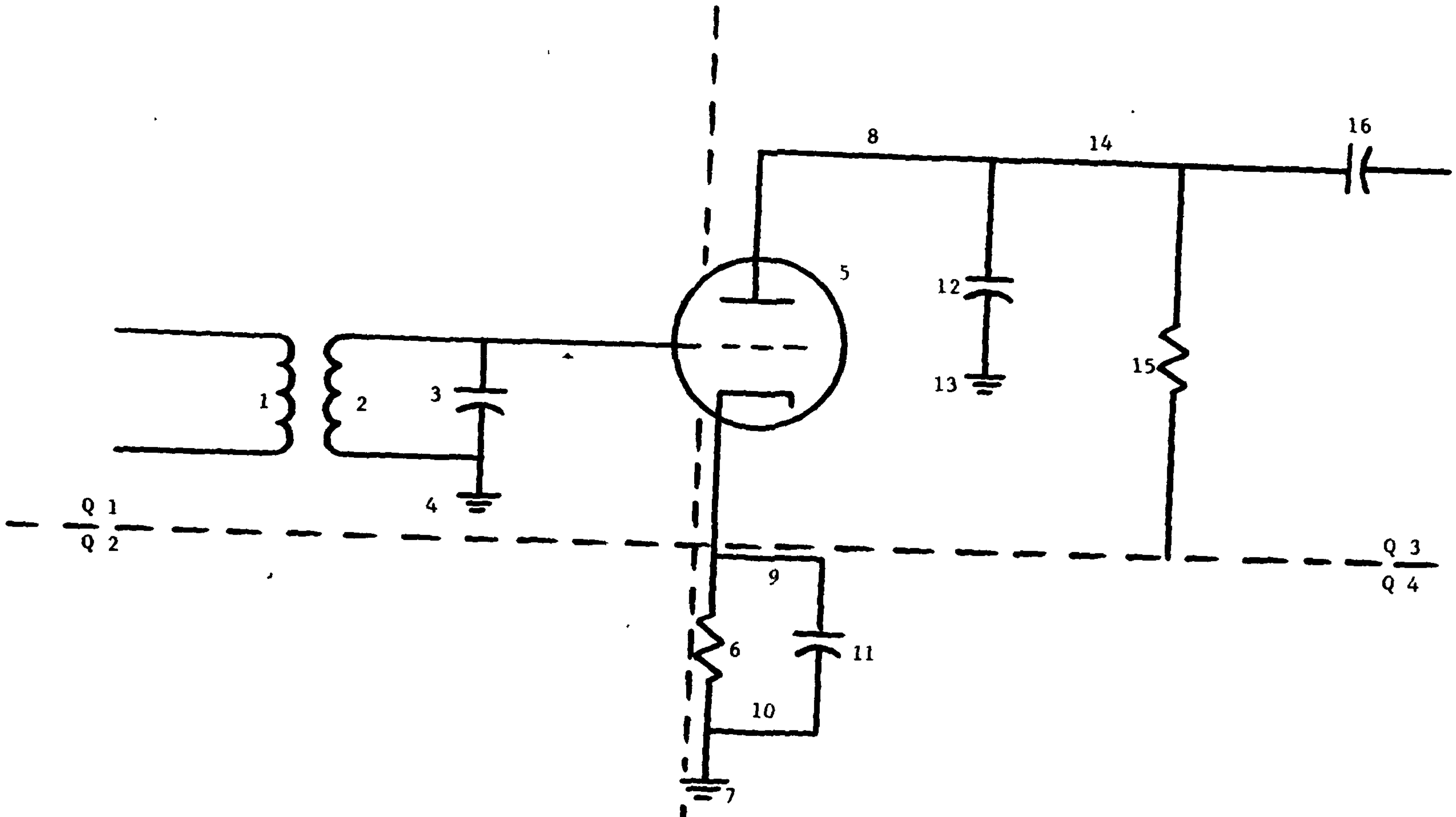

Figure B.10 Plate detector circuit

N = 16 Total Elements

Source: Handbook of Electronic Circuits
Howard W. Sams Co., 1968.

END

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