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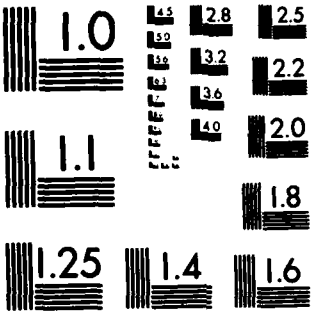

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MENTAL REPRESENTATION OF CIRCUIT DIAGRAMS: INDIVIDUAL DIFFERENCES IN PROCEDURAL KNOWLEDGE

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This work is concerned with the knowledge that electronics technicians possess of electronic equipment, and more generally, with how people operate in tasks that draw upon a complex spatial symbolic knowledge base. A technician's knowledge base is postulated to consist of three types of related knowledge: (1) structural/functional knowledge, which pertains to the actual configuration of a circuit and the role that its components play in the operation of the device; (2) prototypical knowledge, which pertains to the

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general properties common to circuits of a given type; and (b) procedural knowledge, which pertains to the way that a circuit can be modified and to the interaction among knowledge elements of all three types of knowledge. A previous report documented a study of individual differences in structural knowledge; the present report focuses on an experiment conducted to investigate individual differences in procedural knowledge. Novice and expert subjects performed tasks in which they had to either locate and correct an error in a circuit, change the function of a circuit, or complete a missing segment in a circuit. On all tasks, experts were found to be far more accurate than novices; but more important, experts were classified -- on the basis of verbal protocols -- to be considerably more systematic, orderly and directed in their problem solving strategies. The productive procedures used by experts were then translated into specific guidelines toward improving circuit troubleshooting, and the effectiveness of these guidelines will be evaluated in a subsequent experiment. The results of this research program should help in providing guidelines for training electronic technicians to better understand and troubleshoot complex equipment.

ABSTRACT

This work is concerned with the knowledge that electronics technicians possess of electronic equipment, and more generally, with how people operate in tasks that draw upon a complex spatial symbolic knowledge base. A technician's knowledge base is postulated to consist of three types of related knowledge: (a) structural/functional knowledge, which pertains to the actual configuration of a circuit and the role that its components play in the operation of the device; (b) prototypical knowledge, which pertains to the general properties common to circuits of a given type; and (c) procedural knowledge, which pertains to the way that a circuit can be modified and to the interaction among knowledge elements of all three types of knowledge. A previous report documented a study of individual differences in structural knowledge; the present report focuses on an experiment conducted to investigate individual differences in procedural knowledge. Novice and expert subjects performed tasks in which they had to either locate and correct an error in a circuit, change the function of a circuit, or complete a missing segment in a circuit. On all tasks, experts were found to be far more accurate than novices; but more important, experts were classified -- on the basis of verbal protocols -- to be considerably more systematic, orderly and directed in their problem solving strategies. The productive procedures used by experts were then translated into specific guidelines toward improving circuit troubleshooting, and the effectiveness of these guidelines will be evaluated in a subsequent experiment. The results of this research program should help in providing guidelines for training electronic techniques to better understand and troubleshoot complex equipment.

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1. INTRODUCTION

1.1 Summary

This report describes the second year of a three-year program of research devoted to understanding the knowledge base required of experienced technicians to troubleshoot complex electronic equipment. The primary objectives of this program are to (1) describe the mental representations of electronic devices that technicians derive from schematic circuit diagrams, and (2) characterize the ways in which technicians apply these mental representations to trouble-shooting and problem solving. In the first year, we largely accomplished the first objective with a macro-experiment designed to assess the structural/functional knowledge of electronic devices possessed by technicians varying in skill level. Observed performance differences include errors in characteristic places in the circuits and global differences in the structure and organization of the knowledge base.

It was our view that these differences, which are primarily the knowledge of facts about the circuit, were not sufficient to explain the differences in skill between technicians nor are they probably the most interesting for investigation. In particular, they do not address the way that the circuit knowledge is used. One could train novices on the memorization of circuit diagrams until they made few errors in retention, but they would not become experts through this training. Practical tasks require more than static comprehension of a device. The knowledge base is valuable only to the extent that its holder can operate upon it. It was our hypothesis that the increased proficiency of technicians derived through experience is due to the acquisition of more sophisticated procedural knowledge, not simply to the development of a more complex static knowledge base. Accordingly, in the second year, we concentrated on the study of procedural knowledge, with the information gained during the first year providing the necessary background.

The third year of work will focus on an integration and summation of the experiments performed during the first two years. This effort will include an experiment toward the development and validation of guidelines for comprehending circuits, building circuits, and troubleshooting.

1.2 Program Overview

1.2.1 Objectives. Major objectives of the program include the following:

(1) Describe the mental representation of electronic devices that technicians derive from schematic circuit diagrams.
(2) Characterize the procedural knowledge that technicians apply to the mental representation to perform troubleshooting and problem solving.
(3) Characterize the knowledge structures that differentiate among technicians of different skill levels.
(4) Validate the findings of the descriptive studies by means of hypothetico-deductive experimentation.

Three-Year Program. The research tasks targeted for the three-year program are as follows:

(1) First-Year: Exploration of structural and functional knowledge. Develop stimulus material pool. Perform several studies with electronic technicians varying in skill level to assess the structural/functional knowledge they possess of electronic devices as represented by circuit diagrams.

(2) Second-Year: Investigation of Procedural Knowledge. Conduct descriptive studies and hypothesis testing experiments to assess the procedural procedural knowledge that is brought to bear on solving problems with circuit diagrams by both novice and more proficient electronics technicians.

(3) Third-Year: Integration and Summation of Studies Performed During First Two Years. Develop and validate guidelines for comprehending circuits, building circuits, and trouble-shooting. This will include an experiment suggested by the findings from the first two years.

1.3 Overview of the Technical Approach

An overview of the technical approach for the program is shown in Figure 1-1. Work in the first year began with Task 1, the development of a pool of stimulus circuit diagram materials for use in all of the subsequent work. In Task 2, a macro-experiment was conducted to reveal the structural/functional knowledge possessed by electronic technicians varying in level of expertise. The tasks studied in the first year were a memory task and a component-partitioning task.

In the second year, Task 3 investigated the procedural knowledge that technicians apply to the structural/functional representation of electronic devices. Three separate circuit-based tasks were studied in the second year: an error correction task, an alteration task, and a completion task.

Work in the third year will focus mainly on the interplay between the structural/functional knowledge and the procedural knowledge, but also on the development of guidelines for interacting with circuits.

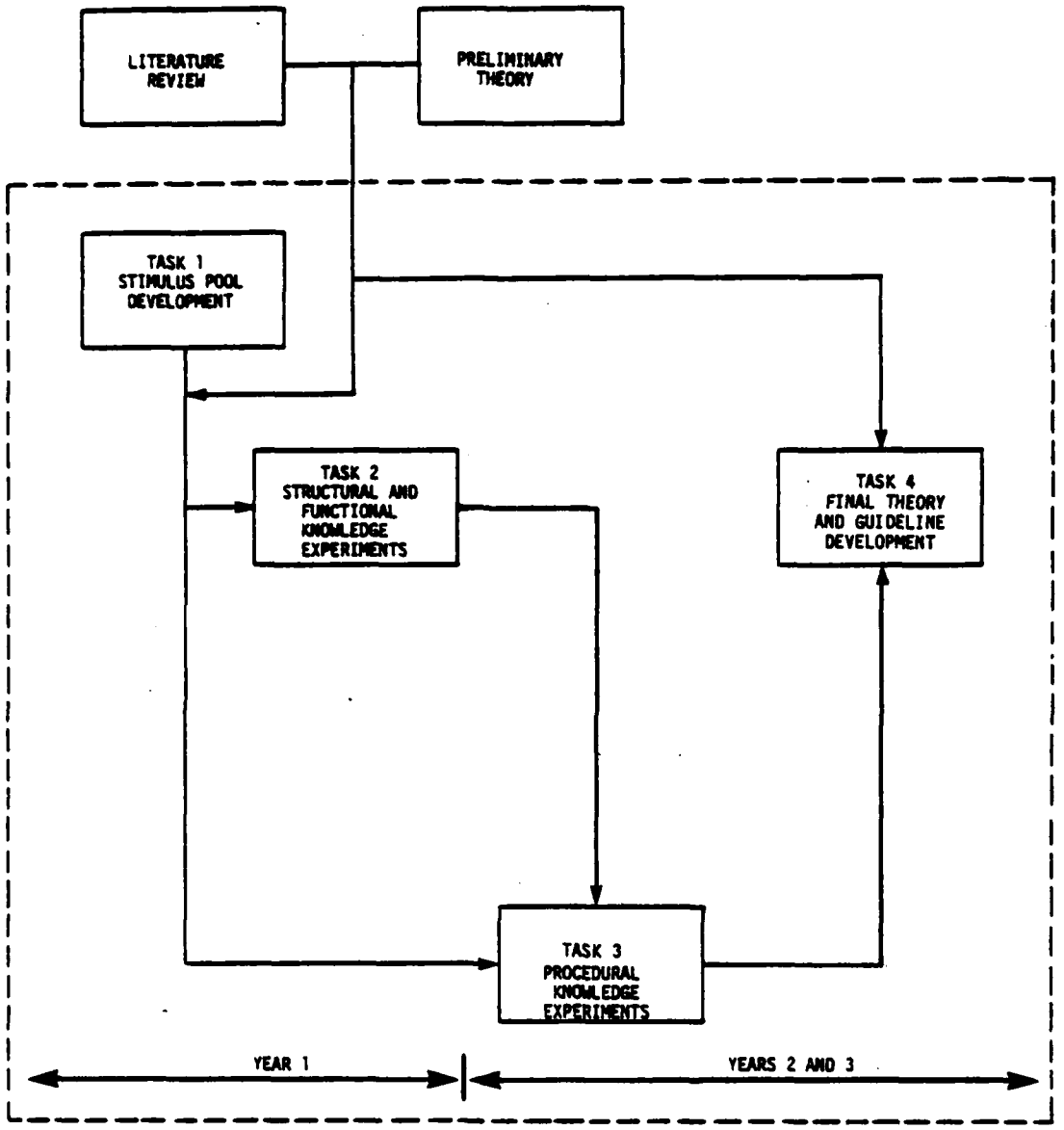

FIGURE 1-1.
OVERVIEW OF EXPERIMENTAL PROGRAM

2. RESEARCH BACKGROUND

2.1 Overview

The performance of complex tasks such as maintaining mechanical equipment, modifying and adapting computer programs, and troubleshooting sophisticated electronic devices requires highly skilled personnel. All such tasks require these personnel to have a detailed understanding of the devices that are being repaired and maintained. Thus, an understanding of how people mentally represent complex devices is necessary to train such personnel and to develop optimal man-machine interfaces that such personnel can use.

It is commonly accepted that the training of personnel to troubleshoot electronic circuits has been less than successful. In a review of the status of troubleshooting in the military services, Bond and Towne (1979) state:

> *The main conclusion of this report...(is that) troubleshooting of very complex systems is difficult for numerous reasons, but the critical factor is that the technician's cognitive map of essential physical relations (electronic, hydraulic, electro-mechanical, and so on) in complex equipment is often incomplete, vague, or incorrect. As long as this is so, any series of checks and test readings, though apparently well motivated and accomplished, cannot 'close in' logically on a faulty unit. (pp. 5-6)*

The premise underlying the present program of research is that training programs are less successful than they could be because they fail to provide troubleshooters with the knowledge required to develop a sufficiently rich conceptual structure of the equipment they are working with. Accordingly, in this research we propose to study the nature of the knowledge base that is necessary to repair and maintain complex electronic devices.

This chapter presents a rationale for the work that will be undertaken. Its purpose is to establish an underlying theoretical framework for the research and to clarify our particular choice of research direction. Section 2.2 discusses the knowledge base required for complex problem solving. Section 2.3 discusses the nature of the mental representation of complex equipment in relation to contemporary theories of long-term memory and the representation of spatial information. Section 2.4 discusses relevant research pertaining to the nature of the mental representation possessed by novice and expert problem solvers. Section 2.5 presents the theoretical perspective that we have adopted for the conduct of the proposed research.

2.2 Knowledge Base and Complex Problem Solving

Troubleshooting entails the isolation and repair of malfunctioning components in a device and, as such, is a form of problem solving. It may be analyzed in terms of problem solving theories (see, e.g., Greeno, 1978, for a review). However, we do not intend to focus exclusively on this aspect of the troubleshooting question. Presumably, the problem-solving procedures operate on a substrate of knowledge, which includes a mental representation, of a device. This underlying structure must be clarified before problem-solving theories can be applied.

Although much attention has been devoted to the study of the procedure people use in problem-solving, less attention has been paid to the study of the knowledge substrate required to solve complex problems. For example, the commonly studied problems (Tower of Hanoi, Missionaries and Cannibals, etc.) require a very limited information base. We feel that, in part, what characterizes good problem solvers from poor ones resides in the knowledge base they bring to problem solving tasks rather than mere differences in their problem solving strategies.

While this position may seem to be uncontroversial, it is instructive to note that much research has been performed that presupposes a very impoverished mental representation on the part of the problem solver. For example, troubleshooting is sometimes viewed as a decision making activity where the troubleshooter's task is to iteratively select and test system components to determine whether they are faulty (e.g., Freedy & Crooks, 1975; Rouse, 1978). From this perspective, the troubleshooter must decide which system component, among many, to test on a given iteration. Some have suggested (e.g., Bond & Towne, 1979; Rouse, 1978) that an optimal strategy to use is a procedure which eliminates half the number of components on each test cycle. To be implemented, a strategy such as this one merely requires the troubleshooter to have a list of system components in his mind. Unfortunately, it is not clear what should be on this list, nor how it is organized. It is here that the real novice-expert differences lie.

We feel that to successfully repair complex equipment, a troubleshooter requires several types of knowledge. First, factual knowledge of the equipment is required. For example, troubleshooters must know that most electronic devices have a power supply. Second, procedural knowledge is needed. Sometimes, such knowledge is quite specific; for example, "To determine whether a capacitor is faulty, take a reading of the voltage at point x. If the voltage departs significantly from value y, the capacitor is faulty." Other procedural knowledge is much more general, as in a set of procedures for identifying what may be wrong when no power is delivered to a device. Third, the troubleshooter requires a mental representation of the faulty device, of its components and their interrelationships to each other. The basis for this representational knowledge is provided by schematic drawings of the equipment. However, the availability of schematic drawings does not mean that the troubleshooter understands the device.

2.3 Nature of the Mental Representation

It is apparent that an expert's mental representation of a complex device is not isomorphic to a schematic drawing of the device. In fact, it contains much more information. (See Brown, Collins, & Harris, 1978 for a similar point of view.) For example, an expert readily can identify functional units within a circuit that are not directly present in the diagram. So the first step is to model the latent knowledge and the cognitive mechanisms that allow the expert to develop an enriched mental representation from a schematic drawing.

Contemporary psychological theorizing provides several approaches to this problem. One approach is to view the mental representation of spatial information in terms of connected networks (Anderson, 1976; Anderson & Bower, 1973; Collins & Loftus, 1975; Norman & Rumelhart, 1975; Schank, 1972). According to such a structural model, individual circuit components are represented by nodes in the network and the interrelationships among components form links between the nodes. Although representations of this sort can be constructured so as to mirror closely the circuit diagrams, they also permit the use of abstract nodes to represent the hierarchical relationship among functional groupings of components. Most of the work with these models has been done in building and testing theories of the organization of long-term memory and thus has been outside the context of problem-solving tasks. An exception is the work of Bhaskar and Simon (1977) who have undertaken an analysis of the structure of long-term memory used by students solving problems in a college-level course in chemical-engineering thermodynamics.

A second approach is to view the internal representation as a second-order isomorphism between an external object and some corresponding representational process with the brain (Shepard, 1978). According to

this view, the relations among imagined objects mirror to some extent the functional relations among the same objects as actually perceived. Studies based on this view (e.g., Cooper, 1975; Kosslyn, 1975; Shepard, 1978) have emphasized the close relationship between the physical nature of material and the chronometric properties of the response. Because of the spatial nature of circuit diagrams, isomorphic representation such as these can plan an important role in any model.

A third approach to the representation of knowledge is procedural. In such a view, what is known is not the static properties of a circuit diagram but ways of operating on it. A worker may know how to modify a power supply to better filter its output, with this information taking the form of procedures for altering the circuit rather than a compendium of facts about supply filters. Because of its active representation, procedural knowledge has found most use in simulation models (e.g., Winograd, 1972) and problem solving (Newell & Simon, 1972). Some models (e.g., Anderson, 1976) have incorporated both procedural and other forms of representation.

deKleer (1979) and deKleer and Brown (1980) have described, from an artificial intelligence point of view, some of the procedural strategies that are required to analyze the operation of a circuit. In particular, they emphasize the need for multiple procedural strategies. For example, deKleer (1979) hypothesizes that people use topological, functional, and geometric representations. In topological analysis, the topology of a new circuit is compared to that of previously recognized circuits; in functional analysis, the behavior of the overall circuit is determined by combining the behavior of the individual components; and geometric analysis relies on the tacit graphical language engineers use when they describe circuit topologies on paper. These representations are used to analyze circuits in terms of its "teleology." Similarly, Stevens and Collins (1980) argue that people maintain multiple representations of physical systems such as of the rainfall process.

2.4 Comparing Novices to Experts

The previous research most relevant to understanding how people represent complex equipment from schematic drawings comes from research comparing the performance of experts to that of novices. Most research in this area has indicated that experts differ from novices more in perceptual memorial abilities than in logical, problem-solving abilities. If it were simply the case that experts know most about the task than the novices, there would be little to be gained from constructing an elaborate representation of the task. However, this seems not to be so. Experts seem to have representations that differ qualitatively from those of novices. Studies supporting this position are becoming common.

Work by deGroot (1966), Chase and Simon (1973), and Simon and Chase (1973), comparing the performance of Master and weaker chess players, indicates that Masters do not "see" ahead further than the weaker players. Instead, the Masters are superior to weaker players in their ability to perform tasks involving the recall of actual chess positions. The superior performance of Masters in these tasks cannot be attributed to a generally superior visual short-term memory capacity of the Masters because when chess pieces are placed randomly on the board, recall is equally poor for Masters and weak players.

Egan and Schwartz (1979) demonstrated that expert electronic troubleshooters have a richer mental representation of circuit information than novice troubleshooters. For example, expert electronic troubleshooters are better able to remember circuit diagram information than are novice troubleshooters, and in reconstruction, the experts recalled the diagrams in groupings of functional units. The skilled technician's advantage in this task did not hold for non-meaningfully arranged symbols.

Badre (1979) has found similar results for the recall of battlefield situation displays. Military experts show a marked advantage over novices for plausible situation displays but not for randomly arranged positions. Furthermore, military experts recall battlefield units on the basis of their functional relationship to each other.

These results hold for other spatial tasks such as the recall of GO positions (Reitman, 1976) and have also been extended to other non-spatial tasks such as for the recall of computer programs (Reitman, McKeithen, Reuter, & Hirtle, 1979) and the solution of physics problems (Chi, Feltovich, & Glaser, 1979; Larkin, 1979; Larkin, McDermott, Simon, & Simon, 1980).

The most influential theoretical explanation of these data is that experts perceive spatial stimuli by coding the stimuli into groups consisting of several elements or chunks. In one version of this theory (Simon & Gilmartin, 1973), the chunks have verbal labels that can be retained in short-term memory and decoded at the time of recall. It is argued that experts quickly represent an entire spatial representation in a relatively small number of chunk labels and that these labels can be used to reconstruct the spatial representation. Pauses between successively recalled elements, the estimated size and number of chunks, and the correspondence of recall groupings in copying tasks support this hypothesis.

The data are in good agreement with the semi-hierarchical theory of the mental representation of complex equipment that we propose in the following section (indeed, were part of the motivation for our model). Moreover, our theory provides a mechanism to account for Egan and Schwartz's (1969) observation that experts can quickly label a circuit diagram as belonging to a given class (e.g., "some sort of power supply").

In sum, we do not feel that the understanding of skilled performance in tasks such as circuit analysis is possible without considering multiple domains of knowledge. All are necessary to explain the richness of an

expert troubleshooter's mental constructs, and our ultimate model must incorporate elements of each. In particular, we believe that the difference between experts and novices lies as much or more in the ability of experts to draw from a larger collection of operations -- or procedural knowledge -- than in an understanding of the structural and functional nature of the parts of the task or in the reference to prototypes. Much previous work has ignored the dynamic, procedural aspects in favor of more static conceptions of the tasks. The following section presents our theoretical position in more detail.

2.5 Theoretical Perspective

As one reviews the literature on the mental representation of tasks or stimuli, one is struck with the extent to which the derived representations are well matched to the task. This suggests to use that the subject is able to adopt a mental representation that is closely concordant with local processing demands. The true mental representation must have latent in it a variety of possible forms and structures. This observation dictates one fundamental principle behind the experiments that we present here: any analysis of the mental characteristic of a domain of knowledge must derive from a variety of tasks and must posit a variety of individual representations.

We start by making a distinction between two ways of classifying the content of a knowledge structure. The first refers to the substantive content of the representation, to what facts it describes; the second to the way in which the information relates to the subjects' knowledge base. Both of these viewpoints can be further subdivided as is discussed below. We emphasize that this is not a dichotomy in the knowledge itself -- a particular piece of information does not belong to one or the other -- but rather two aspects of the same mental structure, both of which must be treated in order to fully comprehend the information processing abilities of a subject.

Content. The content of the mental representation is composed of a number of interrelated and overlapping structures. These structures may be hierarchical in form (although this is not crucial). The hierarchical character arises from the tendency to view portions of the device as units, without examining their fine structure unless necessary. For example, one may think of a logic-circuit component as a flip-flop, without analyzing it further unless forced to do so. This hierarchical tendency has been supported in modern integrated circuits by the physical modularization of rather complex functions in single chips or modules; in computers, for example, CPUs, interface units (e.g., UARTs), and fairly extensive memory drivers may appear as single units.

The overlapping nature of the representation comes from the fact that a particular component participates in several organizations at once. In some computer designs, for example, the circuit representing the fourth bit of an accumulator may logically be analyzed as part of that accumulator, or may be considered as part of the array of fourth bits over a series of registers such as the accumulator, program converter, etc. (It is interesting that both forms of organization are reflected in the physical design of different computers.) As a more prosaic example, an electric fuel pump in an automobile participates in both the electrical and the fuel system of the car. Presumably all of these overlapping organizations are accessible to the subject which is employed at a particular time depending on the dictates of the task. The processing demands that the subject places on the mental representation enables one form or the other.

We feel that the cognitive representation of information given in a circuit diagram may be usefully described as a set of parallel networks. In part, these networks have a hierarchical structure, in that the terminal nodes represent individual circuit components (resistors, capacitors, etc.), the intermediate nodes represent either functional units (rectifiers,

amplifiers, etc.), or physically proximal collections of components, and the highest nodes represent the total circuit (a power supply, an inverter, etc.).

Nature of the Knowledge. The second scheme of organization relates to the way that the information is used. Particular tasks use knowledge in different ways. Although the range of possible uses probably forms a complex and multidimensional space, a good case can be made for classifying knowledge about a complicated mechanism (such as a circuit diagram) into three general classes:

(1) Structural and functional knowledge deals with the way that a device in constructed and the role that its parts play in the operation. One may know, for example, that a transformer serves to change the voltage of an AC supply, that a particular combination of transitors acts as a flip-flop, and so forth. Fundamantally, this knowledge is static; it describes the way that the device works.

(2) Prototypical Knowledge relates one device to more general prototypes. Devices are not understood in isolation, but are related to other devices. For example, experienced technicians are able to quickly recognize that several difficult circuit diagrams represent the same class of device. This suggests a set of procedures that force the constituent elements of a circuit diagram into prototypical configurations. One portion of a circuit is a rectifier, another a Schmitt trigger, etc. Two processes seem to be involved. First, some form of bottom-up mechanism simplifies the representation of the diagram by replacing groups of nodes with a single node. Second, a top-down mechanism attempts to fill in

missing nodes in partially matched prototypes. This knowledge is rarely in the form of an exact parallel between real devices, but relates the operation of any device to an abstracted prototype. This prototypical knowledge reduces greatly the burden of the structural and functional facts.

(3) Procedural knowledge gives ways to manipulate the device. Many tasks require more than a static comprehension of a device, demanding that some modification be made of some operation performed on it. The knowledge necessary to do this is different from the other two types, embodying a series of procedures (algorithmic or heuristic) for changing the device. Procedural knowledge is the most complex of the three, and draws heavily on the others.

We feel that training programs fail because the mental representation is unobservable, and consequently it is difficult to determine whether the troubleshooter has developed an adequate representation. Moreover, it is not clear how such a representation is attained. However we do know that with experience, troubleshooters become more proficient at their job. Presumably, increased proficiency derived through experience is due to a more developed mental representation knowledge base.

Our goal is to obtain a better understanding of the knowledge base that skilled troubleshooters bring to bear in complex equipment. Of the three types of knowledge that we have discussed, procedural knowledge is the most difficult to study, for it is the most abstract, and depends on the structural/functional knowledge for its operation. But it is also the most important, because knowledge is valuable only to the extent that it lets its possessor manipulate equipment. Thus, the first-year work on structional/functional knowledge provided the necessary background to understand procedural knowledge in the second year of work.

We note that at this point we have described a general theoretical position, but not the specific models that instantiate it (for this distinction, see Wickens, 1982, Chapter I). Specific models for these processes could be formulated using a number of conventional representations such as production systems.

3. REVIEW OF FIRST-YEAR WORK: INVESTIGATION OF STRUCTURAL/FUNCTIONAL KNOWLEDGE

3.1 Overview

Reviews of the literature on the mental representation of tasks or stimuli reveal that the derived representations are surprisingly well matched to the task. This suggests that a person is able to adopt a mental representation that is closely concordant with local processing demands. The true mental representation must have a variety of possible forms and structures—that are latent in that representation. Consequently, any analysis of the mental characteristics of a domain of knowledge must derive from a variety of tasks ans must posit a variety of individual representations. Also, the understanding of skilled performance in tasks such as circuit analysis requires consideration of multiple domains of knowledge. That is, different domains are necessary to explain the richness of an expert troubleshooter's mental constructs, and a comprehensive model must incorporate elements of each domain.

The experiment conducted during the first year was designed to assess the structural and functional knowledge of electronic devices possessed by technicians varying in skill level. This work provided the necessary background for the investigation of procedural knowledge as related to electronic trouble-shooting. The experiment performed was a composite of a circuit-reconstruction task and a circuit-partitioning task.

The principal finding evident from the data was the large degree of variability in the performance among the subjects on the reconstruction and cluster-generating tasks, and the extent of overlap between the different ability groups on those tasks. These data stand in contrast to the relatively large differences between skill levels that appeared in the time and error measures with respect to overall performance. Even if a large

sample could provide statistically significant differences between skill levels, the size of the effect as a proportion of variability would probably not be very great. Thus, the investigation of structural/functional knowledge was not the most productive place for further research effort.

Identifiable differences in the organization of a diagram during learning and recall do not appear to be the most sensitive loci of proficiency differences. For reasonably simple and well-learned material, the physical properties of the diagram layout may dominate performance. It is conceivable that differences could appear between subjects of different proficiency levels, with the less proficient subjects being more bound by the physical construction of the target circuit, and the more proficient subjects being more bound by the logical construction. In conventionally well-drawn circuit diagrams, however, these two organizations coincide, minimizing differences in performance.

In contrast, more substantial differences are more likely to appear in the way in which the circuit diagrams are manipulated, that is, in operations that are performed on the diagrams. Even with improperly drawn diagrams, where the logical and physical aspects conflict, the expert's advantage would come through an ability to reorganize the circuit. Thus, the principal performance differences between the most skilled and least skilled subjects may be a result of differences in their respective levels of procedural knowledge. For this reason, the second year of research work was designed to examine performance on tasks that require technicians to manipulate circuits in prescribed ways. Such research, focusing on the investigation of procedural knowledge, complements the exploration of individual differences in structural/functional knowledge performed during the first year of work.

4. REVIEW OF SECOND-YEAR WORK: INVESTIGATION OF PROCEDURAL KNOWLEDGE

4.1 Overview

Knowing the way in which the mental representation of experts differ from that of novices does not directly indicate how the experts' representation leads to superior troubleshooting. Greeno (1978) makes the same point by noting that while current theorizing gives an explanation of the skill that chess masters show in the short-term recall of positions, there has been no strong theoretical analysis showing how the existence of a large store of recognizable patterns contributes to successful problem solving. Thus, tasks that tap procedural knowledge are intended to create a bridge between the structural/functional nature of the mental representation, and the procedures acting on this representation that enable problem-solving and troubleshooting activities.

Three tasks were designed to study procedural knowledge. Each task required the subject to manipulate a circuit diagram in some manner such that differences in algorithmic or heuristic procedures for changing the device can be evaluated as a function of skill level. Our interest here was primarily in the interaction of proficiency with the specific diagram manipulation. Task 1 required the subject to locate an error in the construction of a circuit on the basis of symptoms; Task 2 required the subject to change the function of a circuit; and Task 3 asked the subject to complete a missing segment of a circuit. Each experiment is described briefly below.

4.2 Task 1: Error Correction ("FIX" Task)

In this task, technicians, varying in skill level, were presented with a diagram containing an error in it and with symptoms of its malfunction. The subject's task was to find the error and to correct or fix it. While performing this task, a record was maintained of the operations that the subject used and of their order, so that the nature and order of the procedures could be catalogued and compared across the specified stimulus material and as a function of subject skill level.

4.3 Task 2: Change Function ("ALTER" Task)

A good indication of a subject's deep-level comprehension of a circuit is provided by the readiness with which that circuit can be modified. In this experiment, subjects were presented with a circuit diagram of a device that was complete and would operate as described. The subject's task was to make a specific change in one of the circuit's parameters. For example, in the small diagram used in the first year of work, the subject might be asked to change the frequency of the tuning unit. As in Task 1, protocols of the subject's operations were catalogued and compared.

4.4 Task 3: Complete Circuit ("COMPLETE" Task)

This task required the subject to fill in a missing segment of a circuit diagram so that the circuit would perform a particular function. Circuits were constructed in which a particular segment of the diagram was left blank. These omissions subsumed a functional unit of the circuit (not just a single component), but were not so large as to require substantial redesign. As in Tasks 1 and 2, a record was maintained of the procedural steps used by the subjects to perform the task. These protocols were then summarized and compared between subject groups of different skill level.

4.5 Subjects

The sample of 12 novice technicians for the second year of work were drawn from electronics trade schools in the Los Angeles area which offer a two-year training program in electronics to high school graduates. The 9 expert technicians were currently employed with 2 to 4 years of college education and an average of 5 years of work experience in electronics.

4.6 Materials

Six circuits were designed for use in the studies of procedural knowledge. Three of these are analog circuits with a level of complexity comparable to that of the medium-sized circuit used in the first year's work. The remaining three circuits were drawn from digital materials because (a) much of contemporary electronic equipment is digital, (b) much of the current technical training of technicians is focused on digital circuits, and (c) we wish to study procedural knowledge as it relates to both types of circuits.

Three versions of each dircuit were prepared: a complete working circuit for the alter function task; an incomplete circuit for the circuit completion task; and a modified, non-working circut for the error correctiontask. These circuits are presented in Figures 4-1A to 4-6C. In each figure, the complete, working version is shown in panel A, the incomplete version in panel B, and the modified, non-working version in panel C.

4.7 General Procedure

Three tasks were used to study procedural knowledge. Each task required subjects to manipulate a circuit diagram in some manner such that differences in algorithmic or heuristic procedures for changing the device

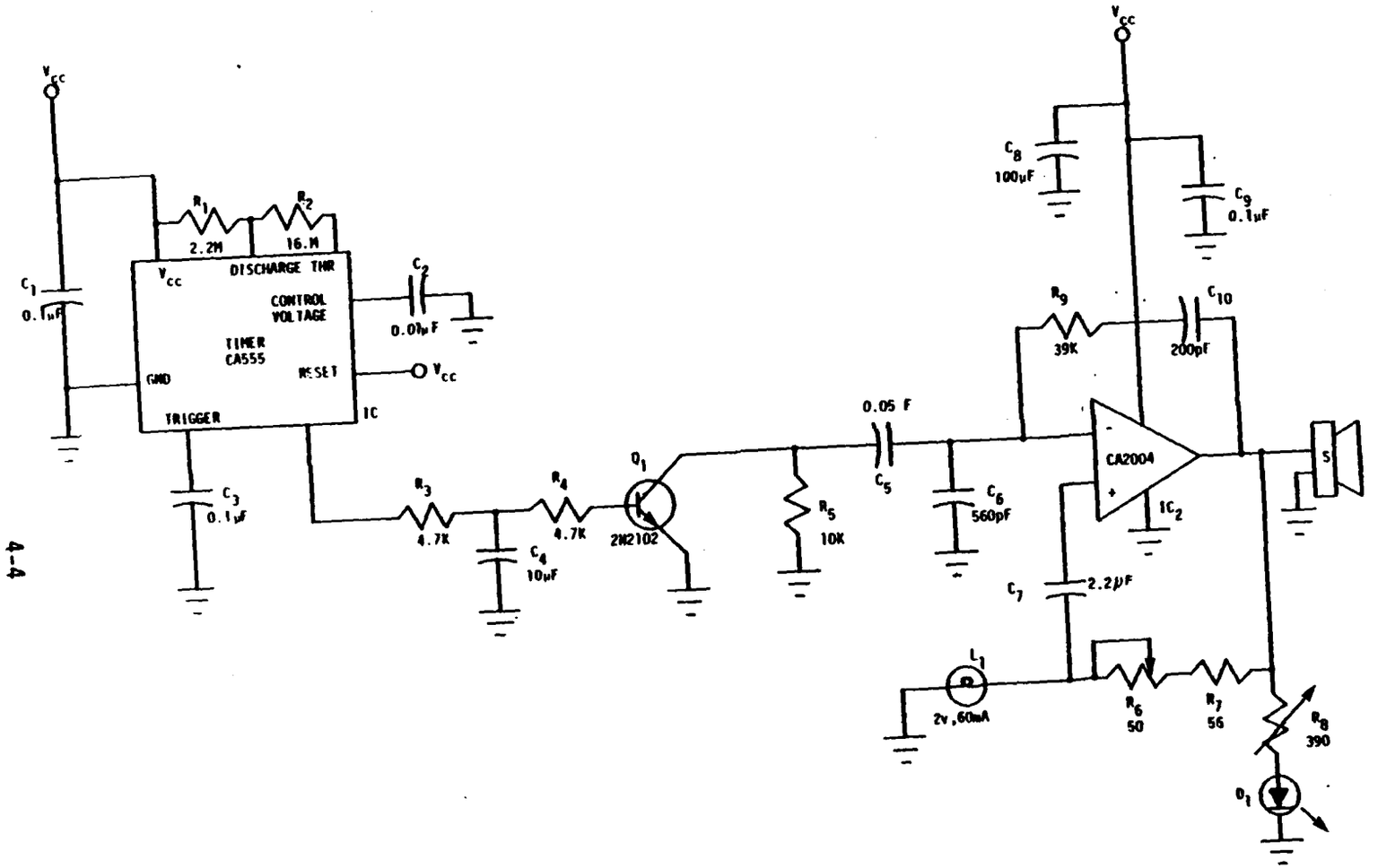

FIGURE 4-1A.
ULTRASONIC RUDENT ELIMINATOR (ANALOG): COMPLETE, WORKING CIRCUIT
[FOR "ALTER" TASK]

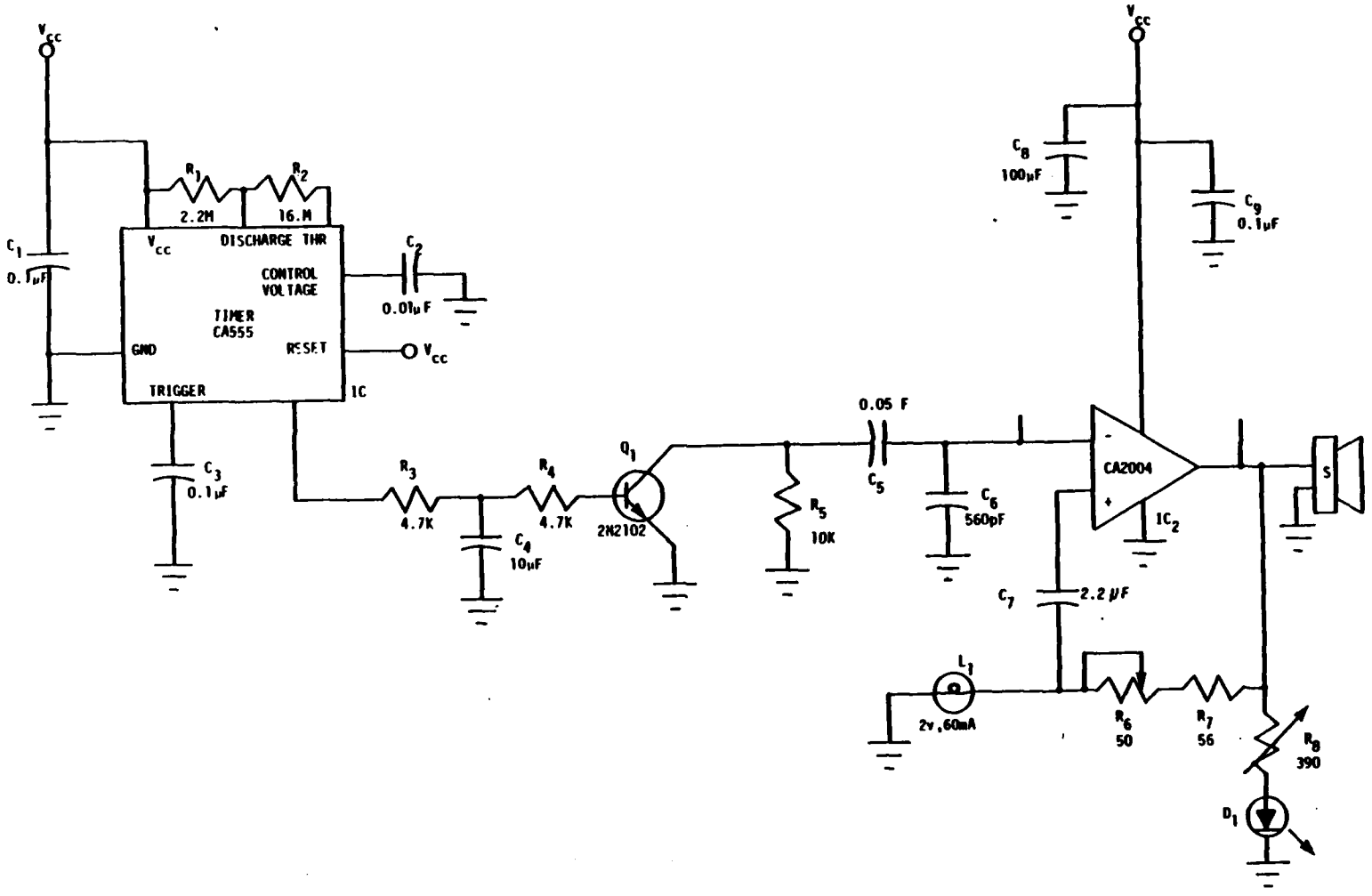

FIGURE 4-1B.
ULTRASONIC RUDENT ELIMINATOR (ANALOG): INCOMPLETE CIRCUIT
[FOR "COMPLETE" TASK]

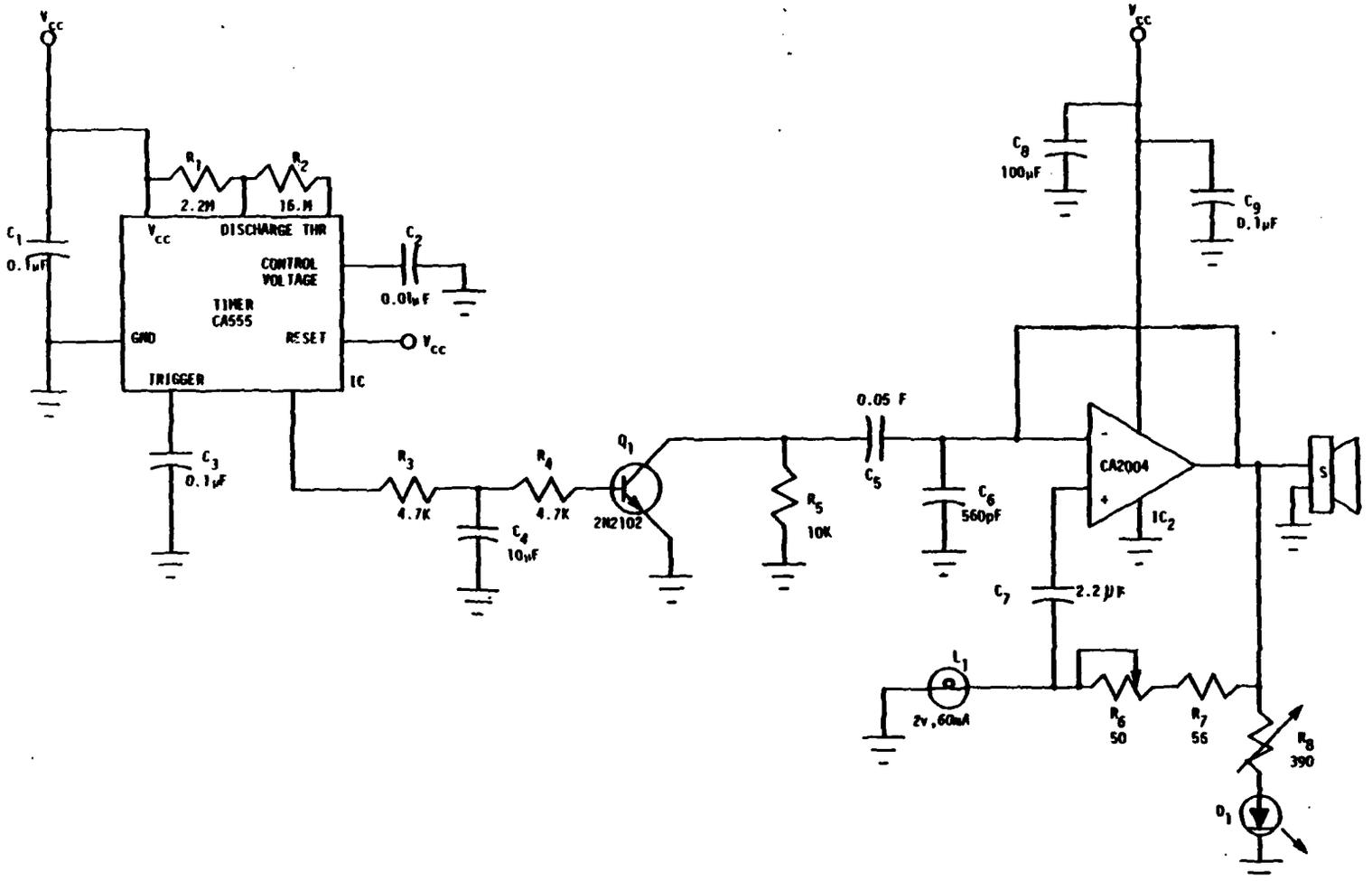

FIGURE 4-1C.
ULTRASONIC RUDENT ELIMINATOR (ANALOG): MODIFIED, NON-WORKING CIRCUIT
[FOR "FIX" TASK]

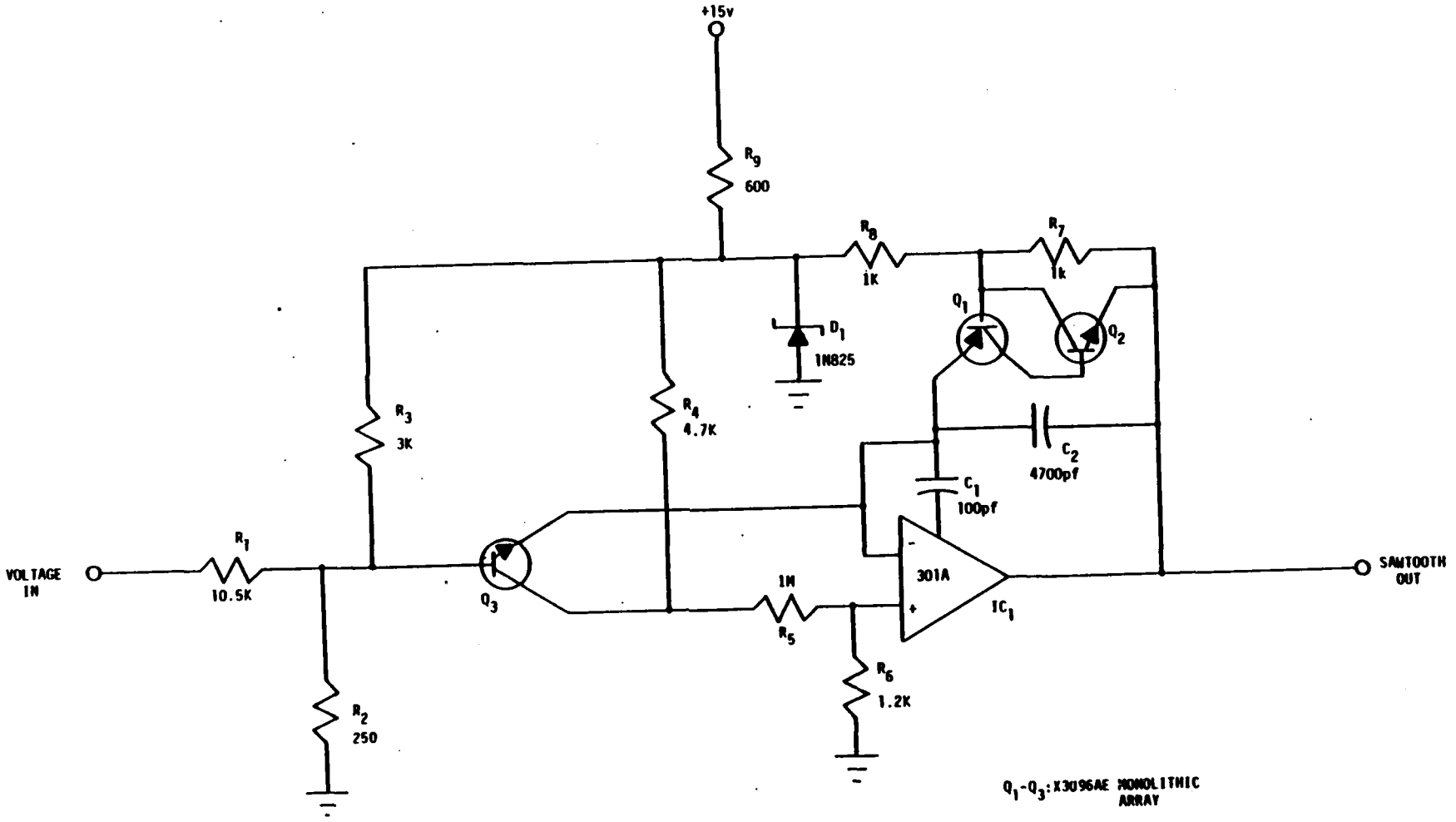

FIGURE 4-2A.
VOLTAGE TO FREQUENCY CONVERTER (ANALOG): COMPLETE, WORKING CIRCUIT
[FOR "ALTER" TASK]

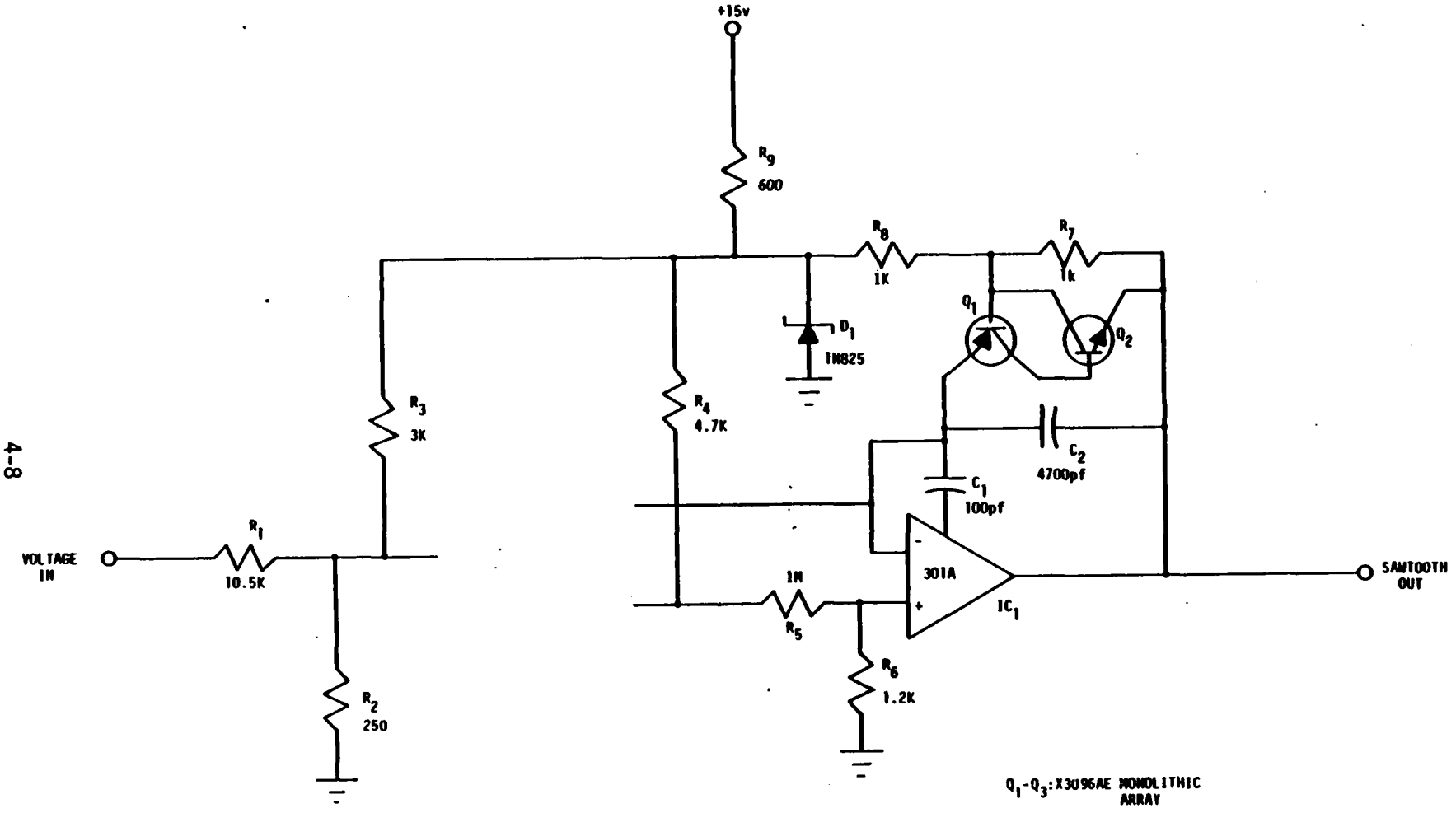

FIGURE 4-2B.
VOLTAGE TO FREQUENCY CONVERTER (ANALOG): INCOMPLETE CIRCUIT
[FOR "COMPLETE" TASK]

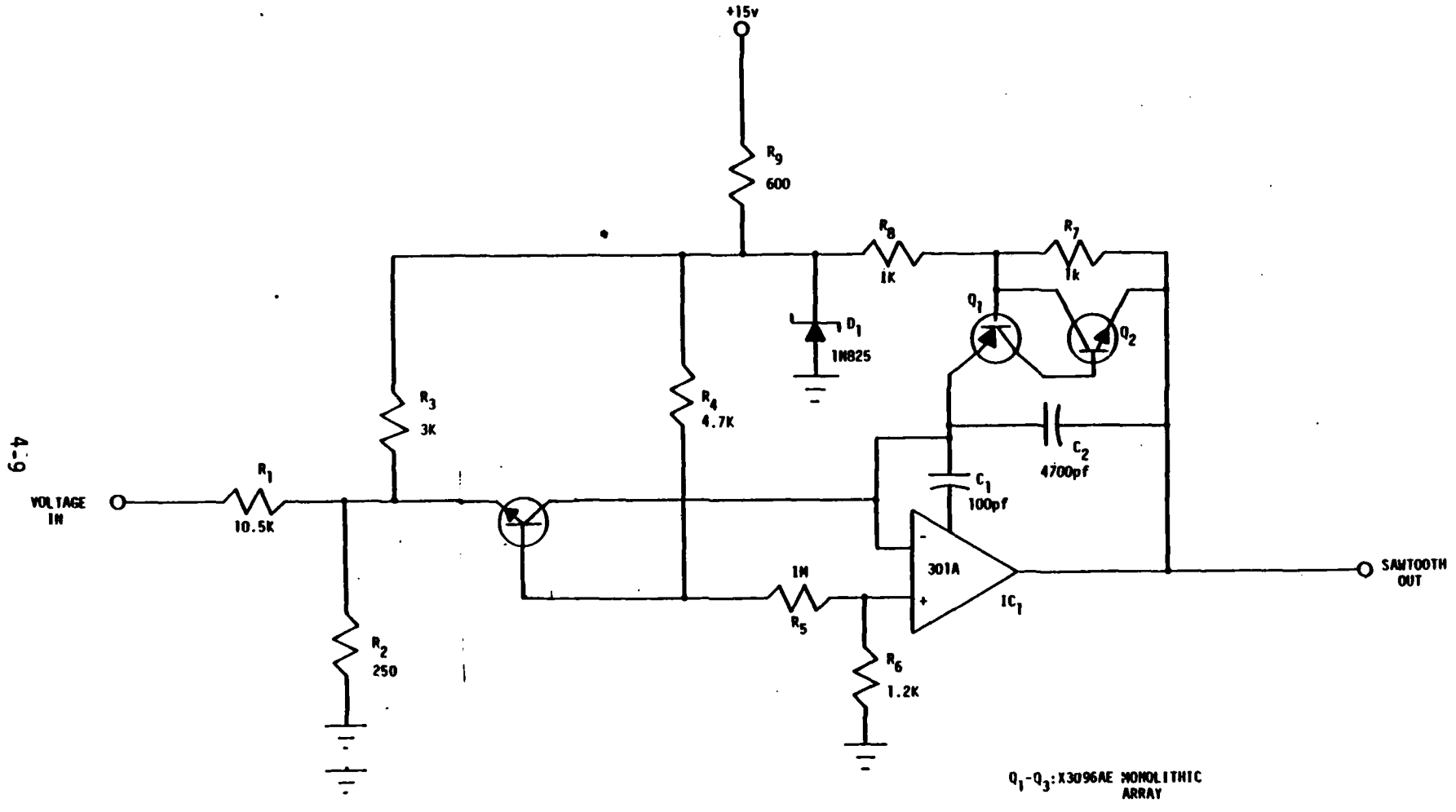

FIGURE 4-2C.
VOLTAGE TO FREQUENCY CONVERTER (ANALOG): MODIFIED, NON-WORKING CIRCUIT
[FOR "FIX" TASK]

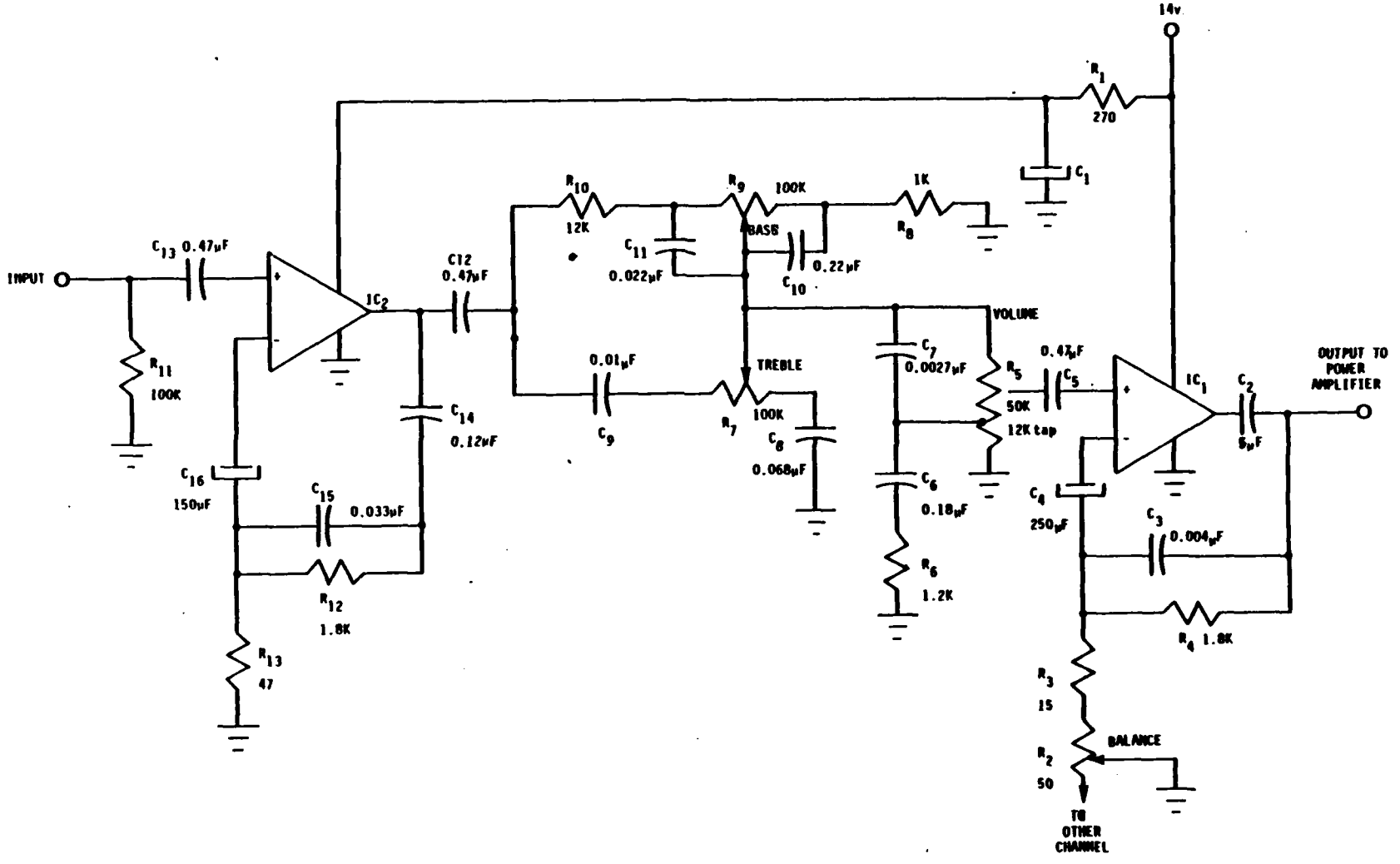

FIGURE 4-3A.
STEREO PREAMPLIFIER - ONE CHANNEL (ANALOG): COMPLETE, WORKING CIRCUIT
[FOR "ALTER" TASK]

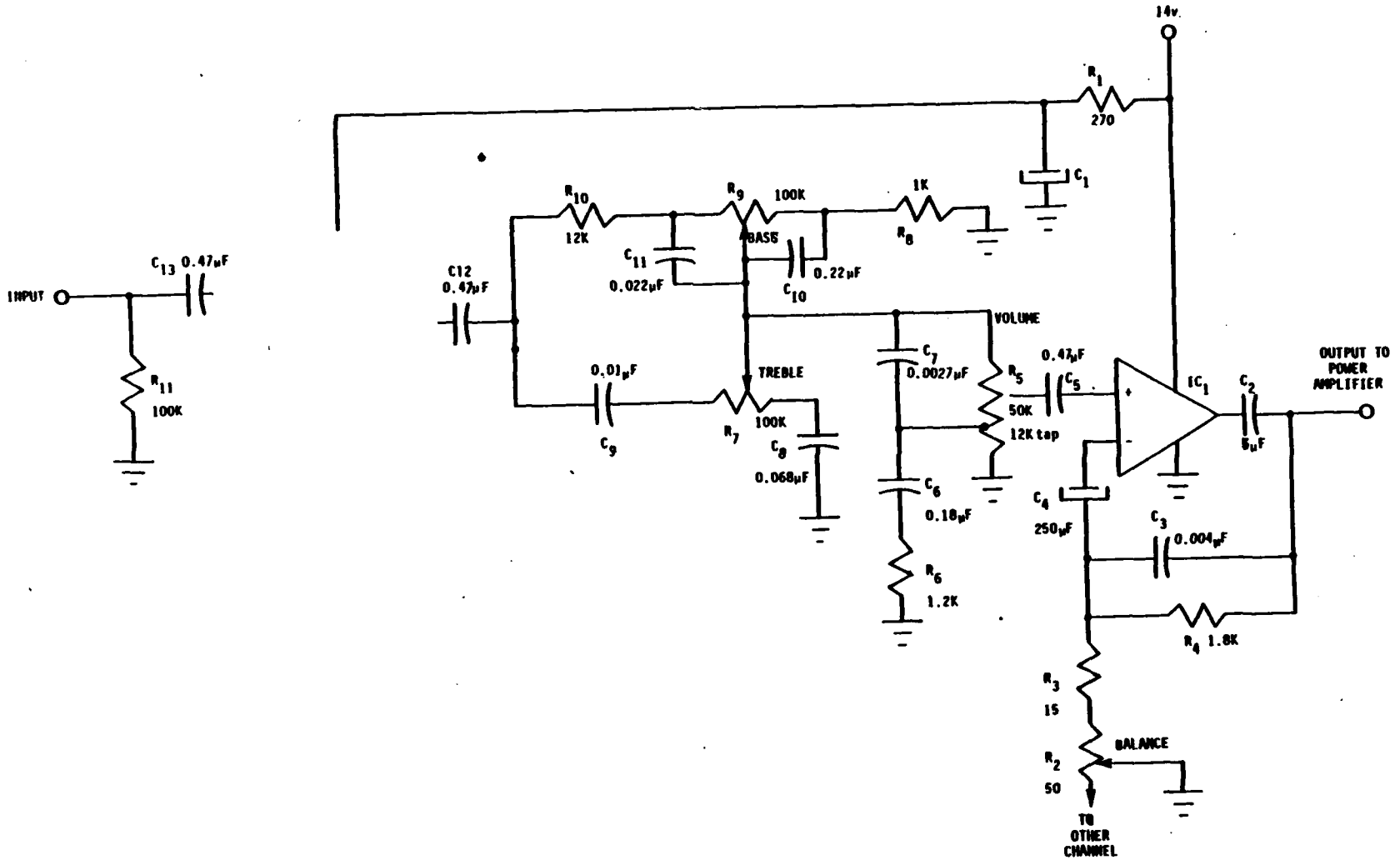

FIGURE 4-3B.
STEREO PREAMPLIFIER - ONE CHANNEL (ANALOG): INCOMPLETE CIRCUIT
[FOR "COMPLETE" TASK]

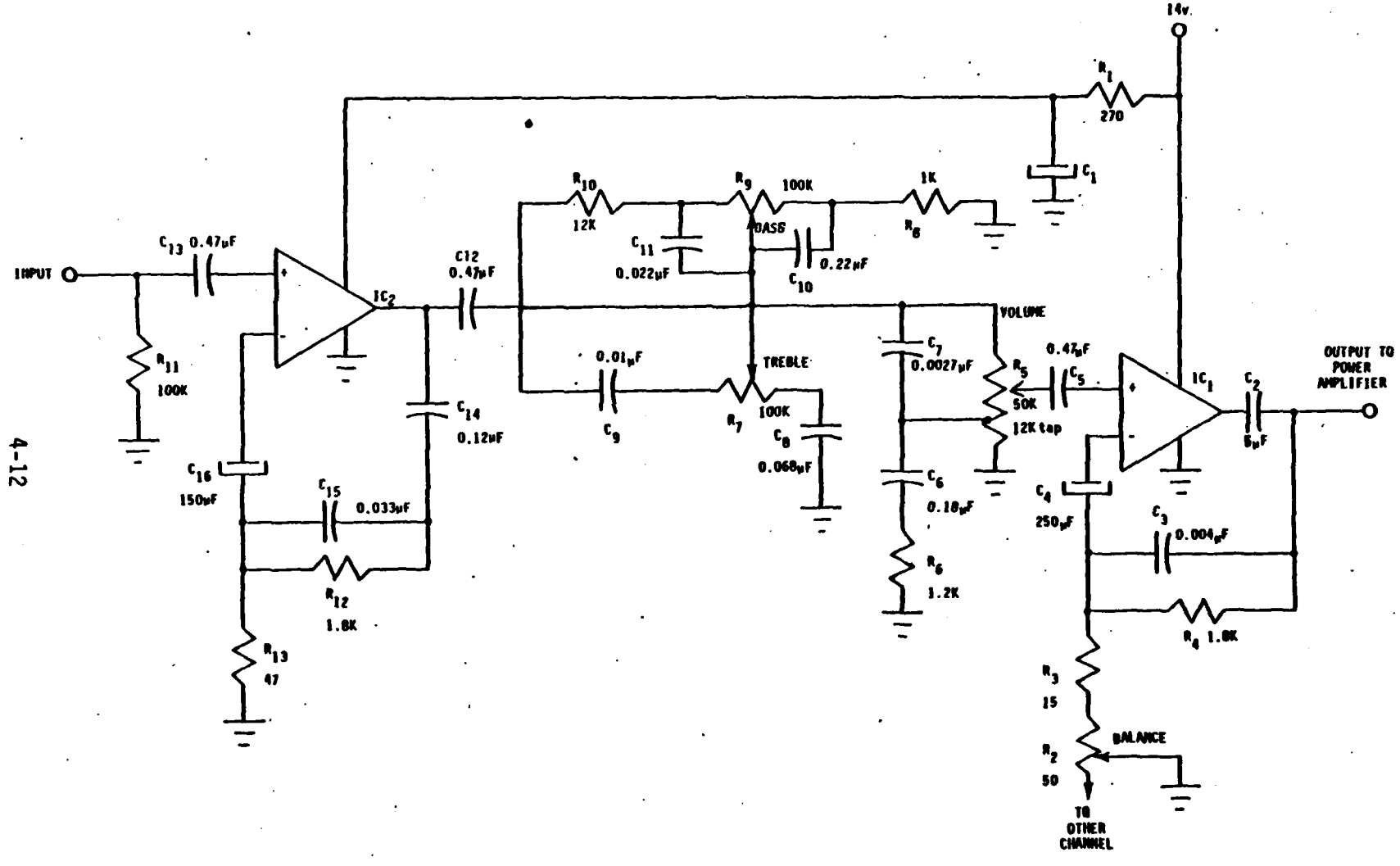

FIGURE 4-3C.
STEREO PREAMPLIFIER - ONE CHANNEL (ANALOG): MODIFIED, NON-WORKING CIRCUIT
[FOR "FIX" TASK]

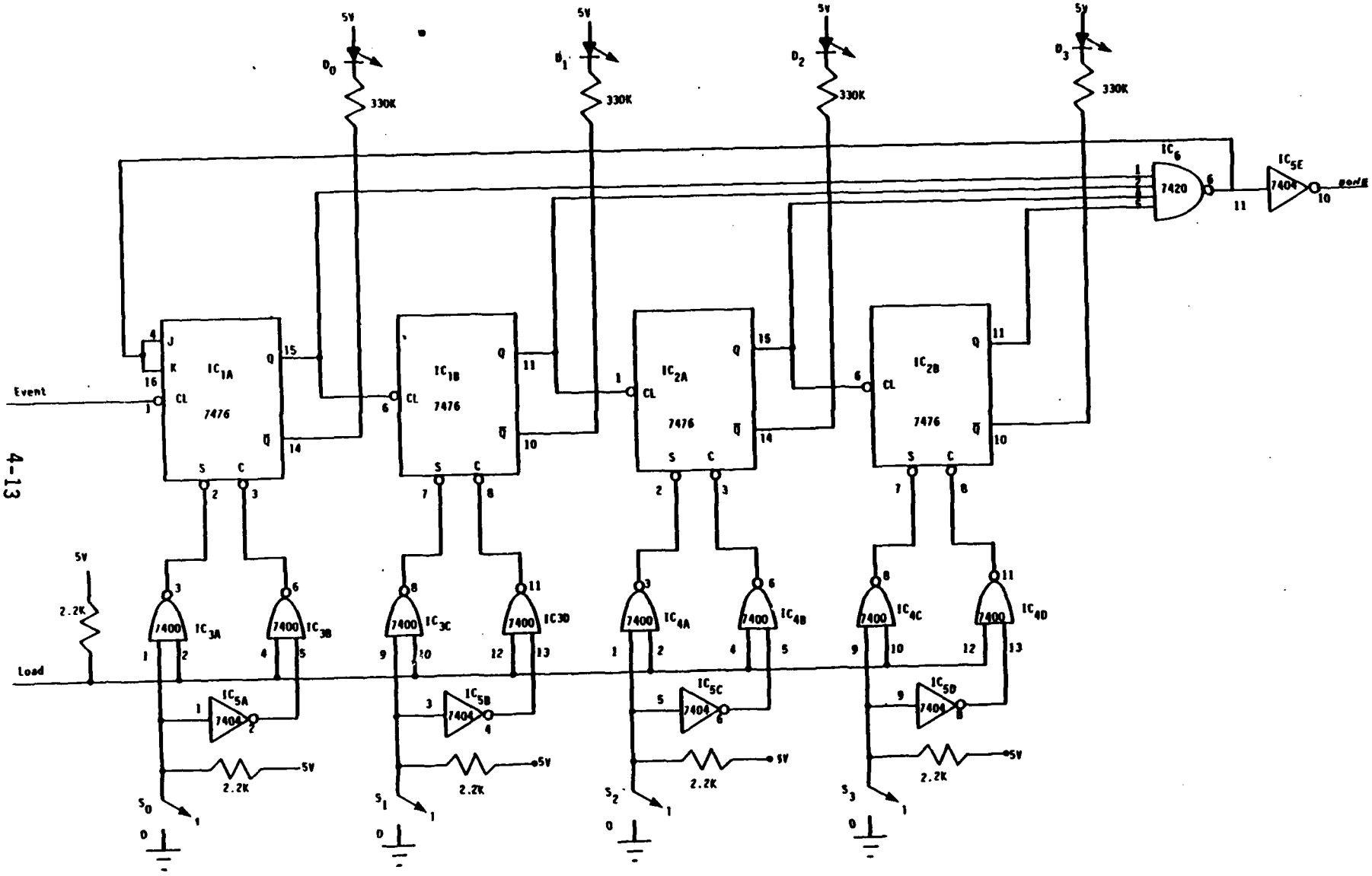

FIGURE 4-4A.
UNIVERSAL 4-BIT BINARY COUNTER (DIGITAL): COMPLETE, WORKING CIRCUIT
[FOR "ALTER" TASK]

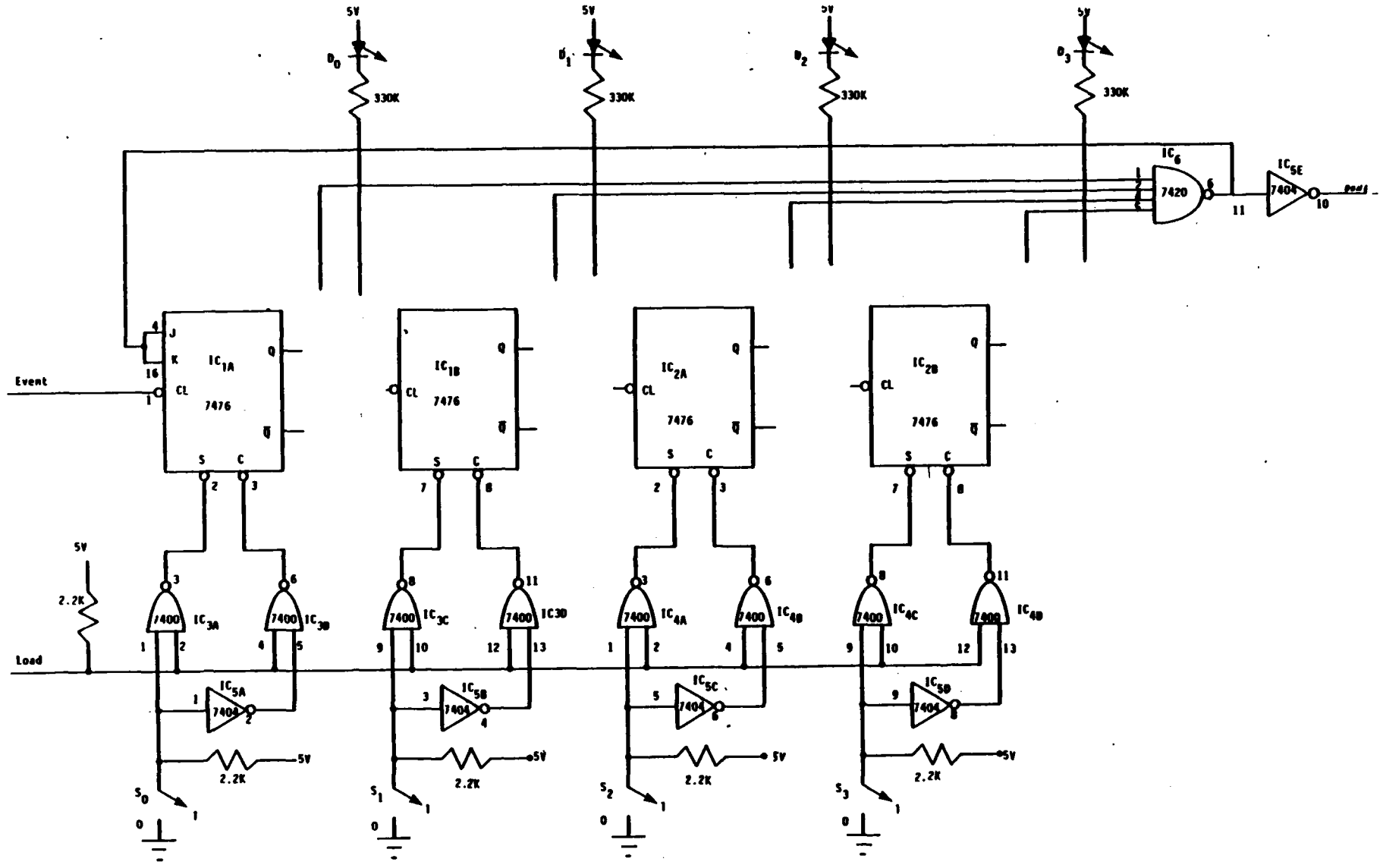

FIGURE 4-4B.
UNIVERSAL 4-BIT BINARY COUNTER (DIGITAL): INCOMPLETE CIRCUIT
[FOR "COMPLETE" TASK]

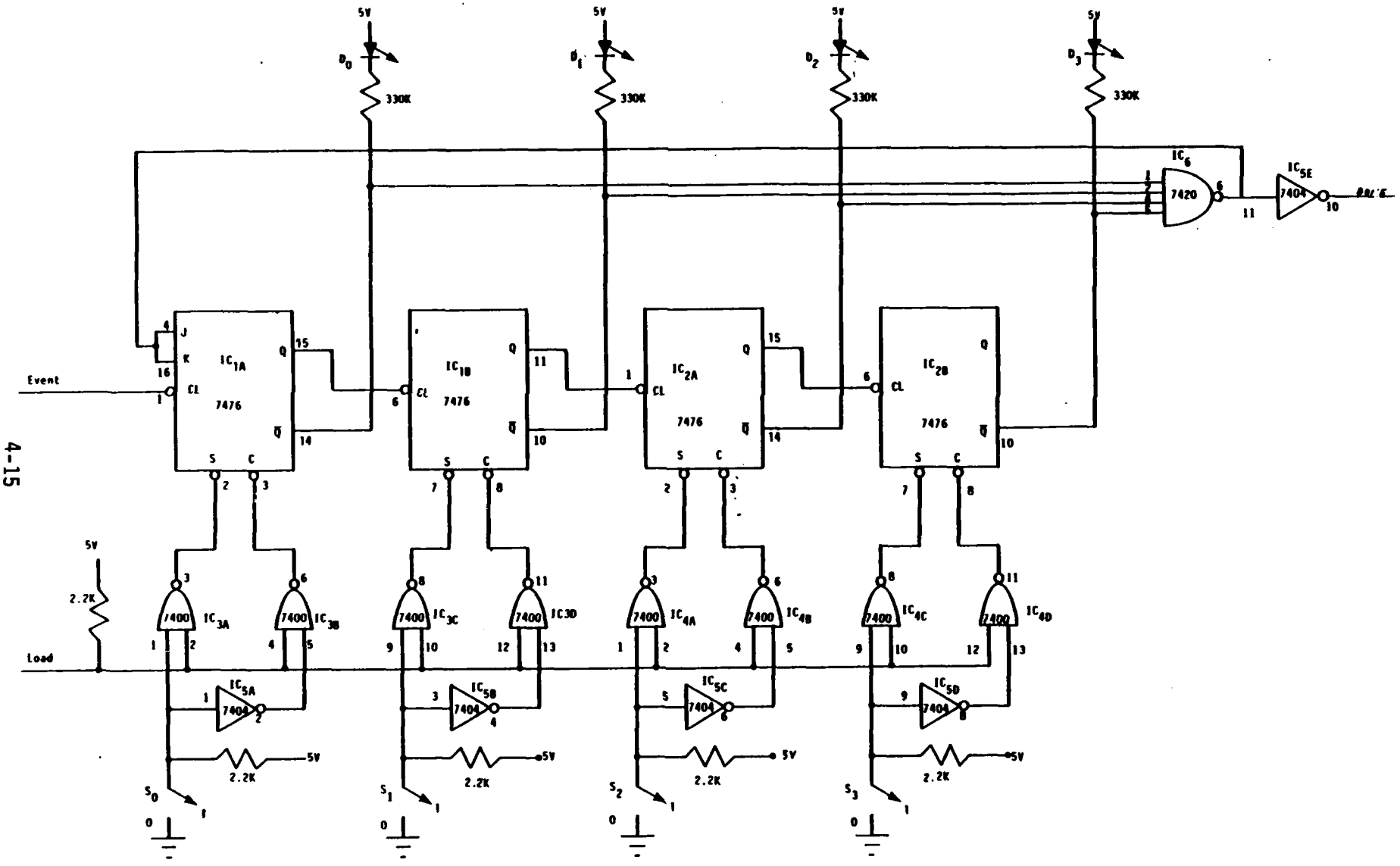

FIGURE 4-4C.
UNIVERSAL 4-BIT BINARY COUNTER (DIGITAL): MODIFIED, NON-WORKING CIRCUIT
[FOR "FIX" TASK]

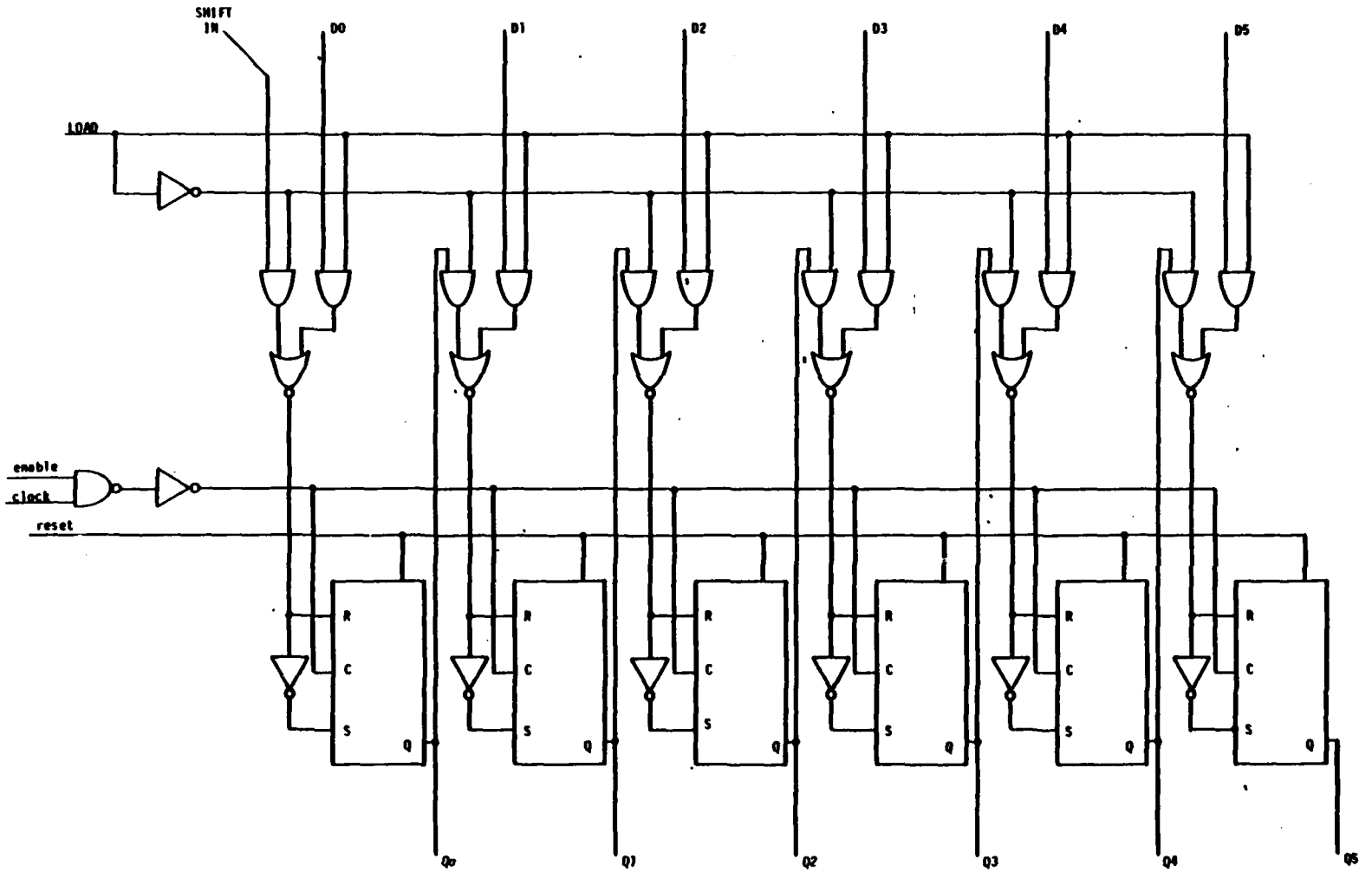

FIGURE 4-5A.
FOUR-BIT REGISTER (DIGITAL): COMPLETE, WORKING CIRCUIT
[FOR "ALTER" TASK]

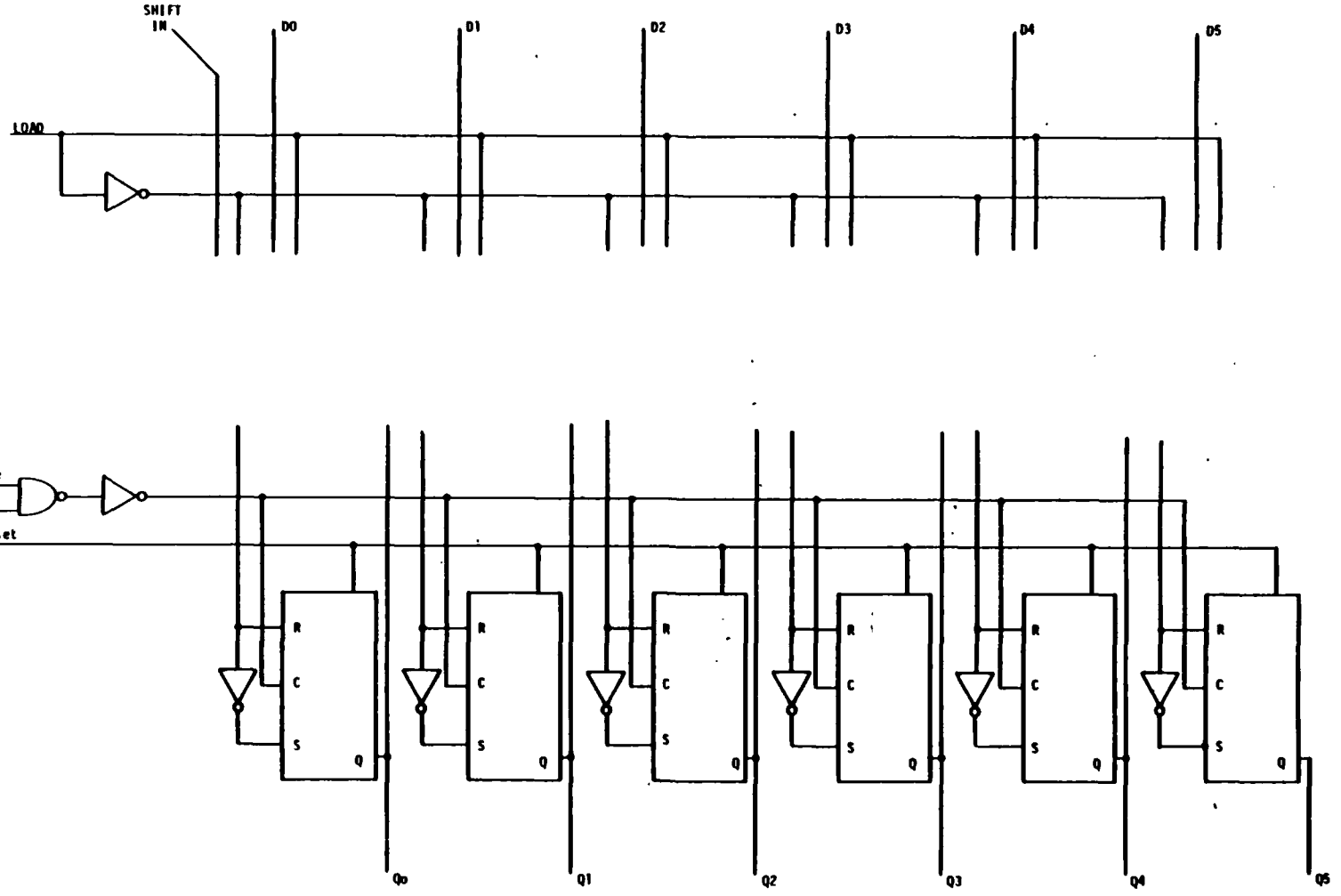

FIGURE 4-5B.
FOUR-BIT REGISTER (DIGITAL): INCOMPLETE CIRCUIT
[FOR "COMPLETE" TASK]

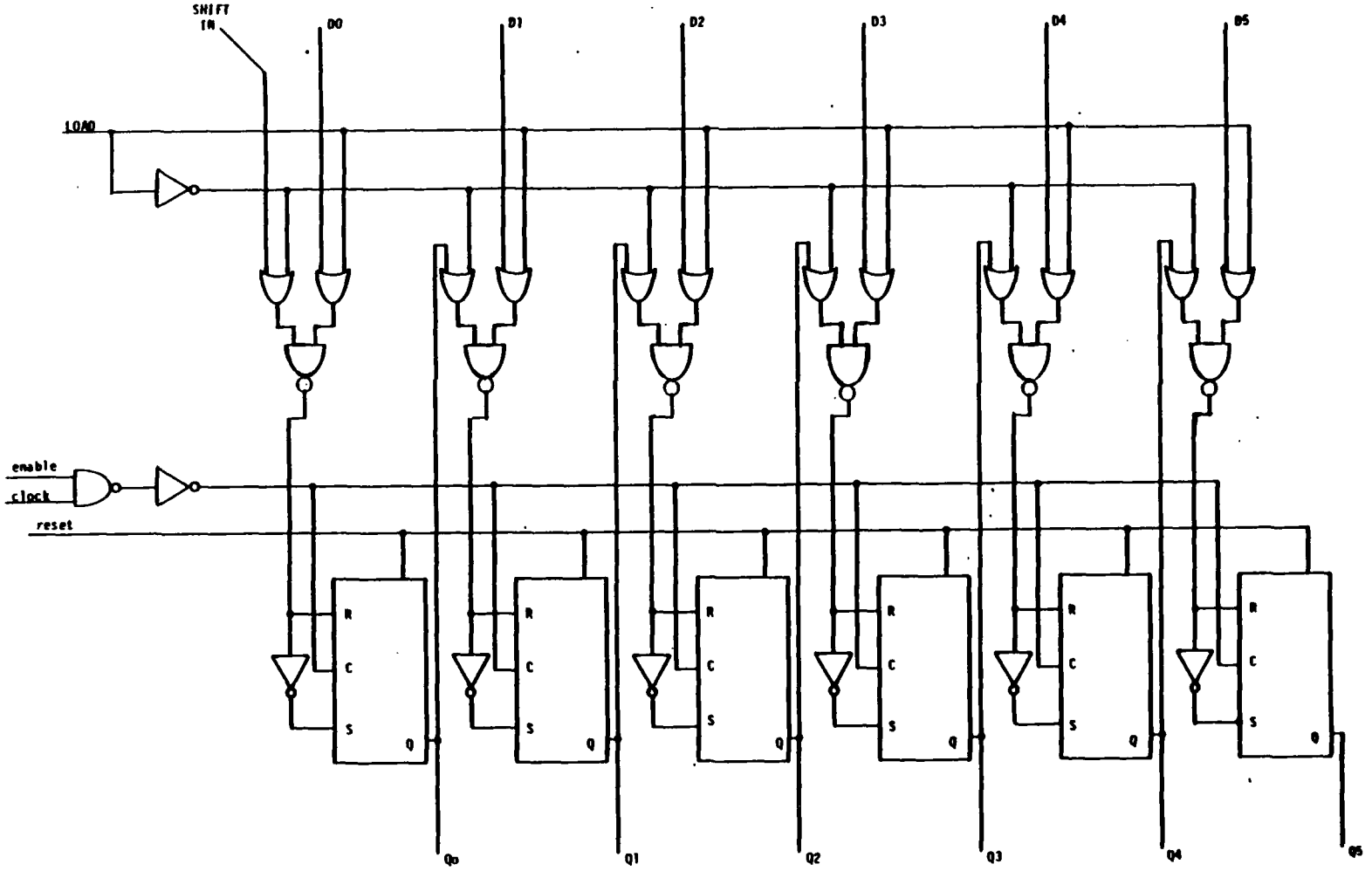

FIGURE 4-5C.
FOUR-BIT REGISTER (DIGITAL): MODIFIED, NON-WORKING CIRCUIT
[FOR "FIX" TASK]

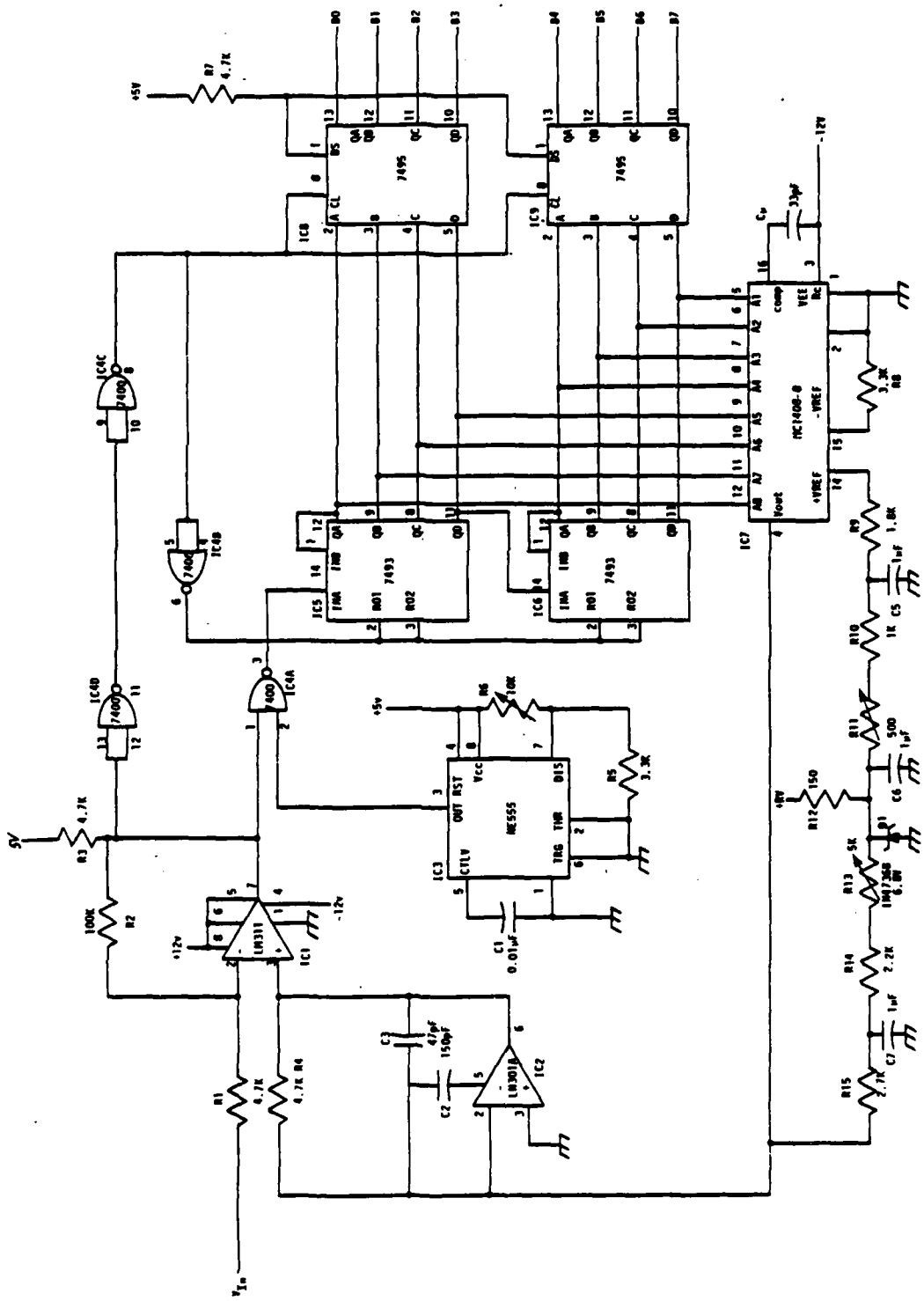

FIGURE 4-6A.
ANALOG TO DIGITAL CONVERTER (DIGITAL): COMPLETE, WORKING CIRCUIT
[FOR "ALTER" TASK]

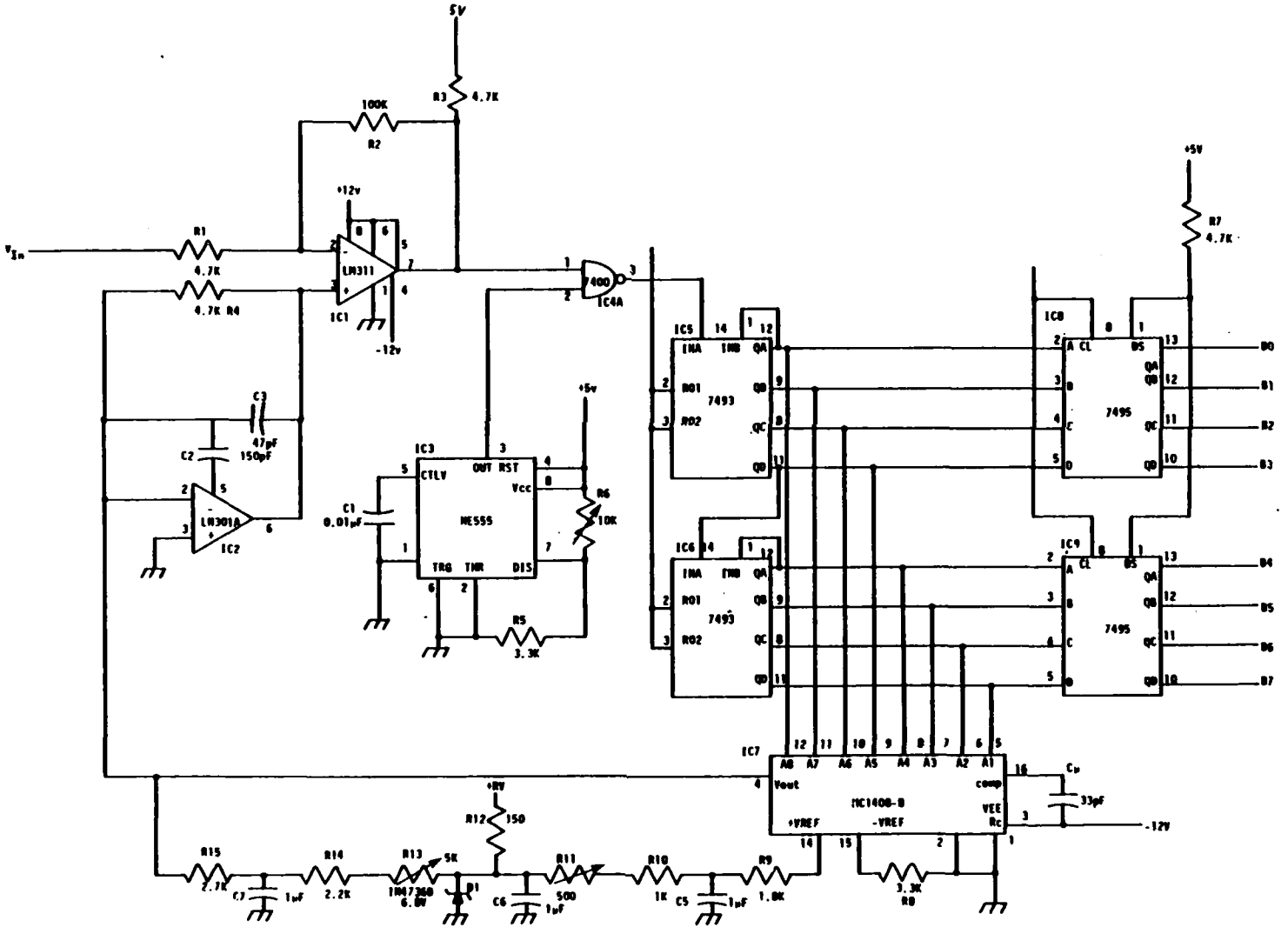

FIGURE 4-6B.
ANALOG TO DIGITAL CONVERTER (DIGITAL): INCOMPLETE CIRCUIT
[FOR "COMPLETE" TASK]

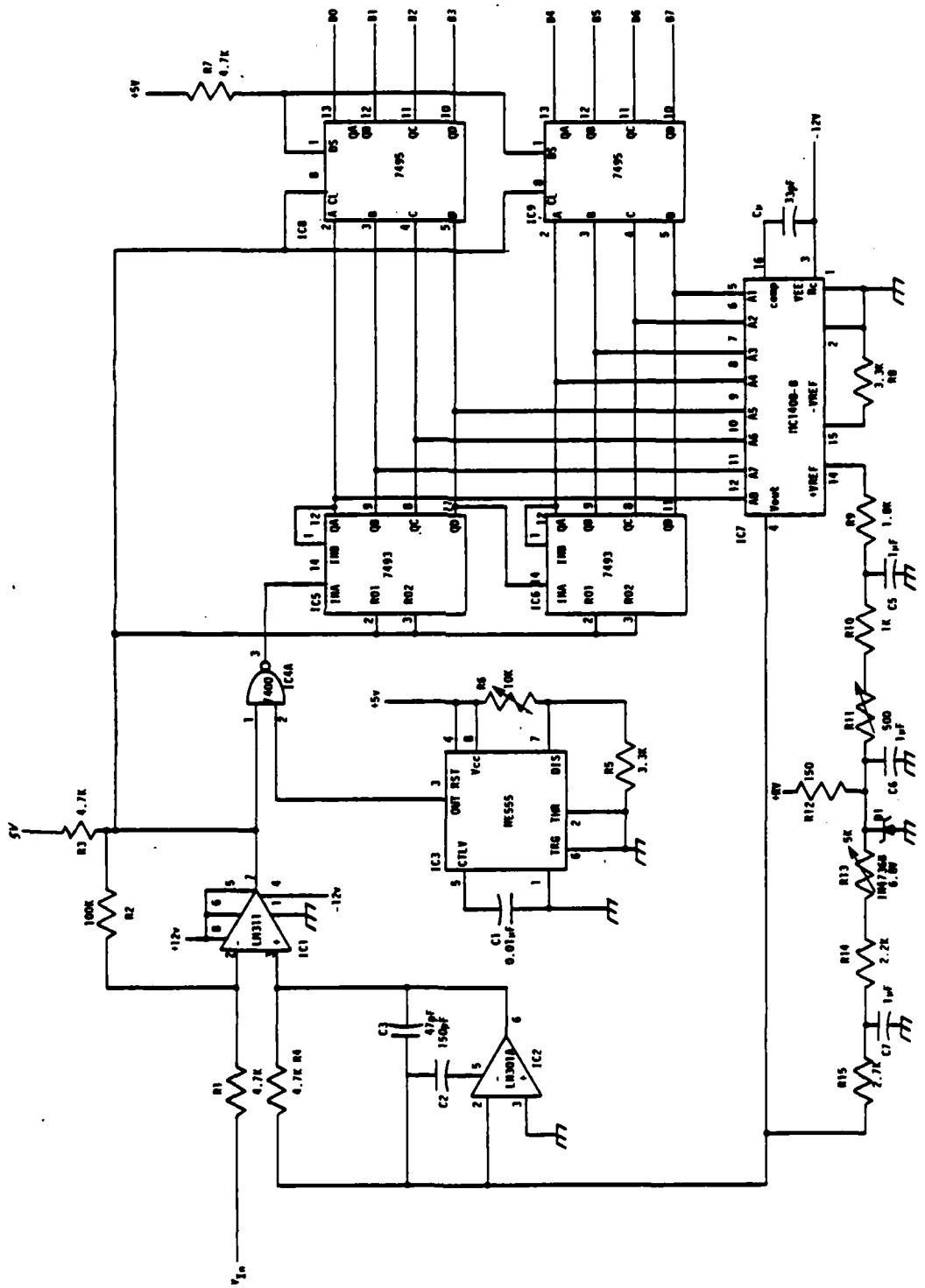

FIGURE 4-6C.
ANALOG TO DIGITAL CONVERTER (DIGITAL): MODIFIED, NON-WORKING CIRCUIT
[FOR "FIX" TASK]

could be evaluated as a function of the subject's skill level. Our interest here was primarily in the interaction of subject proficiency with the specific circuit manipulation required in the diagram.

The first task required the subject to locate and correct an error in the construction of a circuit on the basis of symptoms; the second task required the subject to change the function of a circuit; and the third task asked the subject to complete a missing segment of a circuit. Each subject solved problems of all three types over the course of one two-hour session. Each task was performed twice, once with a digital circuit and once with an analog circuit. The selection of circuits for tasks was counterbalanced across subjects within each skill level; and the order of presentation of the three different tasks was also counterbalanced.

Considerable effort was devoted to training the subjects to produce the verbal protocols while solving the task problems. The following instructions were read to the subjects.

> "We are interested in your solutions to the problems, but we are also interested in how you arrive at your solutions. There may be several different ways to solve the problems and there are certainly several different ways to arrive at any one solution. We would like to keep a record of everything you do in coming up with your solutions. One way that we will do this is to have you think <u>out loud</u> as you are solving the problems. Since most people do not naturally think out loud, this may require some concentration on your part.
>
> First, it would be most useful to us if we could write down a list of distinct steps that you go through to arrive at your final solution. To help us do this, we want you to tell us that you are thinking at each point as you work toward your solutions, and also <u>why</u> you are think about the steps you give us.
>
> It is crucial to us that you do not, for any reason, edit anything out from your thinking. For example, if you see a step that you would like to carry out but you don't see how to do it right away, please describe what you would like to do

4.8.4 Content Differences. Several reliable differences in the content of the protocols as a function of skill level were apparent and these important differences form the basis for procedural guidelines to be established and evaluated during the third year of work.

(1) Experts devoted considerable time at the beginning of each problem "learning how the circuit works" before initiating a problem-solution sequence. Specifically, experts partitioned the circuit while labeling key parts from the problem description and traced the flow of information through the circuit while noting the activity along the route. The novices' initial inspection time was spent in unsystematic viewing of the circuit.

(2) The second major difference was in the establishment of a plan to attack the problem with clearly defined goals, and subjects that link the desired state of the circuit to the current state. The experts were more patient, relying less on a "shotgun" approach.

(3) The experts proceeded through a sequence of steps, making changes, additions, or deletions in the circuit, and each step was followed by tracing the effects of the action taken on the functioning of the circuit. Novices rarely studied the impact of each solution step separately, and on occasion, the impact of the entire solution was not traced through the circuit.

4.8. Results

4.8.1 Accuracy of Solutions. Accuracy data in terms of the proportion of problems for which workable solutions were provided for each task are presented in Table 4-1. The data confirm that the tasks studied here were sufficiently difficult to promote large accuracy performance differences with respect to skill level; and, clearly, the expert subjects did significantly better than the novice subjects on all tasks. Furthermore, given that performance by experts (at least on the FIX and COMPLETE tasks) was not perfect, it is evident that the tasks required procedural knowledge and were not identifiable "textbook" examples of standard problems. Nevertheless, as demonstrated in previous stages of this research, differences in accuracy performance are not particularly useful for understanding procedural knowledge.

4.8.2 Classification of Protocols. The transcribed protocols first were inspected for patterns by an experimenter who was blind to the skill-level classification of each subject. All of the protocols could be described in a general respect using four classifications of problem solving behavior: directed, re-directed, immediate, and trial-and-error. Directed behavior is characterized by an apparent plan toward solution, with goals and if-then operations. Re-directed behavior has the characteristics of directed behavior, plus the addition of at least one decision on the part of the subject that the current direction is incorrect and a new direction is pursued. Immediate solution behavior contains no sequence of operations, but rather a "snap" solution given quickly. Trial-and-error behavior is best characterized as "maybe I would try X; no maybe I would try Y."

This behavioral classification was carried out by one of the project Principal Investigators who was blind as to which protocols were from expert versus novice technicians. Each protocol was classified

systematically based on clear breaks in the solution paths, if-then statements, and admissions of incorrect attempts and guessing. The results are presented in Table 4-2. As is obvious from the data pattern, the expert problem solution protocols were predominantly classified (56%) as "directed" behavior--the highest level of cognitive performance. And, much of the balance of the expert protocols (28%) were clasified as "re-directed" behavior. In contrast to the experts, the novices showed no predominant behavioral classification and only 33% of the protocols were classified as "directed," with nearly the same proportion being classified as "trial-and-error."

The problem solving behavior classifications also revealed interesting interactions between skill level and the nature of the task. Table 4-3 presents those data. In particular, the most dramatic difference between skill levels occurs with the ALTER and COMPLETE task; in these tasks, 75% of the protocols generated by the experts were classified as directed, whereas 49% of the protocols generated by the novices were classified as trial-and-error. The ALTER and COMPLETE tasks are task least likely to have received prior training in the trade schools. It is reasonable that these tasks represent exercises where the novices cannot mimick the systematic behavior of experts, and therefore these type of data may prove most diagnostic in evaluating differences between experts and novices on procedural knowledge.

4.8.3 Solution Time. Table 4-4 presents the average problem solution time as a function of skill level and task. Most striking is the lack of differences in sclution time between skill levels. The only apparent difference is in the COMPLETE task, where the experts studied the diagram for nearly two minutes longer before initiating a solution sequence. This is consistent with the finding that novices resort to trial-and-error behavior on the completion task.

TABLE 4-1

Proportion of Problems for which
Workable Solutions were Provided

	FIX	ALTER	COMPLETE
EXPERT	.50	1.00	.75
NOVICE	. 20	.20	.25

TABLE 4-2

Proportion of Protocols Falling
Into Each Classification As
A Function of Skill Level

	DIRECTED	RE-DIRECTED	IMMEDIATE	TRIAL-AND-ERROR
EXPERT	.56	.28	.05	.11
NOVICE	.33	.23	.13	.31

TABLE 4-3

Proportion of Protocols Falling Into Each Classification
As A Function of Skill Level and Task

	DIRECTED	RE-DIRECTED	IMMEDIATE	TRIAL-AND-ERROR
FIX				
EXPERT	.67	.33	.00	.00
NOVICE	.60	.30	.10	.00
ALTER				
EXPERT	.50	.33	.00	.17
NOVICE	.10	.40	.00	.50
COMPLETE				
EXPERT	.50	.17	.17	.17
NOVICE	.20	.10	.30	.40

TABLE 4-4

Average Solution Time (Min)

	FIX	ALTER	COMPLETE
TOTAL SOLUTION TIME:			
EXPERT	11.9	16.8	14.5
NOVICE	13.8	15.9	8.4
INITIAL STUDY TIME:			
EXPERT	3.2	3.0	5.2
NOVICE	3.3	3.0	2.7

5. EXPERIMENTAL PROGRAM FOR THIRD YEAR

5.1 Overview

The first year of work explored a characterization of the knowledge structures that differentiate among technicians of different skill levels. The second year of work increased our understanding of the procedural knowledge that technicians apply to the mental representation of electronic circuits to perform troubleshooting and problem solving. These latter differences, we believe, characterize the principal differences between skilled and unskilled subjects. The results should then be validated and applied.

It seems possible to combine the validation of our findings with some more practical goals. Based on the differences that we have observed, our next task can be to develop and test procedural guidelines for comprehending circuits, building circuits, and trouble-shooting. Our approach, then, during the third year of work is to describe how expert technicians approach the range of tasks studied during the second year of work, develop specific procedural guidelines based on this knowledge, and then conduct an experiment to validate the usefulness of the guidelines toward improving performance. The latter step will be accomplished by providing one group of less proficient technicians with the guidelines, and comparing their performance to that of a group of technicians with comparable skills who are not given the guidelines. This general procedure has been employed successfully by Samet and Geiselman (1981) to develop guidelines for summarizing tactical intelligence data. The basic notion is that experts have a mental representation of their area of expertise that is concordant with the information processing requirements that operations on the material entail. This representation can be translated to some extent into guidelines that can be used to improve the performance of other individuals who have, as yet, a more limited or otherwise less coherent mental representation of these procedures.

As outlined in the discussion of the second year's experiments on procedural knowledge (see Section 4.8), one striking difference between experts and less-proficient technicians is observed in their initial examination of the circuit. The experts spend a good deal of time, initially, understanding the entire circuit, often without consideration of the specific task at hand. The less-proficient technicians, on the other hand, appear to enter the problem too early, before they actually comprehend the circuit. There are many reasons why this difference could exist, but it lends itself well to the guidelines manipulation outlined above.

It is proposed that one study to be carried out during the third year of work be directed toward an evaluation of orienting tasks that would mimick the initial study of the circuits exhibited by the experts. A general framework for such a study is outlined below. Other studies of this type could be generated based on further analyses of the data obtained from the second year research program.

5.2 Subjects

The sample of novice technicians for the third year of work will be drawn from electronics trade schools in the Los Angeles area. A novice is defined as a student in the early first year of a two-year program. Each subject will be assigned to one of three conditions, based upon a pre-test of structural/functional knowledge of electrical circuitry. The pre-test will insure that the subjects are matched across conditions with respect to this level of structural/functional knowledge.

5.3 Materials

The same six circuits designed for the second year of work (3 digital, 3 analog) and the three tasks (fix error, alter circuit, complete circuit) will be used again. This will allow the data from this study to be compared to those generated by the expert technicians from the second year of work.

5.4 Procedure

Each subject will be assigned to one of three conditions. In the general orienting-task condition, the subject will be required to answer certain questions about the circuit at hand before going on to solve the problem. These questions will serve to elicit information sought by the experts across circuits toward comprehending the circuits prior to problem solution. The questions used in this condition are considered general because they could be asked in the context of any circuit of the types studied here. The instructions derived for this condition are as follows:

> Solving the type of problem that we will be giving you is not easy -- many of our subjects have difficulty. To try to make the task easier, we have some things that you can do to start out. These will help you to understand the circuit. As you start the problems, please try to follow these instructions as closely as possible.
>
> The first thing to do is to try to understand the circuit that you are working with. To do this, you should forget about the problem you have to solve for a moment and concentrate on the original diagram. If you do not know first how it works, you are going to be able to fix or to change it! As you follow the guidelines below, it may be helpful if you go back and forth from one to another, since each question helps to answer all the others.

1. Start with the purpose for the circuit. Does it have an input? An output? Does it do something -- perhaps make a noise. Are there controls that one would adjust in using it? Identify these inputs, outputs, and controls.

2. Try to identify how "information" flows through the circuit. How does the input get to the output? Where is it acted on by the controls? Of course in many circuits there isn't one single path from input to output -- there may be several different connections. Nevertheless, it is often possible to trace one main path.

3. Try to understand what the different parts of the circuit do. What are the various components and how do they act. Two things can be helpful here:

   (a) Do certain groups of components go together and act as a whole? Several parts may form a voltage divider, an amplifier, a counter, or the like. Try to identify these groups and to lable what they do. Then you can think about them together, instead of worrying about their individual parts.

   (b) Are there certain points in the circuit that seem to be particularly important. These might be places where several of the groups you just identified connect with each other. They might be places where several signals come together or diverge or where there is only a single connection between two parts of the circuit. Often they lie on the "information" paths that were described in point 2. Try to decide what the signal is doing at these points.

4. What are the dynanic aspects of the circuit? Try to see what happens when the input or the controls are changed. How does this affect the output? How does it affect the important points you identified. When you change the input, where does the voltage or the current go up or go down?

Now turn to the problem that you are supposed to solve. Start by asking how the changes you are to make will affect the parts of the circuit that you identified. What changes are necessary? If the circuit does not work and you are to fix it, where might the problem be? What changes are necessary? How should the final or complete circuit differ from what you have to start with?

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In the specific orienting-task condition, the subject will be required to answer questions in a similar manner, but these questions will be specific to the comprehension of the circuit at hand and would not necessarily be meaningful for other circuits. In the activity control condition, the subject will be required to answer questions about the circuit. An example of such a task would be to construct a parts list for the circuit, or to re-draw the circuit layout. This manipulation will be included to evaluate the possibility that mere familiarity with the circuit parts and layout leads to enhanced performance.

5.5 Predictions

It is anticipated that the general and specific orienting tasks will influence the nature of and resultant quality of the problem-solution protocols generated by the novice technicians. The protocols should become more systematic, such as those produced by the experts in the second year of work, with less of the "trial-and-error" behavior that should again be exhibited by the subjects in the control condition. It is hoped that the general orienting tasks will be nearly as effective as the specific ones in improving the quality of performance. The derivation of guidelines for the comprehension of circuit diagrams would be more manageable if such a pattern of results were observed.

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