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ABSTRACT

A comprehensive undergraduate engineering program must provide opportunities for the application of theoretical concepts to the solution of realistic engineering problems. As digital systems and computer engineering concepts are integrated into the undergraduate electrical engineering curriculum, many departments are revising their laboratory programs to include more work with digital networks and mini-computers. In the study of the problem of developing undergraduate digital laboratory programs, the two major areas reviewed in this report are: (1) What digital concepts should be included in the laboratory program and how should they be presented? and (2) What type of laboratory facilities and Equipment are needed to carry out the recommended program? (Author)

DIGITAL SYSTEMS LABORATORY COURSES AND LABORATORY DEVELOPMENTS

An Interim Report of the

COSINE COMMITTEE

of the

COMMISSION ON EDUCATION
of the
NATIONAL ACADEMY OF ENGINEERING
2101 Constitution Avenue
Washington, D.C. 20418

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Task Force III	Some Specifications for an Undergraduate Course in Digital Subsystems. November, 1968.
Task Force IV	An Undergraduate Computer Engineering Option for Electrical Engineering. January, 1970.
Task Force V	Impact of Computers on Electrical Engineering Education—A View from Industry. September, 1969.
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DIGITAL SYSTEMS LABORATORY COURSES AND LABORATORY DEVELOPMENTS

I. INTRODUCTION

A comprehensive undergraduate engineering program must provide opportunities for the application of theoretical concepts to the solution of realistic engineering problems. As digital system and computer engineering concepts have been integrated into the undergraduate electrical engineering curriculum, many departments have begun revising their laboratory programs to include more work with digital networks and mini-computers. The development of these new laboratories requires a considerable amount of effort by the faculty as well as the commitment of financial resources by the department. In 1969 a number of faculty members approached the COSINE committee, and suggested that a task force be established to study the problem of developing undergraduate digital laboratory programs. This suggestion was accepted by COSINE and Task Force VI—Digital Systems Laboratory Programs—was established in the fall of 1969, and charged with the responsibility to study two major areas. They were:

A. What digital concepts should be included in the laboratory program and how should they be presented?

B. What type of laboratory facilities and equipment are needed to carry out the recommended program?

The first question is treated in Section II which deals with digital system topics that should be included in the laboratory program. The recommendations included in this section cover both introductory material that should be mastered by all electrical engineering students and material that is suitable for students who wish to carry out advanced laboratory project work in the computer engineering area.

Section III considers the problem of specifying the equipment needed to implement the various aspects of the recommended laboratory programs. This section provides a general evaluation of different classes of commercially available equipment and indicates the types of "in house" equipment that can be constructed. The trade-off between buying equipment and building it is considered in detail. During the study a great deal of factual material has been collected by the Task Force. Since much of this material is of general interest it has been included as appendices to this report.

II. THE LABORATORY PROGRAM

One of the major problems facing an electrical engineering faculty is that of making the student aware of how theoretical material presented in lecture courses can be applied to solve realistic engineering problems. In particular, it is extremely important for a student to be introduced to the practice of engineering as an integral part of his academic program. This need can only be satisfied if the engineering curriculum contains a well organized sequence of instructional and project laboratories which supplement the material presented in lecture courses.

The main purpose of a laboratory program is to allow a student to become familiar with current technology and to develop the skills and confidence needed to apply this technology effectively to the solution of complex engineering problems. However, a well organized and well run laboratory program makes other very important contributions to the educational process. Laboratories can provide an excellent means to motivate a student because they allow him to pursue a topic that interests him for an extended period of time. As he encounters and solves problems of increasing difficulty he will also develop the confidence and initiative necessary to handle complex assignments after graduation.

Another advantage of a well developed laboratory program, taught by experienced faculty members, is the close personal relationships that can develop between the students and the faculty. Informal discussions that develop in the laboratory setting provide an excellent opportunity for a faculty member to provide professional and personal guidance and encouragement to a student. Through these discussions, a student can be shown the relevance of various aspects of his education and he can be introduced to the professional responsibilities he will be expected to assume as an engineer.

In the past many laboratory programs have been organized so that the student is exposed to a series of short experiments designed to illustrate various concepts presented in the lecture courses. While this approach introduces the student to a number of different concepts, it gives him the feeling that laboratory work is only of secondary importance in his studies.

It is now recognized that the laboratory portion of the engineering curriculum should be considered equally important with the student's lecture courses since the laboratory is an ideal place to develop the student's problem solving ability. If the student is to use the laboratory effectively he must first master the basic technological skills needed in the laboratory. He then must undertake the solution of a sequence of increasingly more complex problems, each of which involve an extended period of time. A major advantage of this approach, if he is allowed to work on problems in an area of his current interest, is that it increases his overall motivation. This early concentration might, at first, appear to limit the student's outlook. However, if the laboratory program is properly designed, he soon discovers that there is a body of material that he must know from other areas. This realization then provides an incentive for him to seek out information from those areas that he originally considered of little importance.

The following discussion presents a comprehensive multistage laboratory program that has been designed to cover the complete digital and computer system area. The initial part of this program indicates the skill material that should be mastered by most electrical engineering students. The more advanced work is designed for those students who wish to explore the digital area in greater depth.

2-1 General Organization

The development of a laboratory program must be concerned with several different levels of instruction that take place over a number of semesters. Three distinct types of laboratory experience can be identified. They are:

a) Introductory
b) Intermediate
c) Project

At the beginning of the student's professional studies he should be introduced to the basic skills necessary to use a laboratory and laboratory equipment as a tool in solving engineering problems. This is a rather critical period since any bad habits learned at this stage follow the student throughout his professional career. The introductory program serves to introduce the student to the equipment and devices that he will use in later work and provides him with the confidence that the theoretical material discussed in lecture courses can actually be applied to the solution of practical problems.

Although the material presented at this level might appear to be of a routine nature, the way that it is presented and the quality of the laboratory instruction strongly influences the students' interest and attitude for later laboratory work. Every effort should be made to make the experiments interesting with a minimum number of "make work" type of tasks. In particular, students with previous experience should be encouraged to use it to carry out higher level investigations than those expected of students without previous experience.

The actual material covered and its place in the curriculum will, of course, depend upon the curriculum structure at each school. However, when a student has completed this introductory portion of the laboratory program he should be able to make effective use of the basic laboratory equipment and, hopefully, have developed an interest in conducting experimental work.

By the time a student has completed his initial engineering courses, he has started to develop an interest in one or more specific areas. The intermediate portion of the laboratory program should provide the student with the opportunities to explore his initial interests to see if he really wishes to enter a given area of work. This can be accomplished by allowing the student the freedom to select intermediate level problems from a set of topic areas. Each problem, which might require three to four weeks' work, should provide the student with the experience of developing and carrying out a complete experimental program from initial problem definition through the presentation of a final report describing his solution. While working out these problems, the student should learn how to trouble shoot his equipment and develop the ability to evaluate critically his own work. If proper laboratory instruction and guidance is available he will learn how to document his work and how to report his results.

As the student successfully completes the tasks necessary to solve each new problem he develops an understanding of the technology associated with the problem. In addition he develops the confidence that he can actually solve complex technological problems by applying, with a little initiative, the abstract concepts he has learned in his lecture courses.

After a number of intermediate level tasks have been completed, some students reach a point where they wish to attack much more challenging problems. This is an excellent point to introduce a laboratory project that may take one or even two semesters to complete. Not all students have sufficient motivation to tackle a complete project. However, those who do accept this challenge usually find that the project is one of the high points of their undergraduate education.

Since a project laboratory is carried out over an extended period of time the student has enough time to explore the problem under investigation and evaluate a number of possible solutions. During his investigations he is continually faced with the need to make and evaluate assumptions about the system on which he is working. This provides him with the opportunity to face the situation where he must use his own initiative to learn and apply concepts that are not part of his formal classroom work.

In many situations it is possible to coordinate the project work of the student with some particular research or development effort in the department. This approach has the advantage of allowing the student to work in an environment that is similar to the environment in which he will work after graduation. A successfully completed project of this type also gives the student a sense of accomplishment that is hard to duplicate in any other educational experience. Not only does the student receive the satisfaction of solving a difficult problem, but he also sees that his work will make a useful contribution to a larger effort.

This discussion of general laboratory organization has presented the different types of laboratory activities that must be considered in developing a comprehensive laboratory program. The points discussed have been used to guide the development of the recommendations given in the next sections.

2-2 Ground Rules for Recommendations

This report is concerned with the development of the laboratory program in the digital and computer systems area. Most of the introductory topics that are recommended should be considered for inclusion in the curriculum of all electrical engineering students. The recommendations for the more advanced laboratory work are designed for those students who wish to explore digital and computer concepts in greater depth and need not be taken by all students.

No attempt is made to recommend specific courses since each school has developed its own philosophy concerning the introduction of laboratory material into its curriculum. For those schools that have separate computer science departments, it is quite possible that some of the recommended work will be offered by that department. Similarly, some of the laboratory work offered by the electrical engineering department might be included in the computer science curriculum. When a situation of this type exists, a close working relationship should be developed between the two departments in order to coordinate the development of the area of common interest.

2-3 The Introductory Laboratory Program

Digital system technology has had a major impact upon the practice of engineering. Not only must a student be able to use a computer to carry out lengthy numerical calculations, he must also be able to use logic elements to construct digital networks and be able to understand the application of mini-computers as information processing elements in more complex systems. *The introductory portion of the digital systems laboratory program must, therefore, be designed to prepare students who wish to go further in the digital area. It must also provide an appreciation of the operation and use of digital devices for those students interested in other areas.* Thus, the introductory digital laboratory program has numerous goals, including familiarity with equipment and measurement techniques, illustration of various aspects of logical design, presentation of various practical design techniques for which there is not adequate theory, exposure to debugging techniques, and the elements of machine level operation and programming of mini-computers. These goals can be achieved by providing the student with a sequence of experiments designed to cover these areas and keyed in with the student's overall academic program.

To be able to expose students to such a broad spectrum of topics it is necessary that the digital system laboratory have available both a fairly extensive set of digital hardware and a small digital computer (or mini-computer). Equipping such a laboratory is discussed in Section III of this report. However, it should be clearly understood that a mini-computer alone does not create a digital system laboratory, but the machine in this problem-solving environment is as necessary as other pieces of digital hardware and instrumentation.

It is recognized that many schools will not be able, due to limited resources, to provide immediately a "total digital systems laboratory" environment. Therefore the following discussion is divided into two subsections. They are:

A. Basic Experiments Involving Digital Logic Networks.
B. Basic Experiments Involving a Mini-computer.

This introductory material forms the necessary background for the intermediate and project laboratory work discussed later.

2-3.1 BASIC EXPERIMENTS INVOLVING DIGITAL LOGIC NETWORKS

The availability of integrated-circuit digital logic elements at low prices makes possible a major change in the design and utilization of digital networks. No longer do students have to spend a large amount of time and effort designing and testing gates and flip-flops using discrete components. Instead they are able to use standard integrated circuit gates and flip-flops to design complete combinational and sequential logic networks.

The following discussion presents a list of topic areas that should be included in the introductory digital logic educational program. It is assumed that the student has taken or is taking a concurrent course that presents the theoretical background necessary to carry out each of these tasks. In some cases this material might even be part of an integrated lecture-laboratory course while in other cases the material might be integrated into a standard sophomore or junior laboratory program.

Since most of the material to be covered is of an introductory nature, the greatest effort of the student outside of the laboratory should be in preparing for the laboratory rather than preparing extensive reports describing his results. At this point it is much more important to awaken a student's interest and encourage him to try his ideas rather than hold him to the performance of a rigid set of predefined tasks.

The discussion associated with each topic area illustrates the type of information the student should have mastered when he has completed his work in that area. Appendix A presents a much more comprehensive discussion of the material that could be included on the laboratory work sheets given to a student to cover each of the topic areas. This material is included for guidance only and each faculty member must develop an appropriate set of hand-outs for his own particular program. The list of references at the end of this report also provides an additional source of ideas.

1. Measurement Techniques

It is assumed that the student is familiar with the standard methods of measuring voltage and current. The main emphasis in this area should be upon the use of oscilloscopes for pulse and timing measurements. In particular, the relationship between pulse width and scope bandwidth, the use of the delayed trigger and the use of multiple trace techniques should be well understood by the student.

2. Characteristics and Use of Basic Integrated Circuits

The different families of integrated logic circuits, their typical operational characteristics and logic levels should be examined. The student should explore and understand the meaning of the fan-in and fan-out characteristics of logic elements and how the load presented by a given element can be determined. Studies of the inherent delays of the different types of logic elements should be carried out.

3. Design of Combinational Logic Networks

The student should be required to reduce a word description of the operations that must be performed by a given network to a network that will perform the operation. This task should include cost and logic element availability considerations. The use of multiple level NAND logic should be emphasized since this type of logic is in common use.

4. Flip-Flops, Pulse Generators and Multivibrators

Realization of flip-flops, pulse generators and multivibrators using NAND gates. Characteristics and use of integrated circuit flip-flops and investigation of the switching speed of the flip-flops under clocked operating conditions. Generation and control of pulses and pulse trains.

5. Registers and Counters

The construction and operation of simple registers and counters using integrated circuit flip-flops. Use of clock signal to control serial and parallel information transfer into registers. Design of simple counters, both synchronous and asynchronous. Introduction to some of the standard counting circuits used in digital networks.

6. Synchronous Sequential Network Realization

Design of the logic circuit necessary to realize a simple synchronous sequential network represented by a flow table. Study of the factors that influence the operating speed of the network. Reduction of a word description describing the desired operation of a sequential network to the circuitry necessary to realize the network.

There are a number of different ways that the material listed above can be presented to the student. The main goal is to develop the student's skill and confidence in using digital logic elements to realize usable logic networks. It will be assumed that a student can use these skills as needed to solve the problems presented to him in the intermediate and project portion of the laboratory program.

2-3.2 BASIC EXPERIMENTS USING A MINI-COMPUTER

In the previous discussion a set of experiments was presented which were designed to give students a fundamental knowledge of the properties of digital devices and the organization of these devices into digital networks. In a similar fashion, it is important that a student have a "working" knowledge of the operation of a mini-computer and how it can be used to carry out various information processing tasks.

The widespread availability of mini-computers at reasonably low prices has made it possible to think of the mini-computers as a laboratory instrument or as a component in a complete system as well as a straight computing device. Because of this wide range of applications, the need to provide students with at least a basic understanding of the concepts of assembler language-level programming and software design has increased considerably during the past few years. This need exists for both students who wish to enter various areas of computer engineering as well as students from other areas who wish to make effective use of mini-computers as part of other systems.

An understanding of software concepts cannot be obtained by reading texts and instruction manuals or listening to lectures. A student must write and debug a number of programs that apply these concepts to the solution of actual software problems before he can fully appreciate their importance. Fortunately, it is a relatively simple and straightforward task to learn how to program and use a mini-computer. However, the design of a laboratory environment where the student can learn this skill is not an easily solved problem.

The first laboratory exposure to mini-computers must be organized to teach each student the skills that he needs in order to use the computer. He must be provided with an opportunity to learn how a computer operates and how a uter's machine language influences the tasks that a computer can perform. After the student has mastered the basic programming skills, he should write, debug, and document a number of sample programs.

Experiments designed to provide the student with skills using a mini-computer should cover (at least) the following topics. References 1, 3 and 10 discuss these problem areas in greater detail.

1. Basic Operation of a Mini-Computer

One of the chief advantages of a mini-computer is the relative simplicity of its machine language instruction set. The instruction set is usually restricted to data transfer instructions between arithmetic register(s) [accumulator(s)] and memory, addition, a number of test and skip instructions for conditional transfers, instructions for transmitting information over the I/O channels, and a series of micro-instructions which manipulate the contents of the arithmetic register(s), including an instruction to HALT or STOP the execution of a program. For this reason, programming in machine language gives the student an excellent opportunity to learn and appreciate the relatively small set of basic functions performed by a digital computer (or digital system). Therefore, the first topic to be covered should provide a student with an understanding of a computer from the register level. This can be accomplished by requiring a simple program to be written (such as computing the sum of m-numbers or displaying a changing pattern of lights), then hand-loaded into core, executed, and provided with the necessary test and HALT instructions to stop the computer at the completion of the program.

2. System Software and As[illegible] [illegible]nguage Programming

The programming of most mini-computers for use in a system is carried out using the assembler language associated with the computer. The writing and debugging of assembler programs is simplified if the student masters the operation of the assembler used by the computer to process assembly language programs as well as such system programs as editors and debugging programs. Thus, after the student has been introduced to the basic operation and instruction set of the computer, he should carry out a series of exercises that will teach him how to develop more extensive programs using the computer's assembly language.

3. Programming Techniques and Data Representations

To use a computer effectively, a student must develop such programming skills as counting, indexing, the use of indirect addressing, the use of pointers, looping, and the construction and use of subroutines. These skills, while important in themselves, also illustrate the trade-offs possible between execution time and the amount of storage required to perform a given function using different algorithms. In addition, the introduction of algorithms raises the question of data representation, symbolic data and numerical data (fixed point, floating point, signed numbers).

The problems associated with the mismatch in timing characteristics between a computer and its peripheral input and output devices must be covered. Solutions to these problems such as the use of flags and buffers (asynchronous operation) should be investigated. Once again the student is faced with the question of data representation, this time converting from the internal code of a computer to the external code used by the peripheral device (such as ASCII for the ASR33 teletype) and vice versa. Techniques for packing and unpacking words when converting from one code to another should be included here.

After a student has mastered the digital hardware and mini-computer concepts described above, he will have a good basic understanding of the operation of digital systems and he should be able to apply these concepts to the solution of realistic problems. Thus it is reasonable to expect that most electrical engineering students would be exposed to most of this material. Those students interested in exploring digital system concepts in greater depth should be able to elect additional intermediate and project work in the digital area.

2-4 The Intermediate Laboratory Program

The main purpose of the introductory laboratory work is to teach the student the skills that he needs to carry out more advanced work. As such, the exercises performed by the student are highly structured and require relatively little analysis and design effort. When a student enters the intermediate portion of the program it is assumed that he has mastered the basic skills discussed in section 2-3 and is able to apply them intelligently. *Thus the goal of the intermediate program is to develop the student's ability to define and solve realistic engineering problems.*

Carrying out the problem solution requires the following stages: definition of the problem in exact form, development of possible solutions, testing and evaluation of solution, reporting of results. The intermediate laboratory program must be organized in such a way that the student is introduced to each stage of the problem solving process. This can be accomplished by giving the student a sequence of problems to solve. Each problem should take about three or four weeks of work and should require both in-laboratory experimentation and out-of-laboratory analysis, design and report writing.

The design of the problems to be assigned to the student will depend upon the facilities available in the laboratory, the background of the students and the interests of the faculty. Ideally, the projects should cover a wide range of topics and require the design of hardware networks, mini-computer software programs and interfaces to the real world for their solution. Since a laboratory of this type will require the student to use a wide range of theoretical concepts it is also assumed that an appropriate sequence of theory courses is available to the student either preceding or concurrent with the laboratory.

As indicated previously it is not possible to recommend a "required" set of experiments that should be performed by all students. However the following set of suggested topic areas provide guidelines to the type of material that should be contained in the intermediate level program. Local conditions will, of course, suggest other topics and ways to present the suggested concepts.

1. Transmission and Synchronization of Digital Data

In many digital systems (delay lines, code transmission systems, teletypes) information is transmitted in a serial form from one location to another. A number of different problems must be solved in developing such a system.

When data is transmitted in serial form the receiver must be able to be synchronized with the transmitter. This is usually done by constructing the data sequence in a manner that allows the receiver to derive synchronization information from the received data string. Problems involving synchronization techniques provide students with an excellent opportunity to learn how to handle timing considerations in digital systems.

In many information transmission systems, error detecting and error correcting techniques are used to handle transmission errors. The design of encoders and decoders to realize some of the simpler error detection and error correction algorithms provides a good opportunity to introduce the student to the idea of encoding and decoding data.

2. Basic Information Processing Package

Many of the standard information processing operations such as multiplication, division or square root evaluation require extensive digital networks. Designing a network to perform one of these operations using either a standard or a special purpose algorithm makes an interesting problem.

3. Analog/Digital and Digital/Analog Conversion

The design of an analog to digital converter and the use of the converted data in a mini-computer program provides an excellent introduction to the problem of interfacing analog and digital systems. Students can investigate such things as conversion rate limitations, methods of storing and using converted data, the effect of limited word length on calculations using converted data, and the relationship between computation speed and the bandwidth of the analog information being processed.

4. Digital Filtering

Study of the use of digital techniques to filter analog data. A digital filter could be constructed completely from hardware or a mini-computer program could be developed to carry out the operations. An evaluation of the factors limiting the bandwidth of the filters that can be realized should be emphasized in this experiment.

5. Display System Design

Visual displays form a very important class of output devices. A problem involving the generation of simple patterns on the face of a CRT provides a rich area for problems. These problems can involve the development of hardware networks, software programs or a combination of the two to carry out specific display tasks.

6. Hybrid Computer System

Integrated-circuit operational amplifiers make it possible to construct hybrid analog/digital computers that can be used to carry out simple information processing tasks. Problems built around the design of a hybrid computer to carry out a particular task or the programming of a hybrid system will provide the student with an excellent introduction to the relationship between analog and digital systems.

Depending upon the program taken by the student, the intermediate laboratory program will either be the terminal laboratory experience in the digital area or it will serve as a lead in for more advanced project laboratory work. It is particularly important that the faculty and staff associated with the intermediate laboratory work closely with the student to provide the guidance necessary to develop the student's problem solving ability. The student should be continually asked to defend his work and assumptions. This not only encourages the student to prepare properly for his in-lab work but it also builds up the student's confidence that he can actually carry out a complex design task.

2-5 Project Laboratories

Project laboratories are the least structured of all of the laboratory forms. *The essential features of a project laboratory are that it permits a student or a group of students to choose or originate project ideas and enjoy a high degree of autonomy in the design and realization of the project.* These projects do not necessarily have to be practical or perform any useful function; however, a most important characteristic of a project is that it "works" and that it fulfills some goal close to that stated in the student's initial project proposal. This is important not only for the evaluation of the student's performance, but also because of the sense of fulfillment experienced by the student upon successful culmination of his project.

Perhaps the most difficult aspect of a project laboratory is guiding the student in his choice of a project. Care must be taken to insure that each problem is reasonably complex as to scale and sophistication of design, yet feasible within the limitations of time and available equipment. The student's previous laboratory work often provides some guidance in the selection of a topic. It is also helpful to have lists available of possible projects, together with short descriptions of some of the problems involved in carrying out the project. This list can be the result of suggestions made by faculty members as well as ideas that have been suggested by previous student projects. A library of previous student project reports should be available for inspection by the student.

One of the most difficult tasks that must be carried out is that of matching the capability of the student to the project that he selects. The above average student (and this does not necessarily mean the student who receives all A's in his classroom work) will often find interesting projects associated with some research program being carried out in the university. These projects may be of an interdisciplinary nature and can involve a group of students with varying backgrounds working together. This can provide an excellent educational experience for the better qualified students. However, unless the instructor is willing to devote a great deal of his time to individual work with a student, average students should be encouraged to select less compre[illegible] problems.

It has been found that one very effective way of communicating to the students the scope and complexity of projects they are capable of successfully undertaking is to show a video tape recording of student demonstrations of the previous term's projects. Video tapes used for this purpose need not be of broadcast quality. There are several brands of home-quality video recorders which are currently available.

Some possible projects are listed in the following table. A short description of some of these projects is given in Appendix B.

Although project laboratories are the least structured, the time allotted for any project lab subject is limited and a set of deadlines should be established so that the student knows when he must complete the different stages of his work. The main checkpoints that should be indicated are:

1. Definition of project
2. Completion of first design and analysis
3. Completion of first working solution
4. Completion of experimental work on project
5. Date project report due
6. Date of oral presentation of project results

The initial definition of the problem should be spelled out in a brief project proposal that is submitted to the instructor either before the student is allowed to register for the course or shortly after the course begins. Using this proposal, the instructor can decide upon its feasibility in terms of the availability of adequate laboratory facilities and the competence of the student. Once the instructor accepts the proposal, it is helpful to have the student make an oral presentation of his project proposal to an audience comprised of both instructing staff and fellow students. Very often this type of presentation with its associated question-and-answer period clarifies the scope of the proposed project. In addition, constructive suggestions are often offered both by other students and teaching staff.

The next phase of the project involves the detailed design which must be accomplished before any actual hardware construction is undertaken. During this time, the teaching staff should maintain at least weekly contact with each group of students. This contact should be of a consultive nature and at most supply guidance to the student by giving helpful suggestions or asking leading questions.

After the initial analysis and design has been completed and accepted by the instructor, the next task that must be carried out by the student is to develop the hardware and software defined during the design stage. The teaching staff should monitor this work in detail to keep the students from wasting too much time going down blind alleys. Here again the instructor should only offer advice and suggestions and should not step in and solve the problem.

At the end of each term, each student should be required to deliver both an oral presentation of his project to the instructing staff and other students, and to submit a typewritten project report. In the case of partners, diagrams should be prepared jointly with copies included in each report. Project partners should be encouraged to discuss the content of their reports, but should write their reports independently. In both the oral and written presentations, each student should emphasize those aspects for which he had particular responsibility.

While the major reward for successful completion of the project is the satisfaction that it engenders, an additional and not inconsequential reward is being selected for video taping when this method of instruction is used as suggested previously.

Table II-1 provides a list of representative projects that have been successfully completed at various institutions.

Table II-1

Project Suggestions

A. Game playing machines

1. Blackjack
2. Tic Tac Toe
3. Nim
4. Coin flipping prediction
5. Bowling score computer
6. Jigsaw puzzle solver
7. Bridge-opening bid computer
8. Acey-Deucy
9. Roulette wheel
10. Slot machine
11. Space Chase

B. Arithmetic - binary or decimal, serial or parallel, fixed or floating point

1. An arithmetic unit to add, multiply, divide and form the square root of a number
2. Log and antilog
3. Binary rate multiplier
4. Difference equation solver
5. Matrix inversion or multiplication
6. Vector operations
7. Polynomial differentiation
8. Determinant evaluator
9. A simple computer

C. Control and Miscellaneous

1. Elevator control system
2. Digital television
3. Juke box control
4. Delay line memory and dynamic sketchpad
5. Light pen tracker
6. Dot raster numeric display
7. Sampling pen recorder
8. Facsimile transmission
9. Pulse position, pulse code or delta modulation
10. Error detecting and correcting codes
11. Digital tape recording
12. Time division multiplexors
13. Scope pattern generation
14. Digital sequence detector
15. Priority nets

Edge enhancement

Table II-1 (Continued)

17. Character generation (oscilloscope or paper tape)
18. Digital chord generation
19. Digital cipher machine
20. Interchange sorting
21. Rally computer
22. Flying dot character recognition
23. Music generation
24. Karnaugh map MSP generator
25. Roman numeral reader
26. Hardware test editor
27. Touch tone to dial pulse converter
28. Teletype security system
29. Decode handwritten numerals
30. Automatic telephone dialer

III. EQUIPPING DIGITAL LABORATORIES

The discussion in Section II has emphasized the different types of laboratory experiences that should be available to all electrical engineering students as well as the experiences that should be available to those students wishing to enter the computer and digital system area. To implement these laboratory programs, it is necessary to have adequate facilities. In many schools this will mean that a considerable amount of new laboratory equipment must be purchased. This part of the report presents the considerations that must be evaluated when making these purchases and when setting up the corresponding digital laboratory facilities.

The development of a comprehensive laboratory facility involves a considerable amount of effort and expense. To insure that the desired results are obtained, a long range development plan should be worked out consistent with the funding that is anticipated to be available. Under ideal circumstances, funds should be initially available to fully equip the laboratory with the equipment necessary to carry out the introductory laboratory program and to allow a reasonable number of students to carry out intermediate and project work. After the laboratory is established sustaining funds should be programmed to allow for the purchase of new equipment, expansion of the laboratory, and, of course for replacement and repair of equipment that wears out during normal laboratory use. This continual support is extremely important since the digital system area is changing very rapidly and new technological changes can greatly influence the type of equipment that should be included in the laboratory. Without continual updating of the laboratory equipment, the laboratory facilities will become outdated in a relatively short period of time.

The following discussion provides a guide to the types of equipment available for laboratory use, the relative advantages and disadvantages of each type, and makes recommendations concerning the order in which various classes of equipment should be purchased. Each department must interpret these recommendations in light of its own educational program, the capabilities of its faculty and the funds available for laboratory development. In some situations a considerable amount of money can be saved, if shop facilities are available, by building some pieces of equipment. A number of "how-to-do-it" suggestions are included in Appendix C for those who choose this route. Appendix D presents a brief review of commercial equipment that has been designed for laboratory use.

The equipment needed to carry out the laboratory program discussed in Section II can be separated roughly into three classes. These are:

1. Logic networks
2. Modular components
3. Mini-computers

These classes are listed much in their order of service to the desired pedagogy and, therefore, in the order of their most appropriate acquisition.

Logic networks include the basic logic elements such as gates, flip-flops, switches, etc. needed to build digital networks as well as the associated interconnection scheme such as bread-board or patch-board devices necessary to interconnect these elements. The modular components correspond to complete operational units such as core memories, delay lines, teletypes, display systems, etc. which may be included in a complete digital system.

Mini-computers and the peripheral devices associated with these machines will, of course, play an important role in the overall laboratory program. However, while a mini-computer may certainly be a more glamorous piece of equipment than a mere collection of circuits, sockets, and wires, the temptation to make this purchase must be resisted until the latter equipment, so essential in the basic digital laboratory, has been obtained. The initial laboratory planning should certainly look forward to the introduction of computers in the system, but the initial laboratory efforts should be focused on the fundamental aspects of digital system design and implementation. It has been correctly argued that the premature introduction of computers may actually subvert the pedagogical goals of the digital system laboratory.

3-1 Logic Networks

In developing a digital system laboratory, the following questions must be answered:

1. What logic elements must be made available to the students for system construction?
2. How are the components of the system packaged and how can they be interconnected?
3. How will the students input digital signals and information to the system they are developing?
4. How will the output information generated by the system be indicated?
5. What types of power sources are needed to supply power to the system?
6. What type of measuring equipment is necessary to aid the student in trouble-shooting his system and observing its behavior?

The following discussion presents some of the different ways that these questions can be answered and indicates the relative merits of alternative solutions.

3-1.1 LOGIC FAMILY SELECTION

Central to any logic laboratory unit will be the actual logic elements that form the building blocks of this system. Virtually all modern digital equipment is now built from integrated circuits (IC's) rather than discrete components. There is a prodigious array of IC's available today, and new circuits appear on the market almost daily. The complexity of these integrated circuits ranges from those containing one or two gates, to so-called MSI (Medium Scale Integration) packages providing, for example, 4-bit adders or shift registers in one package, to LSI (Large Scale Integration) units which may contain, for example, a 1024-bit high speed semiconductor memory array and the associated decoding circuitry—all on a single silicon chip. Any digital laboratory program which ignores such rapidly burgeoning developments as these will be of decidedly limited value to the students. Without regard to the particular logic operation, there are a number of different families of integrated circuits that are commercially available at reasonable prices. The articles by Garrett (reference 2) gives the advantages and disadvantages of each major family.

It is highly recommended that TTL (Transistor-Transistor Logic) circuits be selected for any new laboratories or for the updating of established laboratories. This logic family currently enjoys widespread popularity among designers and manufacturers of digital equipment because of its low cost, high speed, good noise immunity, high fan-out capability, and the variety of available logic functions. Also, TTL is the most rapidly expanding family, including most new MSI announcements. TTL integrated circuits are available in a variety of package styles; however, the dual-in-line package (DIP) is best suited for laboratory application. Large and rapidly growing sub-families of TTL circuits available in plastic or expoxy DIP's are particularly attractive to logic lab programs because of their low cost and ruggedness.

The choice of TTL logic as the most desirable logic family for logic laboratory application is motivated by the numerous advantages offered by the family as noted above. As a second choice, DTL (Diode Transistor Logic) would be acceptable in a logic laboratory. This family of logic is in some instances slightly cheaper than TTL but has as a major disadvantage the fact that it is significantly slower than transistor-transistor logic. DTL and TTL units are completely compatible and, therefore, a mix of DTL and TTL IC's in a laboratory should pose no problems of consequence.

Other families of logic, while important to specialized system designers, are perhaps not too appropriate for general use in digital logic laboratories. ECL (Emitter Coupled Logic) for example, has a number of disadvantages in this environment. The most pronounced is, perhaps, the requirement for multiple power supply voltages. The extremely high speed of this logic family also may require very specific lead dress and mounting requirements. As another example, the much older RTL (Resistor Transistor Logic) while still available in fair variety and at moderate cost, is rapidly becoming obsolete. Thus, its use in a laboratory program is somewhat unrealistic and supplies of this family of logic are liable to become scarce in the future. In short, for the present, logic which is compatible with DTL and TTL should prove quite serviceable in a digital logic laboratory.

A desirable option for a logic laboratory program might include the expansion of the facilities to include Metal Oxide Silicon (MOS) devices. In all likelihood, this type of device will gain very much in popularity in the next few years. However, the guarantee of MOS capability should not defer beginning decisions. It is better to have an on-going DTL/TTL lab than to postpone the activity while awaiting decisions regarding MOS compatibility.

3-1.2 SELECTION OF BASIC LOGIC OPERATIONS

Once the logic family has been chosen, the user must then decide upon the particular logic elements to be included in the laboratory. Two types of elements must be selected, combinational logic gates and flip-flops.

Assuming that TTL or DTL circuits have been selected for laboratory use, the most likely choice for the basic gating element is the NAND gate. This is a universal function for which a number of clever design algorithms exist. (See reference 13). For introductory laboratory work a collection of 2, 3, or 4 input NAND gates is satisfactory. However, as the student progresses to the more advanced work, it is desirable to provide him with a more extensive collection of gate types so that he can become familiar with the full range of possible gate configurations.

The basic storage element is the flip-flop. There are a number of different types of flip-flops available. For laboratory use considerations of generality and flexibility are prime considerations. The master-slave J-K flip-flop with separate preset and clear inputs to each flip-flop is the best choice for general laboratory use.

The introductory laboratory program can easily be run with 6 to 8 flip-flops and twenty to thirty gates for each student station. For intermediate level laboratory work experience has shown that typical projects may require on the order of 100 gates and 35 flip-flops. Student projects usually grow to the limits imposed by the availability of equipment. It is not unusual to find student projects that utilize 150 gates and 60 flip-flops.

3-2 Packaging and Interconnection Techniques

It is perhaps in the schemes used to package and interconnect the various logic elements in the laboratory unit that the systems which are available for use show the greatest variety. Several qualitatively different schemes are available for this purpose. Some of the most common of these schemes are reviewed in this section.

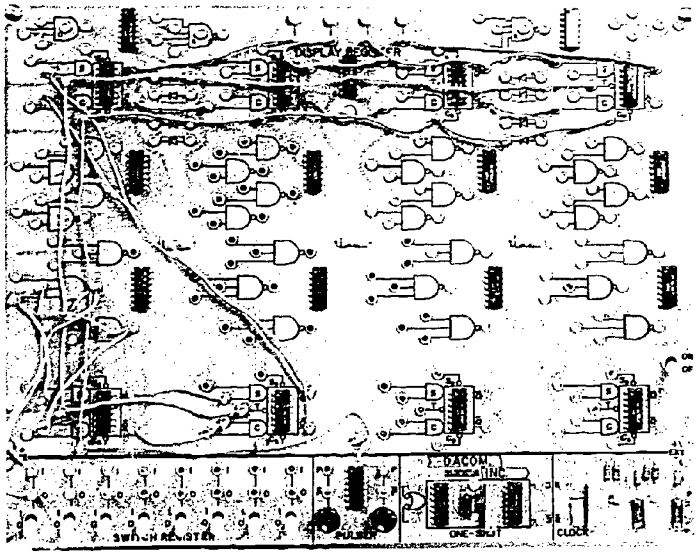
For purposes of discussion, packaging and interconnection schemes may be organized into three general classifications. The first class shall be referred to as fixed patching systems with generally small fixed arrays of logic and some interconnection facility. The second class is the generally larger assembly of modules with a removable patching panel arrangement for interconnection. The third class includes systems which to some extent resemble breadboards of conventional construction techniques. This third class of systems may be further subdivided into two classes depending upon whether the plugable module is at the printed circuit card level or at the integrated circuit package level.

This classification of interconnection schemes is somewhat arbitrary and some few systems do not fit into this classification while others may cross class boundaries. This discussion will deal with the general characteristics, advantages and disadvantages of each of the main classes. Appendix D presents a survey of the different types of commercially available equipment that fits into each of these classifications. Appendix C illustrates how similar equipment has been constructed at various schools.

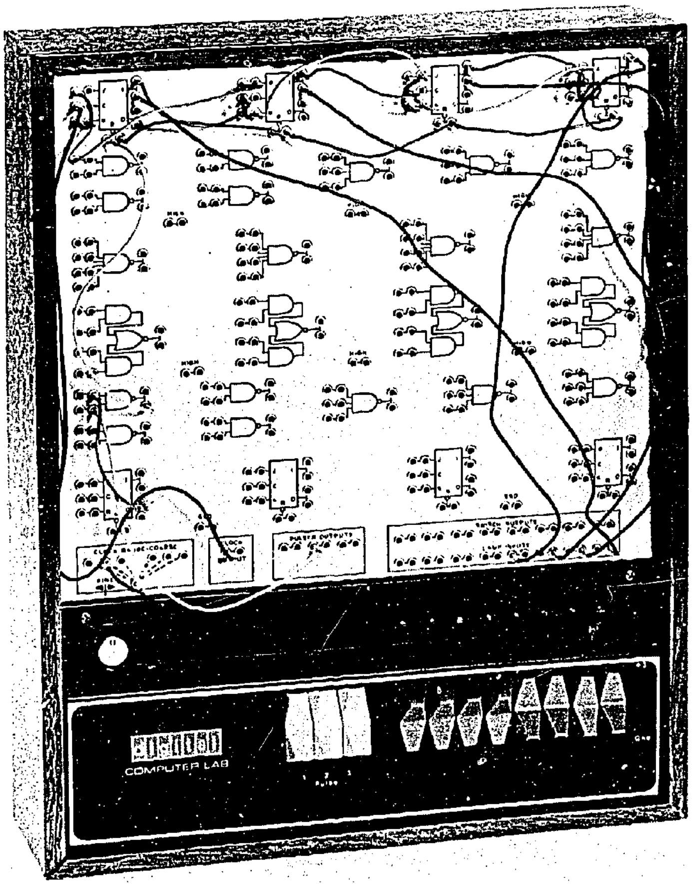
3-2.1 FIXED PATCHING UNITS

One common method of mounting logic elements is the fixed patchboard scheme. In this arrangement, a panel is provided on which standard symbols for gates and other logic elements are silkscreened or otherwise displayed. Corresponding to each such symbol is a "live" logic element hidden somewhere beneath the panel or elsewhere with its input and output terminals electrically connected to jacks in appropriate positions on the patch panel. Switches for input levels or pulses and lamps for output indication are typically provided. Often, a clock pulse and delay multivibrator are available. The units are usually self-contained including power. Typical units have some eight or so flip-flops and perhaps as many as forty gates available for interconnection. In order to experiment with a logic circuit of his own design or from a "cookbook," a student need only interconnect the jacks corresponding to the appropriate leads of the logic element with one another in the proper fashion using patch wires with suitable plugs on each end. Since the actual logic elements are soldered in some hidden part of the units they can neither be easily interchanged nor replaced. Thus it is of crucial importance to make certain at the time of purchase that a lab unit of this type uses a suitable family of logic and provides a sufficient number of logic elements. Expansion beyond the initial choice or any changes in the logic will be very expensive if, indeed, possible at all.

Two typical fixed patchboard units are shown in Figures 3-1 (a) and (b). The first unit is homemade while the second unit is the Computer Lab made by Digital Equipment Corporation. Units of this type are best for introductory lab work where students are working on relatively simple circuits. More ambitious projects ordinarily require the connection of two or more units. Because of their size, it is usually not practical to try to construct circuits that require more than two units.



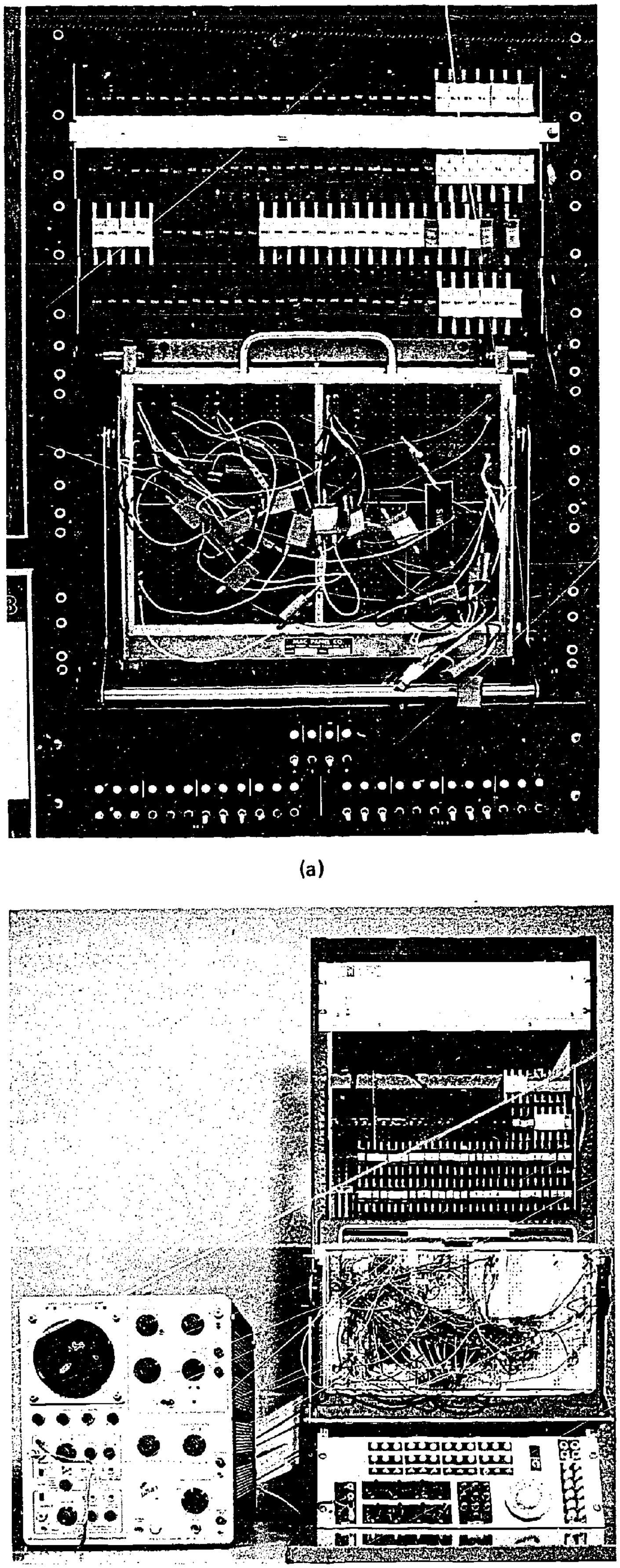
(a)
Homemade Unit



(b)
Commercial Unit
Two Typical Fixed Patchboard Units
Figure 3-1

3-2.2 REMOVABLE PATCHBOARD UNITS

The second variation of patching schemes employs a removable patchboard as illustrated in Figure 3-2. In this scheme, the pins of the integrated circuit modules are mapped to a receiver. The receiver accepts a removable



(a)

(b)

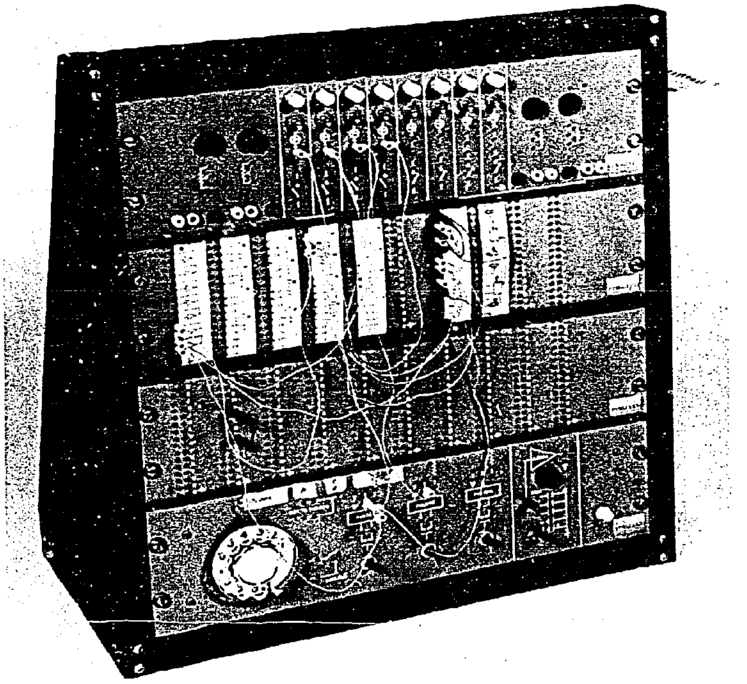
Removable Patchboard Units
Figure 3-2

patch panel upon which the students may connect their logic system. Typical systems of this sort may also have switches, lights, clocks, etc., associated with certain positions on the patch panel. In some situations, larger functional modules such as counters and registers are accessible by patching. Patching points may be provided for communication links to mini-computers, teletypes, delay lines, A-D and D-A converters and other similar types of equipment. Typical units of this construction (one type is detailed in Appendix C) may have some 65 flip-flops and some 160 gates available for interconnection.

This scheme has the advantage of permitting a large number of students to time-share a rather extensive collection of equipment at modest expense. If the patchboard is small enough, students can take it home, wire up their logic design, and later plug it into the carrier which interfaces the patchboard to the logic elements. This arrangement can make considerably more logic elements available to each student than the fixed patchboard.

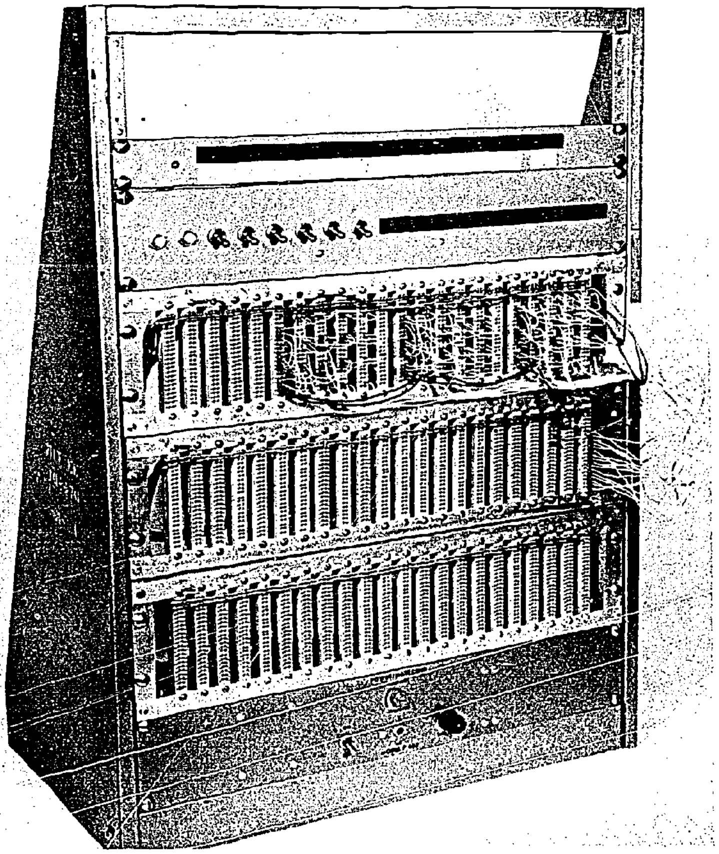
3-2.3 LOGIC CARD UNITS

In one version of the third class of mounting and patching schemes, integrated circuit modules may be mounted on printed circuit cards for insertion into conventional card sockets. The socket pins may be mapped onto a panel for patching as in the Digital Equipment Corporation Logic Lab (Figure 3-3 (a)). This unit has module diagrams which may be inserted on the patching panel in association with the printed circuit card plug-in. Optionally, the socket pins may simply be made available for interconnection patching at the socket terminals as the homemade equipment shown in Figure 3-3(b). In this instance, the logic system wiring resembles the back panel wiring found in many contemporary digital systems. In either the panel or socket connection scheme, the required modules for a given system are inserted in the connectors and appropriate interconnections are established between these chosen modules. The interconnections may extend to additional panels or certain connectors may be routed to additional panels for switch input levels or pulses, output indicating lights, or other external equipment. Generally, a power supply is included with a rack of such card sockets and the cards are arranged so that all cards are powered at the same pins. This permits power and ground circuits to be bussed throughout the system and only the interconnecting logic signals need be patched. Systems of this class are readily expandable in terms of module complement. The typical units shown in Figure 3-3 can be used to build systems with 60-80 flip-flops and 160-200 gates.



Commercial Unit

(a)



Homemade Unit

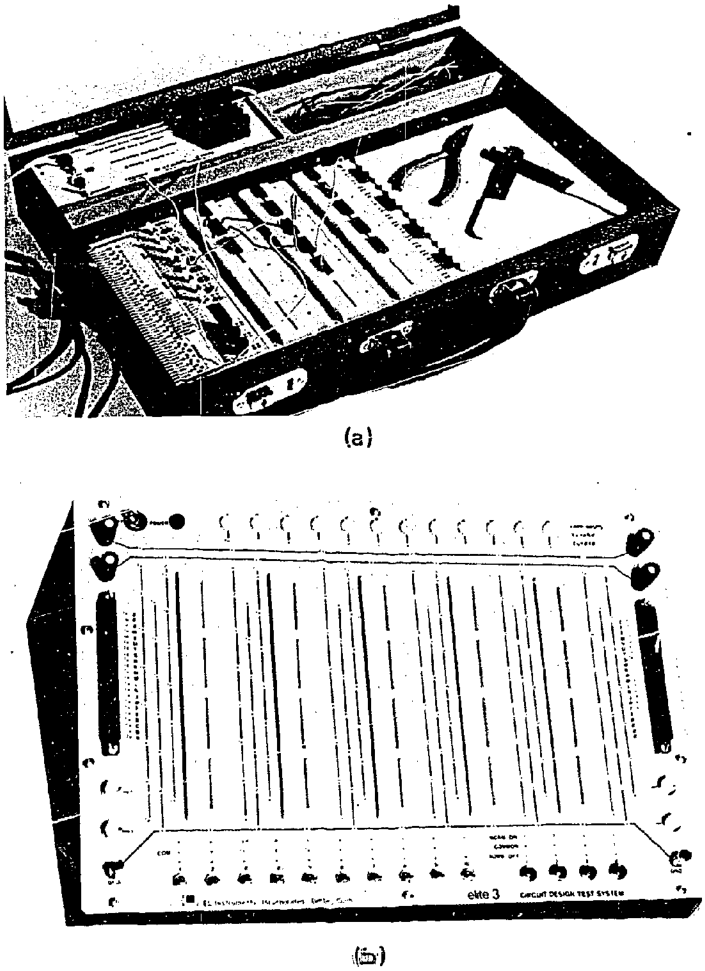
(b)

Two Typical Logic Card Units

Figure 3-3

3-2.4 SPECIAL CONNECTOR SOCKET BREADBOARDS

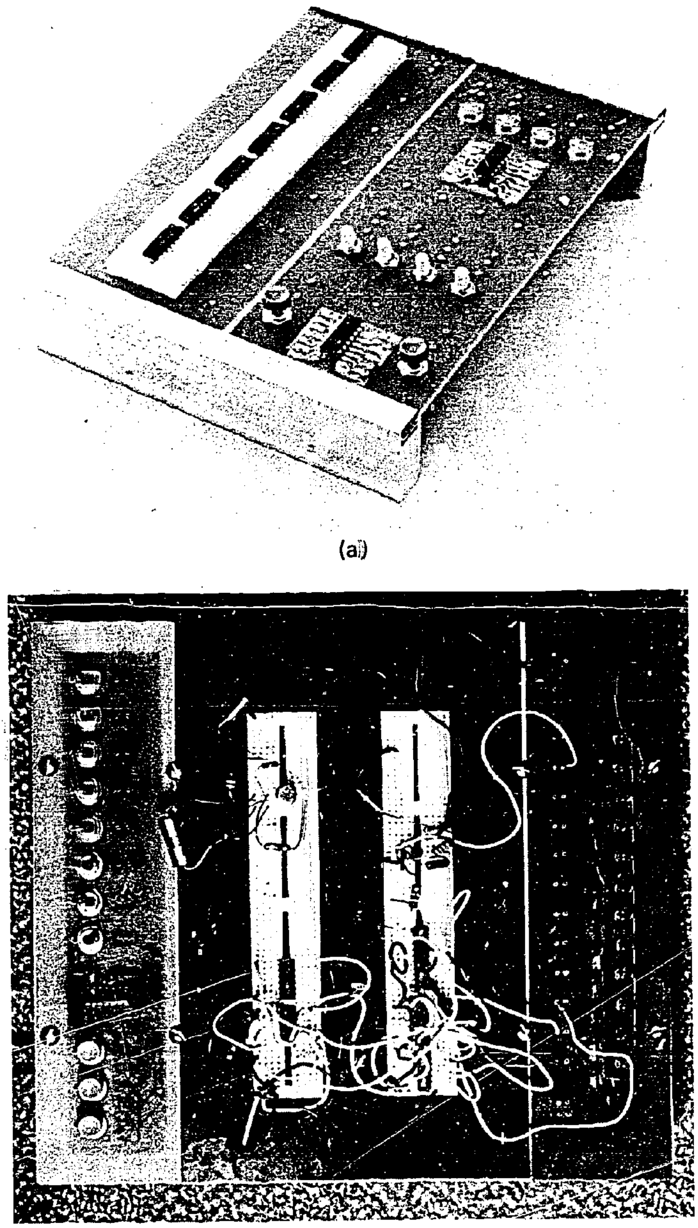
The second version of the third class of mounting and interconnecting schemes involves a rather special connector socket which accepts the integrated circuit in DIP or TO-5 packages as a plug-in device. This socket allows each terminal of the IC to be fanned out to multiple tie points so that the interconnecting wiring may be accomplished. Commercially available systems using this technique are shown in Figure 3-4 (a) and (b) and "homebrew" versions using this concept are shown in Figures 3-5 (a) and (b). An analogy to current construction practices for this scheme is found in the "mother board" concept which is employed in many contemporary digital systems. Generally, the subunits of this type of system carries several IC packs. Other subunits of the system may supply facilities for patching input switches, output lights, etc. Numbers of such boards may be assembled on common rails or in common packaging configurations. The assembly of subunits (mother-board) may have a multi-pin connector which allows the entire unit to be plugged in to a larger system assembly. Again systems of this class are readily expandable in terms of module complement. The systems shown in the above figures have the capacity to handle 8 dual inline packages per mounting strip. Systems involving 50 such packages can easily be constructed.


(a)

(b)

Commercial Breadboard Units

Figure 3-4


(a)

(b)

Homemade Breadboard Units

Figure 3-5

3-2.5 SYSTEM COMPARISONS

At this point it is possible to compare the relative advantages and disadvantages of the different classes of patching and interconnecting schemes described above. There are a variety of factors that must be considered in evaluating any given unit for use in a given laboratory program. Some of these are:

a) Initial Cost
b) Expandability
c) Flexibility
d) Ease of multiple student use
e) Portability
f) Cost of operation and maintenance
g) Size of projects that can be carried out

The weight that should be applied to each of these factors depends upon the type of laboratory program being developed.

The fixed patching scheme has a number of advantages because they are designed to be simple to use. These units are typically self-contained and highly portable, having their own power supplies and pulse generators for clocking signals. If such units are available, students prefer to take them to their home or dormitory so that they may pursue their problems at their own pace.

The small size of these systems may be deceiving. It is true that a problem such as the realization of a twenty-four bit counter is out of the question; however, the realization of a full flow table with, say, eight input variables and eight internal state variables is quite a large and formidable problem. Such a problem can be quite adequately patched on any of these small systems. For this reason, the small systems find considerable use by intermediate and advanced students for flow table realization or the painstaking debugging which may be necessary in the design of some small subsection of a larger system.

The results of a survey conducted by this COSINE Task Force (Appendix E) indicate that this fixed panel patching scheme has been the type of logic laboratory equipment that has won the quickest favor with educational institutions. This popularity is not surprising in view of the fact that commercial units of this type are specifically designed, promoted, and widely distributed as foundation blocks for student laboratory programs. These units are often supplied with a comprehensive description of particular laboratory programs in which they may be employed. Of course, such teaching or self-teaching aids reduce the faculty work load involved with establishing a new laboratory program. The obvious trap is that such "cookbook" programs cannot long serve an active digital laboratory. Further, the usual gamut of "cookbook" experiments hardly explore the real possibilities of these systems.

Obvious disadvantages also accrue to these systems. These, again, largely stem from the design which is directed at simplicity in use. The mapping from logic element to logic symbol often implies that the module is in an inaccessible position and hence, difficult to service. Most commercial units also require leads with special plugs to interconnect the various logic elements. These leads are usually expensive and are easily lost. In addition, the basic logic operations provided are fixed. Thus there is little flexibility in the choice of components available to the student. The design of the fixed patching scheme is not directed to the large project type of experimentation and it is not an appropriate piece of laboratory equipment for some of the more ambitious system realizations. Perhaps the major disadvantage of the commercially available systems is in the cost of providing facilities for student use. For their intended use as a unit to introduce a student to basic logic design concepts, their convenience of use compensates for their high cost per logic unit available. However, this cost factor makes these units entirely unsatisfactory for project work.

The units employing removable patchboards (Figure 3-2) probably provide more logic power per student for a given capital expenditure than any other system scheme which can be employed. Unfortunately, there are currently no systems commercially available that employ this approach. The lack of availability on the commercial market of such removable patchboard units will dictate that anyone wishing to use this scheme must build his own equipment. Plans for a logic laboratory unit employing this scheme are given in Appendix C of this report.

The major advantage of the removable patchboard system stems from the fact that the patching panel is removable. By this technique, for a cost of perhaps thirty dollars, the student can have available to him the time-shared facility of several thousand dollars' worth of logic and peripheral equipment. The patchboard portability allows the student to transfer his design from paper to wiring at his own pace in the laboratory or in the comfort of his home or dormitory room. The modest expense of the removable patchboard also makes it possible for the student to retain his design for an extended period of time. Here again, the modifications which he wishes to make to his design can be made at his leisure. Of course, the actual time during which the student may test out his design is limited since a number of students would typically be sharing equipment connected to the patch panel receiver.

The actual logic elements of such a system are decidedly not portable and can be used only in the laboratory in which they are installed. The majority of the logic elements must be preconnected to specified connections on the patch-panel receiver and these locations must be thoroughly documented. It is, however, desirable to include a "free patching area" where a set of special modules may be plugged in by the student at the time he inserts his patch panel. This of course increases the setup complexity for students who must use the special module sections. It may cause some concern to users of quite high speed circuits that some long lead lengths are generally involved in the mapping from receiver to patchboard. Successful systems have been fabricated using DTL but none have yet been attempted using TTL or faster logic families. The cost of leads used with the patch panel can often represent a major system cost.

The Logic Card Units (Figure 3-3) which employ printed circuit cards and a facsimile of back panel wiring generally exhibit considerable flexibility. This scheme offers some good pedagogy in that there is a strong resemblance between the patched system and regular digital systems. The user is free to choose the required modules and he is further free to exercise his discretion as to module placement. Schemes which allow for logic diagram identification of the modules (Figure 3-3 (a)) generally are not able to achieve the logic density which has been obtained with the locally constructed systems (Figure 3-3 (b)). Information relating to the construction of the latter system is presented in Appendix C.

Systems of this back panel wiring class allow a modular equipment configuration to be allocated to the needs of an individual student project. This allocation provides for maximum equipment utilization. This is important, since in this scheme, all of the logic equipment associated with a particular project must be dedicated to that project for the duration of the student's activities. If one is to maintain a reasonable budget, then it is important that modules not sit in idle rack positions because of inflexible hardware. Projects using these systems may require several thousand patch cords. In some versions, the cost may approach a dollar per cord while others employ wire with rather inexpensive taper pins or slip-on connectors. In these instances, the ratio of logic power per student to the capital expenditure is generally moderate.

The breadboard patching scheme (Figures 3-4 and 3-5) which employs IC's plugged into special sockets and a facsimile of "mother board" wiring have many of the properties of the previous class. This system is pedagogically good. The user is free to choose modules (IC's) which suit his requirements. The system is highly modular and can be configured in almost any size from a "take home" version with about eight IC's to a very large project involving several hundred IC's.

This subclass of schemes is available commercially or can be easily constructed from the specifications in Appendix C. Even if purchased commercially, the ratio of logic power per student to the capital expense is moderate.

The lack of symbolic identification of logic function may be a disadvantage especially to beginning students. In addition the IC's are used with no special packages or carriers. Thus they are quite vulnerable to physical damage through carelessness on the part of the student. Damaged units are, however, easily replaced.

3-3 Auxiliary Devices

Each laboratory station must have one or more means to interface with external devices and systems. This section briefly indicates the types of components that should be planned as part of the logic units selected.

3-3.1 INPUT DEVICES

The most common input device for laboratory logic system projects is the simple switch. Slide, rocker or toggle switches are typically used to provide level inputs, i.e. constant logical zero or logical one signals for an extended period of time, while push-button or some other type of momentary-contact switches are necessary to provide pulse inputs. For the latter types of switches it is necessary to provide some type of debounce circuitry to eliminate multiple pulses which can result from contact bounce in mechanical switches.

In addition to level inputs many logic circuits require various timing, control and clock signals. These signals are usually provided by a pulse generator which may either be built into the basic logic unit or be a separate piece of equipment.

If the systems under design in the laboratory are to be interfaced with other devices, a connector strip having as many as 100 different contacts on a single printed circuit card edge should be provided. For more advanced projects analog-to-digital converters, shaft encoders, telephone dials, keyboards and other special input devices should be available in the laboratory. These devices are particularly important if experiments involving hybrid or real-time systems are planned.

3-3.2 OUTPUT DEVICES

Certainly the most important output device for an elementary logic laboratory unit is the indicator light. Simple incandescent lamps are the most common type of lamp which can be used for this purpose. However, the steadily decreasing prices of much more sophisticated devices such as light-emitting galium-arsenide diodes will probably make these devices very useful for this purpose in the near future. For more special purpose applications, numerical indicators such as 7-segment display units (which may also utilize galium-arsenide light-emitting diodes) may also be a valuable asset in a laboratory unit. Multiple-conductor connectors similar to those used as input connections also provide a useful output function when the basic logic lab is to be used as an element in a larger system.

Digital-to-analog converters, stepping motors and other such special output devices are very desirable for use in more advanced projects. Many of these devices can be purchased as a standard logic package that accept digital signals as inputs. Here again the ability to interface logic networks to the analog world is a very desirable feature to include in the laboratory.

3-3.3 POWER SUPPLIES

The choice of logic elements to be used for the logic laboratory will determine the power supply requirements for the unit. If TTL and/or DTL is selected as recommended above, then the power supply requirement is simply 5 volts at a sufficient current rating. This supply may be as simple as a set of dry cell batteries or as elaborate as a supply regulated by an integrated circuit regulator. The use of battery operated logic lab units will probably be confined to very small scale units as battery life for experiments employing more than perhaps a half-dozen IC's will be very short indeed. Provision should also be made, if possible, for the addition of auxiliary supplies providing 15 to 30 volts for use with MOS logic devices. A supply providing ±15 volts is also desirable if analog elements such as operational amplifiers are to be used as part of a project.

For line-operated power supplies it is highly recommended that the supply be regulated and current should be limited for its own protection. Such features as these involve relatively little additional expense now that integrated circuit regulators are available at very modest cost.

The current requirements of the power supply in the given lab unit depends very much on the number of logic elements being used, as well as on the power requirements of such peripheral elements as indicator lamps used for output. As a rule of thumb, one can plan for about 2 milliamperes of current drain for each gate and 8 milliamperes per flip-flop when using the Series 74 TTL logic. As an example, for a student project employing 100 series 74 NAND gates and 60 series 74 JK flip-flops together with a 12-lamp indicator circuit where each lamp consumes 40 to 50 milliamperes, a 1½ - 2 ampere current power supply will be ample.

3-4 Make or Buy the Equipment?

The decision to make or buy the laboratory units to be used in a given laboratory can only be answered after evaluating local conditions. In some instances this question will have only one possible answer. One wishing to establish a logic laboratory employing, for example, the removable patchboard scheme will have little choice but to build his own equipment. In other instances commercial equipment is available which more or less fulfills the needs of a particular plan for a logic laboratory. In some instances, however, the commercially available equipment which is most suitable will be priced beyond the limits of one's budget. In this case, very satisfactory lab equipment can be made, if one has available adequate shop facilities and adequate support personnel with the necessary skills. The construction of homemade equipment is frequently only "less expensive" if the cost of faculty and technician time is not included in the price of the equipment. However, there are often many fringe benefits to be gained by using in-house facilities.

The design and construction of lab equipment can be a very educational process, particularly in the area of economics, both to faculty and any students involved. Any equipment built in-house can be optimized for the needs of the local laboratory program. If the operation of all the departmental laboratories is coordinated it is often possible to obtain a higher use factor of equipment and in this way justify the purchase of a number of more expensive items.

The necessary labor to design and construct equipment can often be obtained from the student body through volunteer help or paid student labor. At many schools the federally sponsored work-study program will provide funds for hiring students, provided they have a recognized financial need.

3-5 Modular Components

Modular components needed in the laboratory can be classified as test equipment and digital system components. Because of their size and complexity it can be expected that these components will be portable enough so that they can be shared by all the students in the lab. However, a sufficient number of units should be available so that a student can expect to obtain a needed unit for a reasonable amount of time.

3-5.1 TEST EQUIPMENT FOR DIGITAL LABORATORIES

There are two types of measurements which must generally be made in digital laboratories: levels and pulses. Levels are most easily and simply measured by using the lamps which are an integral part of most digital laboratory equipment.

Both pulses and levels can be measured by the mainstay of the digital laboratory—the D. C. coupled wideband oscilloscope. The bandwidth of the scope required is a function of the speed of the logic in use in your laboratory. However, as a guideline, typical propagation delay times associated with the two types of IC's recommended previously are:

DTL - 25 ns
TTL - 10 ns

Generally, instruments with a 30 MHz bandwidth are used for DTL and 50 MHz bandwidth for TTL. There are two other essential features of the laboratory oscilloscope. The first is the ability of the instrument to display at least two signals simultaneously. The second feature is the delayed trigger which allows the user to delay the trigger of one or more of the scope traces with respect to another trace or signal. These features are most helpful when one is debugging timing problems in sequential circuits.

There is one relatively inexpensive oscilloscope accessory without which thousands of dollars worth of laboratory equipment can be rendered useless. That accessory—the high impedence oscilloscope probe—should be provided in adequate quantity so that probe sharing among students is not necessary even though several probes are "broken or misplaced."

A pulse generator is one other piece of laboratory equipment which may be necessary if it is not built into the lab equipment. This equipment does not have to be exotic with such features as variable risetime or bipolar output but should have variable pulse width, amplitude, and frequency and positive going output for DTL and TTL logic. The rise-time of the pulse generator, however, must be fast enough to drive the logic system in use. There are several such pulse generators presently on the market for less than $200.

3-5.2 LARGE SCALE MODULES

Although large scale modules are not required for newly developed laboratories, one undoubtedly will require one or more of them as lab experiments become more complex or especially if one gets involved in project laboratories. These modules should be easily interfaced with the logic laboratory equipment and thus it is often desirable to build the logical interface circuitry directly into the large scale modules. The following is a list of large scale modules which have been found useful in laboratory work at several universities:

1. Teletypes. This is a relatively inexpensive and versatile input/output device—witness its popularity with mini-computer manufacturers. The interface circuitry is simple and easily built into the unit. The main disadvantage of the teletype is its fixed lifetime (approximately 1000 hours for an ASR 33) and the maintenance expense associated with this rather complex mechanical device.
2. Electronic Keyboards. A simple, relatively trouble-free input device which can be purchased from several manufacturers or built in the lab from anyone of several kinds of switches expecially designed for this purpose. Typically low activation force micro or reed type switches are used. Use of a standard code such as ASCII is recommended as this will allow simple interfaces to be built for other systems or large scale modules such as paper tape readers, punches, and teletypes.

3. Core Memory. Small core memories such as 8 bit by 256 words complete with driver, address and buffer circuitry are now available from several manufacturers. Many of these memories come on a large printed circuit card and therefore only power supplies, cabinet, and connectors must be assembled by the user. Also, since most of the memories made today are DTL/TTL compatible, interfaces to logic lab systems which are not DTL/TTL compatible must often be constructed.
4. Delay Lines. Delay lines, such as the wiresonic lines presently available for a modest cost, can easily be used as a dynamic store for laboratory experiments. These delay lines which may have delays for 1 to 10 milliseconds can store from 1500 to 15000 bits of information. Generally electronic driving and pick-up circuitry as well as the interface logic can be easily and inexpensively configured by the user.
5. Paper Tape Handling Equipment. Paper tape readers and punches can be a useful adjunct to a digital laboratory for two reasons. First, they provide relatively permanent storage for information and programs which are to be used in delay line or core memories associated with lab equipment. Second, they provide a relatively simple mechanism through which information associated with a lab experiment can be transferred to a mini-computer system.
6. Digital-to-Analog and Analog-to-Digital Converters. D/A and A/D converters are useful large scale modules not only for application in experimental systems, but they are also interesting devices for study in and of themselves. Experiments or projects in process control and digital filtering are possible when these devices are available. D/A converters and the hardware for constructing high quality A/D converters are now becoming available in IC form at continually decreasing costs.
7. Displays. Large scale modules which can be used to display output data graphically are often useful in the digital laboratory. Experiments involving the generation of alphanumeric symbols or the plotting of dynamic data usually create a great deal of student interest. Game playing projects can often be enhanced by providing a graphic output. The simplest display is the laboratory oscilloscope connected to the logic system through D/A converters. The use of a storage type oscilloscope or display eliminates the need to continually refresh the displayed data. Other graphical display devices such as x-y recorders can also be used effectively in this application.
8. Graphical Input Devices. As laboratory equipment and experiments become more involved, one often finds a need for rapid input to a system which is more "humanly" rather than "machine" oriented. Graphical input devices such as the Rand Tablet and light pen can serve these purposes nicely. A simple light pen can easily be constructed with a photo-diode and appropriate electronic circuitry.
9. Magnetic Tape. An input-output medium which is becoming more attractive for use in digital laboratories are the cassette, cartridge, and reel-to-reel tape recorders and players. Several manufacturers are now offering specially constructed decks for application in the digital area. On the other hand it has been reported that commercially available analog type recorders can be adapted for use in the digital area. (reference 15).
10. MODEM's. A modulator-demodulator system which can be used to couple digital devices through the telephone system is another large scale module which often finds application in the digital project laboratory. Remote data gathering experiments are easily accomplished when one of these modules is available. Another application is the coupling of large time-sharing systems into the laboratory's mini-computer. These modules are commercially available for from $300 to $500; however, these devices can also be constructed locally. (reference 18).

3-6 Mini-Computers

Initially the price of a computer system was so large that it was only practical for universities and colleges to buy a single system and install it in a central computer center for general computational use. Because of this initial policy decision most faculty and administration members think of computers only in terms of their use as a large scale computing device. However the availability of low cost mini-computers has created the need to reevaluate this policy decision.

It is becoming quite common to find digital computers included as an integral part of on-line control systems, data-retrieval and signal-processing systems and other similar real-time applications. In applications of this type, the computer operates in an entirely different environment from that found in a computer center. Consequently, it is reasonable to expect that a well equipped digital system laboratory will have one or more mini-computers available for on-line use by students in the laboratory.

There are several mini-computers on the market that fall within $5,000 to $15,000 for the basic system. These computers, although physically small, have capabilities that allow them to carry out a wide variety of on-line information processing tasks. The versatility and power of the mini-computer thus makes it as valuable to an electrical engineer as an oscilloscope. It almost ranks with operational amplifiers, filters and signal generators in the electrical engineers' "bag of system-realization tricks." If students are to understand and master the use of computers in the context of system applications they must be able to use them in a laboratory environment. Therefore, it is important that the digital system laboratory be equipped with one or more mini-computers. These computers should be considered as laboratory equipment and be completely independent of the control and use of the central computer center. Although it might serve in an auxiliary function as a computing device, in the laboratory its main use should be as an experimental and instructional tool.

The versatility of the mini-computer is somewhat of a mixed blessing because that versatility, coupled with the tremendous variety of manufactured versions of such machines, has made the problem of selection of a mini-computer more than a trivial task. The very detailed specification of a machine in terms of concepts such as how much core storage, what cycle time, what instruction set, what input-output capability, etc., complicates the problem of selection. There are presently some one hundred or so different machines which may, in some sense, reasonably meet the objectives of a digital systems laboratory. A recent article by Jurgen (reference 10) discusses the general capabilities of mini-computers and how they can be used in various system applications.

Currently the mini-computer field is undergoing a very unstable period of growth. New machines are announced almost daily and mini-computer manufacturers seem to have a tendency to fade away. Thus in selecting a computer one should limit his search to the machines that are offered by the more experienced and better organized manufacturers. A more subtle caution is that many of the usual parameters which are used to judge a computing system are simply not relevant to the selection problem for a digital systems laboratory. Therefore, do not pay too much attention to the manufacturer's sales brochure or sales presentation. Try, instead, to consider how each computer would fit into the goals set for the planned laboratory.

The selection of a mini-computer, like the purchase of a new car is a very personal thing and involves a considerable number of intangible considerations. This section will, therefore, not recommend any specific computer or configuration. It will, instead, point out the important factors that should be considered in selecting a computer for use in an undergraduate laboratory situation.

3-6.1 CRITERIA FOR COMPUTER SELECTION

The computer market is rapidly changing, with new computers or modifications of old computers announced monthly. Consequently, one of the first decisions that often must be made is whether to buy a new computer or accept an older computer that has been offered to your department as a gift or at what appears to be a very attractive price. *Unless the used computer is a relatively new model that is in current production, it is strongly recommended that the offer of the older computer be politely but firmly rejected.* Similarly, military surplus computers should not be looked upon as a substitute for the purchase of a mini-computer.

The main reason for this recommendation is that the changes in computer structure and organization which have occurred in the past few years makes any computer more than a few years old a bad investment. Older machines are more costly to maintain, they are more expensive and difficult to add peripheral equipment to, and they do not have many of the expanded computational capabilities of the newer machines. The price of computers has also decreased very rapidly during the past few years. For example, the PDP-5 basic cost in 1964 was approximately $28,500. The new PDP-8E, which has essentially the same instruction set as the PDP-5, but is a much faster and better organized computer, is currently selling for approximately $7,000. Thus, even though older machines might appear to be an attractive gift, if one looks at their original price, it must be remembered that they have relatively little current value in the used computer market.

The selection of a mini-computer for undergraduate laboratory use is an entirely different problem from the selection of a computer for a computer center. In most problems that a student will be assigned, the mini-computer will be part of a complete system and the student will have to carry out both hardware and software design efforts in order to solve the problem on which he is working. Thus the following requirements must be placed on the mini-computer selected for laboratory use.

The basic machine language should be easy to learn and use by the student and the computer should have an elementary I/O structure that makes it easy to interface it with either student constructed or purchased peripheral equipment. The simplicity of machine organization implied by these conditions is extremely important because the success of the laboratory will depend a great deal upon how deeply the student can become immersed in the total system environment.

It is important that the student be able to obtain a complete view of his entire problem and seek a solution which may well involve all of the activities of developing procedures, algorithms, hardware and interface constructions, software support and perhaps even interpreting the final system results. It is important that the role of the computer be properly placed as only one of the blocks in his solution to the problem. Hence, while the range of problems which could be approached might be much greater if one acquired, say, a medium size rather than a mini-computer for this application, such an acquisition might defeat the real purpose of the laboratories in that the limited time available to the student to carry out his laboratory work might all be spent in learning to effectively code the larger machine. Thus, the more meaningful aspects of the project would likely escape his attention. There is time in the student's later development for him to pursue much more exotic systems. It is tacitly assumed that this laboratory experience may well be one of the student's first solo ventures in an in-depth study of a significant problem. It is, of course, required that the problem challenge him, but it is not necessary to overwhelm him.

The maintainability of a computer is another important consideration. Under ideal circumstances, the department should obtain a maintenance agreement along with the computer. Thus, the location of the manufacturer's nearest service center is of critical importance. When a computer is in use in the laboratory program, it is critical that it not be inoperative for any extended period of time. Same day or one-day service should be available on an "on call" basis and replacement parts should be readily available without a long delay while an order is "sent to the factory" for a new part.

In most applications the software supplied by the manufacturer of the computer is not of much use in the laboratory environment. Except for the editor, assembler and debugging programs that are supplied with every machine, all of the other software will probably be disregarded by the students in favor of programs that they develop themselves. Some special software packages aimed at the instructional needs of a laboratory have been developed by faculty members at different schools but these programs are usually not available from the manufacturer.

In most problems that the student will solve, the computer must be interfaced to other parts of a complete system. Since the computer may be required to communicate with man or with the real physical world, this interface capability should be as flexible as possible. In order to support the problem environment, it may be necessary to establish links between the computer and analog signals, switch contacts, elements of digital hardware, data modems, musical instruments, monkeys, mosquitoes, and you name it.

Not only must the immersion of the computer in the laboratory system be versatile, the techniques employed must provide for very rapid and reliable establishment of the interface for a particular problem. Unless one can afford the luxury of a mini-computer and interfacing hardware for each student, a sequential time-shared use scheme is forced. This almost begs for a patchable or plugable arrangement which allows for the rapid establishment of many connections between the computer and its peripheral elements.

Analog-to-digital and digital-to-analog converters can be used to handle analog signals and special buffer registers can be added to interface digital signals.

Another critical problem is that of reading information and programs into and out of the computer. Most mini-computers come equipped with an ASR33 teletype/paper-tape reader/paper-tape punch configuration. This is a very inefficient means of transferring data between the user and the computer. With the teletype paper-tape input it takes an average of twenty minutes to read the assembler into a typical mini-computer. Under the hard usage a teletype experiences when it is the only input/output device, one may have dreadful weeks in which he experiences something on the order of ten minutes of successful reading between teletype failures. Moreover it is next to impossible to find adequately trained service personnel to repair the teletype unit.

The solution to this problem requires an alternate high speed input/output device. At present a high-speed paper-tape reader-punch is the best solution. However, an alternate solution which is certainly attractive from its usage standpoint but not as yet from a cost standpoint, would be one of the variety of keyboard to tape cassette devices, with a cassette reproducer in the computer interface. Either of these devices may yield a spectacular result of reducing the load time of various programs. For example, the load time of an assembler program can be reduced from twenty minutes to something under one minute. This allows the student to get on with the more meaningful aspects of his problem and permits him to get on and off of the machine in a relatively short time. The investment of some three to four thousand dollars additional will permit one to certainly double and perhaps triple the number of students that can make effective use of the system during a given period of time.

The various manufacturers have a full line of additional peripheral equipment that can be added to a mini-computer; however, none of this equipment is as important as the items already mentioned and should be added only if extra money is available.

In summary, the basic mini-computer installation for use in the undergraduate digital system laboratory program should have the following basic configuration:

A. Basic computer with at least four thousand words of memory.
B. A high speed reader/punch
or
a keyboard/cassette device.
C. An A/D and D/A converter.
D. Digital interface capabilities through a buffer register.

The mini-computer associated with the laboratory program should be considered as a laboratory instrument and housed in the digital system laboratory under the direct control of the electrical engineering department. In fact for larger departments, it might be desirable to have more than one mini-computer installation in the laboratory.

IV. CONCLUSIONS

As an initial project, the Task Force conducted a survey in the spring of 1970 to determine the amount of digital system laboratory activity presently underway in various electrical engineering departments. The results of this survey, which are summarized in Appendix E, indicate that an increasing amount of interest in digital system concepts is occurring in most departments. The recommendations contained in this report have been based upon the collective experiences of the task force members in developing undergraduate laboratory programs. However, it is obvious that the digital area is still in a state of flux and continued development work will be needed to keep any digital laboratory program up to date. The following observations indicate some of the trends in digital components equipment that will influence future laboratory development.

MSI and LSI integrated circuits are becoming more readily available at continually lower prices. In the near future, it will be possible to use integrated circuit registers and complete logic networks to implement a system design rather than using individual logic element gates and flip-flops. As MSI and LSI circuits become standardized, students will be able to construct and test complete digital systems in the intermediate and even introductory laboratories. This capability will in turn require a re-design of the basic theory courses to keep pace with the new design techniques that are being developed to analyze and synthesize systems from these new components.

In many schools the curriculum is becoming more design oriented. If this trend continues, project laboratories and design courses will probably be combined into one package. One interesting concept would be to organize a course of this type so that junior, senior and graduate students would work together, along with a faculty member, to solve a given problem. Each student would be expected to contribute according to his capabilities, with the more advanced students supplying the leadership and guidance necessary to carry out the project selected by the class.

The decrease in the price of mini-computers will probably not be as rapid as has been the case in the last few years. Although the price of these computers may remain relatively fixed, their capability should continually increase. The price of peripheral equipment will continue to decrease and better man-machine communication devices, such as graphic display systems, should become available at much more reasonable prices. As these changes occur much more sophisticated real-time information processing problems can be explored by the students.

Digital system concepts are having a large impact upon many non-computer areas of electrical engineering. Digital, rather than analog, signal and information processing techniques are being used extensively in control and communication systems. These changes will create a greater demand for digital system laboratory work by students from these areas. Long range laboratory development programs will be necessary in these areas to introduce these digital systems concepts properly into the related laboratory program.

A properly equipped laboratory supervised by a group of interested faculty members can provide a very stimulating educational experience to the undergraduate student. Unfortunately the development of a laboratory and a laboratory program takes a considerably larger amount of time, effort and money than the development of a lecture course. A major effort is needed to communicate new developments and ideas among the faculty members who are working on laboratory development projects. The following developments would help in the development of digital system laboratory programs.

a) There are a large number of theoretical books that deal with switching theory and the theoretical properties of solid state circuits. However a reference book is needed that will discuss the practical aspects of digital system design and digital system measurement techniques.

b) A considerable amount of time is involved in the development of new educational hardware and software. Whenever a new idea proves successful every effort should be made to publish the results in a journal such as the IEEE *Transactions on Education*. In this way faculty members at other schools will not have to waste their time designing equipment that has already been developed.

c) A considerable amount of the introductory material that a student encounters is intended to teach him a "skill" that he will need in later work. Self-teaching techniques should be developed to allow the student to learn these skills at his own pace. Self-teaching techniques, if properly done, not only motivate the student but they also allow more efficient utilization of the laboratory equipment.

d) The full potential of mini-computers in a teaching laboratory situation is currently hampered by the lack of software that has been explicitly designed for the teaching situation. A development effort is needed to develop programs that will reduce the amount of time a student needs to master the use of the computer and to carry out his experimental work.

APPENDIX A

An Expanded Outline of the Introductory Laboratory Program

The general structure of the introductory laboratory work was presented in section 2-3.1. This appendix provides an expanded outline of the typical material included in each topic area. The final selection of topics will, of course, depend upon local conditions. All indicated references are listed at the end of this report.

A-1 Measurement Techniques

References 1, 17, 21, 23

The main purpose of this experiment is to introduce the student to the problem of measuring the different parameters of importance in digital circuits. It is assumed that the student has already been introduced to the basic operation of oscilloscopes and is familiar with the basic terminology used to describe signals in digital circuits. (i.e. rise time, fall time, pulse width, pulse rate, positive logic, negative logic etc. See reference 21 for discussion of oscilloscope operation and references 1, 21 and 23 for discussion of signal characteristics).

After the student has become familiar with the equipment to be used he should carry out the following exercises:

1. Measure the rise time, fall time and pulse duration of a number of different pulse sources.
2. Investigate the relationship between pulse width and the bandwidth of the oscilloscope needed to observe the pulse. The student should prove that his rise time and fall time measurements are those of the pulses he is observing and not the response characteristics of the scope.
3. The sync and trigger inputs should be used to observe repetitive and non-repetitive pulse trains. Particular properties of each type of pulse trains should be measured to show that the student actually understands the operation of these two inputs.
4. The operation of a multiple-trace scope should be thoroughly investigated. The measurement of the delay between the input and output of a logic element makes a good measurement problem.
5. If a sampling oscilloscope is available the student should be introduced to its operation.

A-2 Characteristics and Use of Basic Integrated Circuits

References 2, 4, 6, 11, 16, 20

Before beginning the experiment portion of the laboratory work the student should be introduced to the general types of IC's (RTL, DTL, TTL) and the main characteristics of each type. (References 2 and 4). A film such as reference 22 can be used to familiarize the student with IC fabrication. Several samples of unpackaged units can be used to give further insight into the physical form of the different devices.

A complete set of specification sheets describing the logic packages to be used in the lab should be available.

Using these sheets a student should familiarize himself with the basic parameters of each unit before carrying out the following exercises:

1. Measure the switching threshold of typical gates and the range of voltage levels that indicate the different logical quantities. Determine how the gate's operation is influenced by output loading.
2. Measure the propagation delay, rise time and fall time of various gates under different loading conditions. Indicate the maximum operating speed of the networks constructed from these gates.

A-3 Design of Combinational Logic Networks

References 1, 5, 12, 13, 20

The biggest difference between the theoretical discussion of combinational logic networks and the use of typical IC packages are the practical restrictions imposed by the properties of the family of IC units available in the laboratory. For example a theoretical design might call for a 5 input NAND gate and the student finds that there are only two input and three input NAND gates available for his use.

In this part of the laboratory program the student should be given a number of problems to solve. Each problem should involve the design, construction and test of a combinational logic network. The statement of the problem should be presented so that the student must make a number of judgments in order to come up with the "best" network. In particular one or more of the problems should involve minimizing the "cost" of the overall network. Several different "cost" criteria should be indicated such as (a) minimal financial cost, (b) minimum number of interconnections, (c) minimum delay, (d) minimum number of types of logic packages used.

A-4 Flip-flops, Pulse Generators and Multivibrators

Reference 14

This part of the laboratory program is designed to introduce the students to different types of circuits that can be used to store information, delay information and generate pulses. The following exercises illustrate these concepts.

1. Mechanical switches exhibit contact bounce which make their direct outputs unsuitable for generation of pulses. A simple contact bounce eliminator can be constructed (p227 of reference 14) to eliminate contact bounce. This circuit uses a simple S-R flip-flop.
2. The students should construct several of the standard flip-flop circuits using NAND gates. Clocked, unclocked and master-slave operations should be investigated. The factors influencing the maximum operating speed of each flip-flop configuration should be considered.
3. In many logic networks it is necessary to generate a single standard pulse from a non-standard pulse or a level change. Monostable multivibrators are useful for

this purpose. The student should construct a monostable multivibrator using NAND gates and study its properties.

4. Astable multivibrators are useful in generating a pulse train. An astable multivibrator should be constructed and its properties investigated.

A-5 Registers and Counters

References 1, 5, 14

Registers and counters form one of the basic building blocks of digital systems. Once a student understands the general operation of these devices it is much easier for him to understand the operation of general sequential networks. The following exercises are designed to cover a number of the typical registers and counter networks encountered in digital systems.

1. The students should build a shift register from flip-flops and investigate the maximum operating speed possible with the flip-flops available.
2. Let A be an r bit register and X an r bit input signal. The student should construct a simple circuit that would form, say X AND A, and place the result in A. This should be a synchronous circuit.
3. The students should build a scale of n counter for one or more values of n.

A-6 Synchronous Sequential Network Realization

References 1, 5, 14

The investigation of registers and counters introduces the student to the general operation of flip-flops in circuits that involve feedback as well as input information. The following exercises are designed to introduce the student to the general properties and design of synchronous sequential networks.

1. The student should build a sequential network to realize a given simple transition table. The influence of the flip-flops chosen to realize this network upon the complexity of the network should be considered.
2. A work statement describing the desired operation of a given sequential network should be presented to the student. He should then be asked to develop a sequential network to carry out the desired operation. Some typical problems would be a combination lock (input sequence recognizer), an automatic change maker or a control sequence pulse generator for some logic unit like a serial adder.

References

At the present time there is not a single book that can be suggested as a reference for all of the topics suggested above. The references indicated provide a discussion of much of the material needed by a student to prepare for his laboratory work. It is suggested that a representative collection of these references be easily available to the student for use before, during and after his actual laboratory work.

REFERENCES

1. Booth, T. L., *Digital Networks and Computer Systems*, John Wiley, New York, 1971.

2. Garrett, L. S., *Integrated-circuit Digital Logic Families*, Three part article IEEE Spectrum, October, November, December, 1970.

3. Gear, C. W., *Computer Organization and Programming*, McGraw Hill, New York, 1969.

4. Hibbard, R., *Families of Integrated Circuits*, Machine Design, January 23, 1969.

5. Hill, F. J., and Peterson, G. R., *Introduction to Switching Theory and Logical Design*, Wiley, New York, 1968, Section 8.5.

6. Hittinger and Sparks, *A Guide to Integrated Circuits*, Electro-Technology, February, 1968.

7. Hittinger and Sparks, *I. C. Course*, The Electronic Engineer, First Half, Aug., 1966, pp. 86-138; Second Half, October, 1966, pp. 62-106.

8. Hittinger and Sparks, *Microelectronics*, Scientific American, November, 1965, Vol. 213, No. 5, pp. 56-70.

9. Hoeschele, D., *Analog to Digital to Analog Converter Technology*, Wiley, New York, 1968.

10. Jurgen, R. K., *Mini-computer Applications in the Seventies*, IEEE Spectrum, pp. 37-52. August 1970.

11. Khambata, A. J., *Introduction to Large Scale Integration*, Wiley, New York, 1968.

12. Maley, G. A., and Earle, J., *The Logic Design of Transistor Digital Computers*, Prentice-Hall, Englewood Cliffs, N. J., 1969.

13. Maley, G. A., *Manual of Logic Circuits*, Prentice-Hall, Englewood Cliffs, N. J., 1970.

14. Malmstadt, H. V. and Enke, C. G., *Digital Electronics for Scientists*, Benjamin, New York, 1969, Chp. 5.

15. Neuker, D. and Buczek, W., "Low Cost Store Recorders Can Adapt to Digital Data", Electronics, Vol. 43, No. 14, p. 90, July 6, 1970.

16. Stern, L., *Fundamentals of Integrated Circuits*, Hayden, New York, 1968.

17. Sifferlen, T. P. and V. Vartanian, *Digital Electronics with Engineering Applications*, Prentice-Hall, Englewood Cliffs, N. J., 1970.

18. Stifle, J. and Johnson, M., "Design Pruning Trims Costs of Data MODEM," Electronics, Vol. 43, No. 15, p. 99, July 20, 1970.

19. Warner and Fordemwalt, *Integrated Circuits*, McGraw Hill, New York, 1965.

20. Wickes, W. E., *Logic Design with Integrated Circuits*, Wiley, New York, 1968.

21. Wedlock, B. D. and Roberge, J. K., *Electronic Components and Measurements*, Prentice-Hall, 1969.

22. Integrated Circuit Manufacture - 35mm film strip and record. Western Electric Educational Aids, 195 Broadway, New York, N.Y. 10007.

23. *Logic Handbook*, Digital Equipment Corporation, Maynard, Mass.

APPENDIX B

Some Typical Student Projects

The following collection of short project summaries illustrates the types of projects that can be successfully undertaken and completed by students in a project laboratory. These are actual student summaries which have been taken from the files of Dr. Don Troxel and represent projects carried out at MIT. Similar projects have been carried out at other schools. All of these projects are within the capabilities of electrical engineering students interested in working in the digital area.

1. Word Sorting by Interchange: Peter Stoll

The device as built sorts words composed of four ASCII characters into numeric order of the ASCII codes. This means that alphabetical characters are in alphabetical order, and numeric order is preserved for numeric characters. For convenience of use, input/output is performed by teletype, which provides the ASCII coding.

On account of its availability in the laboratory and its low cost, a delay line is used as the base of the memory. By operating the line at a bit rate of about 130 kHz, storage is obtained for thirty-two four-character words.

To reduce the size of the working registers, all data handling within the machine is by character, not by word. This leads to a requirement for some rather complex control sequences.

Pairs of words having adjacent addresses are compared one character at a time. If they are in the wrong order, pairs of characters are pulled out into the working registers and interchanged until the whole words have been interchanged. Repeated runs of this kind are made through the list until no more interchanges are to be made. Then the device prints the list as four-letter words.

2. Song Programmer For Tape Recorder: Lloyd Marks

The object of this machine is basically to play, in order, a list of five songs recorded on tape. Each song has associated with it a letter of the alphabet. The letters desired are typed in on a teletype, in the order in which they are to be played. Then a search operation is executed. When the song is located, it shifts into play mode. When it is over, it begins to search for the next song, while at the same time, opening up room for a new title if so desired.

There are several basic sub-units to this machine. First there is a counter which serves as the location memory. It is clocked on pulses recorded on a parallel track to the music. It can count up or down depending on the mode of movement (play, fast forward, rewind). Each pulse is detected in its rather imperfect form (a tape recorder acts as an essentially low pass filter) by comparing the output voltage with a reference threshold level, that ignores successive decayed components of the impulse response. The pulses are placed such that one is located at the point where the machine should be cut off fast forward to glide into the dead space between two songs, another at the point where a rewinding should be stopped to glide into the dead space, and another, right in the dead space. Thus, by counting through a Mod-3 counter followed by a main counter, we are aware of all necessary positions.

The second main unit is a shift register which provides memory for up to five song titles (letters). A "title" in the form of a five bit binary number is shifted into one end of the shift register. (There is a sixth bit which serves as a "contents" bit, which indicates if the title is information to be used). The last five bits of the ASCII code for alphabetic characters are numbers ranging from 1_2 to 32_2. Thus, they are used directly to correlate with the position indicated by the main counting unit. The shift register is designed so that all usable information is shifted as far to the end as it can without running into other usable titles. When a song is terminated, the entire register shifts over.

The next unit is a comparing unit consisting of five cells, to determine whether the counter is greater than, or equal to the contents of the last column of the shift register. This serves to inform the main state machine as to which mode of movement should be implemented at a given time.

The main state machine makes a variety of decisions based upon the information from essentially four sources, the comparing unit, the Mod-3 counter, the start or contents bit, and a delaying pulse, which gives about a half second rest period for the manual tape recorder controls. Basically, it waits until a start bit appears in the shift register. It then looks at the comparing unit. If it gets "a greater than," it rewinds. If it gets a "less than," it fast forwards. If it gets an "equals to," then it plays. If it fast forwards or rewinds, it keeps moving until it gets an "equal to" at which point it goes back to the beginning and enters a play mode. When a song is finished, (determined by the Mod-3 counter state) the register shifts and a search for the next song begins.

3. Numeric Display and Editor: David Quimby

Any number of keyboard/cathode ray tube remote terminals have appeared recently in the literature; their advantages over the more common terminals such as Teletypes include higher speed and a great deal more flexibility. The numeric display and editor is an attempt to incorporate into a project lab scale device some of the more important features of these systems.

The typical commercial system consists of an operator keyboard and the computer communicating through the common medium of the memory and display. Besides displaying the memory (or the active portion of it), the unit should provide flexible editing features to allow data to be corrected on the screen before it is sent to the computer, and to indicate specific sections of text to be transmitted, and so forth.

The condensed version implemented in this project displays seven numeric characters (or fewer) on the screen of an oscilloscope. The input device is a Teletype, and as well as accepting sequential input of characters, some flexibility is added by including a character (the rubout) which erases the screen, and another (the back arrow) which erases the most recent character typed in.

While the features of this limited system sound feeble, the logic needed to implement it was not negligible. About 250 RTL integrated circuits plus a diode matrix read only memory were used to support the implementation. Once the system is conceived with basic features, however, an economy of scale sets in, and additional features are not as marginally difficult to incorporate.

4. A Digital Capacitance Meter: Lawrence Schmutz

A digital capacitance meter is constructed. Built to measure capacitances from 1 pf to 20 μf, it includes automatic range switching, and 100% overrange for each normally 3-figure output. Capacitances beyond the range of the meter's ability are so indicated visually and audibly. The measurements are output on a CRT character display.

The parameter actually measured is the current source charging time of the test capacitor. A capacitor is charged by a precision operational amplifier current source, buffered comparators detect the crossing of two successive voltage thresholds, defining a voltage increment. The first threshold gates a clock into a BCD accumulator, the second gates it off. The accumulator contents are then displayed. An accumulator overflow causes a slower clock to be selected, discharges the capacitor and zeros the accumulator for another test. This process repeats until either a measurement is completed or the capacity of the meter is exceeded.

5. Real Time Rally Computer: Benjamin Roberts

The rally computer system designed in this project was originally conceived to provide a continuous output of information to a car driver during an actual rally situation. Basically, what was wanted was a device which would process data on course lengths, specified speed, and miles travelled to produce in suitable form information on time lost or gained and course speeds to recover time lost or gained. The design called for six basic arithmetic operations—two additions, two divisions and two subtractions, performed by three arithmetic units—a divider, a subtractor and an adder. These units were interfaced in such a way as to allow sequential data flow between them and to secondary units such as memory elements and display units. All data was in ten bit form and all operations were performed sequentially instead of in a parallel manner. This technique added time to the computation but greatly reduced the logic usage, which was deemed the most important factor. The project provided many insights into the complexities of arithmetic processing and sequential data management.

6. Parallel Arithmetic Unit: Paul Magerl

This project consists of a design of a fast arithmetic unit capable of adding, subtracting, multiplying and dividing. It is to be used as part of a larger computing system where speed and repeated use of arithmetic operations justify its cost. Inputs to the machine consist of two binary numbers in two's complement format, an operation code specifying which of the four processes is to be carried out, and a start signal, indicating to the arithmetic unit that the other inputs have been correctly applied. The machine carries out the algorithm for the selected operation at a speed determined by its own clock. The outputs of addition and subtraction are one number of length equal to that of the input numbers. Multiplication outputs one number of length equal to twice that of the input. Division forms a quotient and remainder, both equal in length to the input number.

7. Logicalodeon: Mike Bromberg

The Logicalodeon is two digital devices. The first machine is fed a signal consisting of a series of musical tones, and decodes these tones by their frequencies, then punches this information into paper tape. The second machine takes this tape, or a similar handmade tape, and reproduces it as audible music.

The first machine operates on the principle that the pure major notes of the "C" scale are even multiples of 11 Hz. in frequency. Thus, by simply gating the incoming signal periodically for some multiple of 1/11 sec. and by counting the number of cycles in this time period, it can distinguish the frequency of the note.

This machine will accept any musical source producing square-or sine-wave tones within ±11 Hz. of the pure tones. Only one note at a time may be presented; thus, chords and complex waveforms are unacceptable. Greatest success has been obtained with a digital tone generator as signal source, because of accuracy of tuning and waveform.

8. Game of "37": George Poonen

This machine plays the game "37." This game is played between two players with a die. Initially either player is allowed to choose a particular number on the die manually or by a roll of the die. Thereafter, each player alternately turns the die 90 degrees to bring a new number on top. Thus at each instance only four of the six numbers on the die are available, e.g., if the number on top were 6, the only numbers available to the next player would be 2,3,4 and 5. 6 together with 1, which is directly opposite 6, are not available. A running total is kept of the numbers so chosen. The aim of the game is to reach 37 or to force your opponent to go over 37, e.g. if the running total were 35 and the last number chosen were 5, the appropriate play would be 1 so as to force your opponent over 37 (note: 2 is not available since it is opposite 5).

9. Pinball Machine: Jim Stahler and Joe Holmes

The system described is a programmable digital pinball machine. It is designed to receive properly encoded data from a teletype's paper tape reader, which data is then stored in a delay line memory, and used as the description of the pinball machine's geometry. The system draws the specified geometry on the screen of a CRT, showing line segments as a series of dots, which are either blanked or made bright depending on whether the line segment is to be a flipper, an exit, or a normal edge, such as the edge of a target. The line segments are restricted to angles of 0°, 45°, and 90°; furthermore all collisions are perfectly elastic, and the machine is without gravity. In addition to the CRT output, the system has a buzzer that sounds whenever a point is scored, a counter that keeps score on a bank of lights, and a ball-in-play indicator light.

APPENDIX C

Construction of Digital Laboratory Equipment

In this appendix, plans, specifications and ideas are presented for several digital logic interconnection schemes which may be constructed for laboratory use. These systems have all been employed in university digital systems laboratories and have proved useful in those environments. The various systems may be easily constructed with a minimal shop facility. The systems described include an example of a small fixed-patching scheme, a removable patchboard scheme, two versions of printed circuit card breadboard schemes and several variations of integrated circuit breadboard schemes. Each of these schemes is described in sufficient detail so that construction may proceed without undue difficulty. In those instances in which special tools, connectors, plugs, etc., are required, commercial sources are specified. All commercial sources are listed at the end of this appendix. Only approximate cost information is given.

In several instances, the designers of this laboratory equipment have had printed circuit boards fabricated by commercial shops. In each case where this has been done, the commercial shop has retained the art work and has been instructed to supply the cards to anyone who wishes to order them. Information has been supplied for each of these cases describing the supplier and appropriate ordering specifications. Prices are generally quite nominal (in the range of $4 to $8 per board in small quantities); however, quotations should be obtained directly from the respective suppliers. The name of the designer of each unit is indicated so that the reader may write directly to the designer for any needed additional information.

A Fixed Patching Scheme: (Designer: Professor David Robinson, University of Delaware)

Plans and specifications for the construction of a fixed patchboard logic laboratory unit are presented in this section. This unit can provide a simple, inexpensive logical realization facility for the introduction of digital system concepts. The facility may also prove to be an asset to more advanced students for testing and debugging or simply observing the detailed operations of a subsection of a large digital system. A photograph of this unit is shown in Figure 3-1a of Section III of this report.

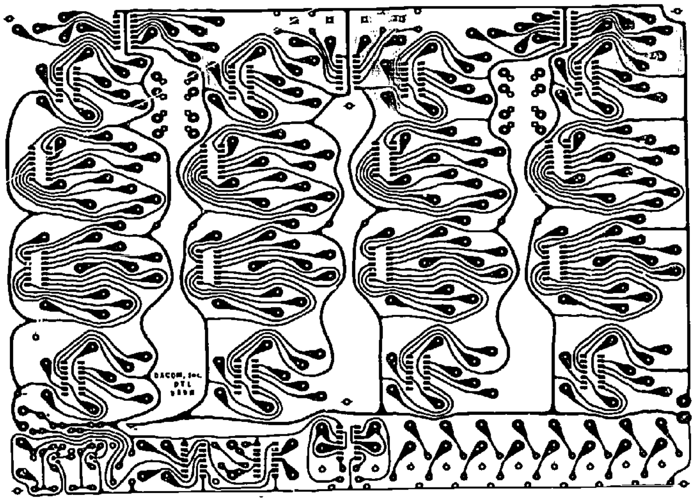
The unit provides the following input-output devices and complement of DTL logic:

8	general purpose flip-flops
32	NAND gates (mix of 2,3,4 and expandable inputs)
8	diodes for gate input expansion
1	variable delay one-shot
1	variable frequency clock
2	debounced pulse switches
8	input level switches (variable and complement available)
4	output indicating lights

All outputs from the pulse devices (one-shot, clock and switches) have both the variable and complement available and are power driven for a fan-out of 25 DTL loads. The light inputs are power NAND gates and hence represent one unit DTL load.

All of the devices are presented on a single printed circuit board and they are described on that board by a standard logic diagram graphic symbol (MIL-STD-806B).* The interconnection scheme is simple, rapid and inexpensive; round wooden toothpicks are used to restrain quite ordinary hook-up wire (almost any gauge from 18 to 24 solid or stranded) in eyelet connection points. These connections have proved to be stable and reliable.

Reduced scale drawings are provided for both the wiring side (Figure C-1) and the symbolic legend side (Figure C-2) of the circuit board. The normal size of these drawings is 10" x 12-1/2". (Note that the spacing for I.C. packages is .1 inches). A full scale reproduction of the drawings suitable to use to fabricate the boards locally can be obtained from Professor Robinson at a cost of $16 for the set of two drawings. If on-campus facilities exist for printed circuit fabrication, it should prove to be a simple matter to produce the circuit board. If such facilities are non-existent, it may not be difficult to find a local manufacturer who would be willing to fabricate the boards or the proprietor of a local silk-screen shop may offer assistance with the project.



Wiring Side Fixed Patchboard Logic Unit.
C-1

The circuit board should be 3/32" glass base epoxy (G-10) and the circuit should be etched from 2 oz. copper clad material. The fabrication should include an over-plating or solder coat on the etched copper side and the legend side should be screened with a heat setting epoxy ink. Estimates of about $70 for commercial preparation of the board do not seem unreasonable.

The drilling schedule of Table C-1 should be observed in drilling the boards.

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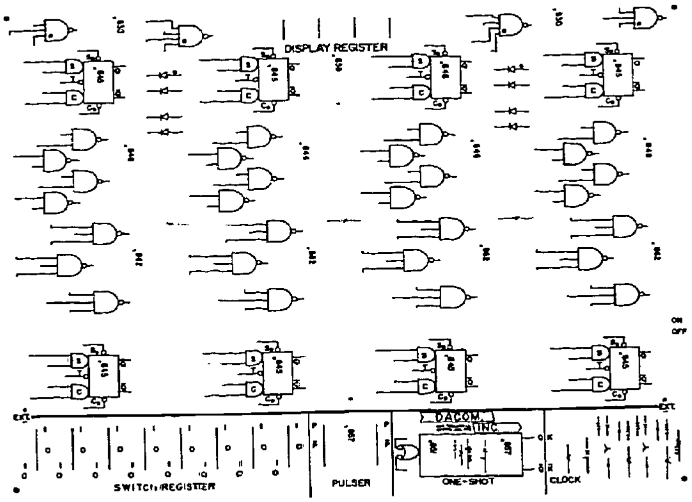
*Note that MIL-STD-806B may be obtained by writing to: The Naval Publications & Forms Center, 5801 Tabor Ave., Phila., Pa. 19120.



Legend Side Fixed Patchboard Logic Unit.
C-2

Table C-1

Drilling Schedule for Circuit Board

Lights (4 holes)	#10 drill
Mounting (6 holes)	#27 drill
Switches (11 holes)	1/4 drill
All large lands	1/8 drill
Wire and I.C. lands, etc.	#68 drill

After all holes are drilled and burrs removed, the eyelets may be set in all 1/8" drill holes. All remaining components are then simply inserted into the marked positions and soldered. Two points on the board require comment. All center switch terminals go to the ground bus, and one jumper wire is required to connect the two pads marked with a minus sign (—) on the wiring side of the board. Other than those cautions, all wiring is routed to the closest available pad and is quite straightforward.

The components listed in Table C-2 are required to implement the logic laboratory unit. In this listing, very specific components are indicated. Substitutions may be made, of course, but the physical, as well as electrical, characteristics should be checked. All components were available from Allied Electronics industrial catalog at the time that this report was prepared. One should check with local suppliers, however, for the best price.

Based on current prices, the total component cost is estimated at about $120 per board in single quantities. This does not include the cost of the printed circuit board.

In addition to these materials, it is also necessary to provide a sheet of 1/4" plexiglass or similar material as a bottom

Table C-2

Parts List for DTL Logic Board

No. Req.	Component	Type	Value
2	Resistors (IRC)	RC1/4 5%	1000Ω
2	Resistors (IRC)	RC1/4 5%	1500Ω
2	Resistors (IRC)	RC1/4 5%	3600Ω
1	Resistor (IRC)	RC1/4 5%	9100Ω
2	Potentiometers (Bourns)	3009Y	5000Ω
4	Capacitors (TRW)	663UW	.01μf100V
1	Capacitor (CD)	CD6	20pf
2	Capacitor (CD)	CD7	470pf
12	Diodes (SYL)	1N914	
9	Switches (ALCO)	105D	
2	Switches (ALCO)	105F	
11	Switch Caps (ALCO)	C-10	
2	Transistors (RCA)	2N5186	
4	Lights (DIALCO)	252-9951-0975	
6	Posts (H.H. Smith)	8349	
300	Eyelets (G.C.)	7257-C	
6	B. H. Screws (G.C.)	7153-C	
6	Lock Washer (G.C.)	7326-C	
6	Oval H. Screws (G.C.)	6540 C	
2	I. C. (MOT)	MC 830P	
8	I. C. (MOT)	MC 845P	
4	I. C. (MOT)	MC 846P	
1	I. C. (MOT)	MC 851P	
2	I. C. (MOT)	MC 857P	
1	I. C. (MOT)	MC 858P	
4	I. C. (MOT)	MC 862P	

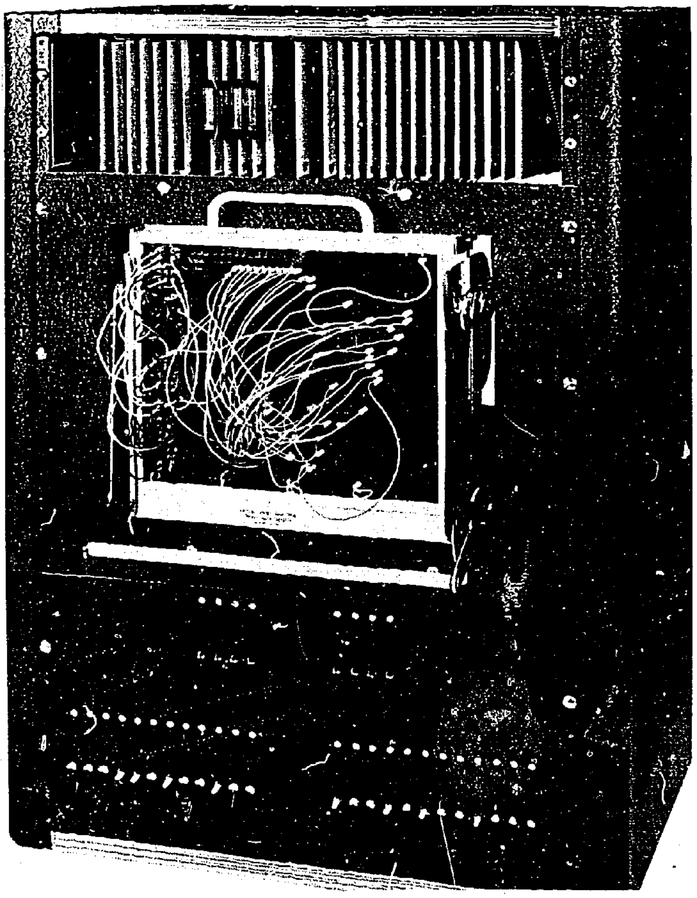
plate. This is to be cut to the same dimensions as the printed board and to be drilled (6 holes) and countersunk for 6-32 body drill to match the holes in the board. Including the printed circuit board and bottom plate, the cost per student should certainly be bounded by $200.

No power supply is included with the logic board. Most conventional laboratory supplies (5 volts) should prove adequate for this task. Total current demand is on the order of 600MA.

A Removable Patchboard Scheme: (Designer: Professor David Robinson University of Delaware)

The construction of a removable patchboard system is not a difficult task and provides a system which yields a relatively large logical array for time-shared student use at a very small cost per student. In the particular unit shown in Figure C-3, the following input-output devices and complement of DTL logic is provided;

- 60 flip-flops
- 160 NAND gates (1,2,3 and expandable inputs)
- 2 variable delay one-shots
- 1 variable frequency clock
- 28 output lights
- 24 input level switches (output and complement available)
- 4 debounced switches



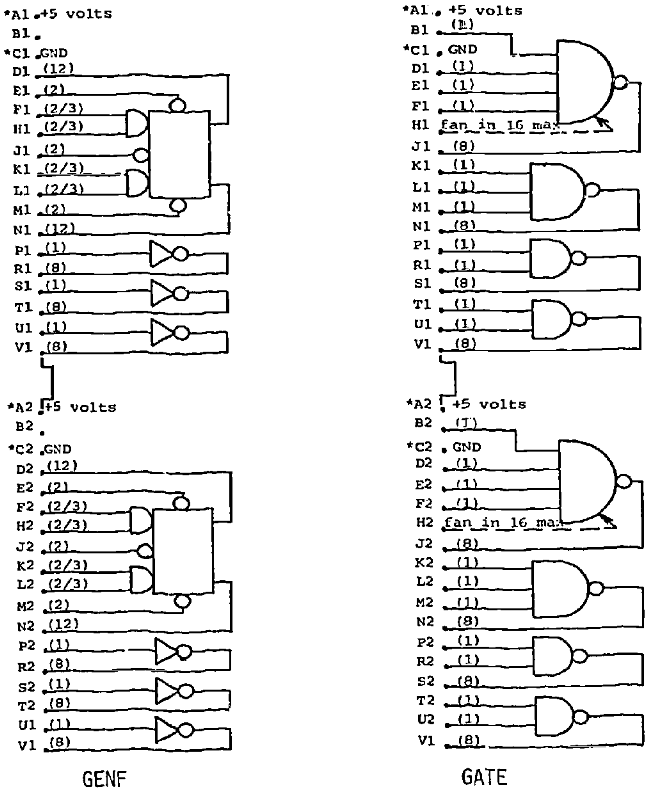
Removable Patchboard Logic System

C-3

All outputs from the pulse devices (one-shot, clock and switches) have both the variable and complement available and are power driven for a fan-out of 25 DTL loads. The light inputs are power NAND gates and hence represent one unit DTL load.

Of course, the logic complement of this device is flexible and cards may be plugged in for arrangements which are more suitable for your particular application. It is desirable to freeze the logic configuration for laboratory use to as great an extent as possible so that set-up time is minimized. Experience has shown that it is advisable to leave 2 or 3 card positions free so that special circuits (as an example a D-A converter) may be plugged in when required. This particular system is arranged to interface a mini-computer. It, therefore, has a front panel patching arrangement which provides access to the 144 pins of a PDP-8E OMNIBUS.

The logic functions for this system are all derived from only four different types of printed circuit cards. The functional pin-outs of these cards are shown in Figures C-4 and C-5. It should be noted that the pin-out arrangement has been organized for ease of patching in the finally completed system. All these circuits (photograph in Figure C-6) are printed on cards which have the same outline shape as the Digital Equipment Company double-height modules. These cards are available from Electrum, Inc. and may be ordered



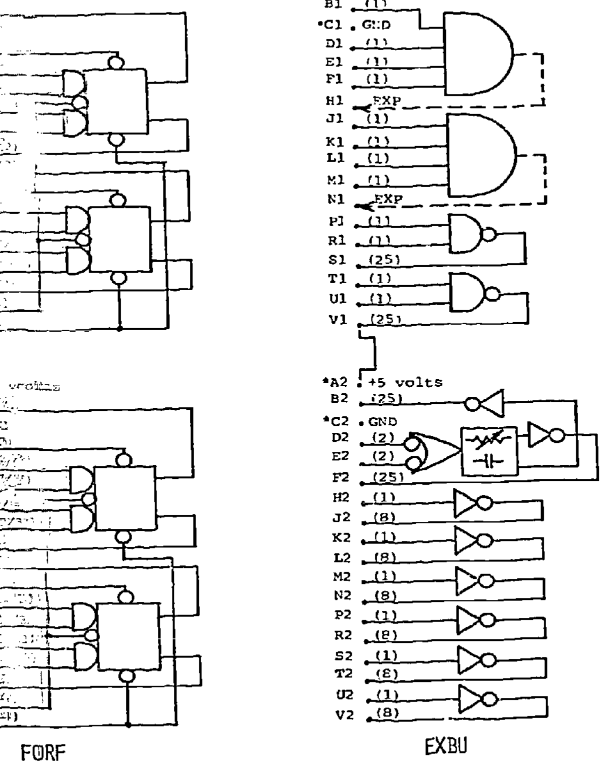
GENERAL PURPOSE FLIP-FLOPS
AND INVERTERS
2 MC845P FLIP-FLOPS
1 MC834P HEX INVERTER

MIXED NAND GATES
1 MC830P EXP. DUAL 4-INPUT
2 MC862P TRIP. 3-INPUT

NOTE: LOAD AND DRIVE FACTORS AT EACH PIN ARE GIVEN IN PARENTHESIS
*PINS A AND C ARE NOT AVAILABLE ON PATCH-PANEL.

Card Pin-Outs and Specifications for GPFF and Gate Cards.

C-4



FLIP-FLOPS WITH COMMON
S AND CLEARS
MC845P FLIP-FLOPS

EXPANDERS, BUFFERS, INVERTERS
AND VARIABLE DELAY ONE-SHOT
1 MC833P DUAL 4-IN EXPANDER
1 MC857P QUAD 2-IN BUFFER
1 MC834P HEX INVERTER
1 MC851P MONOSTABLE
R AND C PASSIVE ELEMENTS

: LOAD AND DRIVE FACTORS AT EACH PIN ARE GIVEN IN PARENTHESIS
*PINS A AND C ARE NOT AVAILABLE ON PATCH-PANEL.

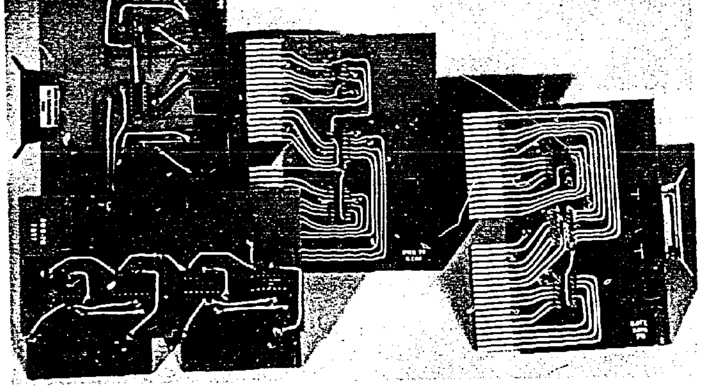
Pin-Outs and Specifications for **FORF** and **EXBU** Cards.

C-5

ifying University of Delaware Printed Circuit Board the 4-letter designation GENF, GATE, FORF, or U. The cards are supplied, printed, etched, drilled and er coated with gold-plated contact fingers. The cards printed on both sides from double copper-clad materials. ets should be inserted in all through drilled holes (GC 7251-C) and soldered on both sides of the card. The grated circuit complement for each card is designated in res C-4 and C-5. The circuit cards have printed I.C. gnations which direct insertion into the appropriate positions so that assembly takes only moments and ires no separate instructions. The cards may be ipped with handles for insertion and removal (Vero ctronics Ltd. #10037) as shown in Figure C-6.

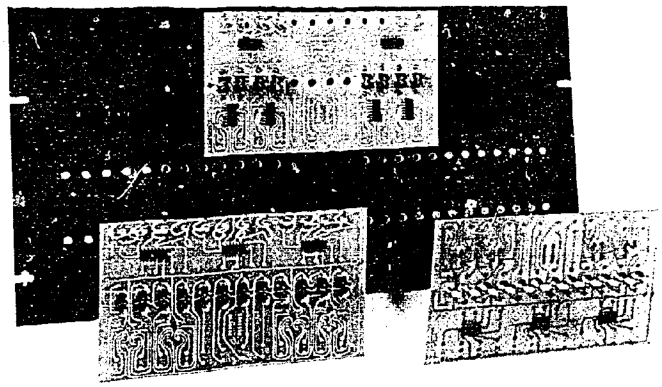
The printed circuit cards may be inserted in a standard ital Equipment Corporation mounting panel (19" unting panel Type K943R). This panel is supplied with s A and C bussed common for power and ground connec-s. This panel may be mounted in any standard 19" relay and set back from that front panel as shown by using ital Equipment Corporation's K980 end plates.

The panel which carries the input switches and output s (Figure C-7) is assembled from three identical printed uit cards which are available from Electrum, Inc. An ropriately drilled mounting panel is required and the printed circuit card itself provides an adequate drilling jig. The ordering designation for this printed circuit card is University of Delaware Board-Switch and Indicator. To complete the assembly of the switch and light panel, the components listed in Table C-3 are required.



P.C. Cards for Logic Systems

C-6



Switch Input and Light Output Panel

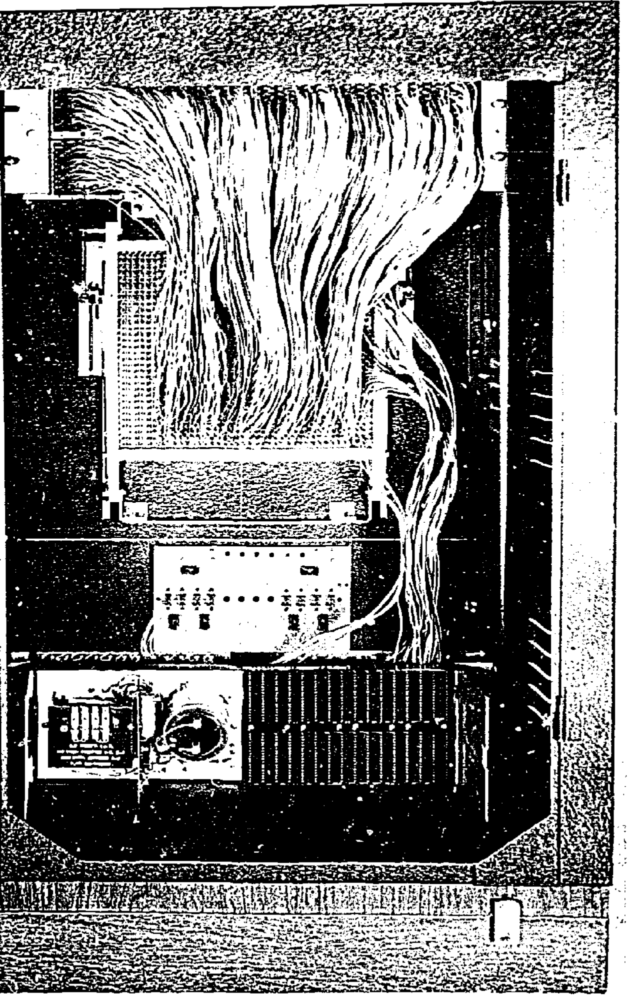
C-7

Table C-3

No. Required	Component & Type
24	Switches (ALCO) 105D
4	Switches (ALCO) 105F
28	Lights Dialco 252-9951-0975
7	Integrated Circuits MC858P
2	Integrated Circuits MC857P

Again, the printed circuit card carries sufficient identifying information so that assembly is straightforward.

A patchboard receiver is mounted in the enclosure. This particular receiver is a Mac Panel, Model 109211 Receiver. One simply maps the inputs, outputs and all printed circuit socket terminals to the appropriate pins of the patch-panel receiver. The completed wiring will resemble the rear view of the system shown in Figure C-8. Note that pins A and C are not mapped out; this implies that the front panel is safe in that any pin can be patched to any other pin or to ground with no component damage. As originally supplied,



Wiring of Removable Patchboard Logic System

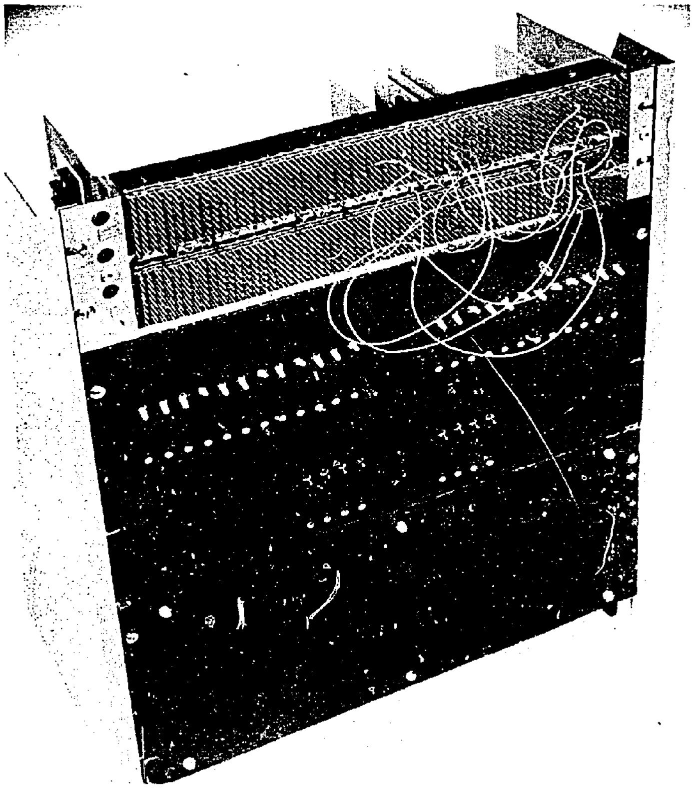
C-8

ceiver connector pins require solder type terminals Panel Type 423201, 1600 required). Small square (Auto-Swage posts, part No. W96-045-975Q) may be ed in these terminals and crimped, using a Mac Panel crimping tool (Type 452000). This procedure permits vrap terminations on both ends of the connecting and considerably speeds up the wiring. A hand ted wire-wrap tool is available from the Gardner r Corporation as part number 14H-1C and should be ped with a No. 26263 bit and a No. 18840 sleeve. this wire-wrapping technique, #24 solid wire should ed and about 5 turns made on each connection point. e particular system shown employs a Digital Equip- Corporation power supply mounted on a panel with sion for the insertion of additional logic modules al Equipment Corporation H910 panel). This is not ically required for the patch panel system and any +5 upply with adequate current capacity and reasonable tion may be employed. As an example of a suitable ative, a 5-volt supply manufactured by Elasco-Eastern, has been found quite satisfactory.

Board) and an assortment of patch wires (available from Mac Panel in a variety of lengths with multiple commons and common connector points) completes the system. It is strongly advised that the patch panel be silk-screened with a descriptive legend to avoid patching errors. If the manufacturer of the panels is supplied with suitable art work, he will supply the panels silk-screened at no additional charge (there is a one time charge for set up). Your local silk-screen shop will also be able to accomplish this task at only a nominal charge. The patch panel and connecting wires are surprisingly inexpensive and experience has suggested that one and one-half panels per laboratory student and 600 assorted patch wires per panel seem to be a reasonable initial purchase. The multiple connection patch wires and the expanding plugs are a necessity since in this arrangement, there is no facility for daisy-chaining or multiple connections on the patch panel itself.

A Limited Printed-Circuit Breadboard Facility (Designer: Professor David Robinson)

The hardware elements described in the previous section (PC cards, rack, socket panel, light and switch registers) with the exception of the patch panel and receiver may be effectively employed as a digital laboratory construction device of the breadboard type. The technique is to simply utilize this hardware and employ slip-on connections to establish the desired wiring of the logic modules. This scheme, shown in Figure C-9, utilizes slip-on connections available from



Limited Printed-Circuit Breadboard Facility

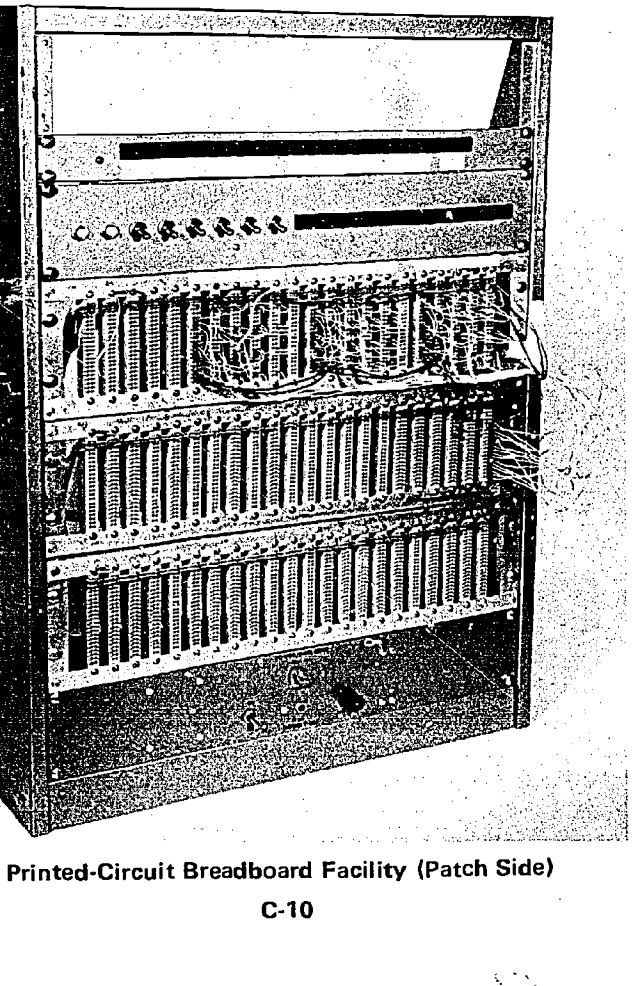
C-9

(Terminal No. 60477-2) which may be clamped on to
0-24 wire with an AMP No. 90087 hand crimping

perience has shown that this technique is very useful
ojects which require rather long-term retention of the
cal set-up. The connection technique is not suggested
equipment is to be set up and torn down with any
rity. The general technique does have an advantage
t if commercially available modules are employed in
f the special modules employed here, then the entire
n is commercially available and no construction is
ed.

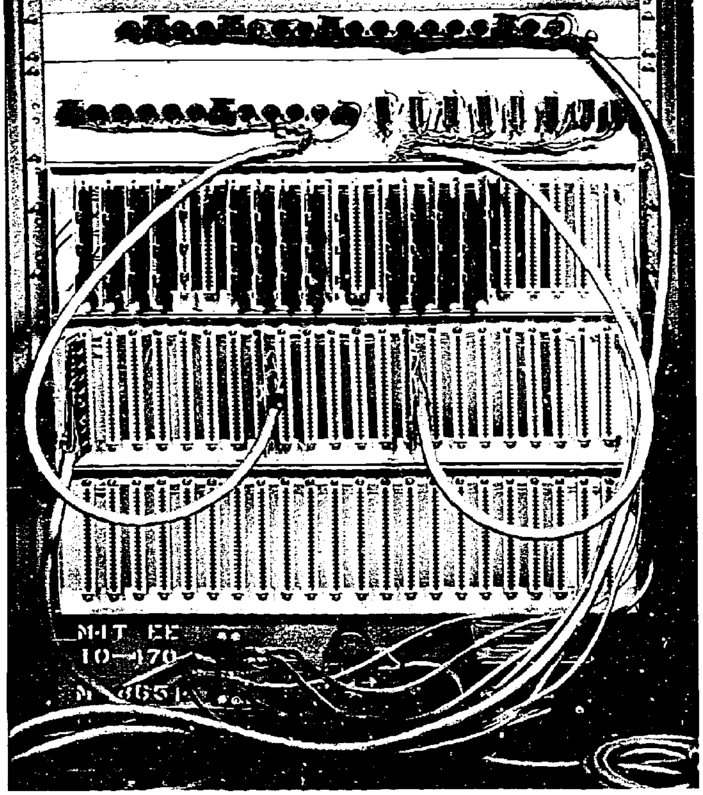
nted-Circuit Breadboard Scheme (Designer: Professor
ld Troxel, M.I.T.)

very effective digital systems laboratory has been
ed using the printed-circuit breadboard patching
ne shown in Figure C-10 and C-11. Utilizing this tech-
, systems can readily be configured in whatever size is
priate to the particular problem. This is, of course,
ct to the constraints imposed by the availability of
vare, since the system must remain intact until com-
n of the project or experiment. The particular system
described employs DTL integrated circuit logic. TTL
ner logic families can easily be used.



Printed-Circuit Breadboard Facility (Patch Side)

C-10



Printed-Circuit Breadboard Facility (Circuit Side)

C-11

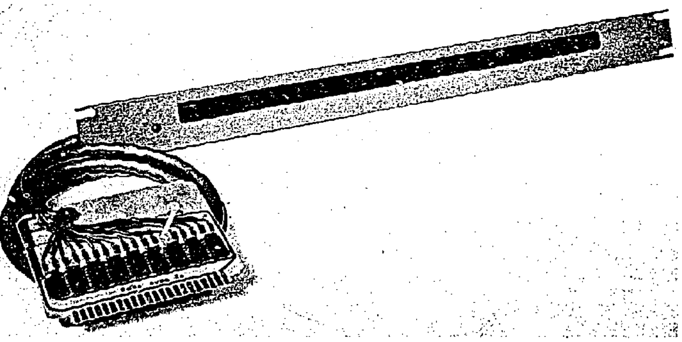
The construction of the system is simple. Aluminum angles (3/4" x 3/4" x 1/16") are formed and drilled to support 22 Amphenol 143-827-1002 connectors. When completed, the frame dimensions are 19" by 5-1/4" (Figure C-14). The complexity of the project or experiment dictates the number of such connector strips issued to a student; experience has shown that one strip shared by two students is sufficient for introductory laboratories while many students' projects may be satisfied by using only two such strips per student.

The basic connector strips are mounted in a conventional bench rack (Bud 1248-HG-24 or 1249-HG-31). A power supply is mounted in the rack. The unit shown is a Power/Mate Corporation P-602 mounted on a 3-1/2" panel with a switch, fuse, indicating light and a screwdriver adjust voltage control. Other power sources are, of course, available. Power may be distributed to all PC card connectors by connecting +5 volts to pin #22 and ground to pin #21.

The interconnection scheme for this unit is accomplished using taper pin connectors (AMP 41744LP) which may be crimped onto #22, 19/34 type E teflon wire. A tool (AMP 47150) is required for attachment of these taper pins to the patch wire. The logical interconnections are accomplished by inserting the connectors, using an AMP 811034-3 insertion tool and the wiring may be later removed using an AMP 380305-1 extraction tool. Experience has shown that about 300 leads per connector strip are adequate for most experimental situations.

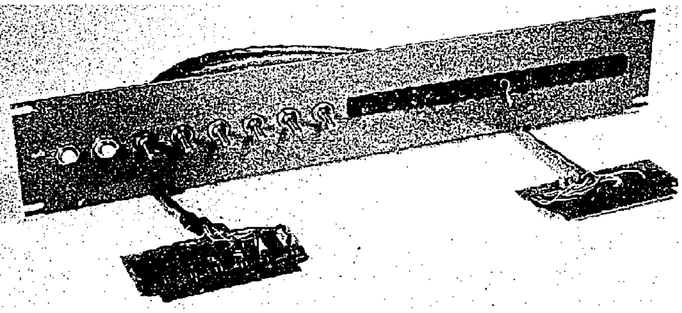
for interfacing connections and driving or contact debouncing circuitry are attached to the switch and light panels (Figure C-12 and C-13). By this technique, one can introduce inputs and outputs as required by the system and on any convenient connector in the system. Specifically, the switches used are AH&H-21350EH toggle switches for level inputs and Licon 76-2350-404 push button switches as momentary contact devices. The indicator lights are Sylvania 6ESB mounted in Sylvania 31275 light strip sockets. The switch and light panels connect to printed circuit boards which are available.

A number of printed circuit cards have been developed for use in this system (Figure C-14). Table C-4 lists the different logic cards that are in use at M.I.T. and their corresponding board number. The pin-outs for these cards can be obtained by writing to Professor Troxel. The printed circuit boards necessary to construct these cards may be obtained from Douglas Electronics and may be ordered by specifying M.I.T. Circuit Board plus the three-digit board type number.



Output Indicator Lamp Strip

C-12



Input Switch and Output Indicator Panel

C-13

An Integrated Circuit Breadboard Scheme

A number of simple breadboard units have been developed using special connector sockets of the type shown in figures D-10 and D-11 of Appendix D. Figure 3-5 of Section III shows photographs of two of these units. These connector sockets allow each terminal of the integrated circuit to be fanned out to a multiple tie-point so that interconnections may be easily accomplished.

P.C. Cards and Connector Strip Details

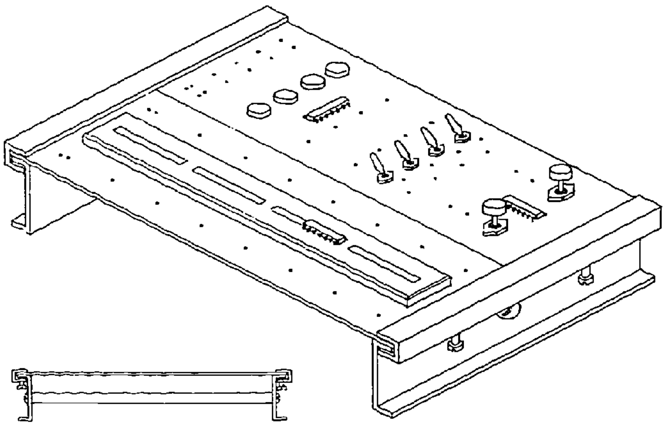
C-14

Table C-4

M.I.T. Logic Board Types

M.I.T. Board Number		Function
600	18	1K Pullup Resistors
601	4	AB + $\bar{C}$DTL Networks
602	4	DTL Transfer Gates
628	2	DTL Monostables
	2	2-input DTL NAND Gates
630	4	4-input DTL NAND Gates
631	6	2-input DTL Buffer NAND Gates
632	4	4-input DTL Buffer NAND Gates
643	6	2-input DTL Power NAND Gates
644	4	4-input DTL Power NAND Gates
645	4	2-input and 4 1-input DTL NAND Gates
646	5	2-input DTL NAND Gates
	1	DTL AB + CD Network
647	3	DTL J-K Flip-Flops with common clock
648	2	DTL S-C Flip-Flops
649	4	DTL Type D Flip-Flops
691	18	Lamp Indicator Assembly

Since these connector strips are so versatile, it is possible to develop a number of different mounting techniques. Figure C-15 is a sketch of one unit developed by Mr. David Kittel of the University of Connecticut working with Professor Taylor Booth. This unit is modular in nature. Two different modules are currently used and others could easily be developed.



Integrated-circuit Breadboard Facility.

C-15

Each module consists of a 3" x 8" piece of G-10 epoxy printed circuit board with the appropriate components mounted on it. The first module contains the terminal strip and small hook-up wire jacks connected to separate bus leads. The second module contains 4 lights, 4 toggle switches and 2 debounced pushbuttons. The spacing and layout of components on each module are not critical and can be done to suit local needs.

The modules are mounted in a frame made up of two 6-inch pieces of extruded aluminum made into a clamp as shown in figure C-15. The two pieces are held together by 6-32 screws. Table C-5 gives the list of parts used to construct the unit shown in Figure C-15.

Suppliers

Table C-6 lists the addresses of the companies mentioned in this appendix. Detailed information concerning the items mentioned can be obtained by writing directly to these companies.

Table C-5

Parts List for Digital System

Breadboard Unit

Qty.	Description	Manufacturer
2	6" length Aluminum extrusion 1/2" x 1/2" x 3/32"	Kaiser HC-21
2	6" length Aluminum extrusion 1-1/2" x 1/2" x 1/4"	Kaiser HC-29
2	3/32" G-10 Circuit board Unclad 3" x 6"	
30	Jacks for #22 wire	Cambion 3703-1-03
4	Indicator	Chicago miniature CM 22-2-01-12
4	Toggle switches	Alco switch MST-1150
2	Pushbutton switches	Grayhill 46-102-12
1	Quad 2-input NAND Gate (switch debounce)	MC 7400P
1	Quad 2-input power Gate (lamp drivers)	MC 858P
4	1/4 watt 2200 ohm resistors	
1	Terminal Strip	AP Inc. or EL Instruments

Table C-6

Commercial Sources of Components, Tools, Printed Circuit Cards, Etc.

Allied Electronics, Inc.
2400 W. Washington Blvd.
Chicago, Illinois 60680

AMP, Inc.
P.O. Box 3608
Harrisburg, Pennsylvania 17105
Telephone: Area Code (717) 564-0101

AP, Inc.
Painesville, Ohio 44077

Auto-Swage Products Inc.
726 River Road
Shelton, Connecticut 06484

Digital Equipment Corporation
Maynard, Massachusetts 01754

Douglas Electronics, Inc.
718 Marina Boulevard
San Leandro, California 94577
Mr. Chad Pennebaker
Telephone: Area Code (415) 483-8770

Elasco-Eastern, Inc.
5 Northwood Road
Bloomfield, Connecticut 06002

Electrostatics
7969 Engineer Road
San Diego, California 92111
Telephone: Area Code (714) 279-1414

Electrum Enterprises
1605 Ayre Street
Newport, Delaware 19804

E L Instruments, Inc.
Derby, Connecticut 06418

Gardner Denver
Grand Haven, Michigan 49417

Mac Panel Co.
2060 Brentwood St.
High Point, North Carolina 27263

Power/Mate Corp.
514 S. River St.
Hackensack, New Jersey 07601

APPENDIX D

Commercial Laboratory Equipment

This appendix discusses a number of commercially available products which are suitable and, in some cases, specifically designed for educational use. Some of these units are supplied with detailed descriptions—including suggested experiments of how they can be used in an educational program.

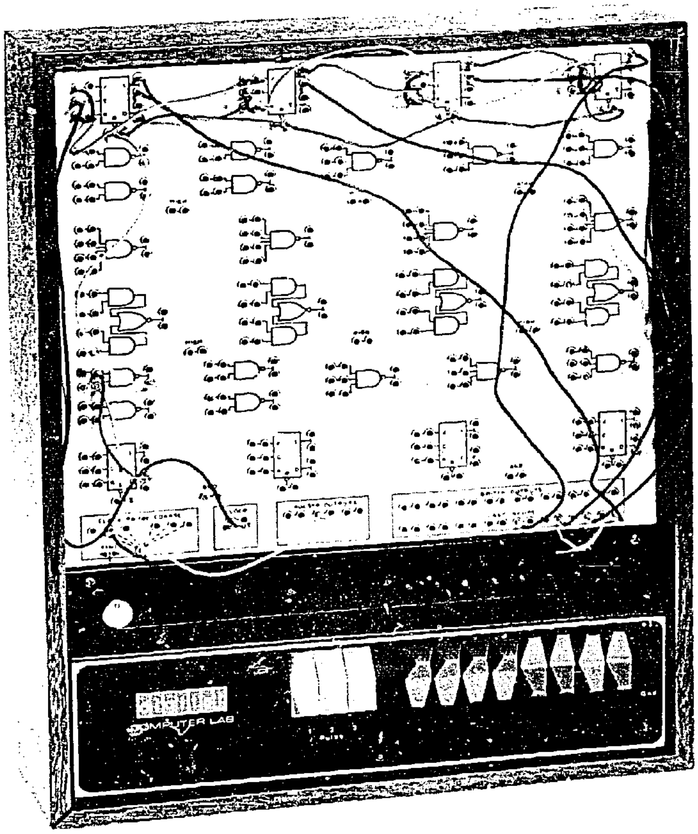
For the sake of convenience the equipment considered is classified (by an admittedly somewhat fuzzy line) into two categories. The first of these will be called the *patchboard* category and the other the *breadboard* category.

D-1 Patchboard Lab Units

The majority of products intended *specifically* for use by students in introductory courses dealing with digital systems falls into this category. As discussed in Section III, a patchboard has a complement of live logic elements hidden somewhere beneath a panel and interconnections are made between elements by using jacks on the front panel.

In addition to jacks for the terminals of the gates and other logic elements provided, most patchboard lab units feature jacks connected to arrays of switches and lamps, to accomplish input and output functions, respectively, jacks connected to fixed-voltage sources providing logical constant signals; and, in some instances, jacks connected to some sort of internal pulse generator to provide clocking signals. Other "peripherals" occasionally found on patchboard units include telephone-dial pulse generators, "Nixie"® tube display units for numerical readout, and various types of connectors (frequently of the printed circuit type) for the purpose of interfacing the lab unit with other components which may range in complexity from comparable lab units to full-scale stored-program computers.

The results of a survey presented in Appendix E indicate that the patchboard type of logic lab has been the quickest to win favor with educational institutions. Over half of the schools responding to this survey are using lab units manufactured by Digital Equipment Corporation of Maynard, Massachusetts, Figure D-1, or by Digiac Corporation of Plainview, Long Island, New York, Figure D-2. These manufacturers' designs are among the most representative of the patchboard-type lab unit described above of all such equipment currently on the market. This popularity is not surprising in view of the fact that, as we observed earlier, lab units of this type are specifically designed and promoted as foundation blocks for student logic laboratory programs. As such, they are usually supplied with comprehensive descriptions of particular laboratory programs in which they may be employed including, in some instances, step-by-step instructions for suggested experiments together with brief discussions of the theoretical aspects associated with each experiment.* The availability of such aids as these, of course, reduces to a minimum the time and work required of faculty members and their assistants to set up and conduct such a laboratory program.



Digital Equipment Corporation's COMPUTER LAB.

Figure D-1

Some patchboard-type units have some unusual features particularly worthy of mention.

The "Computer Logic Trainer" Series, sold by Digiac Corporation is among the most modular of all patchboard-type units on the market (this is not saying much since most commercially available patchboard units are decidedly not modular). The basic "trainer" patchboard mounts in an equipment rack to form the foundation of a lab unit which may be expanded with the addition of other modules containing additional logic gates, telephone-dial input and "Nixie" tube output devices, as well as a "Core Memory Trainer" module and other accessories as shown in Figure D-3.

The Digital Computer Laboratory products sold by Pedagogics, Inc., of Burlington, Massachusetts, comprise a whole family of units designed for use in digital systems laboratories. The "Basic Logic Module", shown in Figure D-4, is the key member of this family. It contains a patchboard through which are made available gates and flip-

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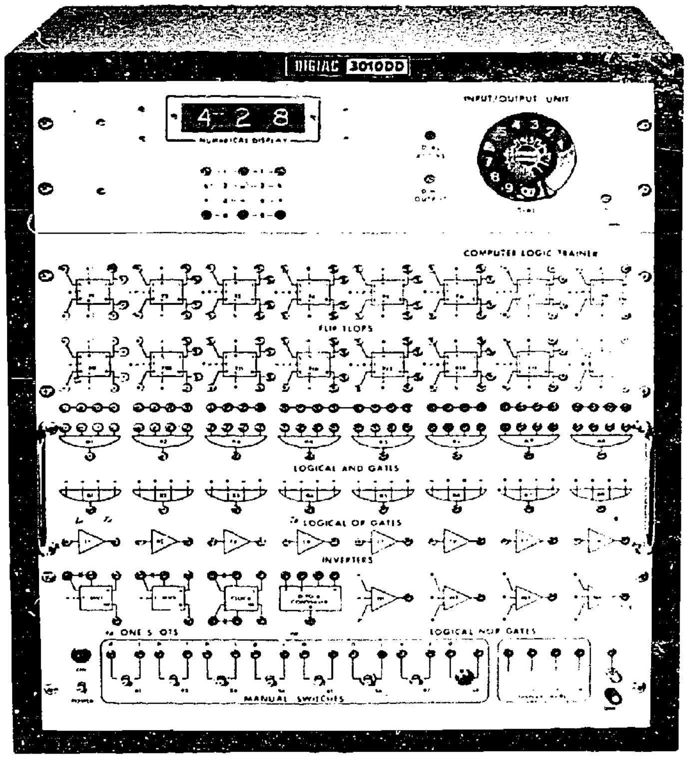
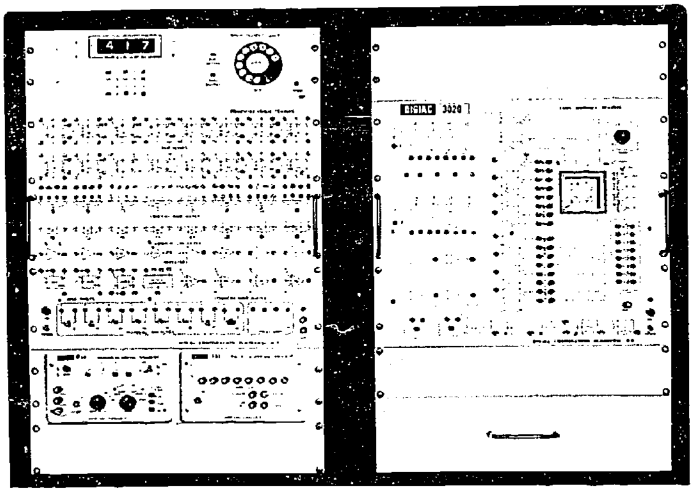
*See, for example, the *COMPUTER LAB Workbook* and the accompanying *COMPUTER LAB Teacher's Guide* published by Digital Equipment Corporation, Maynard, Massachusetts.



DIGIAC's Model 3010 DD Logic Trainer.

Figure D-2

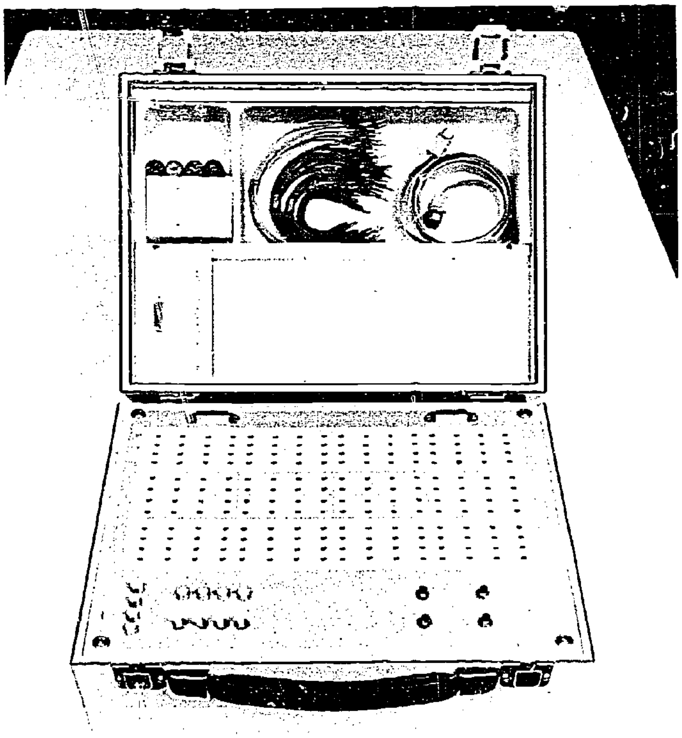


A larger DIGIAC laboratory unit including a Model 3020 Core Memory Trainer.

Figure D-3

flops and arrays of indicator lights and of toggle and push-botton switches. It is housed, together with its own line-operated supply and such miscellany as patch wires in a rugged briefcase-like box, making it highly portable and suitable for take-home use by students.

The patchboard itself in the Pedagogics design is rather unique. Most of the logic elements provided are associated with either the "Gate Field" or the "Flip-Flop Field." The jacks in the "Gate Field" are connected to four "universal gates," each of which can perform any one of the following functions:



PEDAGOGICS' Basic Logic Module.

Figure D-4

- dual two-input AND, OR, NAND or NOR gates
- single four-input AND, OR, NAND, or NOR gate
- single two-input EXCLUSIVE OR gate

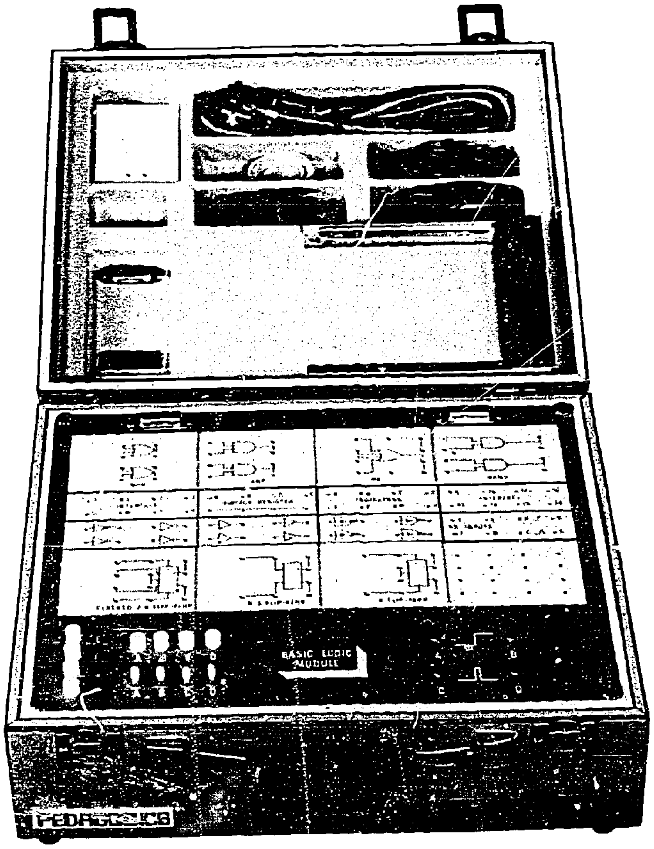
The student selects a desired gate function by placing a plastic overlay, marked with a standard symbol for a gate of that function, over one of the four positions of the universal gate field. Each overlay is so punched that only those jacks associated with a particular selected function are accessible with the overlay in place. Figure D-5 shows the "Basic Logic Module" with several overlays in place. The actual circuitry of each "universal gate" employs somewhat obsolescent RTL (resistor-transistor logic) integrated circuits. The jacks in the "Flip-Flop Field" are connected to four "universal flip-flops", each of which can function as any of the following:

- R-S flip-flop
- T flip-flop
- Clocked J-K flip-flop

Here again, the student selects the specific function desired by placing an appropriate plastic overlay over one of the positions of this "field."

The "Basic Logic Module" can also be provided with one or two monostable multivibrators by plugging "SS" (single-shot) modules, which are available as an accessory, directly into the patchboard. Five different "SS" modules are available, providing pulse widths throughout a range from 500 nanoseconds to 2 seconds.

A "Master Station" is available in a separate briefcase-like box. This unit may be used to provide power to other

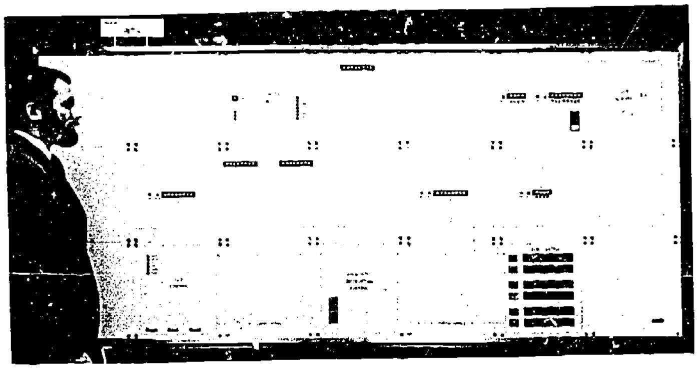


A Basic Logic Module with overlays in place.

Figure D-5

units of the Digital/Computer Laboratory family and as a central source of timing and control signals for experiments involving several interconnected "Basic Logic Modules."

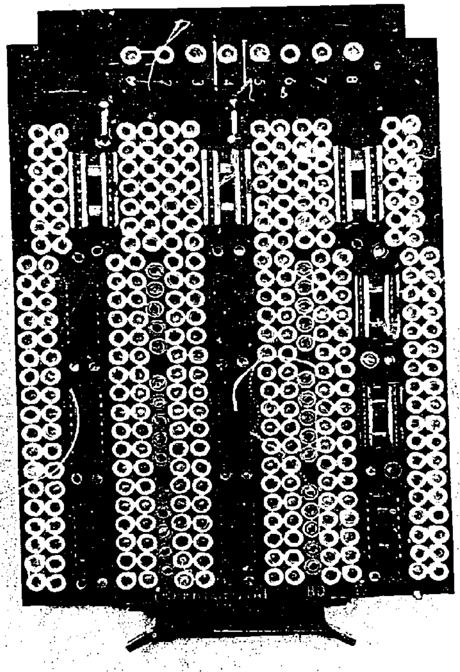
In addition to the above modules, "Core Memory Modules" and "ROM Modules" (read-only memory) are available. All the members of the Digital/Computer Laboratory family are incorporated in the PLC-1 (Pedagogic Laboratory Computer) computer shown in Figure D-6. This is a small, eight-bit word-oriented stored program computer intended to acquaint the student with all fundamental aspects of computer organization.



PEDAGOGICS' PLC-1 Computer.

Figure D-6

For those students developing special projects not readily accommodated by the standard modules in the Pedagogics line, two new products have recently been introduced These take the form of printed circuits boards upon which just about any conceivable circuit can be constructed using integrated circuits in dual-inline packages. The smaller of these "Experimental Boards", shown in Figure D-7, accepts up to twelve IC's and plugs directly into a socket of the "Basic Logic Module." The larger board accommodates more integrated circuits and is provided with wire-wrap pins for use in larger projects of a more permanent nature. The availability of these "Experimental Boards" greatly increases the flexibility of the Digital Computer Laboratory product line and lends it some common features later.

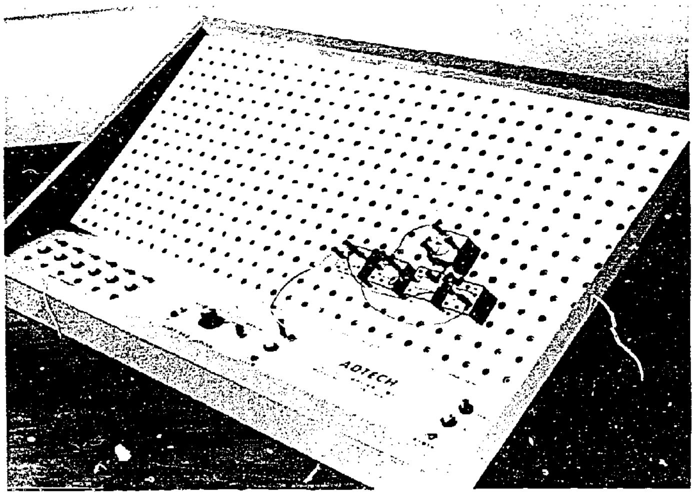


A PEDAGOGICS "Experimental Board."

Figure D-7

Another manufacturer providing equipment of a particularly unique design is Adtech, Inc., of Honolulu, Hawaii. The placing of the Adtech units in the patchboard category is somewhat arbitrary in that the Adtech scheme differs from most patchboard arrangements in important respects and, indeed, has many of the characteristics of the breadboard type of lab unit to be described subsequently.

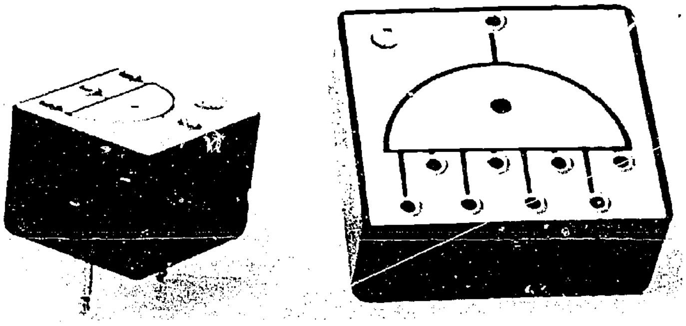
One might describe the Adtech scheme as allowing one to build a "patchboard upon a patchboard." Most of the front panel area of the Adtech units is devoted to a very simple "patch panel" which bears no legend at all and whose jacks are all connected simply to a low-voltage DC power supply. Into each of the jacks of this "Logic-board," may be plugged a "Logicube". A Model 401



An ADTECH Model 401 Logic Laboratory. This view shows the "Logicboard" with several "Logicubes" inserted.

Figure D-8

"Logicboard" with several "Logicubes" inserted is shown in Figure D-8. Each "Logicube" is a roughly cubical package, varying in size from 1-1/2" x 1-1/2" x 1-1/4" to 2-1/2" x 2-1/2" x 1-1/4" and contains a single logic element. The rear face of each "Logicube" is fitted with a plug by means of which the package may be mounted onto the power-supplying "Logicboard." The front face of the cube bears a symbol indicating the function it performs, jacks connected to the input and output terminals of the element contained, and an indicator lamp that lights when the element's output signal is "high" or logical 1. "Logicubes" providing an unusually wide variety of functions are available. AND, OR, NOT, NAND, NOR, EXCLUSIVE-OR, EQUIVALENCE, and MAJORITY gates are all provided by the manufacturer. Typical "Logicubes" are shown in Figure D-9. The available flip-flop collection includes RS, RST, and clocked JK flip-flops as well as simple latch circuits. Such MSI functions as shift registers, BCD counters and parallel adders may also be purchased. One-shots and clock oscillators with periods ranging from one microsecond to one second as well as several other timing and control elements are available. For those interested in experimenting with hybrid circuits, a four-bit current-summing D/A converter as well as a comparator for the construction of A/D converters is obtainable. This is not a complete list of all functions available in "Logicubes," but does indicate the high degree of versatility provided by the Adtech products. For those still not completely satisfied, empty "Logicube" packages, as well as cubes on which are mounted 14- or 16-pin dual-inline IC sockets are available. In all the pre-wired "Logicubes," 20 Mhz TTL (transistor-transistor logic) integrated circuits with a typical fanout of 10 is employed.



Typical ADTECH "Logicubes."

Figure D-9

Once the desired set of "Logicubes" has been plugged into the "Logicboard," the logic elements are interconnected with patchwires as in the case of all patchboard-type lab units.

Also somewhat atypical of patchboard-type logic laboratory equipment but certainly warranting consideration are the products in the Heath/Malmstadt-Enke digital laboratory equipment line sold by Heath Company of Benton Harbor, Mich.The degree of sophistication of these products makes them perhaps more valuable for research and development applications than for introducing students to the lab. This line of equipment is too extensive to describe in full detail in this report, thus our attention is restricted to some of the features of that unit which would be of most use in student logic labs: the Heath Analog Digital Designer (ADD) and some of its accessory modules. The front panel of the ADD exposes the controls of the power supply for the unit, and the controls of the "Digital Timing Module" and the "Binary Information Module." The power supply provides the following DC outputs: 5V at 2A, 170V at 50mA, and ± 15V at 150 mA. The "Digital Timing Module" generates square-wave, complementary pulse, and sawtooth outputs at levels of 4 volts peak (typical) and frequencies from 0.1 HZ to 10 kHz. The "Binary Information Module" provides ten neon indicator lamps and 10 rocker switches and associated circuitry permitting direct connection to DTL and TTL logic circuit outputs and inputs, respectively.

The "patchboard" of the ADD is under the top cover of the unit. As in the case of the Adtech unit, the ADD's patchboard may be tailored to an individual user's needs. The patching panel consists of up to fourteen individual 32-jack strips, each approximately 3/4" wide and 5-1/2" high. Each such strip is mounted on the edge of a printed circuit card containing TTL IC logic elements. A legend using standard symbols is printed on each strip to identify gates and terminals provided on the PC card below. The jacks on the strips are designed for "wire-patching"—i.e., they accept ordinary hook-up wire and component leads without any special mating plugs. This in itself is a valuable feature; most other patchboard lab units require patch cords specifically designed for the unit which cost as much as $1.00 or more. Each strip and its attached PC card plugs into the ADD; thus the functional cards may be easily interchanged. The "standard equipment" complement of cards supplied with each ADD consists of: four NAND gate cards, each providing two 4-input and four 2-input gates; two flip-flop cards, each containing two master-slave clocked J-K flip-flops; one card containing two independent one-shot circuits ($10\ \mu s \leq$ period ≤ 1 sec); one card providing seven SPDT relays with TTL-compatible transistor drivers; one card containing a comparator and voltage-to-frequency converter for hybrid circuit experimentation, one card on which there is an operational amplifier together with a logic-driving amplifier; one card containing two 16-pin dual-in-line sockets; and one blank card with which the user can do anything he wishes. Additional cards of the types described above as well as other types of special-purpose cards are available as extra-cost options. The Heath "Analog Digital Designer" is designed to be directly compatible with other products of the Heath/Malmstadt-Enke Modular System line for use in a broad spectrum of applications.

With the Adtech logic laboratory equipment, as well as the Heath products described above, it is possible, using empty "Logicubes" or blank cards, or else using cubes or cards which simply provide IC sockets, to concoct a variety of different "building blocks" limited only by one's imagination and the contents of the innumerable large catalogs of electronic components in existence today. This lends the Adtech and Heath equipment an important similarity to the laboratory units in the other category which we are about to consider.

D-2 Breadboard Lab Units

The distinguishing characteristic of a breadboard type of lab unit is that it provides simply a convenient medium for temporarily or semi-permanently constructing a logic circuit out of individual electronic devices or components. A decade ago, the basic "device" would have been, perhaps, a transistor, resistor, or semiconductor diode. Virtually all modern digital equipment is now built out of integrated circuits, however, and all of the lab units to be discussed below use as their most important building blocks, IC's—either directly from the device manufacturer's box or mounted in some sort of "carrier." Precisely for this reason, the breadboard type of lab unit is unquestionably the most versatile, adaptable, and obsolescence-proof such unit one can buy. There is a prodigious array of IC's available today and new circuits appear on the market almost daily. The breadboard type of logic lab makes it feasible to incorporate at modest expense such new products as soon as they appear.

As do patchboard lab units, breadboard units typically provide a power supply and arrays of lamps and switches to accomplish output and input functions.

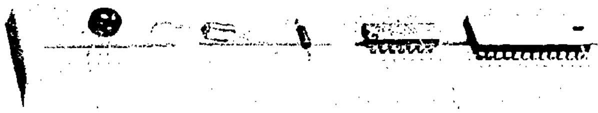
The choice of power supply immediately restricts the class of devices with which a breadboard unit may be used. For relatively simple units employing a single-voltage supply, an output of *5 volts* is strongly recommended without reservation. Such a choice will permit the unit to function well with nearly all DTL and TTL logic circuit families on the market. For student projects of up to moderate size (up to perhaps 30 IC's) a current capacity of 1 to 2 amperes should by ample. the supply should be fused and/or current limited for its own protection.

There are several units which allow convenient breadboarding of logic networks by students in laboratory courses. Of the three that are discussed, only one, the unit by Perfection Electronics Products, is made specifically for ent use.

One of the most recently introduced breadboard units, and one which the Task Force has not had an opportunity to inspect is being produced by a small firm owned by a French family, Besnard et Fils.* The Besnard unit comes in a easel-like box containing a power supply, switches, other miscellany, and logic modules. A user plugs an IC of his own choosing into a socket on the hidden back side of each such module and then mounts the module in its appropriate place in the box. The front of each such module bears jacks connected to the IC sockets below by printed wiring. Once the logic modules have been mounted, the logic elements may be interconnected by means of patchwires plugged into these jacks. This characteristic makes the Besnard unit, once the logic modules have been fitted with IC's and installed, seem much like the "patchboard-type" of lab unit discussed above. Indeed, an Adtech lab unit fitted only with "Logicubes" with empty IC sockets or a Heath ADD containing only cards bearing empty IC sockets as described above would be exceedingly similar to the Besnard product.

At present, the Besnard unit is intended for use with TTL only (but it is strongly suspected that it could be used with DTL as well). The basic box for a 21-logic-module unit is priced at about $285. The power supply sells for about $90. The cost of each of the logic modules ranges from roughly $20 to $40 (sans IC), thus making this one of the more dearly priced breadboard units available.

The remaining breadboard units to be described have an extremely significant feature in common: in each, the foundation of the breadboard itself is a collection of very versatile terminal strips that can be used to mount components and leads without the need for special patch cords or soldering connections. At present, there are two manufacturers of these strips. AP Incorporated of Painesville, Ohio offers a full line of these strips. The AP terminal strip most commonly used is the 'full-double terminal strip shown in Figure D-10. This AP product accepts 14-, 16- and 24-pin DIP and *any* other components having lead diameters from 0.010 to 0.032 inches. Each terminal has four tie points thus allowing one to use "daisy-chain" wiring to achieve fanout factors limited only by component capabilities. Components mounted on the AP strips may be interconnected using standard solid hook-up wire in sizes from #26 to #20 (experimentation by the authors and others indicates that #22 is about optimal). The individual contacts in the strips are spring-loaded beryllium copper, heat-treated and gold-over-silver plated. It is felt that the availability of a terminal strip such as this AP product is a great boon to all builders of either commercial or "homebrew" breadboard-type logic lab units.



The "Full-Double" Terminal Strip of AP, Incorporated.

Figure D-10

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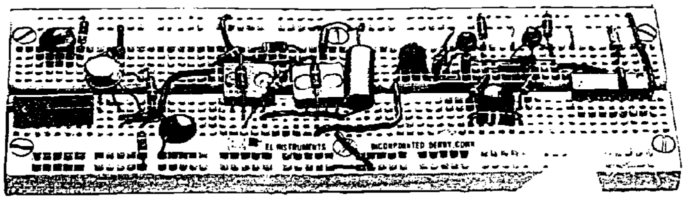
*See *Electronics*, March 30, 1970, p. 72.

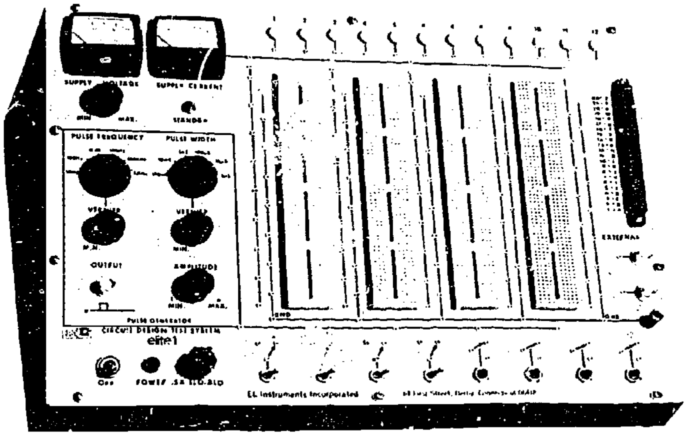
A terminal strip similar to the AP strip has been developed by EL Instruments, Inc., of Derby, Connecticut. As shown in Figure D-11, this strip is slightly larger than the AP strips and somewhat more versatile. It also has the advantage of requiring less force for the insertion of components, thus reducing the likelihood of bent IC pins.



The SK-10 Terminal Strip of EL Inst.

Figure D-11

One family of commercial breadboard unit emp g terminal strips of this type is the ELITE Product line nufactured by EL Instruments, Inc., of Derby, Connecticu The ELITE 1, shown in Figure D-12, uses four strips to accommodate up to 32 14-pin DIP. Four toggle and four pushbutton switches and an array of twelve indicator lamps are provided for "I/O." A 22-pin connector at one edge of the unit facilitates interfacing the unit with other equipment. The pulse generator provides pulses continuously variable in amplitude from 1-6 volts, in width from 1 μs to 100 ms, and in frequency from 10 Hz to 1 MHz. The built-in supply provides an output of up to 2 amperes over a voltage range of 2-10 volts, making this lab unit suitable for use with almost any type of logic available with the exception of families (such as ECL) requiring multiple supply voltages. The price of the ELITE 1 is $650.

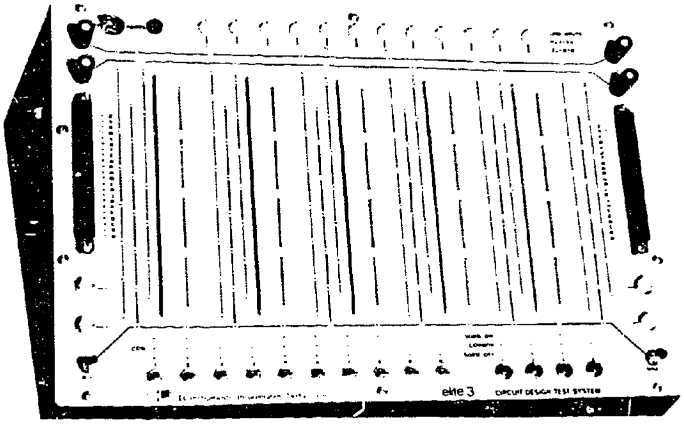


EL Instruments' ELITE 1.

Figure D-12

EL Instruments also manufactures the ELITE 2. This unit is quite similar to the ELITE 1 in all respects. It has, however, three independent power supplies: 2-10 volts at 2 amperes and two 5-30 volts at 200 mA. This eliminates the need for auxiliary supplies when experimenting with MOS logic circuits and with linear IC's (such as operational am- ers). In addition, the waveform generator of the ELITE 2 is much fancier; among many other features, it offers sine, triangle, square-wave, and positive and negative pulse outputs. These and other niceties such as additional switches, a one-shot, etc., boost the price of the ELITE 2 to about $1300 -twice that of the ELITE 1.

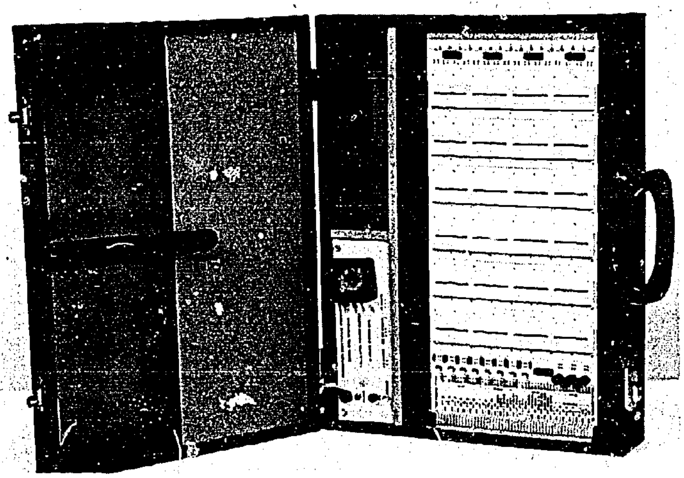
The ELITE 3 shown in Figure D-13 has been recently introduced for those who do not require the more sophisticated features of the ELITE 1 and ELITE 2. It incorporates five terminal strips—thus accommodating up to 25% more logic than the other two units—but does not provide a pulse generator or a variable voltage power-supply. Several options are available. The options deemed most useful are a 5-volt, 1-ampere power supply and debouncing circuitry for each of the four pushbutton switches. Thus equipped, the unit is called ELITE 3A by its manufacturer and sells for $415



The ELITE 3 of Elite Instruments.

Figure D-13

The last lab unit to be considered is the "Logilab Mod1" manufactured by Perfection Electronic Products Corporation (PEP) of Royal Oak, Michigan and shown in Figure D-14. This unit offers the advantage of a highly modular design. Each module is built upon a printed circuit strip which is



Perfection Electronic Products' "Logilab Mod 1."

Figure D-14

mounted between two metal rails which in turn serve both as structural supports and as a power supply bus.

The power supply provides 5 volts current limited at 2 amperes. An additional output connected to a simple circuit connected to the secondary of the power supply provides an almost-square-wave at an amplitude of 5 volts and a frequency of 60 Hz for use as a "cheap and dirty" clock pulse. The supply in a unit tested by one of the authors of this report not only did not work but showed indications of marginal engineering throughout. Since that time we have been informed that this transformer has been redesigned. However as of this writing the new unit has not been tested.

Each Breadboard Strip consists essentially of an AP strip of the type described above mounted on a PC strip.

The Switch Strip contains 8 toggle and 3 pushbutton switches. The pushbutton switches are provided with "debouncing" filters employing DTL logic.

The Indicator Strip contains 16 indicator lamps, each driven by a 2-input NAND gate (implemented in DTL) permitting either a single logical 1 input and an open input or two logical 1 inputs to light a lamp. The lamp drivers used have the annoying property that unless at least one of the inputs of an unused lamp circuit is grounded (connected to a logical 0), that lamp is lit continuously—a bothersome distraction and a waste of power.

The Connector Strip contains a 100-contact printed circuit edge connector to facilitate interfacing the "Logilab" with other equipment.

"Standard equipment" for the "Logilab" consists of six Breadboard Strips and one of each of the other modules described above as shown in Figure D-14. Extra-cost options include: a variable-voltage power supply; solid-state pulse generator, telephone-dial pulser; and custom options built to purchasers' specification.

The cost of the "Logilab" outfitted with standard equipment is $395.

The commercial laboratory equipment market is in a state of flux. Many of the manufacturers mentioned in this appendix have indicated that they are in the process of updating or redesigning their equipment. In most cases, this redesign involves updating the components in their unit rather than a radical change in the basic organization of the unit. The latest information about any unit of interest can best be obtained by writing directly to the manufacturer.

APPENDIX E

COSINE Task Force VI—Survey Results

One of the initial activities of the Task Force was to survey all electrical engineering departments to determine the current level of digital laboratory activity. This appendix summarizes the results of this survey which was completed in early 1970.

Replies were received from 142 institutions, 127 in the United States and 15 in Canada. There are 858 faculty members in these schools teaching both programming and hardware oriented courses in computers of which 476 (56%) are teaching programming courses and 512 (61%) are teaching non-programming courses in the digital area.

Lab Facilities

The extent that digital logic laboratories have been established is most interesting as 110 or 77.5% of the schools responding have some form of undergraduate digital logic laboratory work in their program. Further, 103 (78%) have commercially made logic equipment. The most popular lab equipment is DEC (Digital Equipment Corporation) followed closely by Indiana Instruments as shown in Table I.

Table I. Breakdown of Commercially Made Equipment Now in Use

Manufacturer	Number of Schools that have this equipment
Digital Equipment Corp. (DEC)	61
Indiana Instruments	25
Digiac	14
Hickok	5
Feedback, Inc.	5
Adtech	4
Fabri-Tek	3
Honeywell	2
Heath	2
Bi Tran	2
Signetics	2
Ketchum	2
NORC	2
E.S.E.	2
Hewlett Packard	1
Other	20

Twenty-five schools or 17.6%, utilize equipment which can be used in the student's room or dormitory. This equipment varies from small commercially made hardware to special locally built hardware which was designed for this purpose.

A significant number of institutions, 61 (43%) have either undertaken the construction of their own laboratory equipment or have obtained surplus computer modules and [illegible] ted them to their laboratories.

The impact of integrated circuits is also wending its way into laboratory work as 76% of the schools responding make use of integrated circuits in their laboratories. A breakdown by type and packaging is given in Table II. Several have indicated that their use of Flat Packs has been dictated by their proliferation in "College Gift" packages and many are interested in better, less expensive ways to mount and utilize devices in this kind of package.

Table II. Types and Packaging of Integrated Circuits in Schools Which Are Using Them

IC type	Percentage of schools using them	IC Package	Percentage of schools using them
RTL	47	D.I.P.	71
DTL	66	TO-5	48
TTL	74	Flat Pack	60
ECL	10		
CTL	7		

Extension of Lab Facilities

The response to the rather open question, "What additional laboratory equipment do you require?" indicates an increasing interest in mini-computers. Forty schools indicated this was the equipment they required. The type of mini-computer desired varied from a modular computer that could easily be torn down and built up by students through the popular PDP-8 series, to small time sharing systems of modest size. Table III contains a listing of equipment which the various respondees have indicated they require.

Table III. Laboratory Equipment Required

Equipment Required	Number of Schools
Mini-Computer	40
Logic Labs/or Kits	37
I/O and Interface equipment Including AD/-DA, Teletypes, etc.	33
IC's and other components	21
Logic Modules	19
Memory-Core, Tape, Disc, Drum, etc.	19
Power Supplies and Test Equipment	15
IC Sockets and Mounts, Breadboards	14
Hybrid Equipment	6
Logic Simulation Program	1

The reasons that equipment required cannot be obtained vary from "none" to "lack of understanding of the advantage of hands-on experience" presumably by those who hold the purse strings. As shown in Table IV, the ever-present problem of funding has not disappeared. Note that responses of "none" to this question disqualified the respondees' requirements inclusion in Table III.

Table IV. Reasons Additional Lab Equipment Cannot Be Obtained

Reason	Number Responding
Lack of Funds	96
Lack of Faculty Interest, Faculty Time, or Technical Support	24
Poor Enrollment	5
Not Commercially Available	1
Lack of Space	1
Lack of Understanding of Advantage of Hands - On Experience	1
Pressure to Share Large Machines	1

COSINE and Labs

In response to the questions concerning an NSF sponsored workshop on laboratories, 108 (85%) wanted a two-day workshop and 64 (36%) wanted a two-week workshop. Some indicated both while others suggested one week and still others didn't want any.

The open question, "What kind of information and digital laboratories do you think COSINE should compile and distribute to interested persons?" yielded a plethora of requests as compiled in Table V.

Table V. Laboratory Information Desired from COSINE

	Information Desired	Number Requesting
1.	What others are doing, including: Lab experiments and equipment, Lab organization, Lab projects and Lab manuals.	76
2.	What equipment is available both commercially and what can be built locally.	43
3.	Description of locally built equipment in use at other schools.	20
4.	Ratings of Commercial Equipment Comparisons of Commercial and "Home brew" equipment - A consumers' report of lab equipment.	17
5.	What is the relationship between lab and remainder of curriculum?	7

Table V. (Continued)

	Information Desired	Number Requesting
6.	Use of Mini-Computers in lab.	7
7.	Objectives of digital lab.	6
8.	Results of this survey.	5
9.	Bibliography of digital systems texts.	4
10.	Faculty and graduate assistant time required to run lab.	4
11.	Description of a minimal set of experiments and equipment.	4
12.	A comparison of hardware vs hardware simulation.	3
13.	Logic simulation programs.	2
14.	Student reaction to labs.	2
15.	IC and logic applications.	1
16.	Use of lab equipment in room or dorm.	1
17.	Create logic standards.	1
18.	Start a users' group.	1

Computer Facilities

The number of schools with computing centers was 141 or, all but one of the schools responding had a computer center of some kind. The types of machines by manufacturer are given in Table VIa. Note that there are more computers indicated than there are respondents to the questionnaire. This is because some schools have as many as 6 computers available. The computers in this table do not include those rented on a time sharing basis with only remote terminals on campus.

The breakdown of the large number of IBM machines is given by class in Table VIb.

A most interesting result of this survey is the number of departments which have computers that are available to undergraduates—98 or 69% of the schools responding. The number of computers in departments by manufacturer is

Table VIa. Number of Computers on Campus as Function of Manufacturer

Manufacturer	Number on Campus
IBM	160
CDC	23
UNIVAC	10
D.E.C.	8
G.E.	6
XDS	6
Burroughs	5
RCA	2
HP	1
Honeywell	1
NCR	1
Philco	1

Table VIb. IBM Machines by Class

Class	Number on Campus
360 systems	108
7040/7090	10
1107/1500	22
1620/1800	17

given in Table VIIa. The large numbers of DEC and IBM machines in departments is given by type numbers in Table VIIb. The list of peripherals which departmental systems have and the percentage of users is given in Table VIII.

Finally, 40 or 28% of the schools responding make use of a program which simulates a small computer on a large computer in teaching computer courses.

Table VIIa. Number of Computers in Departments by Manufacturer

Manufacturer	Number in Departments
DEC	51
IBM	11
XDS	5
CDC	5
Univac	4
HP	4
Bitran	3
RCA	2
GE	1
Varian	1
Honeywell	1
EAI	1

Table VIIb. DEC and IBM Computers in Departments

Computer		Number in Departments
DEC	PDP-8, PDP-8I	24
	PDP-8L, PDP-8S	7
	PDP-5	4
	PDP-9	4
	LINC-8	3
	PDP-15	2
	PDP-11	2
	PDP-7	1
	PDP-10	1
	PDP-1	1
IBM	1620	9
	7700	1
	360	1

Table VIII. Peripherals on Departmental Machines

Peripheral	Percentage of Users
Teletypes	63%
High Speed Paper Tape	51%
Magnetic Tape	39%
Disc	35%
Drum	13%
Display Graphics	43%
Punched Card	47%
A/D and/or D/A	62%
Analog Computer	78%