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THE MAN MADE WORLD, LABORATORY MANUAL.
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DESCRIPTORS- *CURRICULUM DEVELOPMENT, *COMPUTERS, *INSTRUCTIONAL MATERIALS, *LABORATORY MANUALS, *MATHEMATICS, *PHYSICAL SCIENCES, *SECONDARY SCHOOL SCIENCE, *SCIENCE ACTIVITIES, *TECHNOLOGY,

THIS LABORATORY MANUAL, THE COMPANION VOLUME TO THE STUDENT'S TEXT FOR THE "MAN MADE WORLD" HIGH SCHOOL COURSE, CONTAINS 31 EXPERIMENTS DEALING WITH THE THEORY, CIRCUITRY, AND OPERATION OF COMPUTERS, AND RELATED TECHNOLOGY. THE COURSE WAS WRITTEN BY SCIENTISTS, ENGINEERS, AND EDUCATORS, AND IS INTENDED AS A PART OF THE CULTURAL CURRICULUM FOR ALL STUDENTS WHO WILL HAVE RESPONSIBLE ROLES IN SOCIETY. BASIC TO THE COURSE IS THE THEME OF MAN'S ABILITY TO SHAPE HIS OWN FUTURE, AND CENTRAL TO THIS, HIS ABILITY TO COMMUNICATE VAST AMOUNTS OF ACCUMULATED KNOWLEDGE AND DATA EFFICIENTLY AND RAPIDLY. THE COMPUTER IS THE OBJECT OF ATTENTION AS AN EXAMPLE OF HOW MAN'S INSIGHTS AND INSPIRATION CAN PRODUCE PRODUCTS THAT SHAPE HIS FUTURE. LABORATORY EXERCISES INCLUDE ACTIVITIES RELATED TO THE FOLLOWING TOPICS--(1) LOGIC CIRCUITS, (2) BINARY NUMBER SYSTEMS, (3) MEMORY CIRCUITS, (4) COUNTING CIRCUITS, (5) MEASUREMENT AND ELECTRICAL INSTRUMENTS, (6) ANALOG COMPUTERS AND OPERATION, AND (7) SIMULATION PROBLEMS. (DH)

Laboratory Manual

The Man Made World

A high school course / developed by
Engineering Concepts Curriculum Project

A Program of the Commission on
Engineering Education / Washington, D.C.

NOTE TO THE STUDENT: Throughout the text of this lab manual you will find numerous questions. Those which are preceded by an asterisk and a number (for example, *5) should be answered in the lab manual or otherwise as directed by your teacher. You should answer unmarked questions to your own satisfaction as you do the labs.

EXPERIMENT I

Introduction to the Logic Circuit Board

The Logic Circuit Board (Model II) consists of a low voltage power supply, 4 lamps, 4 slide switches and 4 relays. The positive terminal of the power supply is internally connected to the lamps and the relays. All other terminals are connected to eyelets in the wiring field.

You wire circuits using the taper pin jumpers supplied. Inserting a taper pin into an eyelet with a slight twisting motion gives a reliable electrical connection. Always remove jumpers with a twisting pull on each end. Never pull them out by the wire as this will quickly break them.

Each terminal is connected to 2 eyelets. This is sufficient to connect any desired circuit since an arbitrary number of terminals can be connected together by a chain of jumpers. (As a convenience, extra eyelets are supplied for the negative power supply terminal since it is used so much.)

To aid you in wiring circuits, the eyelet wiring field (Fig.1) is labeled with the same symbols used in the circuit diagrams. Although the notation used may seem strange at first, you will quickly find as you become familiar with it that it has many advantages over the more pictorial notation sometimes used.

(1) Slide Switches

Figure 2 shows a slide switch cut away so that you may see how it works. In Fig. 2 (a) the switch is in the "0" position. The metal bridge carried by the insulating handle is connecting the terminal b to the terminal c. Since the lamp is wired to the battery through terminals m and c there is a gap in the metallic path between m and c and the lamp is not lit.

In Fig. 2 (c) the switch has been operated; the slider is in the "1" position. Now the metal bridge connects terminals m and c; since there is a complete metallic path from the battery through the lamp, it is lit.

Figure 2(b) is a circuit diagram arranged to show how the circuit symbols correspond to the switch, lamp, battery and wires in the pictures. Between terminals m and c we have a make contact on switch A. This is shown in the diagram by the symbol —X— (a). Remember that a make contact is closed only when the switch is operated (A = 1). The break contact is drawn with the symbol —|— (a). This of course is closed only when the switch is not operated (A = 0).

Notice further that the circuit diagram does not indicate whether the switch A is actually operated or not. It can be in either state. That is, a circuit diagram shows the logic of the connections but not the state of the switches.

LOGIC CIRCUIT BOARD

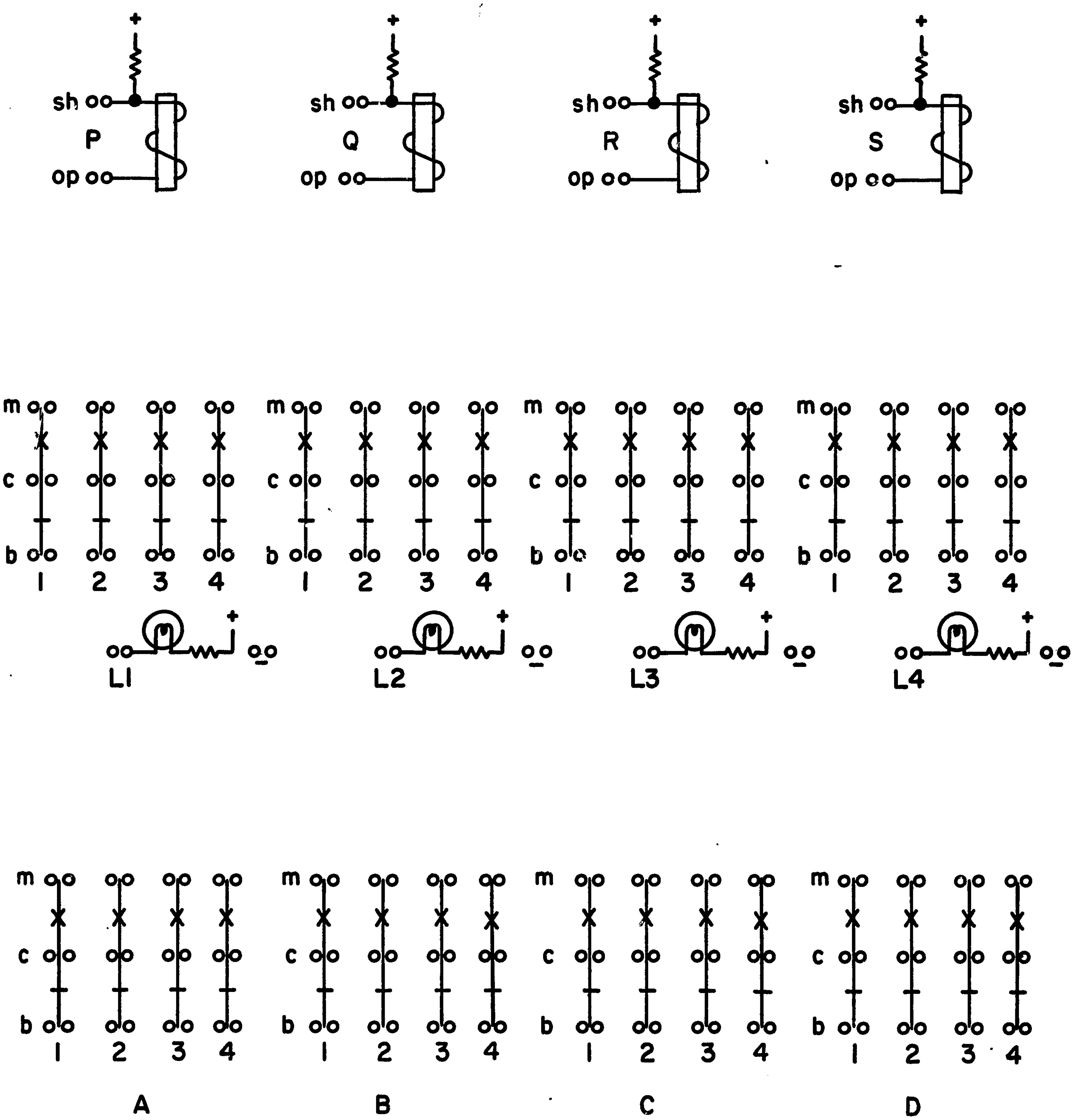


Fig. 1

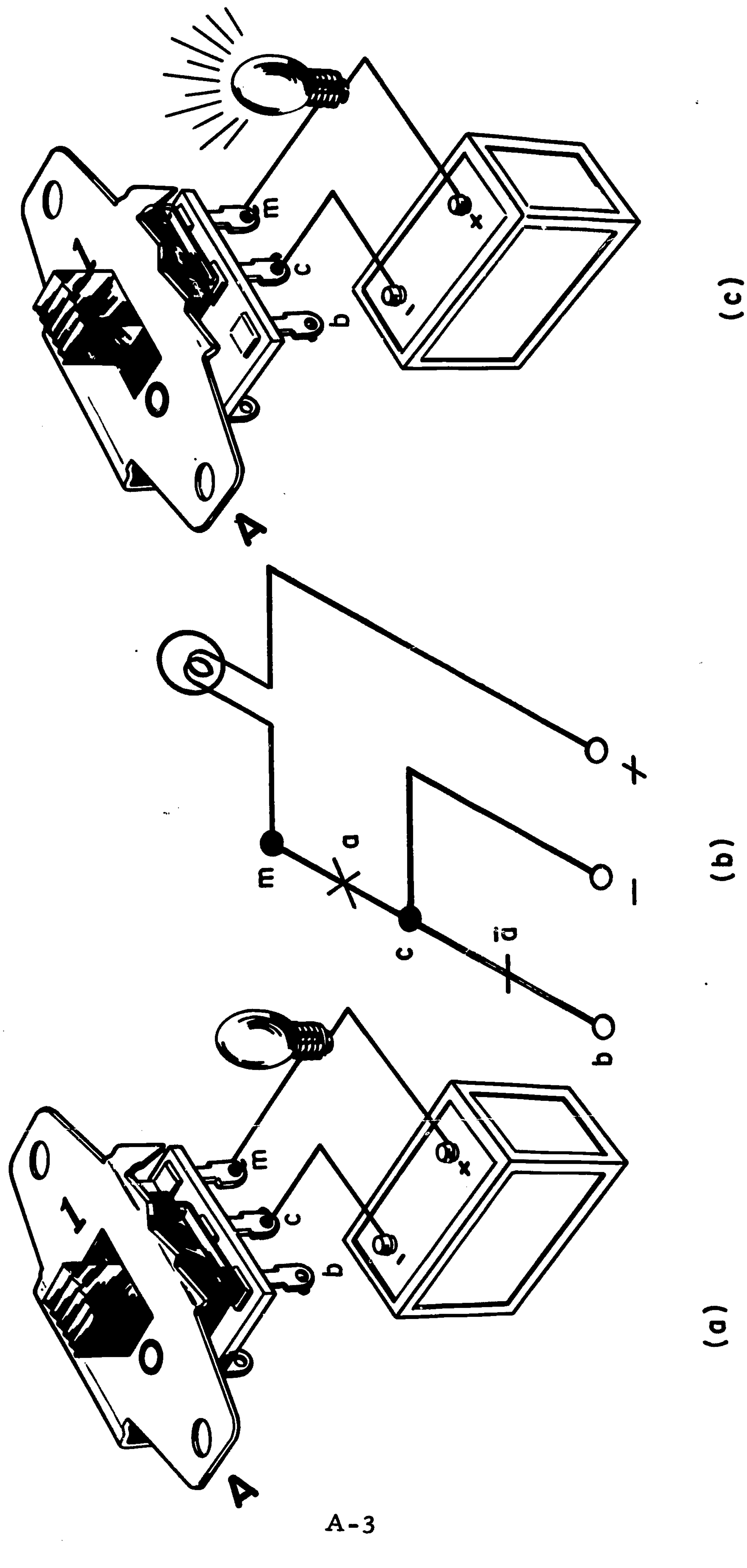


Fig. 2

What happens as Switch A is operated? Explain the result. (*1) Complete the Truth Table, Fig. 6.

(*2) A street intersection has 8 lamps RN (Red North), RE, RS, RW and GN (Green North), GE, GS, GW. These lamps are all controlled by contacts on a single Switch A. If A = 1 means East-West traffic can flow, show the complete circuit diagram.

(3) AND Circuit

Connect L1 and two contacts of Switches A and B as shown in Fig. 1.7.

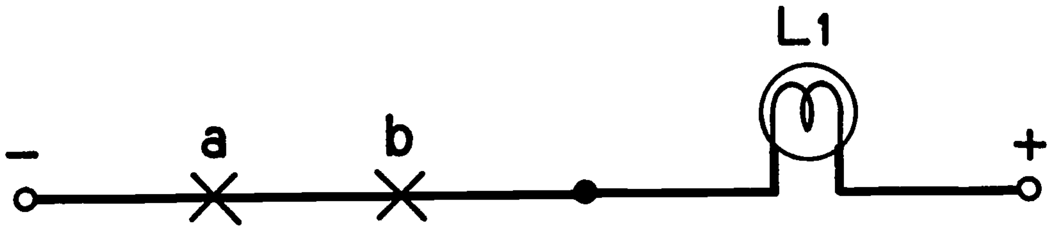


Fig. 7

A	B	L1
0	0	
0	1	
1	0	
1	1	

Fig. 8

(*3) By operating Switches A and B and observing lamp L1, complete the Truth Table, Fig. 8 . Why is the circuit called an " AND" circuit? How many ones are there in the output column of the Truth Table? (*4) How many ones has the output column of the Truth Table for A " AND" B " AND" C?

In a telephone booth, in order to initiate a call, the receiver must be lifted and a coin deposited in order to obtain a dial tone. Each of these acts operates a switch. Prepare a diagram of a circuit that meets these requirements.

(4) OR Circuit

Connect L1 and contacts of A and B as shown in Fig. 9.

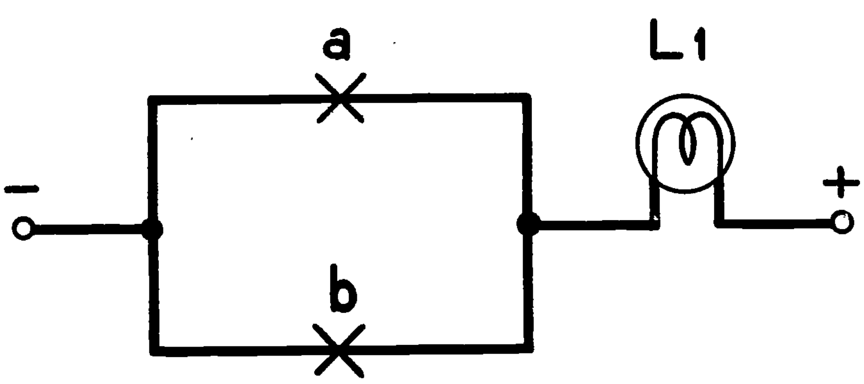


Fig. 9

A	B	L1
0	0	
0	1	
1	0	
1	1	

Fig. 10

What is the effect on L1 of operating (1) A only, (2) B only, (3) A and B? Explain your results. (*5) Complete the Truth Table, Fig. 10. Explain why this circuit is called an "OR" circuit. How many ones in the output column of the Truth Table? (*6) How many ones has the output column of the Truth Table for A "OR" B "OR" C?

The fire alarm system of a school has a number of switches located throughout the building. Prepare a diagram showing how any one of four switches may be used to sound the alarm.

(5) A Problem

Here is a circuit problem for you to solve. You are given Switches A and B and lamp L1. Draw a circuit that will light the lamp only if A is operated "AND" B is "NOT" operated. Prepare a Truth Table for this problem. Wire your circuit and check it against the Truth Table. If necessary correct your circuit. (*7) Draw the correct circuit and Truth Table as Figs. 11(a) and 11(b).

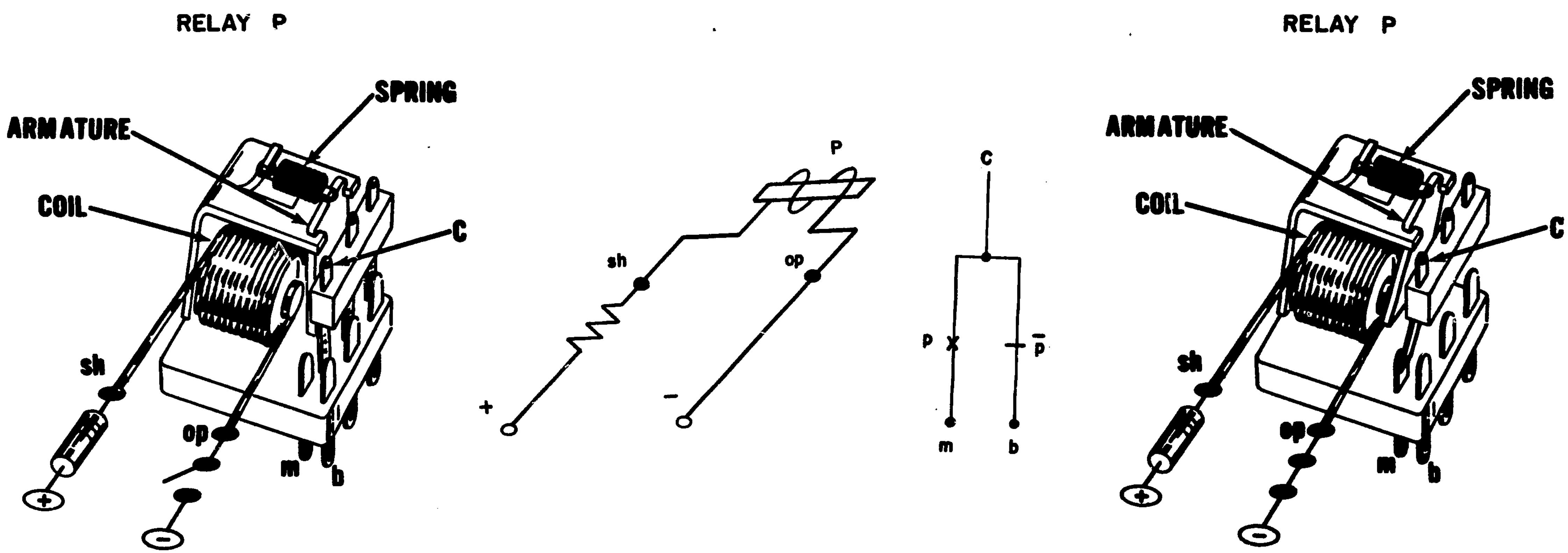
Fig. 11(a)

Fig. 11(b)

Problem - An industrial concern uses a beam of electrons to sterilize packages on a conveyor belt passing below a linear accelerator. Switch A operates whenever a package is in line with the accelerator. At times employees must be in the area near the accelerator. Switch B operates whenever an employee is standing on the floor near the accelerator. Design a circuit to control the power to the accelerator to insure that an employee will not be exposed to harmful radiation.

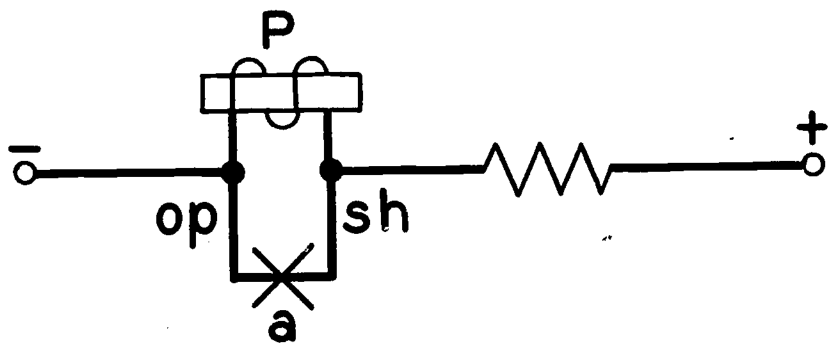
(6) The Relay

As more complicated circuits are developed we need a method of controlling one set of contacts from a network of other contacts without using a person to operate a switch. We use the relay such as shown in Fig. 12 to do this. Fig. 12 (a) shows the relay P in the released state. Since the wire between the negative power supply terminal and the op terminal is open, there is no current through the relay coil. The spring pulls on the iron armature which is hinged above the coil as shown. Mounted by an insulating block to the armature is a spring strip connected to the terminal c. The armature forces this strip against the terminal b. Thus there is a metallic path between the terminals c and b.



(a) RELEASED (b) CIRCUIT DIAGRAM (c) OPERATED

Fig. 12



A	L1	L2
0		
1		

Fig. 17

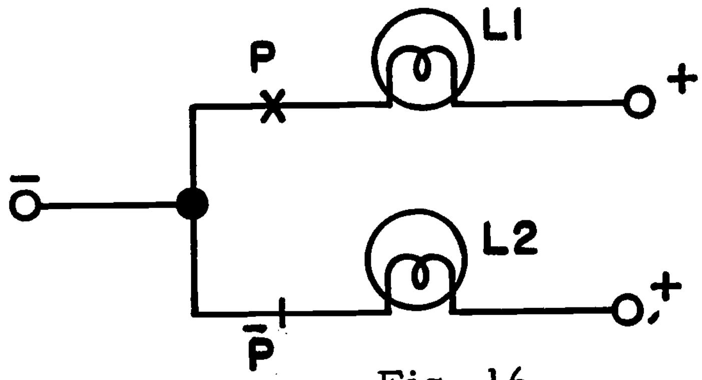


Fig. 16

Wire the circuit shown in Fig. 16 and compare it with the previous circuit. (*9) Summarize your results in the Truth Table, Fig. 17. (*10) What advantage or disadvantage does the circuit of Fig. 16 have compared to Fig. 13 for relay operation?

(*11) A relay coil is part of a burglar alarm operating on dry cells; which coil control method would be preferable? Suggest other situations where these considerations would be important.

EXPERIMENT II

Binary Numbers

In order to build an adder for binary numbers we need two kinds of circuits. We study them first and then build an adder.

(1) Odd Parity Circuit

Connect Switches A and B as shown in the circuit Fig. 1.

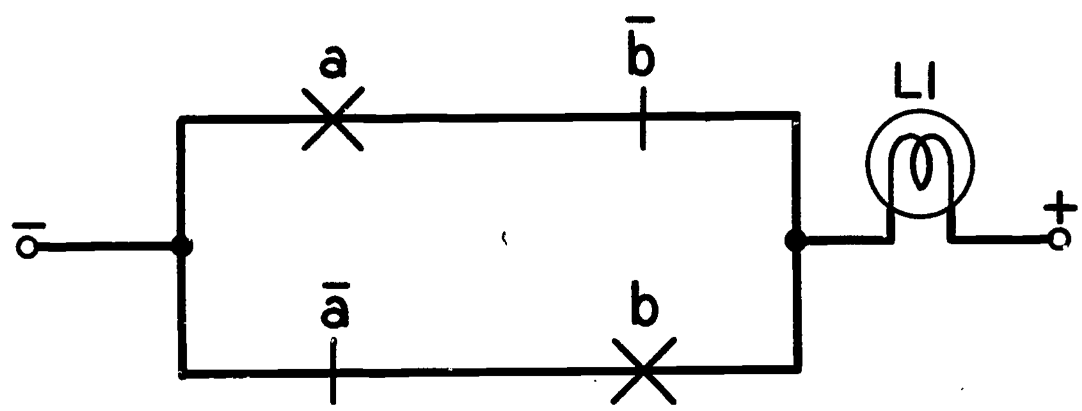


Fig. 1 An Odd Parity Circuit

(*1) Analyze this circuit by completing the following table listing the condition of each set of contacts, and of the lamp, for all input settings of A and B.

A	B	a	$\bar{a}$	b	$\bar{b}$	$a \cdot \bar{b}$	$\bar{a} \cdot b$	L1
0	0							
0	1							
1	0							
1	1							

Fig. 2

Operate the switches to confirm the results of your analysis. (*2) Why is the term "odd parity" appropriate for the circuit?

As circuits become more complicated, the wiring of a circuit directly from its diagram becomes difficult. An intermediate step which helps is a list of the terminals that are to be connected together. Such a list is called a "Running List". To make the list we need a notation for the terminals to be connected. First we number the various contacts on a switch or relay. We label a contact terminal in three parts:

First a capital letter for which switch or relay;
Next a number for which contact;
Finally m, c, or b for which terminal.

Relay coil terminals are labeled with a capital letter followed by op or sh. The negative power terminal is Neg.

Examples: The terminals of make contact a2 (on switch A) are A2c and A2m. The terminals of break contact $\bar{a}2$ are A2c and A2b. The terminals of break contact $\bar{b}1$ (on switch B) are Blc and Blb. From now on we will give contact numbers in the diagrams. You will find them an aid in finding wiring errors.

A sample running list for the odd-parity circuit is:

Alm, Blb; Alc, Neg;

Alb, Blm; Ll, Blc.

The first line of this running list is read:

"Connect terminal lm of Switch A to terminal lb of Switch B. Connect terminal lc of Switch A to the negative power supply terminal.

(*3) Write two more sentences for the second line.

Figure 1 is an odd-parity circuit for two variables. The following circuit, Fig. 3,is an odd-parity circuit with three variables. Use this Running

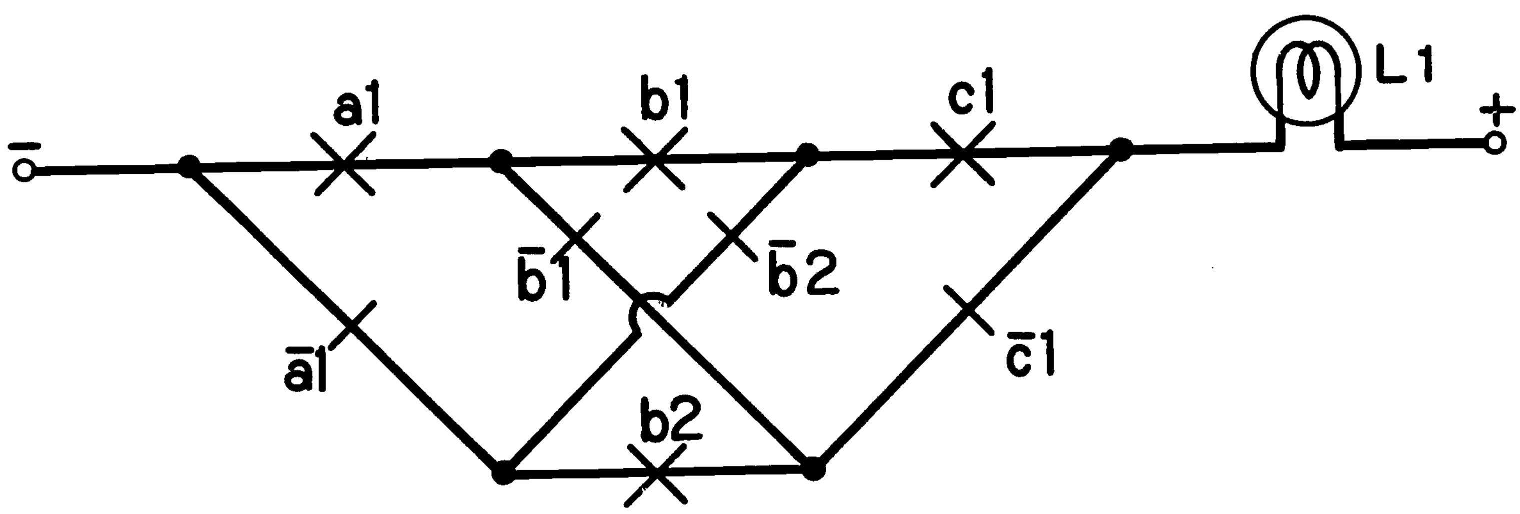


Fig.3

List to wire it quickly and easily. There is a comma in the list for each wire; the fourth line means :Run one wire from terminal lm of Switch B to terminal 2b of Switch B and run another wire on from terminal 2b of Switch B to terminal lm of Switch C." Notice that in Fig. 3 we have shown the contact numbers used i this <u>Running List.</u>

Neg,	Alc;	
Alm,	Blc;	
Alb,	B2c;	
Blm,	B2b,	Clm;
Blb,	B2m,	Clb;
Clc,	Ll.	

(*4) After you wire the circuit, operate the switches and summarize your re sults in the Truth Table, Fig. 4.

A	B	C	L1
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

Fig. 4 Truth Table for 3-Variable Odd-Parity Circuit

(2) The Majority Circuit

A majority circuit is shown in Fig. 5.

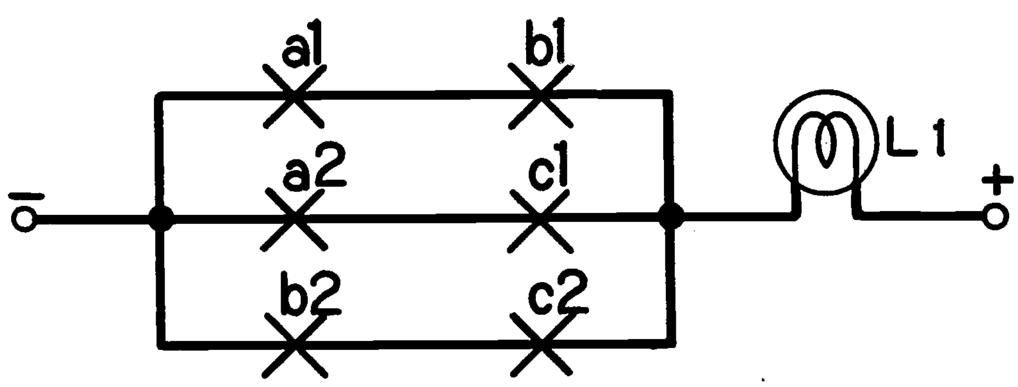


Fig. 5 Majority Circuit

The Running List for the circuit is:

Neg, Alc, A2c, B2c;
Alm, Blm;
A2m, Clm;
B2m, C2m;
Ll, Blc, Clc, C2c.

(*5) By operating the switches complete the truth table Fig. 6

A	B	C	L1
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

Fig. 6 Truth Table for the Majority Circuit

Modify the circuit of Fig. 5 so as to eliminate one of the a contacts. Wire and test your modified circuit.

(3) Binary Adder

Let us combine some of the logic circuits that we have studied to make a circuit that can take as its input two binary numbers of two digits each, and give a binary output that is the sum of the input numbers. This type of circuit can be extended to add larger numbers. The section of your text on Binary Numbers should be reviewed in preparation for this experiment.

Wire the circuit of Fig. 7 on the logic circuit board. You may use the Running List that is given below. This Running List is designed to wire the circuit board so that one of the input numbers is to be set up on the Switches A and B; the other input number on Switches C and D. When so set up, the lamps L2, L3, and L4 light up to indicate in binary form the sum of the input numbers.

Running list for two-digit binary adder:

Neg, A1c, A3c, B2c, B3c, C1c, R1c; B3m, D3c; D3m, Sop; B2m, D2b; B2b, D2m; D2c, L4; A1m, S3m; A2m, C1m, S1m; A2c, Rop, S1c, S3c; A3m, C3c; A3b, C2c; C3m, C2b, S2m; C2m, C3b, S2b; S2c, L3; R1m, L2.

(*6) Make a Truth Table for this circuit. It will have four input columns and three output columns.

(*7) Can you eliminate relay R from this circuit?

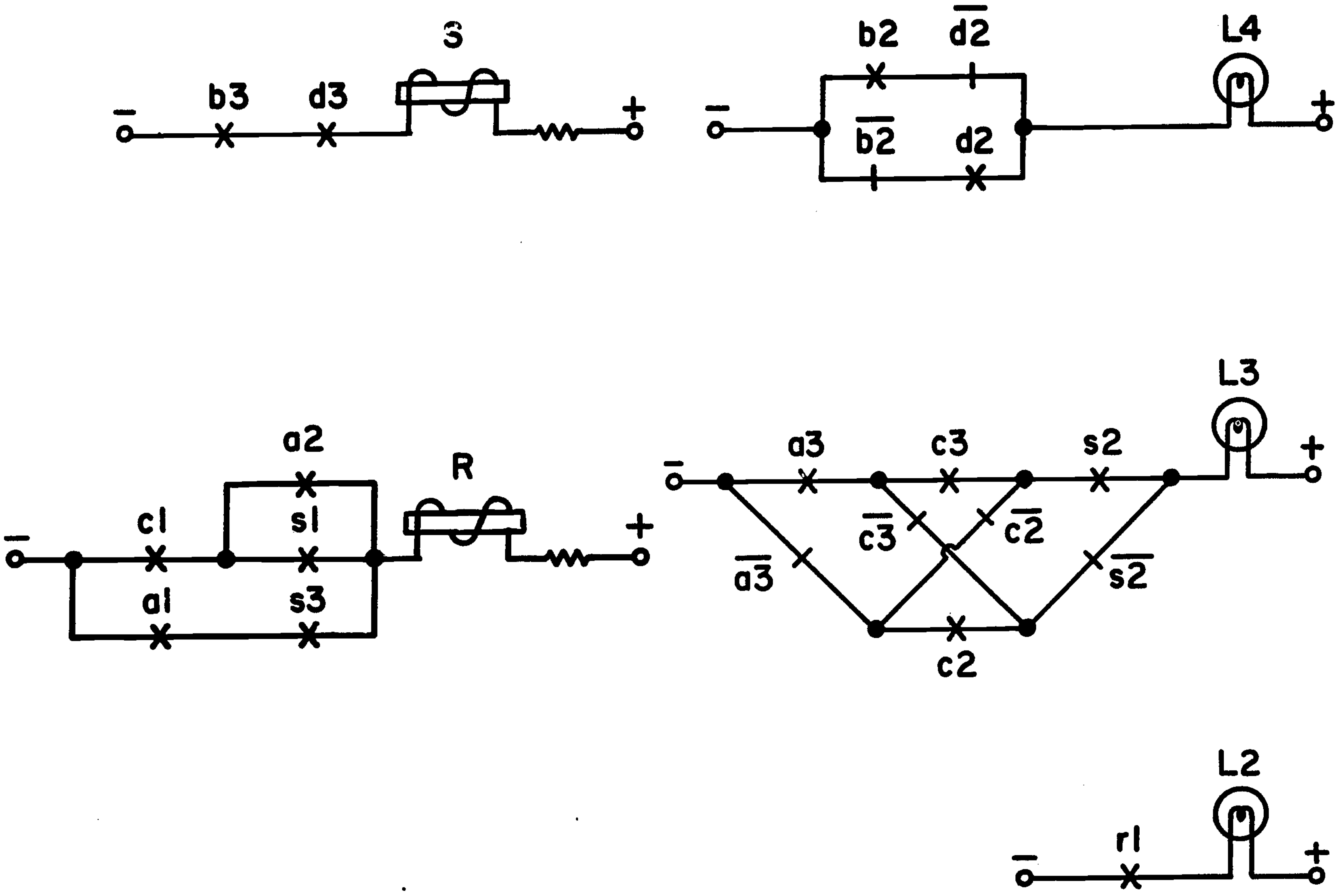

S
b3
d3
b2
$\overline{d2}$
$\overline{b2}$
d2
L4
a2
c1
s1
a1
s3
R
a3
c3
s2
L3
$\overline{c3}$
$\overline{c2}$
$\overline{a3}$
$\overline{s2}$
c2
L2
r1

Fig. 7

(4) Large Binary Adder (Optional, for newer model logic circuit boards o

By connecting several logic circuit boards together you can make an ac for large binary numbers. You get two more digits of each input number for every additional logic board. One input number goes on all A and B switches, t other on C and D switches. The carry into the least significant end will automatically be correct but you will want to connect a lamp to see the carry out o the most significant end. Figure 8 gives the circuit diagram and here is th running list.

Running list for large binary adder:

Wiring on this board:

Neg, Dlc, B3c, Blc, A3c; Dlm, B2m, Slm; Blm, S3m; B2c, Rop, Slc, S3c; B3m, D3c; B3b, D2c; D3m, D2b, S2m; D3b, D2m, S2b; S2c, L4; A3m, C A3b, C2c; C3m, C2b, R2m; C3b, C2m, R2b; R2c, L3; Alm, R3m; Clm, Rlm, A2m; R3c, Rlc, A2c; Clc, Alc;

Interboard wiring:

Alc, (this board), Neg (next board);
A2c, (this board), Sop (next board).

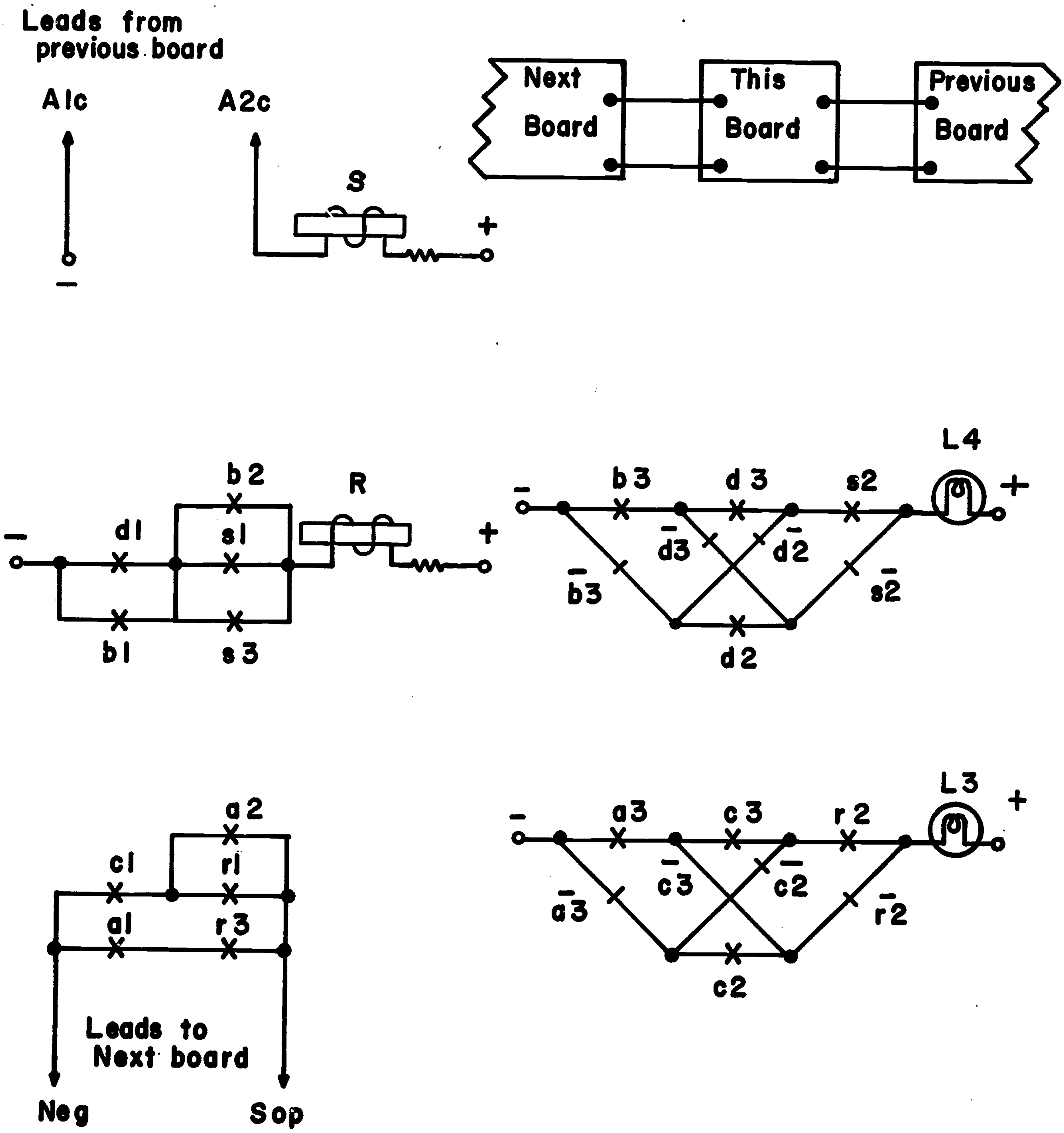

Leads from
previous board
Alc
A2c
S
+
−
Next
Board
This
Board
Previous
Board
b2
R
−
dl
sl
+
bl
s3
L4
+
−
b3
d3
s2
$\overline{d3}$
$\overline{d2}$
$\overline{b3}$
$\overline{s2}$
d2
a2
cl
rl
al
r3
Leads to
Next board
Neg
Sop
L3
+
−
a3
c3
r2
$\overline{c3}$
$\overline{c2}$
$\overline{a3}$
$\overline{r2}$
c2

Fig. 8

EXPERIMENT III

More Circuits That Do Not Require Memory

(1) River Crossing Problem

In this experiment we see how a circuit can help solve a problem by serving as a model of a situation. Using the model, various approaches to the problem can be tried without setting up the actual situation. The river-crossing problem is an example of this method of problem solving.

Problem - A boatman must carry a wolf, a goat and a cabbage across a river in a boat which is so small that he can carry, at most, one of them with him in it at a time. Moreover, whenever the wolf and goat are together, he must also be present to keep the goat from being eaten. Neither can he leave the goat with the cabbage. How can he carry all of them from the south bank of the river to the north bank?

To assist in representing the conditions of the problem on the logic circuit board, switch A will represent the position of the goat. When A is operated, the goat is assumed to be on the north shore. When the switch is not operated, the goat is assumed to be on the south shore. The same conventions will apply to switch B representing the position of the boatman, C representing that of the cabbage, and D that of the wolf. Study the circuit in Fig. 1, then hook up the circuit from the Running List.

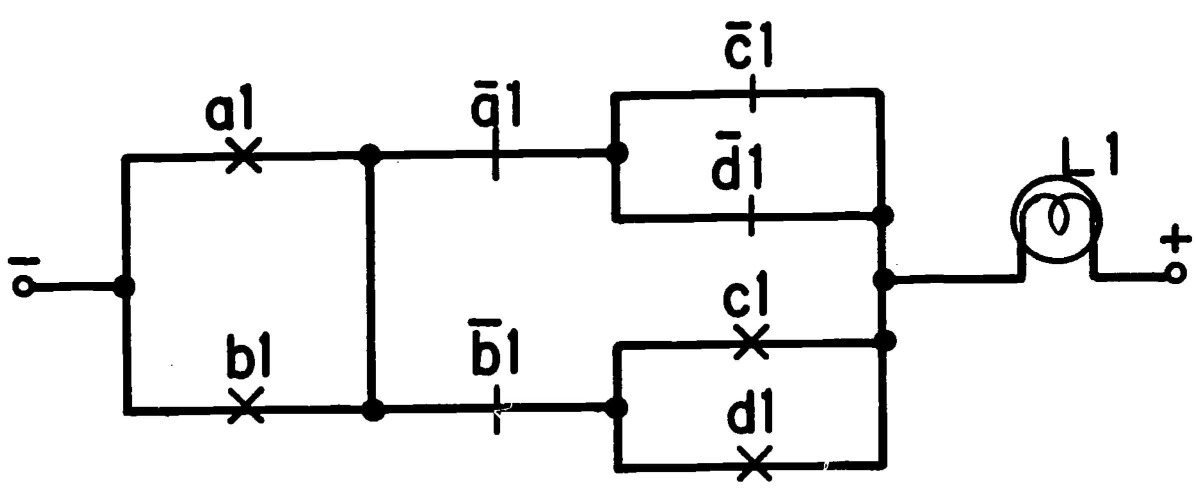


Fig. 1 Circuit for River Crossing Warning Light

Running List:

Neg, Alm, Blm; Alb, Clb, Dlb;

Clc, Dlc, Ll; Blb, Clm, Dlm;

Alc, Blc.

Remember that this circuit cannot solve the problem, but it does allow you to set up a tentative solution and test its agreement with the conditions of the problem. If the warning lamp lights, the tentative solution includes a forbidden step.

(*1) Using the circuit (and without referring to the solution given in the textbook), complete the table, Fig. 2 .

	SWITCHES			
STEP	A (GOAT)	B (BOATMAN)	C (CABBAGE)	D (WOLF)
Initial	0	0	0	0
1		1		
2		0		
3		1		
4		0		
5		1		
6		0		
Final	1	1	1	1

Fig. 2 Solution to River Crossing Problem

Compare your solution of the problem with that of your text. If the text solution differs from yours, test the text solution by using your circuit.

If your solution is identical to that in the text, find a slightly different solution with the same number of steps. When you find the alternate solution, indicate it on Fig. 2.

(*2) Why must the boatman column in Fig. 2 have alternating zeros and ones?
(*3) Looking at Fig. 1, which two switches are logically equivalent? (Interchanging logically equivalent switches will not change the operation of the circuit.)
(*4) What does this equivalence mean in terms of the original problem?

(2) Tree Circuits

Tree circuits are used for selecting. A complete tree with N control signals will make a connection to any one of 2^N terminals. Figure 3 shows a 2 stage tree. Wire it on your logic circuit board using this running list.

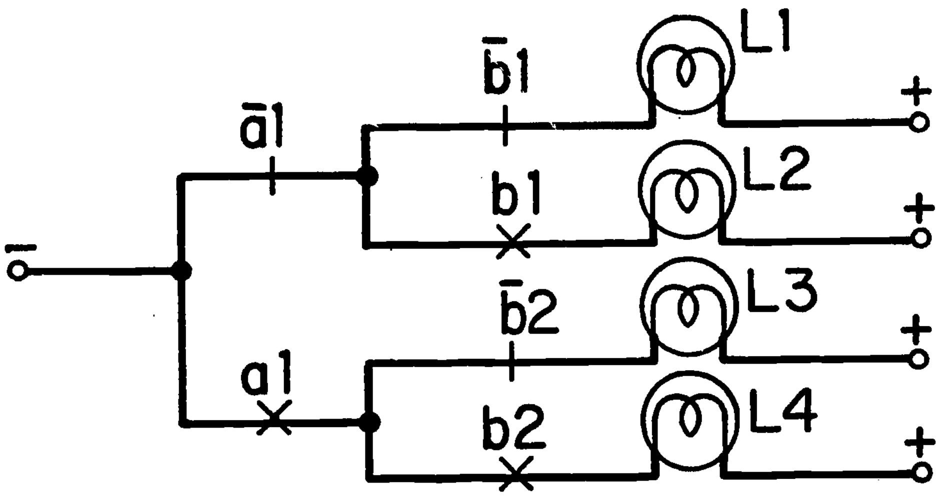


Fig. 3 A Complete 2-Stage Tree

Running List:

Neg, A1c; A1b, B1c; A1m, B2c; B1b, L1; B1m, L2; B2b, L3; B2m, L4.

(*5) Complete the truth table, Fig. 4, using the circuit you have wired.

A	B	L1	L2	L3	L4
0	0				
0	1				
1	0				
1	1				

Fig. 4 Truth Table for 2-Stage Tree

(*6) Are any two lamps in Fig. 3 ever connected together by the tree contacts?

Figure 5 shows a partial 4-stage tree. We have changed the order of the contacts in some branches so that it will fit on the switches. This tree can be used to convert binary numbers to decimal. If we represent a binary number on switches A, B, C and D in the usual order (A has weight 8, B weight 4 etc.), then the lamps can be labeled 0 through 9 so that the lamps give the decimal equivalent of the binary number on the switches. Assuming for the moment that the switches are never set to binary numbers greater than 1001, label the lamps in Fig. 5 with the appropriate decimal digits, 0-9. (Example: The next to bottom lamp is labeled 4 since it lights when the switches are set 0100, that is this lamp has a path to Neg. through $\bar{A}B\bar{C}\bar{D}$.)

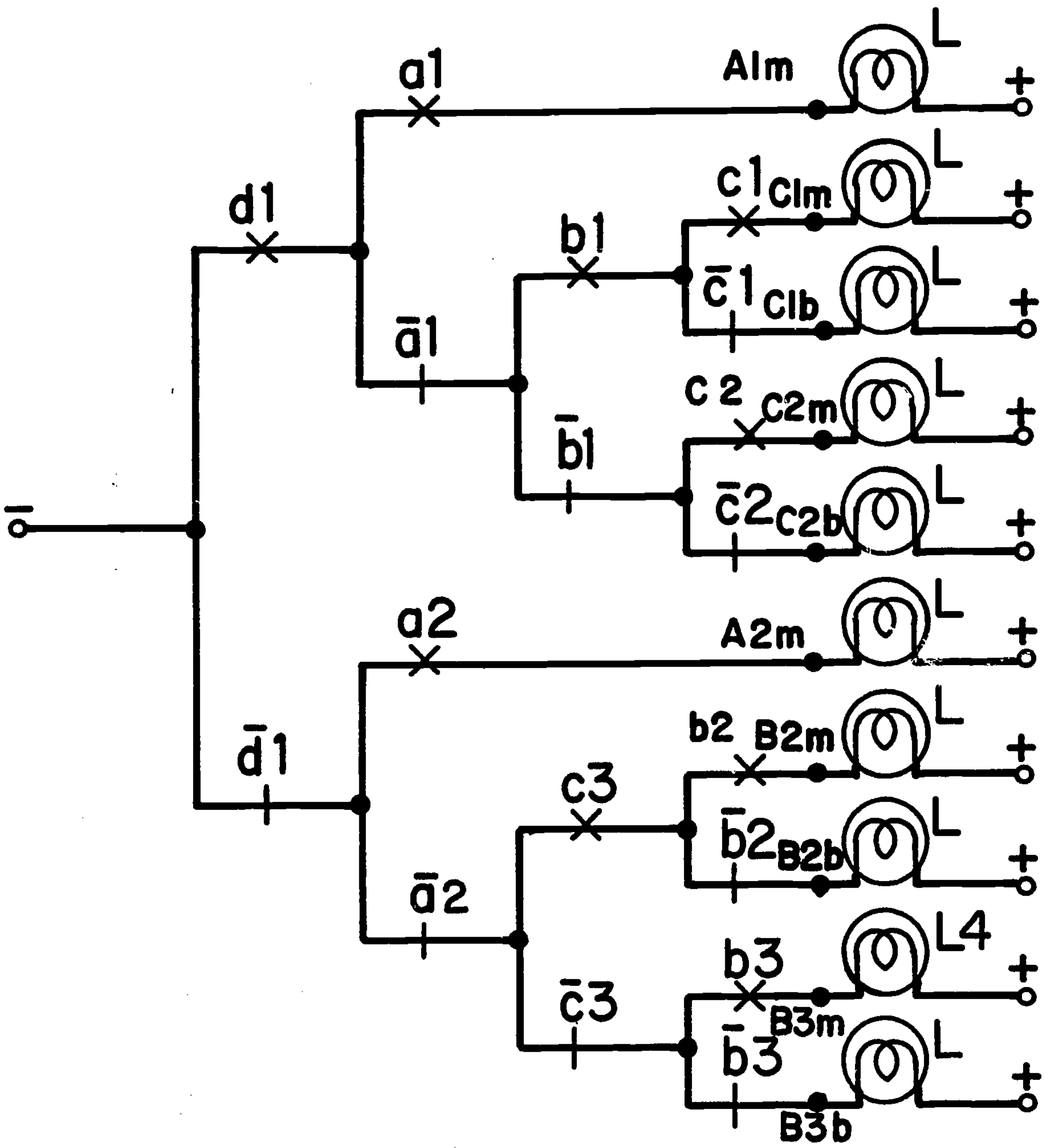


Fig. 5 A Partial Tree for Binary to Decimal Translation

Since the logic circuit board has only 4 lamps, we must test this circuit in steps. Using the following running list, wire the tree part of the circuit on your logic circuit board.

Running List:

Neg, Dlc; Dlm, Alc; Dlb, A2c; Alb, Blc; Blb, C2c; Blm, Clc;
A2b, C3c; C3m, B2c; C3b, B3c.

To aid you in connecting the lamps, we have labeled the output terminals of the tree in Fig. 5. Begin by connecting L1, L2, L3, and L4 on the logic circuit board to represent L0, L1, L2, and L3 in Fig. 5. (You . ay wish to use bits of paper to re-label the logic circuit board lamps temporarily.) (*7) Now test the lamp labels you have put on the diagram (Fig. 5) by completing the truth table, Fig. 6. At this point you can do only the first four columns, L0 through L3.

(*7) Now rewire Ll through L4 on the logic circuit board to represent L4 through L7 on the diagram, and complete columns L4 through L7 of the table.

(*7) Finally, rewire Ll and L2 on the circuit board as L8 and L9, and complete the last two columns of the table.

(*8) What contacts must one add to Fig. 5 so that L8 and L9 do not light on binary numbers greater than 1001?

	A	B	C	D	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
0	0	0	0	0										
1	0	0	0	1										
2	0	0	1	0										
3	0	0	1	1										
4	0	1	0	0										
5	0	1	0	1										
6	0	1	1	0										
7	0	1	1	1										
8	1	0	0	0										
9	1	0	0	1										
10	1	0	1	0										
11	1	0	1	1										
12	1	1	0	0										
13	1	1	0	1										
14	1	1	1	0										
15	1	1	1	1										

Fig. 6 Truth Table for Circuit of Fig. 5

(3) Symmetric Circuits

The circuit shown in Fig. 7 is called a symmetric circuit. It is really a neat combination of four separate circuits. Lamp L1 lights only if none of the switches is operated. Lamp L2 lights if exactly one of the switches is operated. L3 indicates that exactly two of the switches are operated and L4 lights only if all three switches are operated. Since the circuit indicates how many switches are operated but does not tell which switches are operated, it is logically symmetrical with respect to the switches. That is you can interchange the names of the switches as many times as you wish without changing the truth table for the circuit.

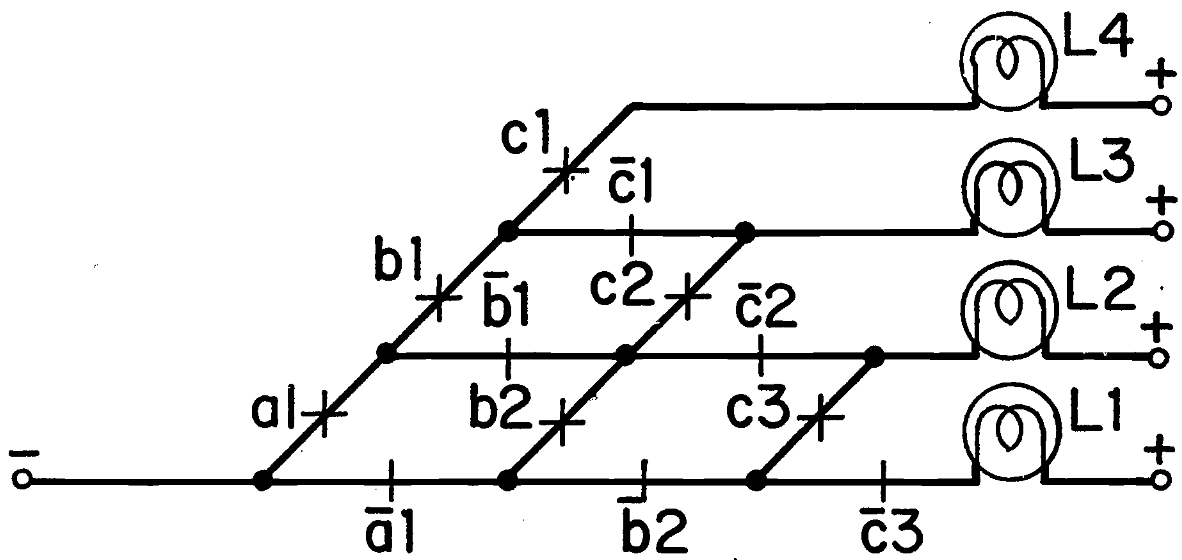


Fig. 7 A Three-Variable Symmetric Circuit

Using the running list wire the circuit and test that it does what it should.

Running List:

Neg, Alc; Alm, Blc; Alb, B2c; Blm, Clc; Blb, B2m, C2c;

B2b, C3c; Clm, L4; Clb, C2m, L3; C2b, C3m, L2; C3b, Ll.

(*9) Draw a five-variable symmetric circuit. (Notice in Fig. 7 how each operated switch moves the "signal" from Neg. up one level while each unoperated switch keeps the level the same.)

(*10) Design a circuit with 9 switches and 4 lamps which a baseball team might use to keep track of the number of outs during one inning. Hint: USE only as much of the complete SYMMETRIC CIRCUIT as you need.

EXPERIMENT IV

NOTE: Some of the running lists in Experiments IV through VI cannot be wired on the older model logic circuit boards, which have only three sets of contacts per switch. In such cases, an alternate running list has been provided, giving an equivalent circuit.

Circuits with Memory

(1) Stable and Unstable Circuits

A feedback logic circuit, or roughly speaking, a relay circuit with relays controlling themselves, can be either stable or unstable. We shall experiment first with simple stable and unstable circuits and then examine some more complicated ones.

Wire the two unstable circuits (buzzers) shown in Fig. 1.

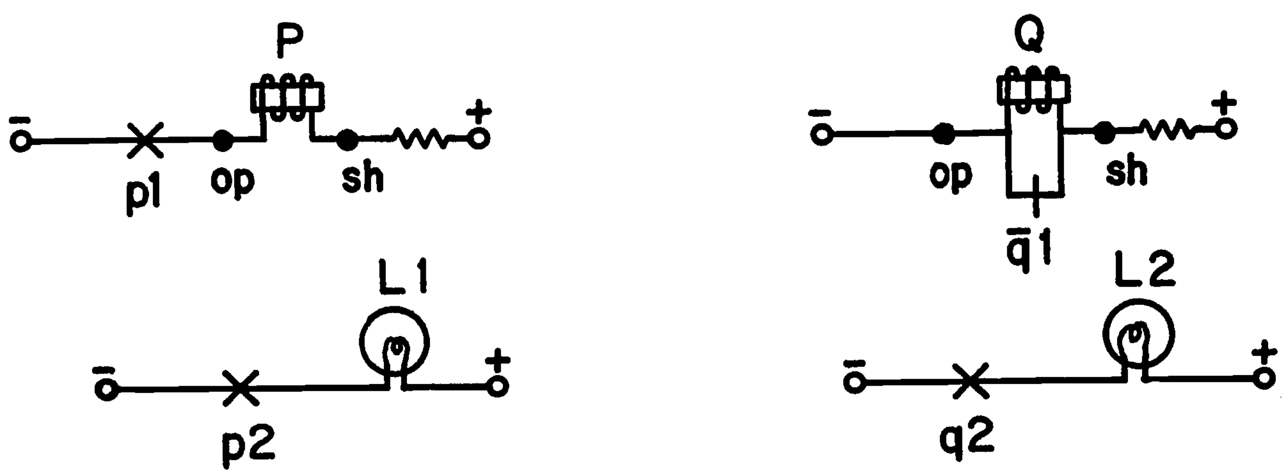
(Use q2 contact on older LCB.)

(a) (b)

Fig. 1 Two Buzzers

(*1) Which circuit buzzes faster?
(*1) Can you explain why?

Figure 2 shows two stable circuits.



(a) (b)

Fig. 2 Two Stable Circuits

Wire both of these circuits. (To make it easier to observe, we have added a lamp to indicate the state of each relay.) Take another wire and place one end in a negative terminal. Momentarily touch the op terminal of Relay P. This causes Relay P to operate and remain operated. Momentarily touching the sh terminal of Relay P causes P to release. You have demonstrated that P has two stable states.

Relay Q is clearly stable in its released state. Just as clearly, touching its op terminal to negative will not cause it to operate. (*2) What must you do to demonstrate that Fig. 2 (b) is also stable with Relay Q operated?

It is not necessary that a relay have its own contacts in its control path in order to have feedback. Two or more relays can control each other and give either stable or unstable behavior. (*3) For example, analyze the circuit of Fig. 3 and predict if it is stable or not. Now wire it and check your prediction.

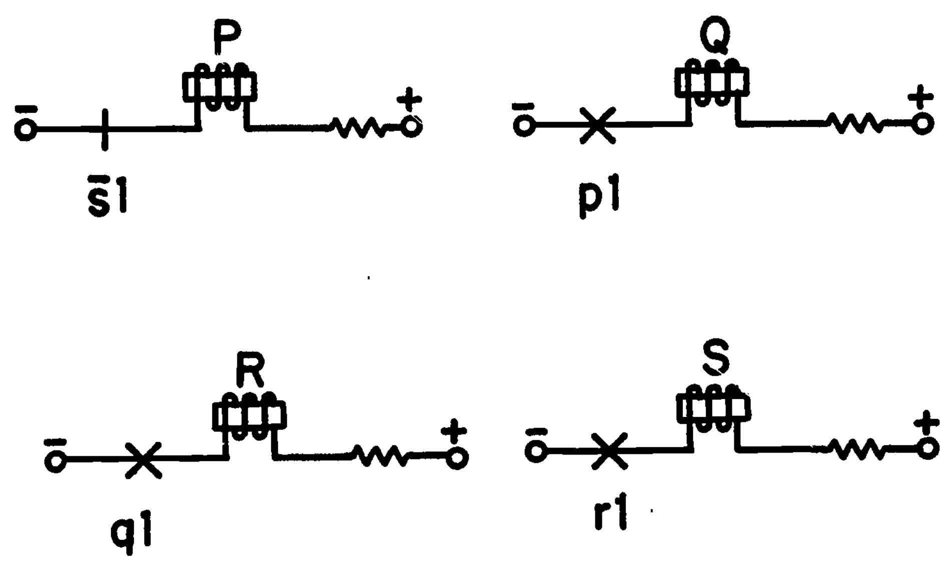


Fig. 3 A circuit to analyze and test for stability.

(*4) What is the effect of changing the $\bar{s}$ contact, controlling the P relay, from a break to a make contact, s? (*5) How many stable states does this circuit have?

Usually buzzing is an indication that a logic circuit has something wrong with it. Sometimes, however, a circuit needs an internal pulse source, for example as a clock. In this case one deliberately designs a buzzer circuit.

(2) <u>Memory with Control</u>

While the circuits of Fig. 2 do exhibit two stable states, they are not of much use as a memory until we add some control circuits. If we start with Fig. 2 (a), we can add contacts on switch A and on switch B to get the circuit of Fig. 4.

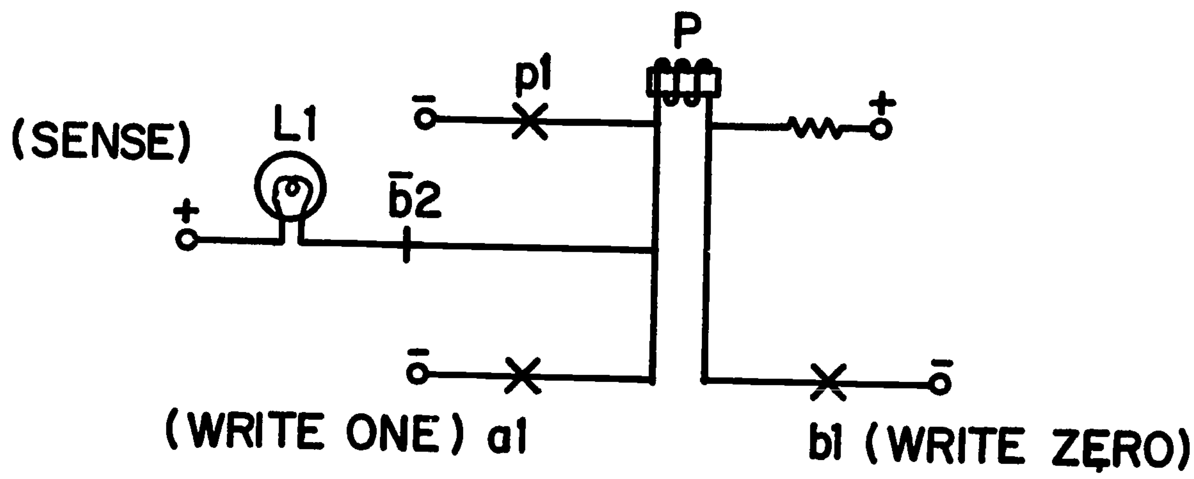


Fig. 4 One bit memory with control contacts and sensing lamp.

We use a break contact on switch B to prevent current from flowing in a sneak path (starting from (+), through the lamp, and then backwards through the relay, then through the b make contact to (-)). This permits us to use just one p contact for indicating the state of Relay P and also as a holding contact for P. The reason for this appears in the next section.

Since the Relay P has two stable states we call this circuit a one bit memory. We say that when P is operated (and holding itself in) the circuit is storing a "one". When P is released it is storing a "zero". It is then natural to call switch A the "write one" switch since momentarily operating A will set P to "one". In the same way switch B is the "write zero" switch. We can "read" the memory circuit by looking at Lamp L1; if the lamp is lighted the circuit is storing "one", otherwise, "zero". (Later we shall want to replace this lamp with a relay.)

Wire the circuit of Fig. 4 from the following running list: Neg, P1c; A1m, P1m, Pop, B2c; B2b, L1; Neg, A1c, B1c; B1m, Psh. Operate it until you are convinced that what we have said so far is true and reasonable. What happens if you try to write both "one" and "zero" at the same time? Short out the b2 contact and observe the effect of the sneak path mentioned above.

(3) Memory with Four Cells each Storing One Bit

The central memory for even a small computer contains many thousand bits. In order to use such a memory we must have a way of selecting the relatively few bits desired at any instant. This is called the access circuit of the memory. The control signal to the access circuit is a binary word which is called the Address of the selected part (or Cell) of the memory. We use two copies of a tree circuit for our access circuit. Fig. 5 shows the circuit diagram of the 4x1 (four cells, each one bit) memory which you are using in this part. The copy of the tree on the left side of the diagram steers both the "write one" signal and the sense lamp to the selected one of the four memory relays, P, Q, R, and S. (The reason for eliminating the extra p contact as described in section IV (2) was to save building a third copy of the access tree for the sense lamp.) The copy of the tree on the right side steers the "write zero" signal to the selected memory relay.

Running list for 4 x I Memory:

Neg, Blc, Alc, Plc, Qlc, Rlc, Slc; Blm, C2c; C2b, D3c; C2m, D4c; D3b, Psh; D3m, Qsh; D4b, Rsh; D4m, Ssh; Alm, B2b, Clc; B2c, Ll; Clb, Dlc; Clm, D2c; Dlb, Plm, Pop; Dlm, Qlm, Qop; D2b, Rlm, Rop; D2m, Slm, Sop.

Alternate list for older LCB: Neg, Blc, Alc, Plc, Qlc, Rlc, Slc; Blm, C2c; C2b, T2c; C2m, T3c; T2b, Psh; T2m, Qsh; T3b, Rsh; T3m, Ssh; Alm, B2b, Clc; B2c, Ll; Clb, Dlc; Clm, D2c; Dlb, Plm, Pop; Dlm, Qlm, Qop; D2b, Rlm, Rop; D2m, Slm, Sop; Neg, D3c; D3m, Top.

Wire the circuit of Fig. 5 from the above running list, set switch C = 0, switch D = 0; this is the address of the cell using Relay P. Operate switches A and B momentarily several times to successively write "ones" or "zeros" in cell 00. Leaving cell 00 with a "one" go to cell 01 (C = 0, D = 1; Relay Q). Successively write several "ones" and "zeros" into this cell. Leaving cell 01 with a stored "zero" go back to cell 00 and check that it has not been disturbed by writing into cell 01; that is cell 00 should still contain a "one". Test all the cells in a similar fashion until you feel your understanding of this circuit is complete.

(*6) What is the address of the cell using Relay R? Relay S?

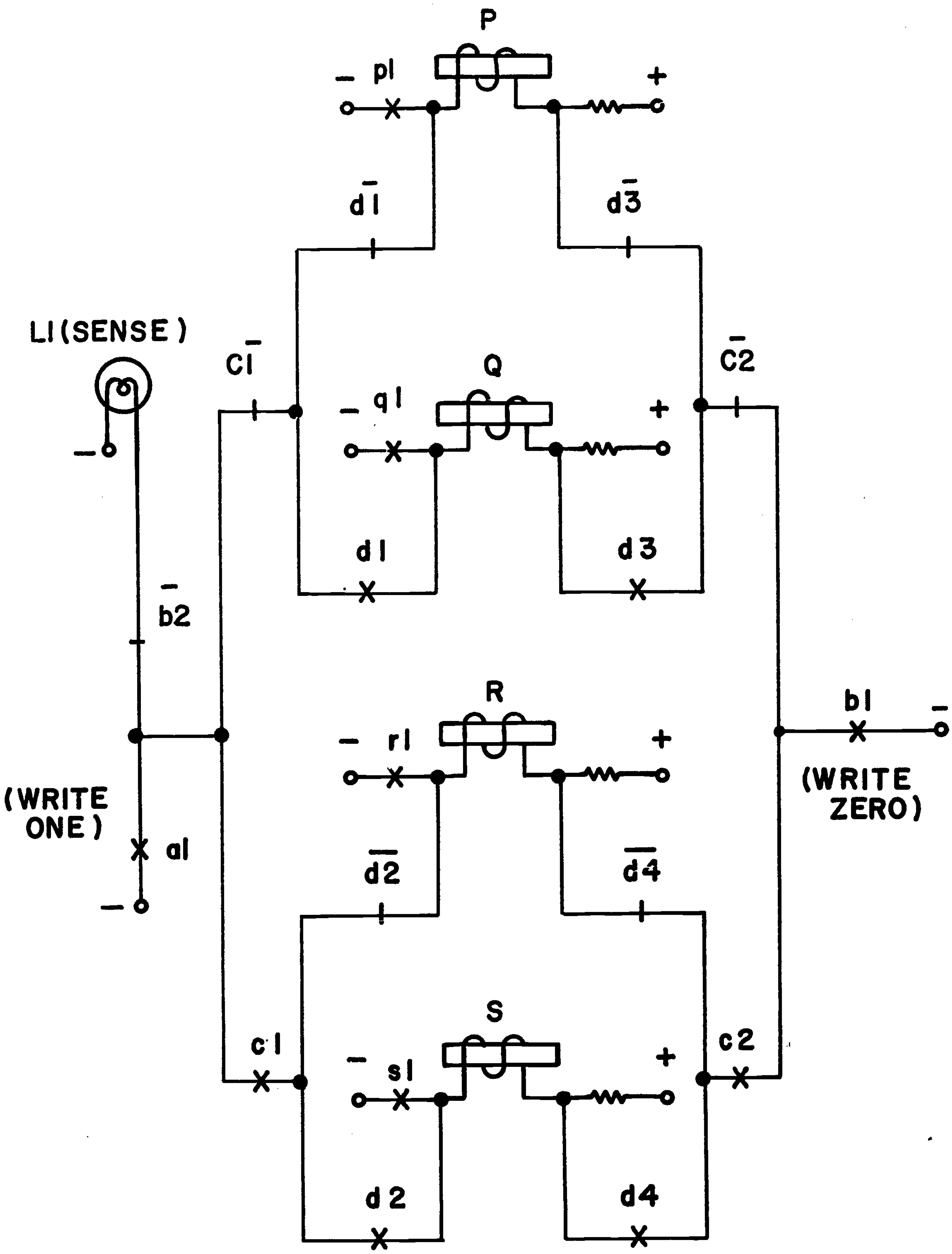

P
–
p1
+
$\overline{d1}$
$\overline{d3}$
L1 (SENSE)
$\overline{C1}$
Q
–
q1
+
$\overline{C2}$
–
d1
d3
$\overline{b2}$
R
–
r1
+
b1
–
(WRITE ONE)
a1
(WRITE ZERO)
–
$\overline{d2}$
$\overline{d4}$
S
c1
–
s1
+
c2
d2
d4

Fig. 5

EXPERIMENT V

Circuits with Memory -- Counting and Shifting

Circuits with memory are frequently referred to as sequential circuits. This is because the behavior of such circuits depends on the past sequence of signals into the circuit as well as the present inputs. Some types of sequential circuits are used so often that they are given special names; in particular, counters and shift registers are very frequently needed.

(1) Single Stage Counter

You know from your textbook that a K-digit binary counter can be made by cascading K identical stages together. We shall first experiment with a single stage before building a 2-digit counter. Wire the circuit of Fig. 1, using the following running list:

Running list for single stage counter:

Neg, D3c, D2c, D1c, S4c, R2c, R1c; D3m, L3; R2m, L1; S4m, L2; R1m, Rop, Sop, D1m; D2m, S1c; S1m, Rsh; S1b, Ssh.

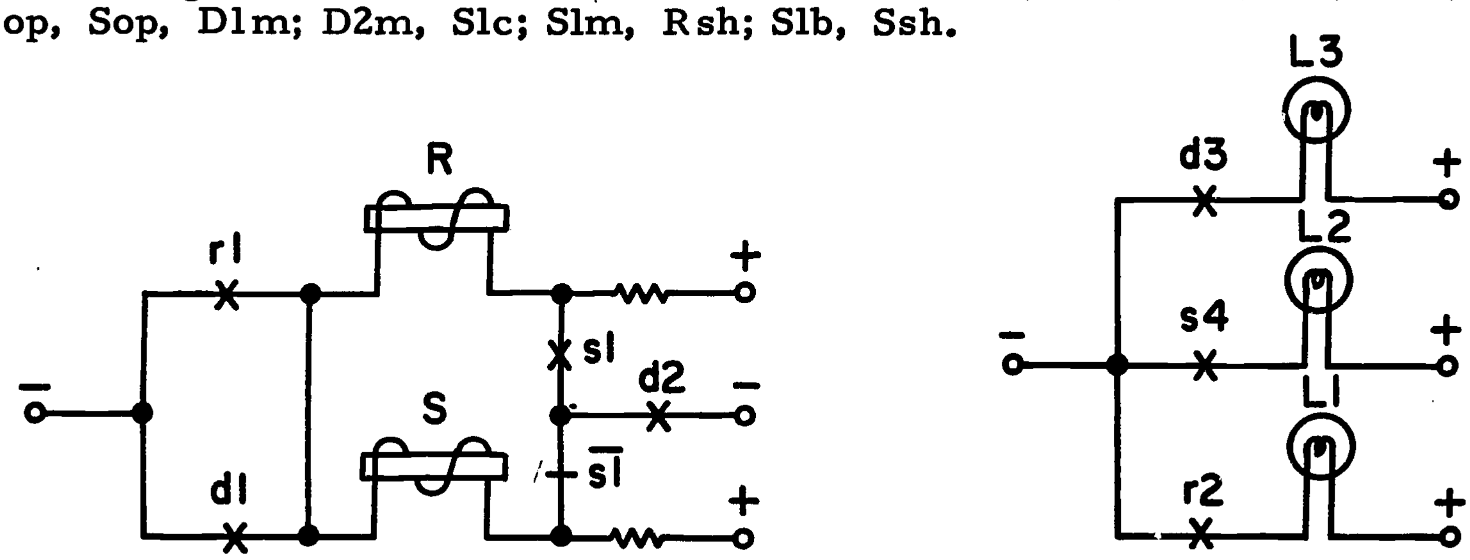


Fig. 1 Single Stage Counter

Notice that we have connected 3 lamps using make contacts on each of the relays and the switch so that the detailed operation of the circuit can be easily observed. Starting with the switch and both relays released, operate and release switch D enough times to take the circuit through two complete cycles. (NOTE: For proper operation of these circuits, switch D must be operated or relased quickly; any dealy may cause erroneous results.) (*1) After each change of D record the states of D, R and S in the sequence chart, Fig. 2.

TIME	0	1	2	3	4	5	6	7	8
D	0	1	0	1	0	1	0	1	0
R	0								
S	0								

Fig. 2 Sequence Chart for Single Stage Counter

(2) Two Stage Counter

We are now ready to add another stage to make a counter which will count four pulses. (A pulse is one complete on-off cycle of the input switch.) Follow this running list to add a second stage. When finished you will have Fig. 3

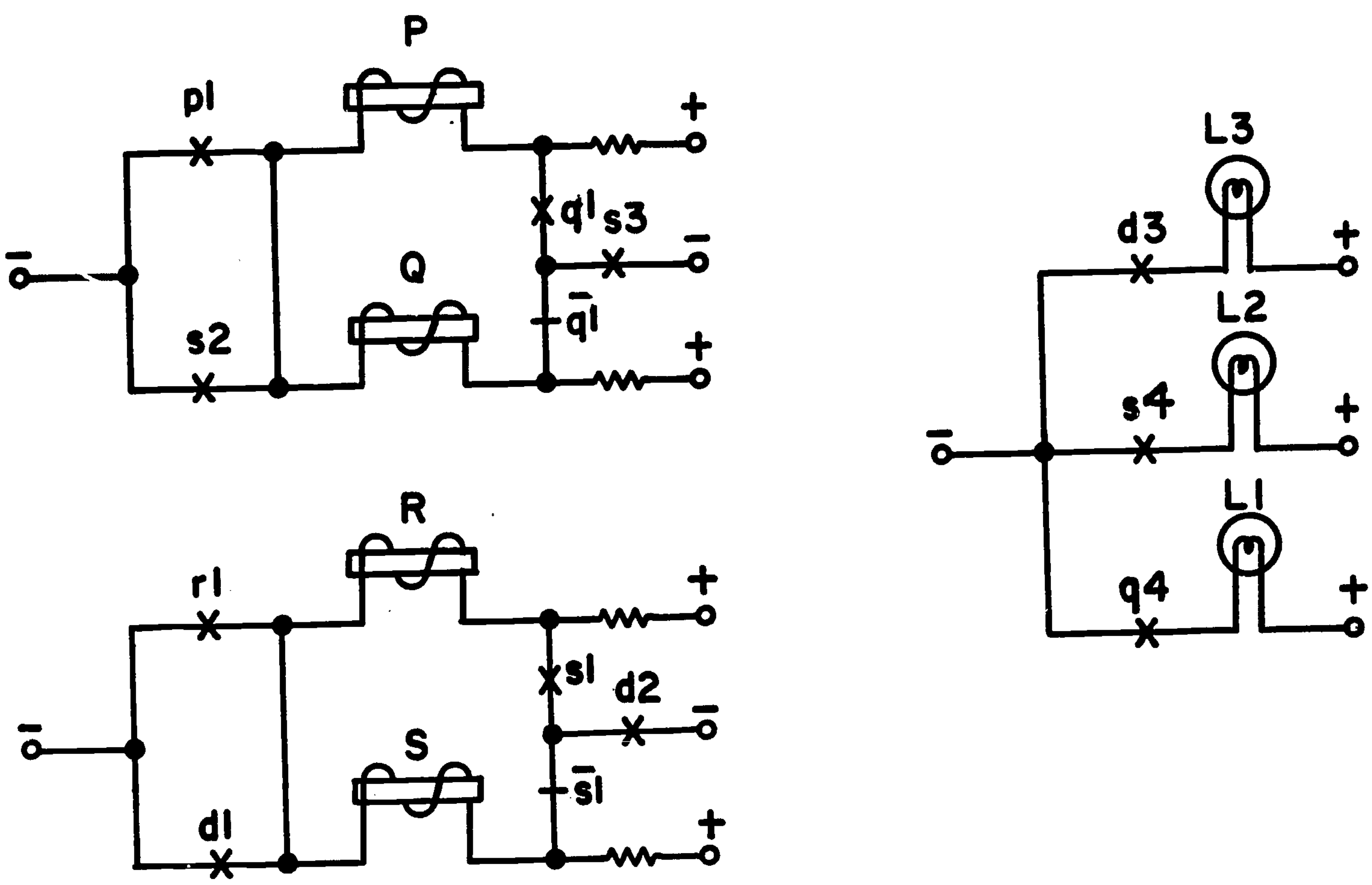


Fig. 3 Two stage counter

Running list for second stage of counter:
Remove: R2m, L1 .
Add new wires: Neg, Plc, Q4c, S2c, S3c; Q4m, L1; Plm, Pop, Qop, S2m; S3m, Q1c; Qlm, Psh; Q1b, Qsh.

(*2) Prepare a sequence chart (Fig. 4) showing a full cycle of the states of relays Q and S and switch D (Lamps L1, L2, and L3).

TIME	0	1	2	3	4	5	6	7	8
Q	0	1	0	1	0	1	0	1	0
S	0								
D	0								

Fig. 4 Sequence Chart for two stage counter

We can interpret the states of Q and S as a binary number which counts the number of pulses (on-off cycles) of switch D . (*3) What is the effect on this interpretation of replacing the make contacts d1, d2, s2 and s3 with break contacts $\overline{d}$1, $\overline{d}$2, $\overline{s}$2 and $\overline{s}$3?

(3) Optional

Make a 4 stage counter with two logic circuit boards. Replace the d1 and d2 contacts on the second board with contacts q2 and q3 on the first board to drive the R-S stage on the second board. Join the Neg terminals of the two boards together.

(4) Two Stage Shift Register

Figure 5 shows a shift register which you can wire on the logic circuit board.

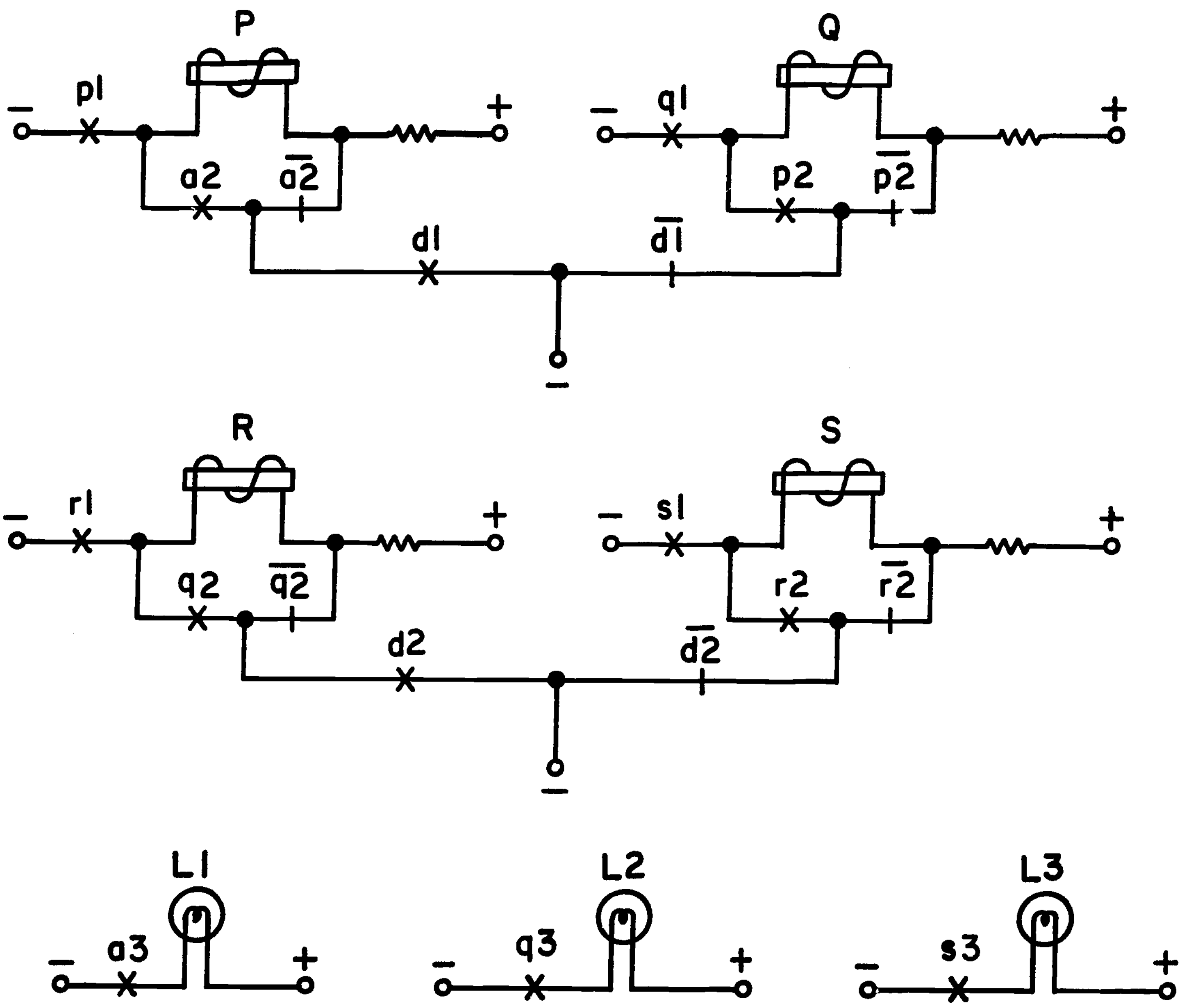


Fig. 5 Two stage shift register

Running list for two stage shift register:

Neg, A3c, P1c, Q1c, Q3c, R1c, S1c, S3c, D2c, D1c; D1m, A2c; D1b, P2c; D2m, Q2c; D2b, R2c; A2m, P1m, Pop; A2b, Psh; P2m, Q1m, Qop; P2b, Qsh; Q2m, R1m, Rop; Q2b, Rsh; R2m, S1m, Sop; R2b, Ssh; A3m, L1; Q3m, L2; S2m, L3.

Switch A is the input and switch D is the shift control. One on-off cycle of D causes information to move one stage to the right from A to Q to S in that order. By changing A when D is off you can determine whether "zeros" or "ones" are shifted into the register. Manipulate the register until you are sure that it is working as it should.

(5) Optional(for newer model logic circuit boards only)

Use two logic circuit boards to make a four stage shift register. Join the Neg terminals of the boards together. Use contacts 3 and 4 on switch D of the first board to shift the second board. Use s2 and $\overline{s2}$ from the first board to control relay P of the second board.

EXPERIMENT VI

An Automatic Morse Code Transmitter

(See Experiment VI-A if you are using old model logic circuit boards.)

One of the essential parts of a computer is a control circuit which is called the operation decoder. We want to experiment with a very similar circuit which does a job with which you may already be familiar. The task is to transmit Morse Code automatically. Figure 1 shows a block diagram of the desired circuit.

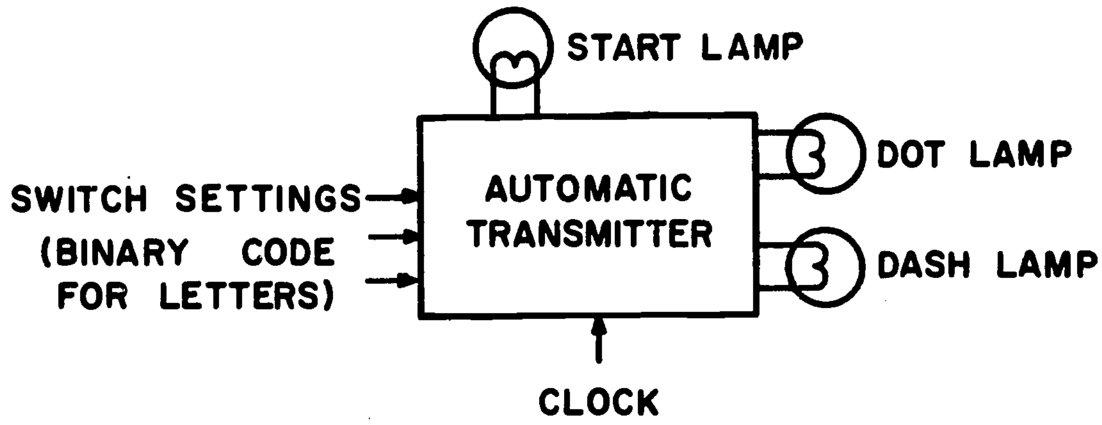


Fig. 1 Block diagram of automatic Morse Code transmitter

This circuit, which we wire on the logic circuit board, will for simplicity use just the first 8 letters of the alphabet. On three switches we can set a binary number which represents the letter that we wish to transmit: 000 for A, 001 for B and so on to 111 for H. Having entered the binary code for a letter, we operate and release a "Clock" switch 4 times. This should cause the "Dot" lamp and "Dash" lamp to light in the proper sequence giving the Morse Code for the letter represented on the binary switches. The "Start" lamp indicates that the circuit is ready to transmit a new letter. The desired action of the circuit is summarized in the tables of Fig. 2. These tables are labeled with the lamps and switches used on the logic circuit boards.

Fig. 3 shows the circuit diagram. Relays P, Q, R and S make a two-stage counter which counts the operation of switch A, the "Clock" switch. The tree circuit uses contacts on switch A and relays Q and S to provide the time 1, 3, 5 and 7 signals. These signals are steered to the Dot and Dash lamps by the "network" contacts on switches B, C and D. If you compare these "networks" with those described in your text, you will find we have combined the contacts in order to fit the circuit on the logic circuit board. Each of the separate networks can be found embedded in the combined network.

In wiring a complicated circuit such as this one, it is helpful to do it in pieces, testing and correcting each piece if necessary before adding the next. Use the running list to wire the counter (a) first. Test it against the table of Fig. 2(a). When you have the counter working correctly, add the tree (b). Test the counter plus the tree by temporarily connecting lamp L2 to the points labeled "TIME 1" (S2b), "TIME 3" (S3b), "TIME 5" (S2m) and "TIME 7" (S3m). For each point check that lamp L2 lights only at the proper time as you operate switch A through

COUNTER	RELAY S	0	0	0	0	1	1	1	1
	RELAY Q	0	0	1	1	0	0	1	1
	SWITCH A	0	1	0	1	0	1	0	1
	TIME	0	1	2	3	4	5	6	7
	LAMP 1	1	0	0	0	0	0	0	0

(a) Clock Circuit Specification

Letter	Binary Code Input			Morse Code Output (L3 = ●, L4 = ▬)							
	Switch B	Switch C	Switch D	Time 0	1	2	3	4	5	6	7
A	0	0	0				●		▬		
B	0	0	1		▬		●		●		●
C	0	1	0		▬		●		▬		●
D	0	1	1		▬		●		●		
E	1	0	0				●				
F	1	0	1		●		●		▬		●
G	1	1	0		▬		▬		●		
H	1	1	1		●		●		●		●

(b) Morse Code Specifications

Fig. 2 Summary of Morse Code Circuit

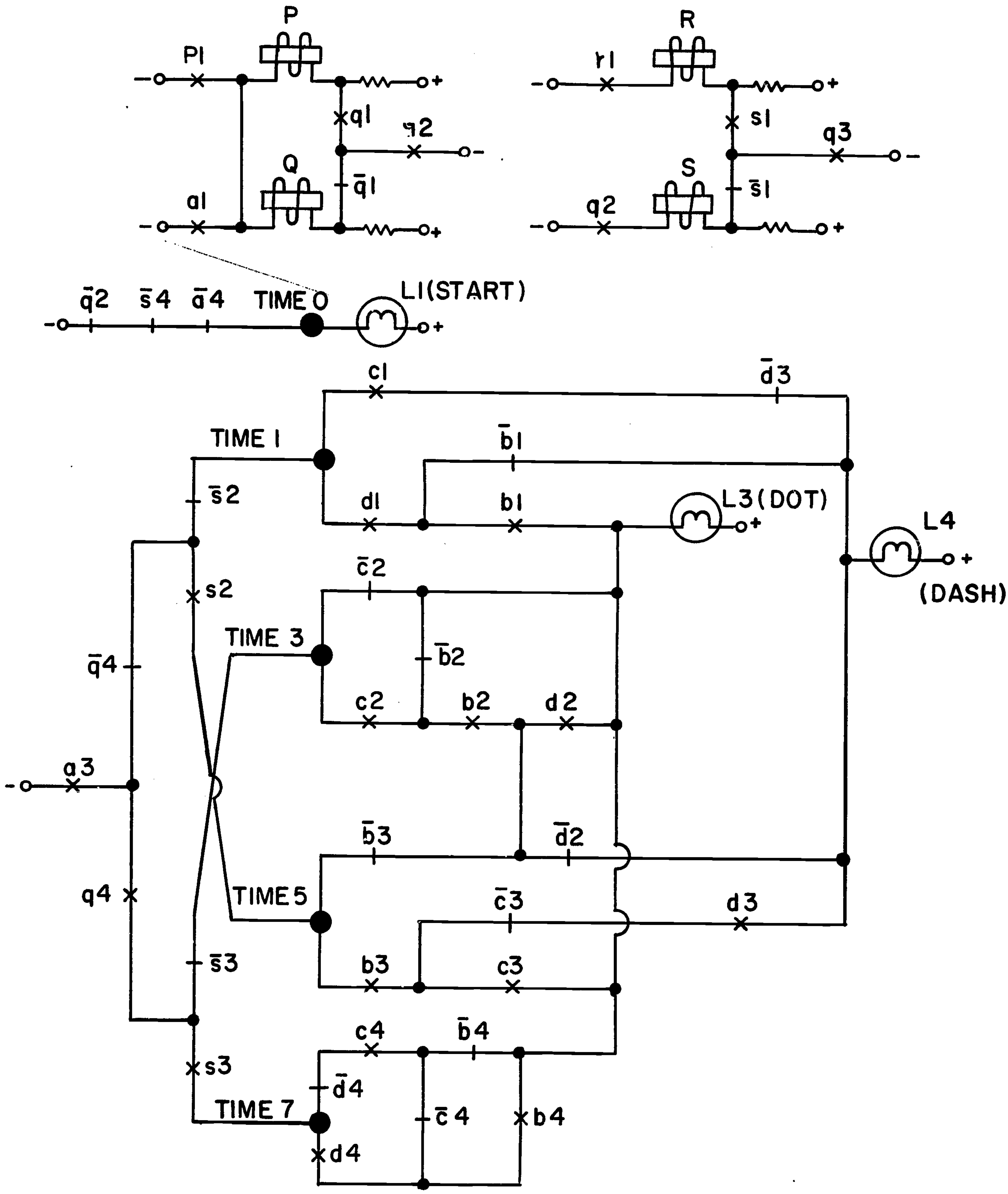


Fig. 3 Automatic Morse Code transmitter

4 complete cycles starting at "TIME 0" (L1 ON). When this much is working properly, remove the temporary wire to lamp L2 and add the networks, part (c). Test that the circuit works for each of the 8 letters as given in Fig. 2(b).

Running List for Automatic Morse Code Transmitter:

(a) Counter

Neg, A3c, A2c, A1c, P1c, Q2c, Q3c, R1c; A1m, P1m, Pop, Qop; A2m, Q1c; Q1m, Psh; Q1b, Qsh; Q3m, S1c; Q2m, R1m, Rop, Sop; S1m, Rsh; S1b, Ssh; Q2b, S4c; S4b, A4c; A4b, L1.

(b) Tree

A3m, Q4c; Q4b, S2c; Q4m, S3c .

(c) Networks

S2b, C1c, D1c; C1m, D3b; D1m, B1c; S3b, C2c; C2m, B2c; B2m, B3b, D2c; S2m, B3c; B3m, C3c; C3b, D3m; S3m, D4c; D4b, C4m; D4m, C4b, B4m; C4c, B4b; L4, D3c, D2b, B1b; L3, D2m, C3m, C2b, B4c, B2b, B1m .

If you were to design a similar automatic Morse Code transmitter for all 26 letters:

(*1) How many input code switches would you need?

(*2) How many stages would your counter require?

(*3) How many lamps would you need?

EXPERIMENT VI-A

An Automatic Morse Code Transmitter

(See Experiment VI if you are using new model logic circuit boards.)

One of the essential parts of a computer is a control circuit which is called the operation decoder. We want to experiment with a very similar circuit which does a job with which you may already be familiar. The task is to transmit Morse Code automatically. Figure 1 shows a block diagram of the desired circuit.

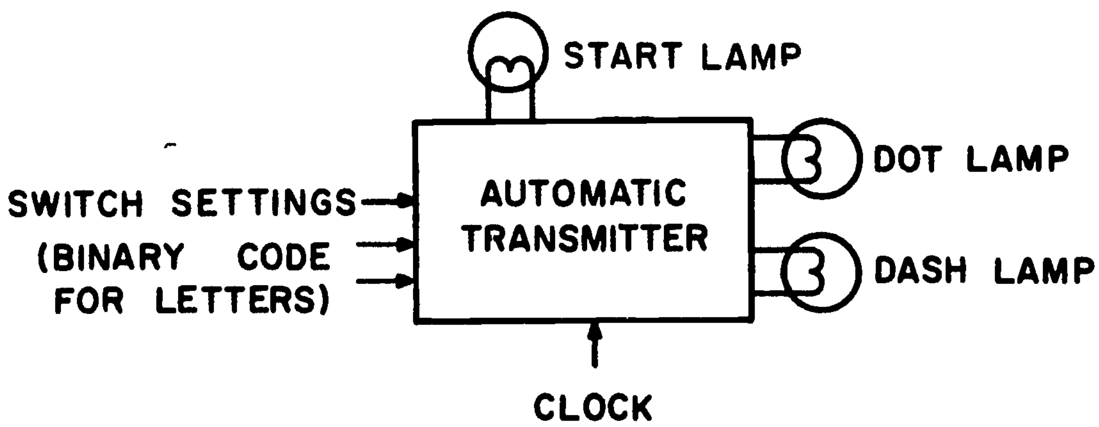


Fig. 1 Block diagram of automatic Morse Code transmitter

This circuit, which we wire on the logic circuit board, will for simplicity use just the first 8 letters of the alphabet. On three switches we can set a binary number which represents the letter that we wish to transmit: 001 for A, 002 for B and so on to 111 for G and 000 for H. (This representation differs slightly from that in your textbook because of differences between the two models of the logic circuit board.) Having entered the binary code for a letter, we operate and release a "Clock" switch 4 times. This should cause the "Dot" lamp and "Dash" lamp to light in the proper sequence giving the Morse Code for the letter represented on the binary switches. The "Start" lamp indicates that the circuit is ready to transmit a new letter. The desired action of the circuit is summarized in the tables of Fig. 2. These tables are labeled with the lamps and switches used on the logic circuit boards. (Note again that these differ from the text because of the nature of the older logic circuit boards.)

Fig. 3 shows the circuit diagram. Relays P, Q, R and S make a two stage counter which counts the operation of switch A, the "Clock" switch. The tree circuit uses contacts on switch A and relays Q and S to provide the time 1, 3, 5 and 7 signals. These signals are steered to the Dot and Dash lamps by the "network" contacts on switch D and relays T and U. (These relays are used only to gain more contacts than are available on switches E and F; their contacts are logically equivalent to the corresponding switch contacts.)

In wiring a complicated circuit such as this one, it is helpful to do it in pieces, testing and correcting each piece if necessary before adding the next. Use the running list to wire the counter (a) first. Test it against the table of Fig. 2(a). When you have the counter working correctly, add the tree (b). Test

COUNTER									
	RELAY S	0	0	0	0	1	1	1	1
	RELAY Q	0	0	1	1	0	0	1	1
	SWITCH A	0	1	0	1	0	1	0	1
	TIME	0	1	2	3	4	5	6	7
	LAMP 1	1	0	0	0	0	0	0	0

(a) Clock Circuit Specification

Letter	Binary Input Code			Morse Code Output (L5 = •, L6 = —)							
	Switch D	Switch E	Switch F	Time 0	1	2	3	4	5	6	7
A	O	O	1				•		—		
B	O	1	O		—		•		•		•
C	O	1	1		—		•		—		•
D	1	O	O				—		•		•
E	1	O	1				•				
F	1	1	O		•		•		—		•
G	1	1	1				—		—		•
H	O	O	O		•		•		•		•

(b) Morse Code Specifications

Fig. 2 Summary of Morse Code Circuit

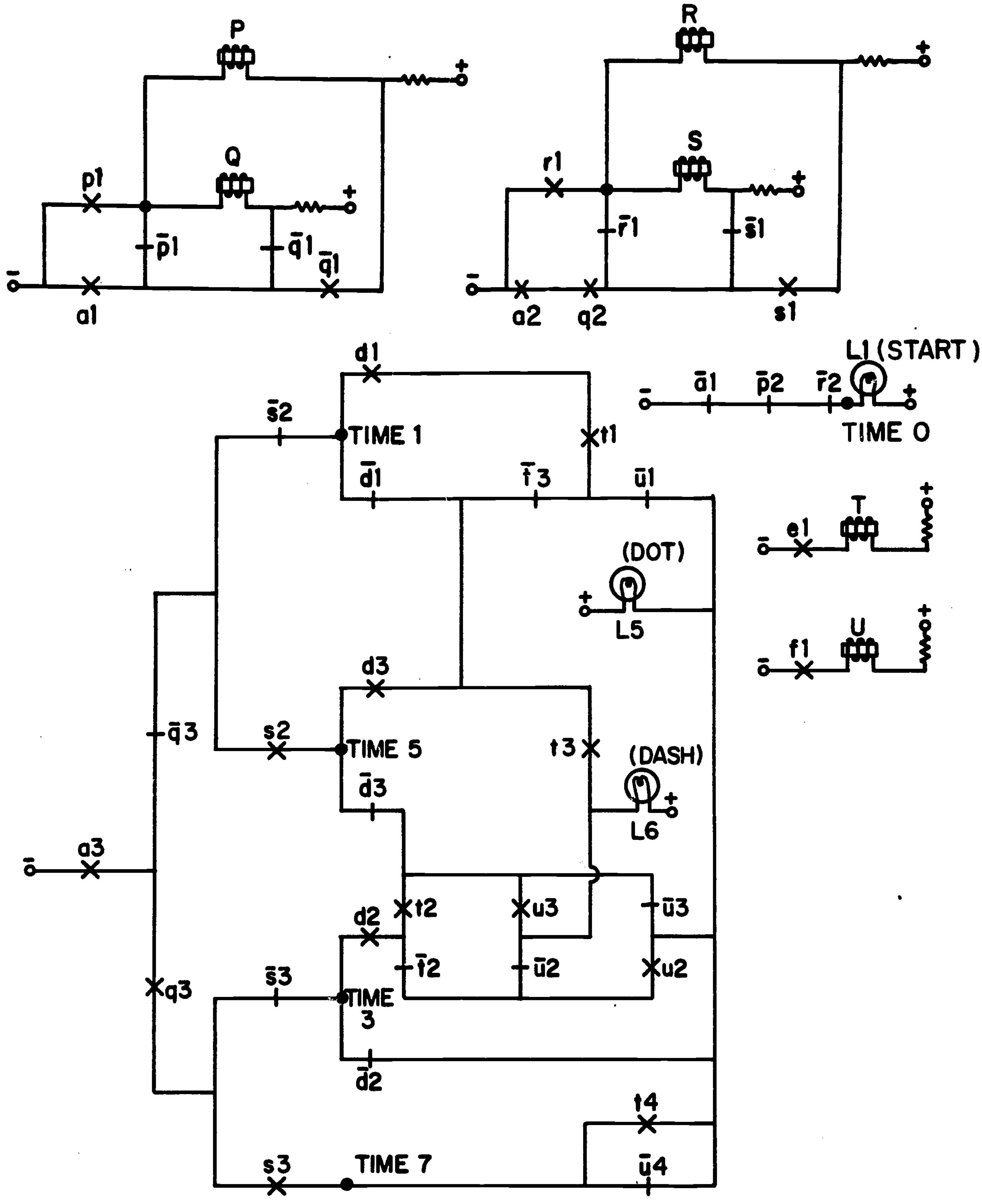


Fig. 3 Morse Code Transmitter (old model LCB)

the counter plus the tree by temporarily connecting lamp L2 to the points labeled "TIME 1" (S2b), "TIME 3" (S3b), "TIME 5" (S2m) and "TIME 7" (S3m). For each point check that lamp L2 lights only at the proper time as you operate switch A through 4 complete cycles starting at "TIME 0" (L1 ON). When this much is working properly, remove the temporary wire to lamp L2 and add the networks, part (c). Test that the circuit works for each of the 3 letters as given in Fig. 2(b).

Running List for Automatic Morse Code Transmitter:

(a) Counter
Rlm; Neg, A3c, A2c, Alc, Plm; Alm, Plb, Qlc; Alb, P2b; Plc, Pop, Qop; P2c, R2c; R2b, L1; Psh, Qlm; Qsh, Qlb; Q2m, Rlb, Slc; Rlc, Rop, Sop; Rsh, Slm; Ssh, Slb; A2m, Q2c.

(b) Tree

A3m, Q3c; Q3b, S2c; Q3m, S3c.

(c) Networks

S2b, Dlc; S3b, D2c; S2m, D3c; S3m, T4m, U4b; Dlm, Tlm; T3c, D3m, Dlb; D2m, T2c; D2b, L5, Ulb, U3b, U2m, U4c, T4c; Elm, Top; Neg, Elc, Flc; Uop, Flm; Tlc, T3b, Ulc; T2b, U2c; D3b, T2m, U3c; T3m, U3m, U2b, L6.

If you were to design a similar automatic Morse Code transmitter for all 26 letters:

(*1) How many input code switches would you need?

(*2) How many stages would your counter require?

(*3) How many lamps would you need?

EXPERIMENT VII

Introduction to CARDIAC

CARDIAC, CARDboard Illustrative Aid to Computation, is a mechanised flow chart of the digital computer described in Chapters A-5 and A-6 of your textbook. In this course we shall use it for two main purposes:

(i) To see how the organization of a computer described in Chapter A-5 functions and produces useful results.

(ii) To introduce you to some of the basic ideas of programming.

As you work with CARDIAC following the printed instructions, observe that every task you are asked to do could be done by one of the logic circuits or mechanisms described in Part A of your textbook. It is important to notice that nowhere are you exercising any judgement. You are only performing rote operations which can be done by a mechanism.

(1) Adding Two Numbers

We shall start with a simple program which reads two numbers from input cards, adds them and puts out a card giving the sum. As you do this you will follow through several instruction cycles. You will see the use of the following instructions:

0	Input
1	Clear and Add
2	Add
5	Output
6	Store
900	Halt and Reset

Using the special pencil provided, (use only this pencil in writing on CARDIAC; ordinary pens and pencils will damage it) copy the following program into the memory. Erase with paper tissue or a cloth. (In the next section we see how programs are loaded.)

CELL NO.	CONTENTS
10	017
11	018
12	117
13	218
14	619
15	519
16	900

Place one of the bugs (you have several spares) into the hole in cell 10. This bug is the Instruction Counter; it keeps track of which instruction is to be executed next.

For convenience in handling, the input and output "cards" are fastened together in strips. The individual "cards" are numbered starting at the lower end of the strip. Take one of the strips and with the special pencil write 521 on first card and 437 on second card. These are the two numbers to be added. Feed the strip, lower end first, into the slot above the word "INPUT". Position it so that the first card (with 521 on it) shows through the window just under the word "INPUT". (As CARDIAC advances through the "deck of input cards" the end of the strip will come out of the slit below the window.)

Take another strip and in the same way position the blank first card in the OUTPUT window.

A few words about the Accumulator are needed before you begin. The accumulator proper is the lower row of four boxes. The upper two rows are only a scratch pad for convenience in doing additions or subtractions. The left-most box is for the Overflow digit. This box normally has zero in it; however, if you add two numbers whose sum is greater than 999 then the overflow digit becomes a one. When the accumulator is copied into memory only the right three boxes are copied since the memory cells can only hold a three digit number. You learn in the next experiment how to use the overflow digit. The sign of the accumulator is set with the slide to the immediate left of it.

Begin at the arrow labeled "START"; that is, move the three slides so that 017 shows in the window above the box that reads "Move slides to agree with contents of the bug's cell." If CARDIAC is resting on a flat surface, this is easily done using a finger on the printed "button" on the exposed part of the slides at the bottom of CARDIAC.

Follow the colored line doing exactly as told. When you get to the "STOP," the first output card should have 958 on it.

(2) Loading Program and Two Simple Loops

Two new instructions are used in this section:

3 Test Accumulator Contents

8 Jump

Again a program is used, not because of the wonderful things it does, but as an illustration of basic ideas. Executing the program will cause the computer to generate 3 output cards with - 9, - 5, - 1 and then stop. Before executing the program we must load it into the computer. To do this we use another program with a short loop. This loading program which has the property that it will load itself into a brand new computer, whose memory contains only one wired-in instruction, is sometimes called a Bootstrap Routine. Here is the loading program. By proper sequence of input signals the loading program - as well as the program to be loaded and executed - is stored in the memory.

LOADING PROGRAM

Cell No.	Instruction	Comment
00	001	Read a card into cell 01
01	0xy	Read a card into cell xy
02	800	Jump to cell 00

Here is the program which we wish to load into CARDIAC. Look it over but do not copy it into memory yet.

PROGRAM TO BE LOADED AND EXECUTED

Cell No.	Instruction	Comment
20	126	Clear accum., add cell 26 to accum.
21	526	Output from cell 26
22	227	Add cell 27 to accum.
23	626	Store accum. in cell 26
24	321	Test sign of accum.
25	900	Stop
26	- 009	Number increased by 4 each cycle
27	004	Four

Now take one of the input strips and copy the following input deck onto it. Compare the input deck with the two programs given above. Notice how the cell numbers have been used as input instructions. Place the deck in the input slot with the first card showing in the window. Put a blank strip in the output slot. The bug should be on cell 00. Begin at "START."

INPUT DECK

Card No.	Contents	Comment
1	002	Loading Program
2	800	
3	020	
4	126	
5	021	
6	526	
7	022	
8	227	
9	023	Program to be Loaded and Executed (with addres
10	626	
11	024	
12	321	
13	025	
14	900	
15	026	
16	- 009	
17	027	
18	004	
19	(Blank)	Stop Loading*
20	820	Start Execution

*CARDIAC will stop when loading is finished. Begin again at "START" for execution.

EXPERIMENT VIII

Double Precision Subroutine

In this experiment we see how CARDIAC, a 3-digit machine can be programmed to imitate a 6-digit machine. This double precision programming is an example of how software (programs) can be used instead of hardware; that is, one has a choice of either building a 3-digit machine and writing double precision routines or building a 6-digit machine. We also want to study subroutines and calling sequences. Finally we shall look closely at some more details of the instruction repertoire of CARDIAC to convince you that:

(i) In the process of executing a program a computer does a very large number of small steps. Each of these steps can be done by circuits which you have studied. There is nothing mysterious going on.

(ii) Every one of these many steps must be correct in all details. Any error at all will cause completely wrong results. Successful computer design as well as successful programming requires close attention to every detail.

(1) Overflow

In a 3-digit machine when one adds two numbers whose sum is greater than 999 (or less than -999), overflow occurs; that is, the sum cannot be written with only 3 digits. This is handled in CARDIAC by having, in the accumulator only, a fourth digit. Since none of the other registers can accept the fourth digit special steps must be taken. For instance, store the right 3 digits and then shift right to bring the overflow digit to where it can be used.

(*1) Write a program which adds the number in location 20 to the number in location 21, put the sum in location 22 and the overflow in location 23. Test your program on CARDIAC. (*2) Does it work for all possible signs of the two numbers? (*3) If you add two numbers having different signs, can overflow occur?

(2) Double Precision Subroutine

Anyone who does very much programming will soon notice that certain pieces of programs are needed over and over again. For example, if one is doing trigonometry he may frequently need the sine or cosine of an angle. It is advantageous to write a single program, called a subroutine, to do such a repetitive task. Rather than copy the subroutine into the main program each time it is used, it is better to have a single copy of the subroutine and to jump from the main program to the subroutine whenever it is needed, jumping back to the main program when the subroutine is finished. Some way must be provided for transferring data to and from the subroutine as well as getting back to the right place in the main program after the subroutine is done. The short program which is put in the main program in order to use a subroutine is called the calling sequence for the subroutine.

Suppose that you need more than 3 digit precision but your computer like CARDIAC has 3 digit hardware. What can you do?

You can represent 6 decimal digit numbers in CARDIAC by using two locations to store a single number, one location containing the 3 least significant digits, the other the 3 most significant. We will arbitrarily assume that the two locations are adjacent and that the most significant part is in an odd numbered location with the least significant part in the next higher numbere location. Thus, the number 186324 might be stored with 186 in location 95 and 324 in location 96.

We can imagine writing a set of ten subroutines, one for each of the ten instructions. Each subroutine then causes CARDIAC to do the 6 digit operation which is equivalent to the 3 digit instruction built into CARDIAC. A program can then be changed from single to double precision by replacing each ordinary instruction by the corresponding double precision subroutine calling sequence. We will illustrate with an addition subroutine.

Double Precision Subroutine for
A + B = SUM

To use this subroutine the calling sequence must place A in locations 95 and 9 and B in locations 97 and 98. Next a jump is made (from location XX) to location 86. After the subroutine is finished it will return to location XX+1. The least significant part of SUM will be in location 98 and the most significan part in the accumulator.

Here is the subroutine program; copy it into locations 86 through 9

SUBROUTINE PROGRAM

Location	Instruction	Comment
86	199	Prepare Exit
87	694	
88	196	Add Leasts
89	298	
90	698	
91	403	Shift overflow right and add mosts
92	295	
93	297	
94	8(xx + 1)	Return

Here is the main program which is a double precision version of the simple program from Experiment VII (1). It reads in two double precision number A and B (4 cards, most significant part first), and puts out the SUM (2 cards Copy this program into locations 50 through 58.

MAIN PROGRAM

Location	Instruction	Comment
50	095	Input and
51	096	Calling Sequence
52	097	
53	098	
54	886	
55	659	
56	559	Output
57	598	
58	900	Stop

Prepare the 4 card input deck with the two numbers to be added. Place a blank strip in the output slot and start with the Bug on cell 50.

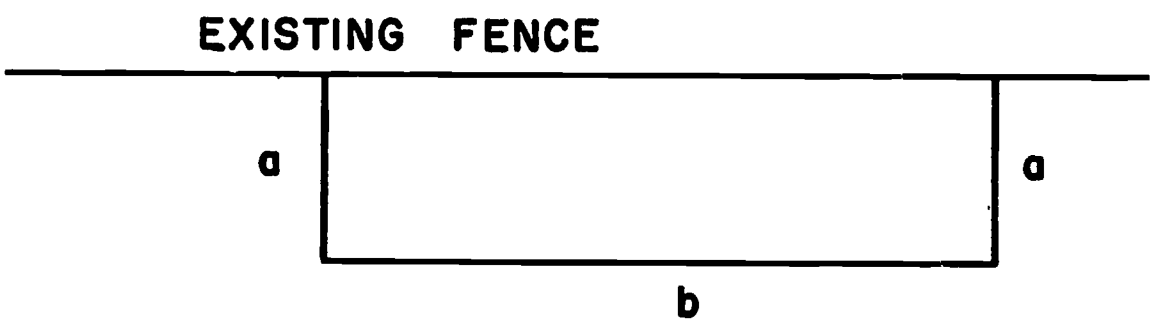
(*4) Under what conditions does the subroutine fail? (Hint: let A = +123456, B = -100457) (*5) How can you detect overflow from the most significant parts? (*6) Write instructions for locations 80 through 85 so that the subroutine can be used for either addition or subtraction; that is, entering at location 86 gives A + B as before, but entering at location 80 gives A - B. (Hint: A - B = A + (-B)).

EXPERIMENT IX

The Farmer and the Field

Part A: A farmer is preparing to plant a new experimental variety of corn in an enclosed area. The field is located along an existing length of fence.

He has 1000 feet of fencing available and must decide on the dimensions of the field which will enable him to plant the most corn within a rectangular area. Since the existing fence acts as one side of the rectangle, his fencing will only run along the three remaining sides as shown in the figure below:



The solution to the farmer's problem is clearly one of Optimization and therefore must contain the four fundamental elements of a decision-making problem.

THE MODEL
THE CRITIERIA
THE CONSTRAINTS
THE OPTIMIZATION TECHNIQUE

(*1). What are the criteria in this problem? (*2) What are the constraints in the problem?

Procedure: Using several sheets of cross-sectioned graph paper, some pipe cleaners and a ruler (for scaling),design a satisfactory scale model for this proble Search for an optimum solution by experimenting with different fence designs on your model. Remember to keep always within the constraints.

(*3) If the farmer were to build the fence according to your conclusions, how much area would the fence enclose?

Use your model to determine the optimum fence design assuming a field that has a curved border. Include some irregularly shaped borders in your trials.

(*4) What would be the maximum planting area if the farmer used a curved fence?

Part B: A Mathematical Model

You have been using a scale model and the technique of trial and error to solve the farmer's optimization problem. This method is widely used by enginee to solve very complex problems which cannot be readily solved b other means.

We have used this technique because it is a quick and fairly accurate way of determining the maximum area.

If we limit our considerations to rectangular fields, another approach is possible. Let us now try to develop a Mathematical Model. We were able to use the pipe cleaner scale model because it related the length of the fence to the area enclosed by the fence. Once we had this information for several different fence designs, we were able to choose the optimum design.

The mathematical model should be set up to give us the same information, that is, a relation between the perimeter of the field and the enclosed area. A rectangular field has the length of its sides represented by a and b.

The fenced perimenter can be represented by the equation:

$$P = 2a + b \tag{1}$$

The area of the field is:

$$A = a\,b \tag{2}$$

Solve the perimeter equation for b:

$$b = P - 2a$$

and substitute b into equation (2)

$$A = Pa - 2\,a^2$$

This last equation allows us to calculate the area of the rectangle when we know the fenced perimeter of the rectangle and the length of one of the sides. It is therefore a good mathematical model for our optimization problem. To obtain a solution, we simply calculate the area for different values of " a" and then select the value of " a" which gives the maximum area.

<u>Procedure:</u> Calculate the area for the values of "a" indicated in the table below:

Length " a" (feet)	Area (ft.^{2})
0 ft.	
50	
100	
150	
200	
250	
300	
350	
400	
450	
500	

(*5) Plot a graph of Area vs. Length " a".

(*6) Estimate the value of " a" which results in a maximum area . What is the corresponding value of " b" ? Do these results agree with your findings from the scale model?

EXPERIMENT X

Design of a Remote Heater

The task in this experiment is to design an electric heater which is located in a shed a long distance away from a source of electric power. All electric heaters contain an element called a resistor, which heats up when it is connected to a source of electric power.

In the electric toaster or broiler, the heating resistor is a coiled wire whic gets red hot when the power is turned on. In our design we have the additional problem that a very long electric cable is needed to connect the heater to the power supply and the cable itself has inherent electric resistance. We construct a crude but very useful model of this system by using small cylindrical carbon re sistors.

The model heater is set up as shown in Fig. 1 . The electrical power for the heater is obtained from the terminals on the lower right hand side of the POLYLAB which are labeled +15 and GND (Ground). The large cylindrical resistor is used to simulate the resistance of the long cable and in this experiment it has a resistance value of 82 ohms (a unit of electrical resistance is called an ohm).

Our problem is to determine which one of the small resistors will make the best heater. (Each resistor has a different resistance, which can be identified by the colored bands on the resistor. Table 1 lists the resistances and the respective color code.) The best heater will be the one which heats up the shed the fastest.

We are using a small birthday candle to simulate the shed. The resistor which melts through the candle the fastest is the best heater. Remember we are using the small resistors to model the heater, the candle to model the shed, and the large resistor (82 ohm) to model the cable.

Experiment Procedure: With power off, connect the resistors as shown in Fig. The large resistor is 82 ohms; use the 300 ohm resistor as the first small resis tor as shown in Fig. 2 . Turn the power on and let the resistor heat up for 1 minute to allow it to reach a stable temperature. Lay the candle across the small resistor (Fig. 2) and start timing. Use the second hand of a watch to measure the time to melt through the candle.

Repeat the same procedure for the other four small heating resistors.

If the time for complete melting is over 5 minutes, remove candle and estimate the time for complete melting from the amount already melted (size of depression).

Use the chart on the right to record data:

(*1) Based on the data, plot resistance vs. time.

(*2) Does there appear to be some optimum value of heater resistance? What is it?

Resistance	Time sec
300 ohms	
120	
82	
39	
20	

We can check our experimental result by the following mathematical model:

The electrical power dissipated by the heating resistor is given by the mathematical expression

$$\text{Power} \propto \frac{E^2 R_h}{(R_h + R)^2}$$

where E is the supply voltage (15 volts)

R_h is the heater resistance in ohms

R is the resistance of the large resistor (82 ohms)

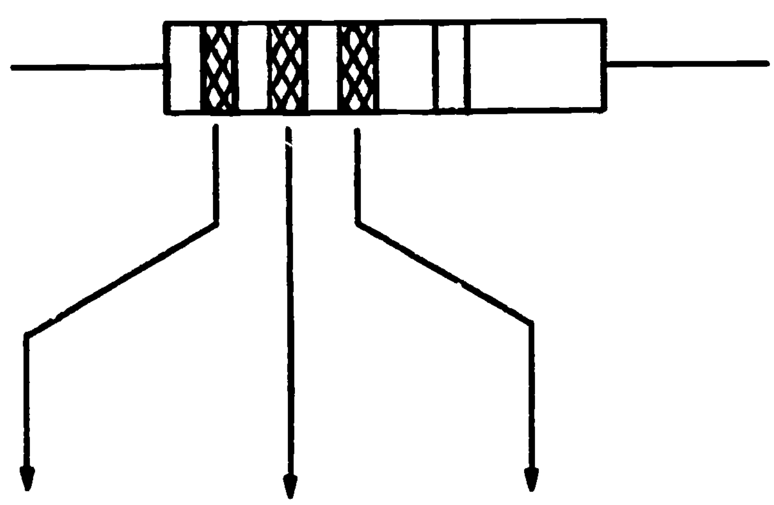
(*3) Plot on graph paper the power expression (unit for power is watts) versus R_h.

(*4) Which value of R_h results inmaximum power? How does this R_h value compare with the experimental R_h for least heating time?

(*5) In general what must be the relationship between R and R_h for an optimum design?

Table 1

Values of heater resistances:



			Resistance Value Ohms
Red	Black	Black	20
Orange	White	Black	39
Gray	Red	Black	82
Brown	Red	Brown	120
Orange	Black	Brown	300

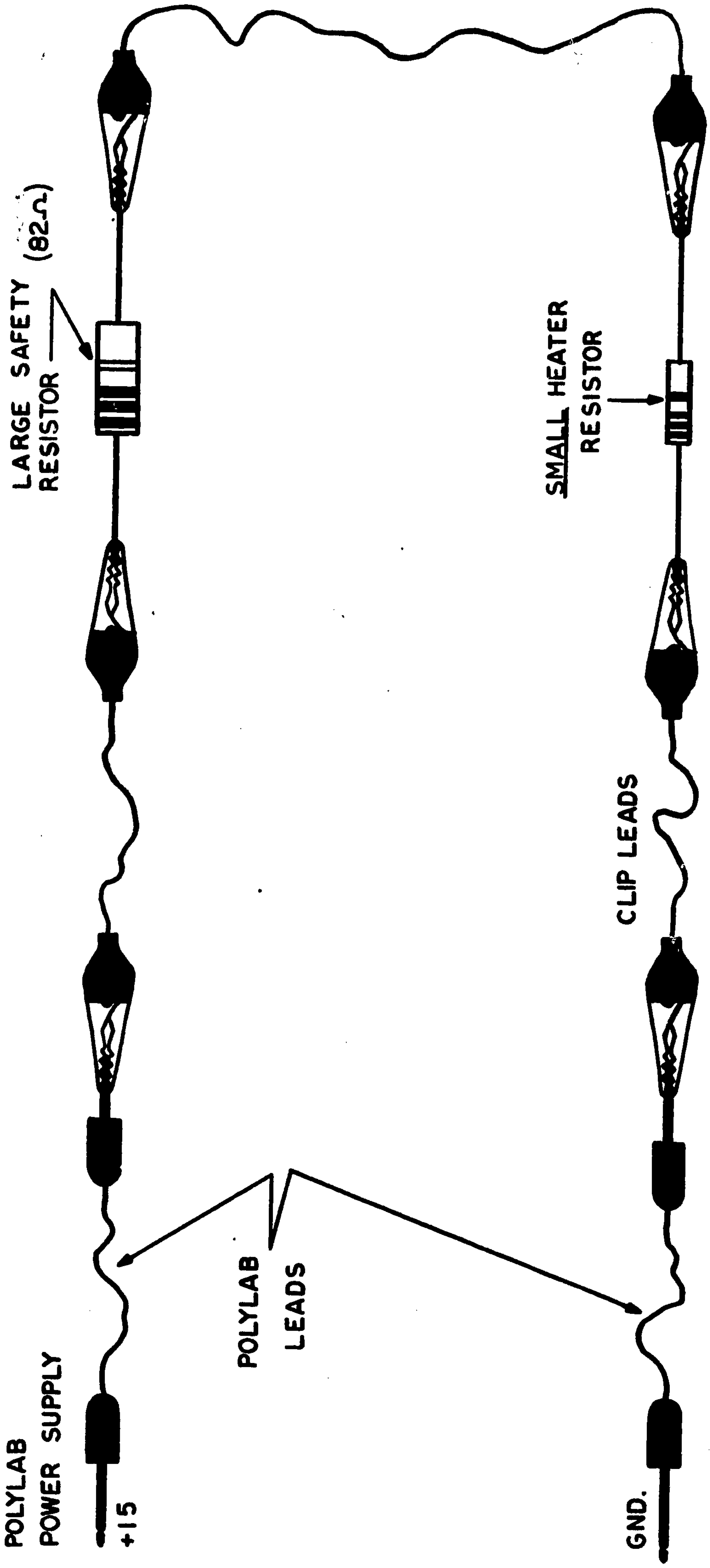


FIG. 1 MODEL OF AN ELECTRIC WATER HEATER

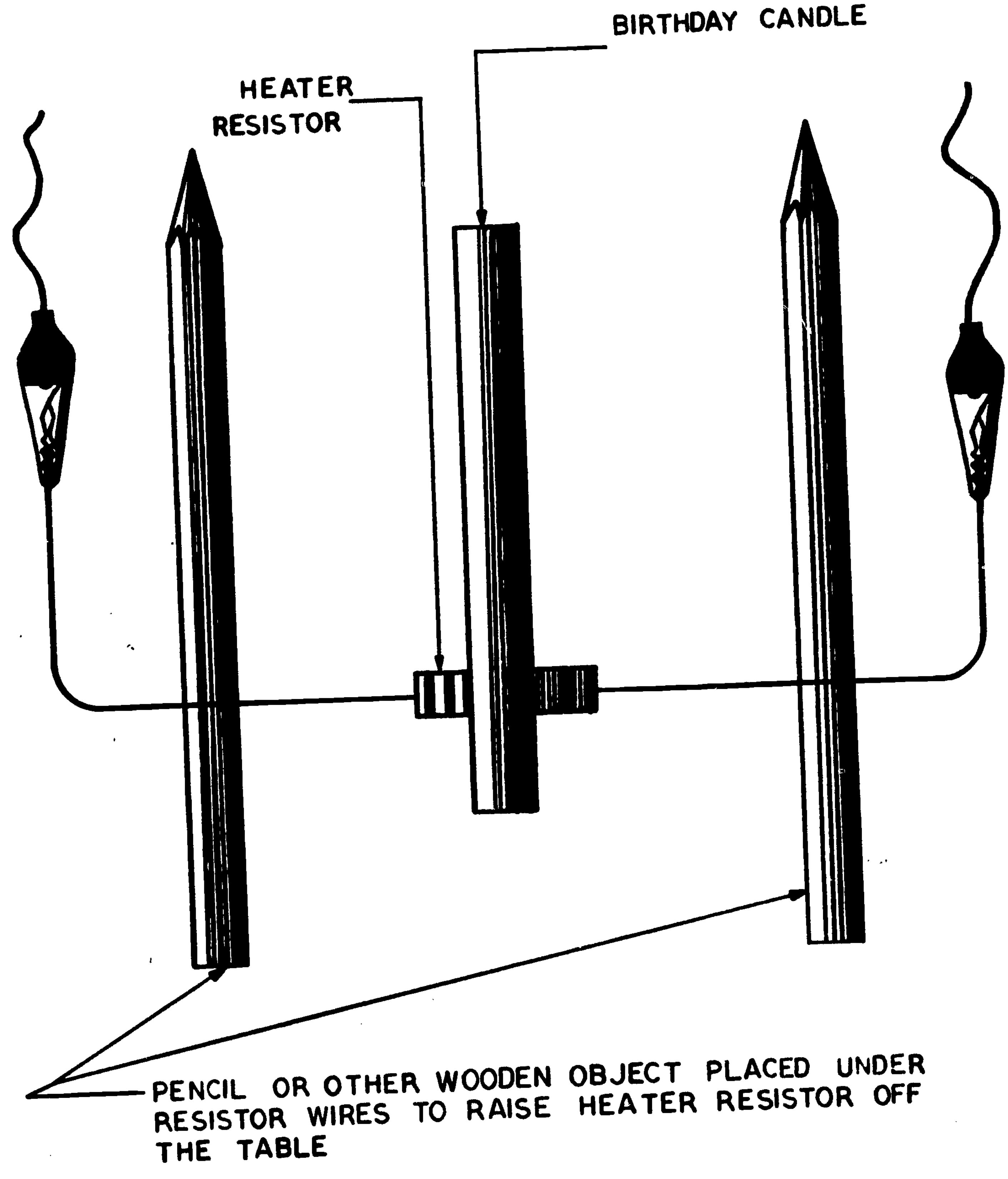


FIG. 2 MEASUREMENT OF HEATING TIME

EXPERIMENT XI

Queueing

You have undoubtedly stood in or at least watched the waiting line (queue) in your school cafeteria, at the nurses' office or at the checkout counter of the local supermarket. In this experiment you are going to study a situation which involves waiting on line or queueing. You will try to decide how much of an improvement might be made in reducing the number of people waiting on the line.

The ECCP class will select a system or systems for study. You will then make the necessary observations and take sufficient data to see how well the queueing formulas which are given in Chapter B-2 of the text predict the observed conditions. Next you will consider what could be done to reduce the size of the line and estimate how much of a reduction in queue length you expect. It is important to select a system which satisfies the constraints which the text places on the use of the queue length equations.

(*1) What are these constraints?

Experimental Procedure

Observe the system you have selected and:

1. Tabulate the " servicing time" for each of the customers who enter the facility.

2. Tabulate the time interval between the arrivals of customers at the end of the line.

3. Tabulate the length of the waiting line at fixed intervals of time.

Take as much data as you can. The more data you take, the better your results will be.

4. From the observed data calculate:

   a) The average servicing time

   b) The average inter-arrival time

   c) The Utilization factor : $\beta = \dfrac{\text{avg. servicing time}}{\text{avg. inter-arrival time}}$

   d) The average queue length

The average of any set of readings is defined as the sum of all the readings divided by the number of readings.

5. Look at your data for the servicing time and for the inter-arrival time. Do these data satisfy the constraints necessary for the queue length equations to be valid models of the system you are observing?

For a constant servicing time, the average number of people waiting in line (queue length) can be approximated by the formula:

$$q = \frac{\beta \left(1 - \frac{\beta}{2} \right)}{1 - \beta}$$

If the servicing time is random: $q = \frac{\beta}{1 - \beta}$

6. Use the most appropriate of the above equations and calculate the average queue length. Use the appropriate value of β calculated in step 4 (c).

7. Does the calculated value of queue length compare reasonably with your observed value?

8. What could be done to reduce the average queue length? Keep the suggestions within the constraints of the problem.

9. If the improvement suggested in step 8 were made, what is your prediction of the resulting average queue length?

EXPERIMENT XII

Is It an Elephant?

Chapter B-3 begins with the story of the six blind men who tried to identify an elephant. Since you are not blind, it might be difficult to appreciate their plight. However, in this experiment you will be faced with a similar predicament. You will be compelled to predict without complete information.

Objective of the Experiment

The purpose of this experiment is to try to predict the contents of a container without any access to the interior.

Procedure

Take the container furnished by your teacher, and with all the facilities (touch, weight, motion) at your command (without actually looking inside the container) try to determine the contents of the container.

Some of the questions you should try to answer are:

1. How many objects are in the container?
2. What are the shapes of the objects?
3. What is the material of which they are made?

Additional Comments

After each student in the class has had the opportunity to make his predictions the teacher will open the container to let the class see the contents.

For those whose models were closest to the "real world" we offer congratulations. To the others, just be thankful that you are not blind.

Discussion

Try to answer some of the following questions after you have discussed them with your classmates:

(a) How do you predict the contents of a forthcoming examination in order to prepare properly for it?

(b) Can you predict your grade for the term at the end of the first third? The first half? The last third? What factors do you use for making these predictions? Are the same factors useful in all your subjects?

(c) Do your college-board examination scores predict your scholastic accomplishments at college? Why? What factors should be used by a college admissions oifficer in making a decision? Why?

EXPERIMENT XIII

Measurement, Modeling and Prediction

Introduction

Problems of prediction are common in all technical as well as non-technical fields. The automobile designer must predict range of the height of the seats in the car and the proper placement of the mirror for various sizes of driver.

The same automobile manufacturer must predict the number of sales in order to work out his production schedule and price range for maximum profit.

In each case the prediction must be as accurate as possible. The construction of a model from which legitimate predictions can be made depends on accurate data and on the creative capacity of the decision maker.

Object of this Experiment

In this experiment we will attempt to construct a model of one aspect of the real world, and to use this model as an aid to prediction of conditions that exist beyond the limits within which we collected our data. The data required in this experiment are available at your school.

The Problem

Let us assume that a manufacturer of graduation gowns normally used at high school graduations at your school produces a special type which must be carefully fitted to the height of the student. The following table indicates the relationship:

Height of Student				Gown Size
5'00"	to	5'2"		A
5' $2\frac{1}{4}$	to	5'5		B
5' $5\frac{1}{4}$	to	5'9		C
5' $9\frac{1}{4}$	to	6'0		D
6' $0\frac{1}{4}$	to	6'3		E
6' $3\frac{1}{4}$	to	6'6		F

Ordering of gowns must be done at the middle of the junior year to be ready at graduation of the following year. The gowns are not returnable.

How many gowns of each type would you order for your entire junior cl

Suggested Procedure

(a) Determine the actual distribution of heights of juniors in your ECC class. Does this distribution hold true for all other juniors in your school? Check this using available school data. Does the distribution of heights chang during the year? If so, how much of a change should be included in your calculations for the gown order?

(b) Set up a scheme for predicting heights in order to supply the inforr tion needed regarding gown sizes 18 months from now.

(c) On the basis of the data you secured in part (b), determine the nur of gowns of each size that must be available next year for your class graduatic

Additional Comment

People are called upon to make predictions based on models which are built on less definitive data.

For instance: who will the Republicans and Democrats nominate for Presiden the next presidential year?

How will a particular community react to the planning of a low cost ho project in its midst?

What automobile body style will be most appealing to the 18 to 25 year old male?

Which school in your athletic conference is most likely to win the bask ball championship?

Legend has it that the ancients would predict the outcome of a battle b consulting oracles and seers. Even today we hear of predictions based on astrology, reading of tea leaves and corns in tight shoes. What do you think about the validity of these methods?

EXPERIMENT XIV

Traffic Flow

Introduction

Traffic flow problems exist all around us. The problem of air traffic flow is an extremely complicated one -- planes coming into airports from different directions at varying speeds and altitudes each containing passengers who want to be first to land. Yet there is only one available runway at most airports. The problem of rail traffic into and out of large cities is similar to the air traffic problem because of the limited number of available tracks. Auto traffic flow is a very complicated problem with varying times at which peak traffic flows past a given point. Added problems arise from changes in weather and road conditions, accidents which shut off ramps to super highways, etc.

Object of the Experiment

If a traffic engineer is to predict future situations from present situations he must construct a model of the traffic flow in and around the airport, railroad yard, or city. The following experiment is designed to give you some experience with this type of modeling for prediction.

The Problem

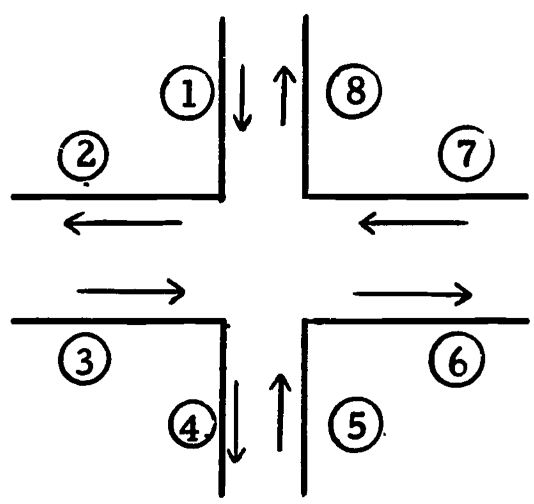
You are to measure the traffic density at various places in the corridors of your school during a particular passing time, and from the data construct a model of the traffic flow. From these data and other available data you will be asked to predict the traffic flow for various times during the day.

The area of traffic flow which you will model will be that area of the school which will be assigned to you by your teacher and principal. The following procedure will be adopted.

Procedure

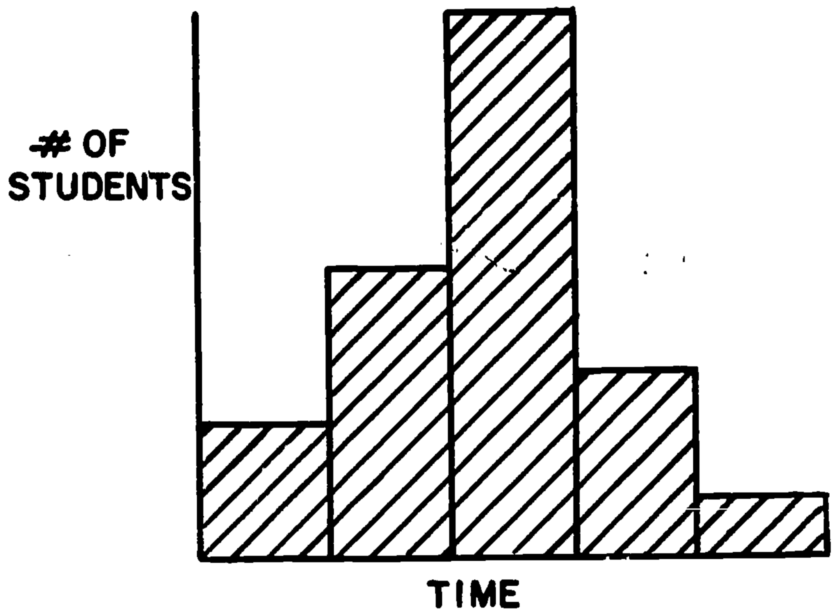
1. Obtain or draw a floor plan of the area of the school which your class will study.

2. Station students at the various intersections as in Fig. 1 for the entire interclass period just prior to your ECCP class.



Students at positions 1, 3, 5, and 7 will count the number of students who enter the intersection each minute from their corridor. Students at positions 2, 4, 6, and 8 will count the number of students who leave the intersection each minute and move past them.

3. Upon returning to the laboratory each person will construct a graph of number of students counted as a function of time. Such a graph may be similar to the following:



Graph for position No. 1 between periods 2 and 3 12/18/66.

4. On a single floor plan (using arrows of different lengths to represent different numbers of students, and by different colors to represent different times of observation) display the traffic flow pattern for the interclass movement.

5. Using the master schedule of your school and the traffic flow charts which you have developed, predict the traffic problems which may develop during different interclass periods when the number of students entering the corridors from various rooms is markedly different from what it was during the time when you made the traffic study. Check your prediction.

What are some of the factors which could affect the model you used for your prediction?

Additional Comments

There are many other areas in which you can make the same type of study and prediction. A group of students might very well study traffic flow during a fire drill, or city street traffic at various times during the day (during a vacation period).

Be on the lookout for articles in the press regarding traffic problems to see if they have resulted from a model of traffic flow based on real data or on the imagination of the writer using very little data.

"Science and Technology"
September 1966 has an excellent article on Traffic Safety.

EXPERIMENT XV

Introduction to the Polylab

To the person who sees it for the first time, the Polylab is an imposing piece of laboratory equipment. It consists of a cathode-ray oscilloscope (CRO), a signal generator, an electronic voltmeter, an electronic switch, and a power supply. It looks like something which engineers would use, and in fact it really is. Similar units are designed for precise laboratory research in industry and universities but they cost at least five times as much. The POLYLAB will, however, perform quite well in the experiments which you will do in this course, and it will give you a good understanding of how these devices assist the engineer in creating the Man-Made World.

For some years after the invention of the cathode-ray oscilloscope it was used mainly by physicists and engineers. Magazine editors insisted that photographs of engineers include at least one CRO in the background to indicate without words that the person being photographed was really an engineer. The image portrayed was of course the truth, but certainly not all the truth. Today a CRO of some sort is used by biologists, chemists, doctors, economists, sociologists, commercial fishermen, medical technologists, and military personnel.

Actually, there are millions of homes in the U.S. which have modified CRO's in the form of television receivers. The laboratory CRO which you will use has some of the same controls as your TV set,i.e., focus and intensity, and operates on the same basic principles.

Many years ago man learned that a picture is worth a thousand words. The CRO is a device which follows that philosophy by giving a picture of some event or the output of some device rather than a meter reading.

The first experiments you do with the CRO are devised to give you a CRO "picture" of an event with which you are familiar.

The SIGNAL GENERATOR is a device which generates several kinds of periodic signals. These signals can be used to simulate various physical situations, such as bumpy roads, radio signals, and sound waves. They can therefore serve to excite various types of systems so that we can study how the systems behave under the simulated conditions. Hi-Fi speakers, for example, are often advertised as being able to respond to a certain range of frequencies. The determination of this response is accomplished through the use of a signal generator.

In this course the signal generator is used to provide periodic inputs to study resonant systems, damping, sound waves, and other vibratory situations.

The ELECTRONIC VOLTMETER is used to measure the strength of electrical signals. In this course we use it to measure the input and output of signals on the analog computer and the signal generator.

EXPERIMENT XVI

Familiarization with the Electronic Voltmeter - Part A

The electronic voltmeter is an instrument that can measure the strength (or amplitude) of electric signals.

Before we use this instrument to measure the amplitude of signals we must first properly adjust it.

(1) With the power switch on POLYLAB in the OFF position check to see if the needle on the voltmeter reads zero. If it does not, ask your instructor to make the necessary adjustment.

Now set the three position switch on the VOLTMETER panel to the D.C. position. Turn the power ON and wait for a few minutes while the instrument "warms up".

(2) Now slowly turn the ZERO knob on the VOLTMETER until the needle reads zero. If you turn the knob too rapidly the needle will stop and begin to move in the opposite direction. When this happens turn the knob, very slowly, the other way. The needle will once again move towards the zero point. You may have to reverse the direction of the zero knob several times before you set the needle to zero.

The voltmeter is now ready for use. The RANGE switch to the left of the meter determines the range of signal amplitudes which can be measured. Notice that the meter has two scales on it. One reads 0 to 1 and the other reads 0 to 2.5. When the selector switch is at 1.0, the upper scale on the meter will have a range of 0 to 1 unit. When the selector switch is on 2.5 we use the lower scale and the meter has a range of 0 to 2.5 units. When the selector switch is on 10 we again use the upper scale but now the meter range is 0 to 10 units. The lower scale is again used if the selector switch is on 25. The meter then reads 0 to 25 units. The maximum signal which the meter can indicate is 100 units. In this voltmeter each unit on the meter corresponds to an electrical signal amplitude of 1 volt. (Before we proceed any further turn the BEAM control knob on the CRO all the way to the left, since we won't be using it for a while).

We shall use the VOLTMETER to measure the amplitude of some of the electrical signals which are available on the AMF Analog Computer.

Open the Analog Computer and remove the top cover by sliding it to the right. The lower right hand section of the Analog contains the switch which turns the power to the Analog on and off, and also a source of constant electrical signals which will be used in the solution of some of our problems. A diagram of this section of the computer is shown in Fig. 1. The Analog is provided with a set of four long leads which are used to transfer signals between the Polylab and the Analog. We call these transfer leads. Note that one of these leads is black. This lead should be used to connect any of the COM terminals on the Analog to the GND (ground) terminal of the Polylab. Do not use any of the other leads for this purpose and do not use this black lead for any other connection. This is called the "ground" connection and must always be made whenever the Analog Computer and the Polylab are used together.

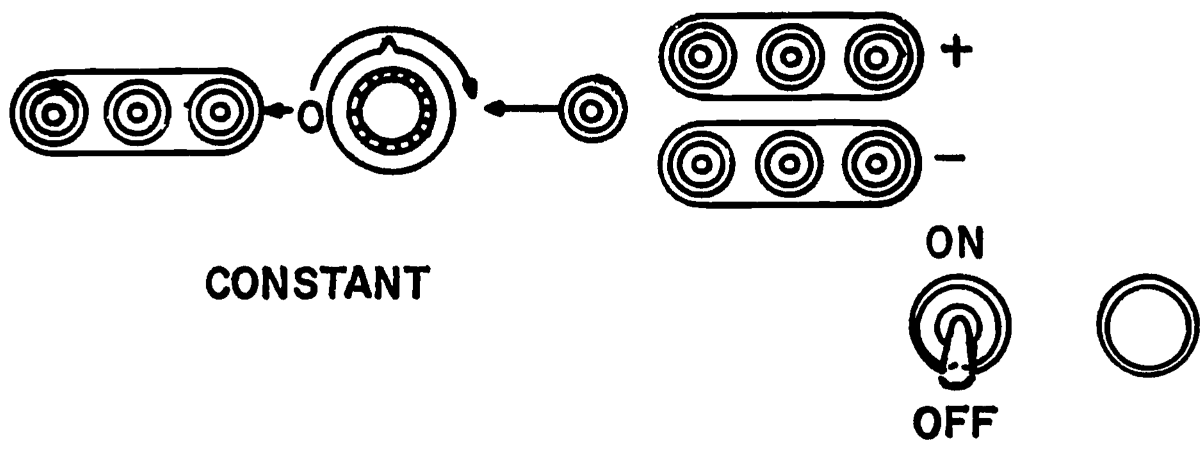


Fig. 1 Signal source with power switch and CONSTANT

(3) Connect the "ground" lead between the Polylab and the Analog Computer.

(4) Set the RANGE switch on the voltmeter to 25 and reset the zero adjustment if necessary.

(5) Turn on the Analog Computer.

(6) Connect the INPUT terminal on the VOLTMETER to one of the terminals marked "+" on the ANALOG by means of a transfer lead.

Notice that the light next to the + sign on the voltmeter goes on. This indicates that the signal is positive.

(7) Remove the transfer lead from the + terminal and put it into one of the terminals marked "-". Notice now that the light next to the - sign on the voltmeter goes on. This indicates that the signal from this terminal is negative.

(8) By now the needle of the voltmeter may have drifted out of its zero adjustment. To check this, put the three-position switch on the voltmeter to the ZERO position and observe the reading of the meter. If it is not at zero, readjust the voltmeter with the ZERO knob to make the meter read zero again. The voltmeter may continue to drift slowly for about 20 minutes after it is turned on. Therefore, during the first twenty minutes it is necessary to check the zero reading frequently and to readjust the zero knob to maintain the proper zero reading. Always set the switch to ZERO whenever the zero adjustment is being made.

(*9) Reset the switch to the DC position and read the signal amplitude on the lower meter scale. Recall that since the selector switch is at 25, the meter scale represents a signal amplitude range of 0 to 25 volts. Remove the lead from the "-" terminal on the Analog and put it into the "+" terminal. Read and record the amplitude of this signal:

+ signal: volts

- signal: volts

Since we have reversed everything, we expect the readings to be the same. If they are not, recheck zero and both voltage readings; if they still differ, consult your teacher.

Part B

The Analog also provides constant signals of smaller amplitude.

(10) Take one of the short black leads which come with the Analog and connect it as shown in Fig. 2. [The short black, blue and yellow wires are used to transfer signals between terminals on the Analog. We call these patch leads.]

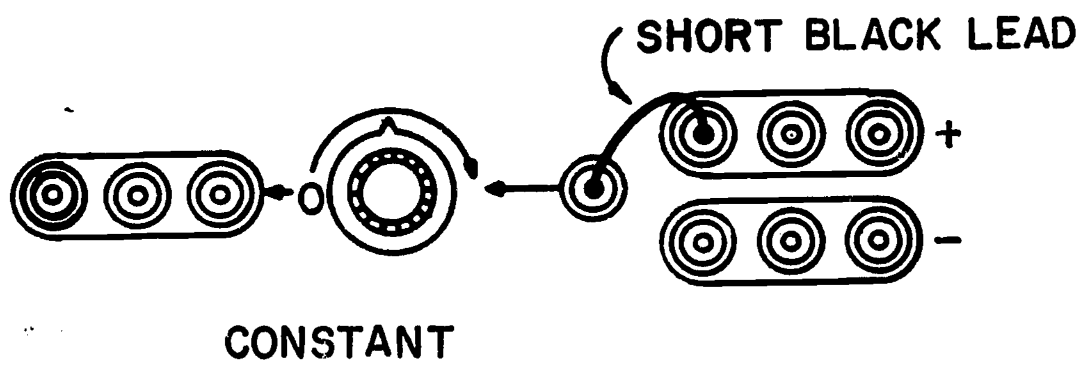


Fig. 2 Connection for positive signal

With this connection the amplitude of the signal at the terminals indicated by the letter "a" in Fig. (2) can be varied by rotating the CONSTANT knob. We call these terminals the CONSTANT terminals.

When you use the voltmeter to measure the amplitude of a signal the RANGE selector switch on the voltmeter should always be set to a position which will cause the meter needle to deflect more than about 1/4 of its full-scale deflection. That is, if the selector switch is at 25 you should only take measurements at this setting if the needle reads higher than about 6 units. If the deflection is less turn the RANGE switch to the next lower range. This will produce a larger needle deflection.

There are two reasons why the voltmeter should not be used with small deflections. First, the accuracy is poorer when the deflection is small and secondly, the lights which indicate the + or - sign of the signal do not go on until the needle deflection reaches about 1/10 to 1/5 of its full scale deflection. In this latter case the voltmeter may not indicate the sign of the signal or it may indicate the wrong sign, if the needle deflection is small.

(11) It is necessary to set the CONSTANT to the following values. In each case, what RANGE setting should be used for greatest accuracy?

a) .4 ______

b) 1.7 ______

c) 2.4 ______

d) 9.0 ______

e) 13.1 ______

(12) Connect the INPUT terminal on the VOLTMETER to one of the CONSTANT terminals on the ANALOG.

(*13) Turn the CONSTANT knob to its full counter clockwise position. Slowly turn the knob in the clockwise direction and observe the change in the meter reading.

What is the maximum value of the output signal from the CONSTANT terminals?

(*14) Remove the black patch lead from the -terminal on the ANALOG and plug it into one of the + terminals. Again observe the reading of the VOLTMETER as the CONSTANT knob is rotated from its extreme counterclockwise to its extreme clockwise position.

What is the maximum value of the output signal in this case?

(15) Return the CONSTANT knob to its zero position. The position of the pointer on the CONSTANT knob should be approximately in the position shown in Fig. 3.

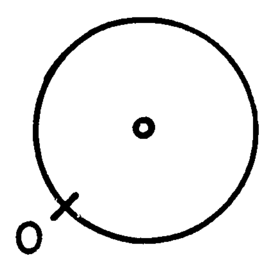


Fig. 3 Position of CONSTANT knob for various signal magnitudes

(16) Reset the zero position on the voltmeter if necessary.

(*17) Slowly rotate the CONSTANT knob to the right until you obtain a signal magnitude of +1 volt. Use the 2.5 RANGE on the meter. Show on Fig. 3 the approximate position of the CONSTANT knob pointer for the one volt output signal. Indicate on the figure that the position represents 1 volt.

Now rotate the CONSTANT knob until the signal is +2 units. Mark and identify this knob position on Fig. 3. Repeat this procedure for CONSTANT signal amplitudes of 4, 6, and 8 units and for the maximum amplitude available. Use the proper RANGE setting on the VOLTMETER.

Observe that you had to turn the knob much further to change the signal amplitude from 0 to 4 volts, for example, than you did to change it from 4 to 8 volts. This property in which equal increments of rotation of the knob do not produce equal incremental changes in output signal is called a NON-LINEAR characteristic. If the CONSTANT knob had a LINEAR characteristic, the 2 volt increments in signal amplitude would be evenly spaced around the circle in Fig. 3.

(18) Try to set the CONSTANT signal amplitude to 1.1, 1.2, 2.1 and 2.5 volts. Now try to set the CONSTANT to 7.1, 7.2, 8.2 and 8.6 volts. Observe that the NON-LINEAR characteristic makes it easier to get an accurate setting of signal amplitudes at the lower amplitudes. This is desirable because a small error in amplitude setting will be more noticeable in signals with small amplitudes than in signals with large amplitudes.

(19) Turn the CONSTANT knob on the ANALOG all the way to the left and set the RANGE switch to 1. Observe how easy it is to set the CONSTANT signal amplitude accurately to values such as .01, .02, .21 and .26 volts.

EXPERIMENT XVII

Introduction to the ANALOG COMPUTER

The Analog Computer is a device which can perform certain mathematical operations on signals which are fed into it. Large sophisticated computers can add, subtract, scale (multiply a signal by a constant coefficient), integrate, multiply two signals, square, take the square root, divide and perform certain trigonometric operations. The AMF unit can only perform the operations of addition, subtraction, scaling and integration. However, this is adequate for us to solve a wide variety of engineering problems.

In most analog computers today the mathematical operations are performed by circuits of electric and electronic components. Each circuit has an input and an output terminal and when an electric signal is connected to the input terminal the circuit generates a signal at its output terminal which is the result of its having performed a mathematical operation on the input signal. If an electric signal is connected to the input terminal of a Scalor circuit, the signal at the output terminal will have the same shape as the input signal but its magnitude will have been multiplied by some constant factor. An Adder circuit has necessarily more than one input terminal and the signal at its output terminal is always the sum of the signals which are connected to its input terminals. In an Integrator circuit the output signal represents the area under a plot of the input signal versus time.

The output signal from one circuit can also be connected to the input of another circuit so that a sequence of several mathematical operations can be performed. This feature enables us to solve mathematical equations on the analog computer. Suppose, for example, that we wish to obtain the solution of the equation:

$$Y = 4 + \int (0.3X)\, dt$$

You can see that if we let some electrical signal represent the magnitude of the variable X, the magnitude of the variable Y can be obtained by performing the following sequence of operations on X:

1. Multiply the signal X by the coefficient 0.3 to obtain the signal 0.3X
2. "Integrate" the signal 0.3X
3. Add 4 to the integral of 0.3X

We can perform this sequence of operations on the analog by connecting the Scalor, the Integrator and the Adder circuits in proper order. The signal at the output terminal of the Adder will then represent the magnitude of the variable Y.

Open the ANALOG COMPUTER and remove the top cover by sliding it to the right.

If you look at the top panel of your COMPUTER you will see that it contains many terminals. These are the input and output terminals for various circuits that are contained within the computer. The circuits themselves are drawn on the panel in symbolic form and are identified in Fig. 1. Also shown in this figure are the equations which describe the mathematical operation which is represented by each symbol.

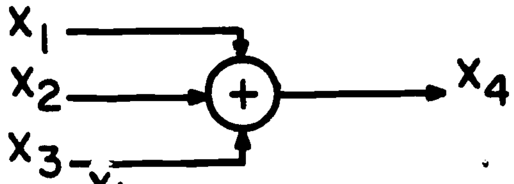
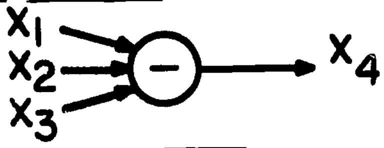
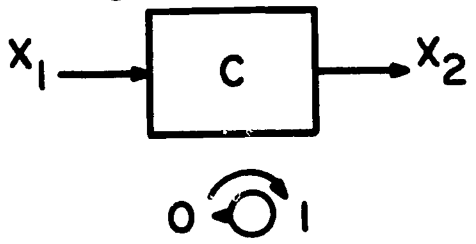
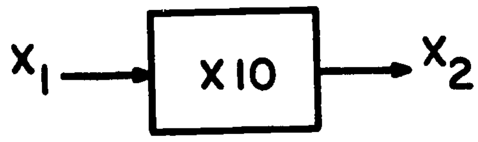
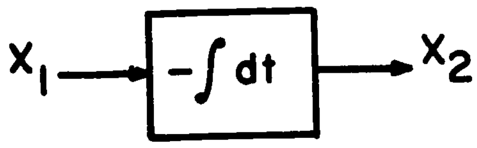
SYMBOL	NAME	MATHEMATICAL OPERATIO
	ADDER	$X_4 = X_1 + X_2 + X_3$
	NEGATIVE ADDER	$X_4 = -(X_1 + X_2 + X_3)$
	VARIABLE SCALOR (The value of the coefficient C can be set to any value between 0 and 1)	$X_2 = CX_1$
	TEN SCALOR	$X_2 = 10X_1$
	INTEGRATOR	$X_2 = -\int X_1 \, dt$

Fig. 1 Identification of Analog Computer symbols.

Notice that some of the circuits on the AMF computer have already been connected in sequence. In the upper left hand corner of the top panel you see that t output of an ADDER and NEGATIVE ADDER are directly connected to the input the VARIABLE SCALOR. Similarly, the input to the INTEGRATORS in the lowe left hand section of the panel are obtained from the outputs of ADDERS. Notice also that each ADDER and INTEGRATOR has a TEN SCALOR inserted after one of its input terminals. These connections simplify our work in setting up the solutions of problems on the computer and in fact can be built into the computer at very little additional cost.

EXPERIMENT XVIII

Scaling on the Analog Computer

Let us now study the operation of the three groupings which combine operations of adding and scaling. The arrangement of one of these groupings is shown in Fig. 1. We give this combination the name Summing-Scalor.

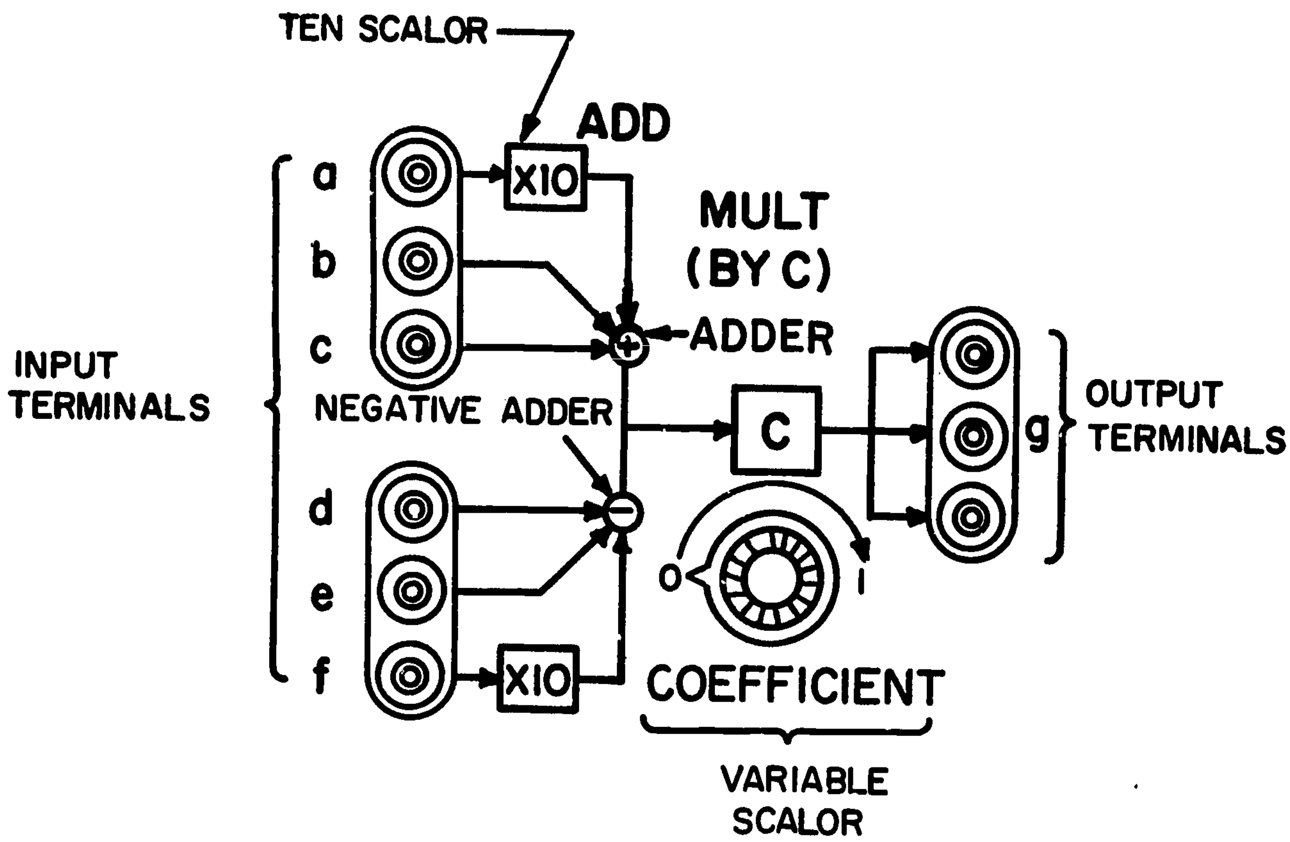


Fig. 1 Summing-Scalor

Notice that the grouping combines four diff rent operations: two Ten Scalors, an Adder, a Negative Adder and a Variable Scalor. In this experiment we see how scaling operations are performed. The terminals in Fig. 1 have been given letter identifications to facilitate the discussion which follows.

A signal connected to either of the input terminals "b" or "c" produces a signal at any of the three output terminals, g, which could be represented by the expression:

Output signal = C x input signal, where C can be adjusted for any value between 0 and 1.

If the input signal is connected to terminal "a" then:

Output signal = 10 x C x input signal.

If the input signal is connected to either of terminals "d" or "e" then:

Output signal = -C x input signal.

(1) Turn on the power to the POLYLAB and the ANALOG COMPUTER, and let them warm up.

(*2) What is the expression which represents the value of the output signal if an input signal is connected to terminal "f"?

(*3) What do you expect the amplitude of the output signal at terminal "g" to be:

a) if the coefficient C is set to a value of 0.5 and an input signal of + 4 volts is connected to terminal "b"?

b) if C is set to a value of 0.3 and an input signal of + 8 volts is connected to terminal "e"?

c) if C is set to a value of 0. 5 and an input signal of + 0. 6 volt is connected to terminal "a"?

(*4) If there are no signals connected to the input terminals and the coefficient C is set for a value of 1, what should be the value of the signal at the output terminal "g"?

(5) Connect ground lead between a COM terminal on the Analog Computer and the GND terminal on the POLYLAB.

(6) Turn the Coefficient knob on each of the three Variable Scalors all the way to the right. Set the RANGE switch on the Voltmeter to 1 and check the zero position of the meter. With one of the transfer leads, measure the amplitude of the signal at the output terminal of each of the Variable Scalors (terminal g, as shown in Fig. 1). If the amplitudes of these signals are not zero then your computer is not properly balanced. Ask your teacher to balance the computer for you. (This balance check should be performed at the beginning of each laboratory session.) Once the unit is balanced however, you can use it for several hours without rebalancing.

(7) Set the amplitude of the CONSTANT signal on the Analog Computer to a value of + 1 volt. Recall how you did this in Experiment XVI and use the 2. 5 volt Range on the meter. Connect one of the blue patch leads between one of the Constant terminals and the input terminal "b" on one of the Adders.

Rotate the Coefficient knob on the Variable Scalor from its extreme clockwise to its extreme counterclockwise position.

(*8) What are the maximum and minimum values of the output signal?

maximum value volts

minimum value volts

(*9) What then is the maximum and the minimum value to which the Coefficients can be set? Remember that you are using an input signal of + 1 volt.

maximum value of C__________

minimum value of C__________

(*10) Does the coefficient knob have a linear or a non-linear characteristic?

To set the coefficient C to a specific value we would connect some convenient known signal into one of the Adder input terminals (either "b" or "c") and then adjust the Coefficient knob until the value of the output signal had a value which was equal to C times the value of the input signal. It is most convenient to set the value of the scalor input signal to + 1 volt. Then the output signal will read the value of C directly.

(11) Connect a + 1 volt input signal to Adder input terminal "b" and set the Coefficient knob to the values given below.

a) 0.02 b) 0.25 c) 0.50

d) 0.83 e) 1.0

Since the Variable Scalor can only multiply signals by a Coefficient between 0 and 1 we have to use the Ten Scalor at terminal "a" (or terminal "f") if we wish to multiply an input signal by coefficients whi are greater than one. If a signal is connected to terminal "a" or "f" the coefficient is then 10 x C.

When we require coefficients greater than 1, we first set the Variable Scalor Coefficient to 1/10 of the desired value by the procedure used in step (11). Then the input signal lead is connected to terminal "a" or "f", which are connected to the Ten Scalors.

(12) Let us set up the computer so that the amplitude of the scalor output signal is represented by the equation:

Output signal = 4.0 x input signal.

First set the coefficient C to 0.4 (use a constant signal of + 1 volt co nected into terminal "b"). Now the input signal should be connected t terminal "a" to give an overall coefficient 4.0.

Set the Constant signal of the computer to an amplitude of + 0.5 volts Connect a patch lead from the Constant terminal to terminal "a" on t Adder. What is the magnitude of the output signal at "g": Is it what you expected? Use the proper range on the voltmeter.

One word of caution: The Analog Computer cannot produce output si nals larger than approximately 10 to 12 volts, because of power limi tations. If you are to avoid errors in your results you should never put signals into the Adder which, if correctly processed, would mak the signal at the input tc the Variable Scalor greater than 10 volts.

For example, if a + 2 volt signal is connected into terminal "a", the correct output of the TEN SCALOR should be 20 volts. But because the above limitation the signal cannot go any higher than 12 volts. I the COEFFICIENT is set to 0.5 the output signal at terminal "g" would be 0.5 x 12 or 6 volts and not the correct value of 0.5 x 20 or 10 volts. We discuss this problem again in later experiments.

The procedure which was used in step 11 can be used to determine the value of a Coefficient for a particular setting of the coefficient knob. We can define the value of the coefficient C by the expression:

$$C = \frac{\text{Value of Variable Scalor Output Signal}}{\text{Value of Variable Scalor Input Signal.}}$$

If a 1 volt signal is connected to the Adder input terminal "b" or "c" the value of the output signal (at terminal g) represents the value to which the coefficient C is set.

(13) Remove the transfer lead momentarily from the Scalor output terminal. Set the Coefficient knob to any arbitrary position. Use a + 1 volt input signal and determine the value of the Coefficient with the Voltmeter.

Repeat the above procedure for several different Coefficient knob positions.

EXPERIMENT XIX

Adding on the Analog Computer

In this experiment we see how the Analog Computer adds electrical signals and how signals can be combined to solve algebraic equations. A diagram of the Summing-Scalor is shown in Fig. 1.

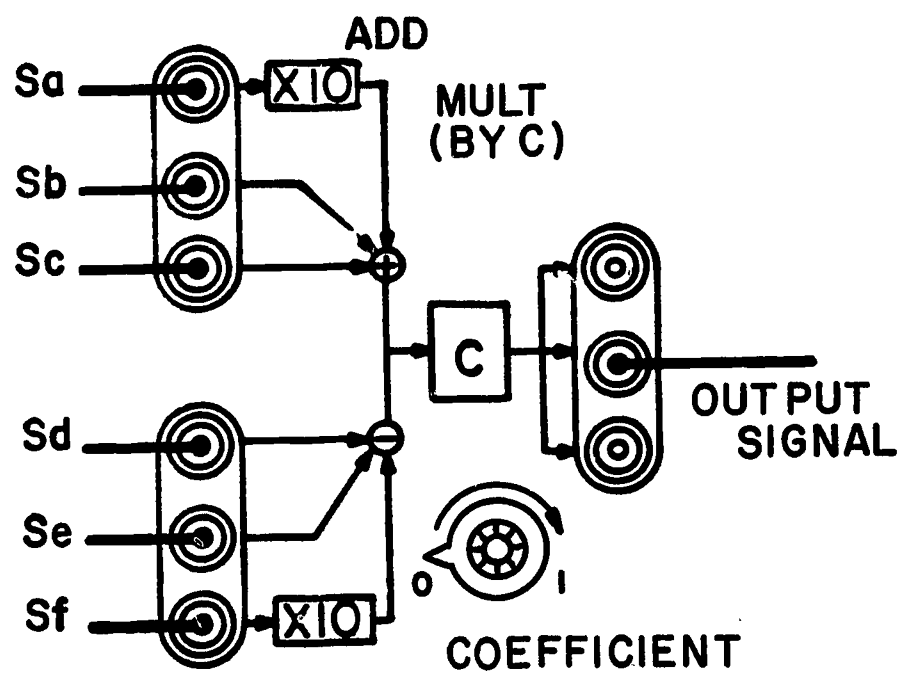


Fig. 1 Summing-Scalor

If S_a through S_f represent the amplitudes of six electrical signals which are connected to the input terminals of the SUMMING SCALOR (as shown in Fig. 1), the amplitude of the output signal is:

$$\text{output signal} = C \times (10S_a + S_b + S_c - S_d - S_e - 10S_f)$$

(1) Turn on the Polylab and the Analog Computer and let them warm up.

(*2) If the input signals to a Summing-Scalor and the Coefficient have values as indicated in the table below, calculate what the magnitude of the output signal from the Summing-Scalor should be:

	S_a	S_b	S_c	S_d	S_e	S_f	C	Output Signal
a)		+3.0			+1.0		0.5	
b)	+0.1		+2.0			+0.4	1.0	
c)		-3.0	+4.0		-1.5		1.0	
d)	+0.5			+5.0			0.5	

(3) We now use the computer to perform some algebraic calculations.

Suppose that we should like to obtain a signal, which we designate Z, whose amplitude is a function of two other signals, X and Y. The desired function is to be represented by the equation

$$Z = 0.2X + 0.5Y$$

This computation can be performed in the following sequency of operations:

a) multiply the signal X by a coefficient of 0.2 to yield 0.2X

b) multiply the signal Y by a coefficient of 0.5 to yield 0.5Y

c) add the signals 0.2X and 0.5Y to obtain the desired output Z.

We can accomplish these operations by connecting the three Summing-Scalors in the proper sequency as shown in Fig. 2.

(4) Study Fig. 2 and make sure you understand how this arrangement solves the given equation. It is best to set the coefficients of the variable scalors to their proper values before you wire up the computer.

(5) Set the coefficients of the Variable Scalors to the values indicated in Fig. 2. For convenience, the signal which is available at the CONSTANT terminals of the Analog we call X. The signal at one of the output terminals of the Integrator we call Y. This integrator output signal can be used as an additional source of constant signal if there is no input signal connected to the Integrator. The magnitude of this constant signal can be adjusted by pushing the RED SET button on the Analog and turning the Initial Condition knob just to the right of the output terminals. (The SET button must be depressed while the Initial Condition knob is being turned.) It is advisable to depress the SET button again for a few seconds before you make any measurements on the Analog.

(6) Wire up the Analog Computer as shown in Fig. 2. Use the short colored patch leads.

(7) Set the Constant knob halfway between its extreme positions, depress the SET button and set the Initial Condition knob to any position.

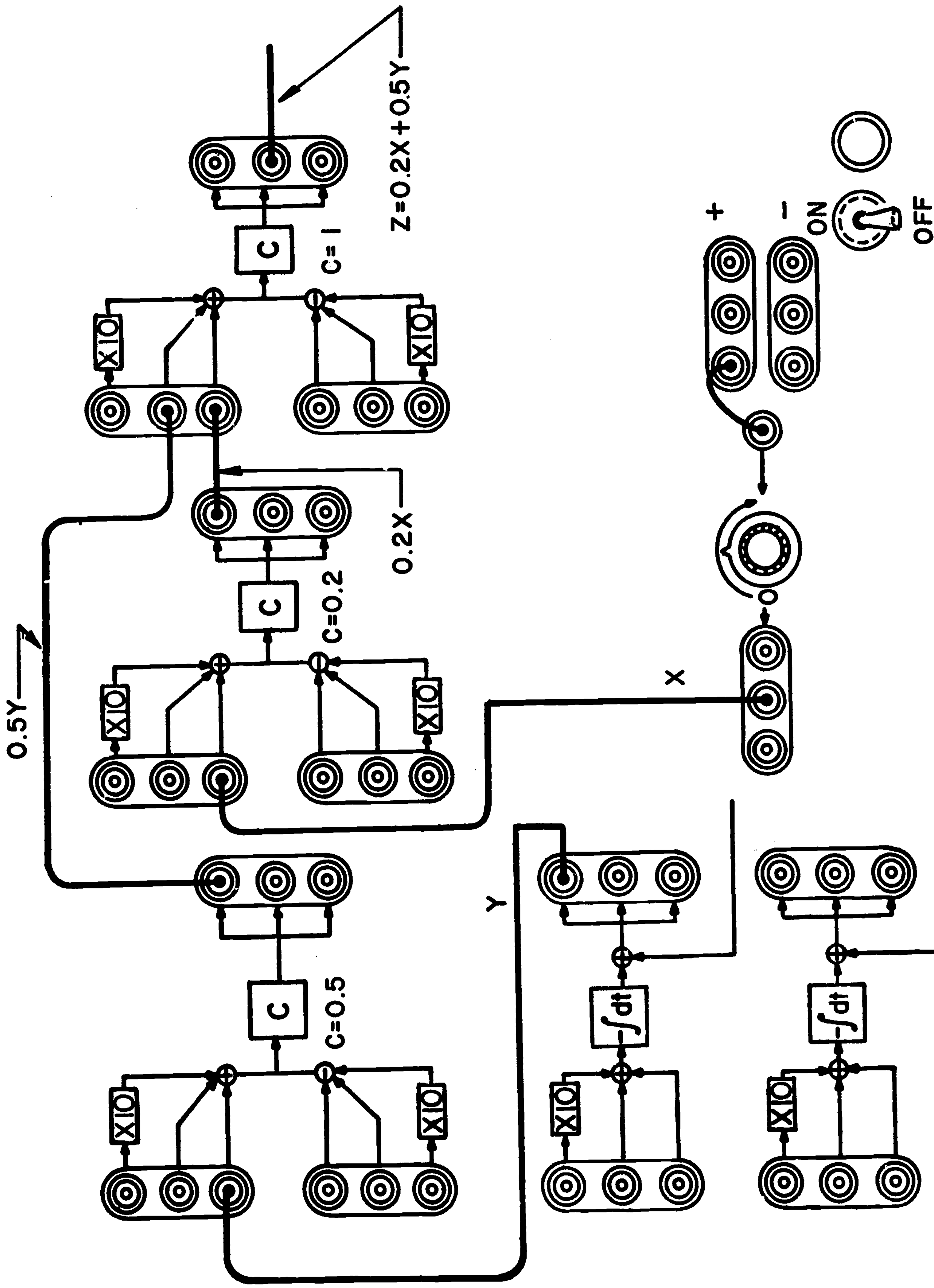
(8) Since we don't know what the value of Z will be, it is best to first set the RANGE switch on the VOLTMETER to a position which will cover all possible values of Z. Therefore, set the RANGE switch to 25. If you find that the value of Z is very small, you can change the RANGE setting accordingly.

(9) Zero the voltmeter.

(10) Connect the ground lead between the Analog and the Polylab.

(11) Connect a transfer lead between the INPUT on the VOLTMETER and and any one of the output terminals on the last SUMMING-SCALOR.

(12) Measure the values of Z with theVOLTMETER. Depress the SET button before you take any readings to insure that the Initial Condition


Z=0.2X+0.5Y
C=1
C=0.2
C=0.5
0.2X
0.5Y
X
Y
+
−
ON
OFF
C
X10
−∫dt

is at its proper value.

(13) Now check the computer calculation by measuring the X and Y signal amplitudes with the VOLTMETER and calculate what the value of Z should be.

(14) Set the Analog for the values of X and Y indicated in the table below and use the Analog to measure the value of Z.

	X	Y	Z
a	+5.0	+1.0	
b	-7.0	+4.0	
c	+6.0	-5.0	

EXPERIMENT XX

Solution of Simultaneous Equations on the Analog Computer

One of the most useful applications of the Analog Computer is to the solution of simultaneous equations. In this experiment we use the Analog to simulate a system whose mathematical model contains simultaneous equations.

A problem which arises in starting small industries in underdeveloped countries of the world is the difficulty of transporting necessary products such as gasoline, fuel oil and kerosene to remote areas. In countries with mountainous terrain there are few passable roads and it is often best to transport these liquids from a coastal seaport or a railroad terminal to the isolated region by pipelines.

Fig. 1 is a diagram of a proposed pipeline which is intended to carry kerosene from a storage tank at a river boat landing to two villages. One village is located in a valley and the other on top of a 500 foot cliff.

We wish each village to simultaneously receive the same amount of kerosene Thus we must put some additional restriction in the pipeline to Village A so that it is just as difficult for the kerosene to flow to Village A as it is to flow uphill to Village B. This restriction takes the form of a valve (similar to the one in the bathroom sink, but larger) which is placed in the branch of the pipeline which goes to village A.

The rate of flow of kerosene to Village B can be expressed by the equation: $Q_B = K(P-h)$ where Q_B is the flow rate of kerosene in gallons per minute; (

h is the height of the mountain in feet, P is the pressure (measured in feet) in the pipeline at the bottom of the branch, K is a flow coefficient which depends on the restrictions (valves in the factories, etc.) which are placed in the pipeline at Village B Note: the fewer the restrictions the larger the value of K and vice versa

We assume that the pipeline restrictions in Village A are the same as those in B with the exception of the additional valve which was mentioned above.

For these conditions the rate of flow of kerosene to Village A can be expres by the equation:

$$Q_A = \frac{KK_A}{K+K_A} P \qquad ($$

where:

Q_A is the flow rate of kerosene to Village A in gallons per minute.

K_A is the flow coefficient of the additional valve which is placed in the bran line to Village A. K_A is directly related to how far the valve is opened. T more the valve is opened, the higher the value of K_A. When the valve is closed, $K_A = 0$.

We assume now that the pump can pump Q gallons of kerosene per minute. We then have the final equation:

$$Q = Q_A + Q_B.$$

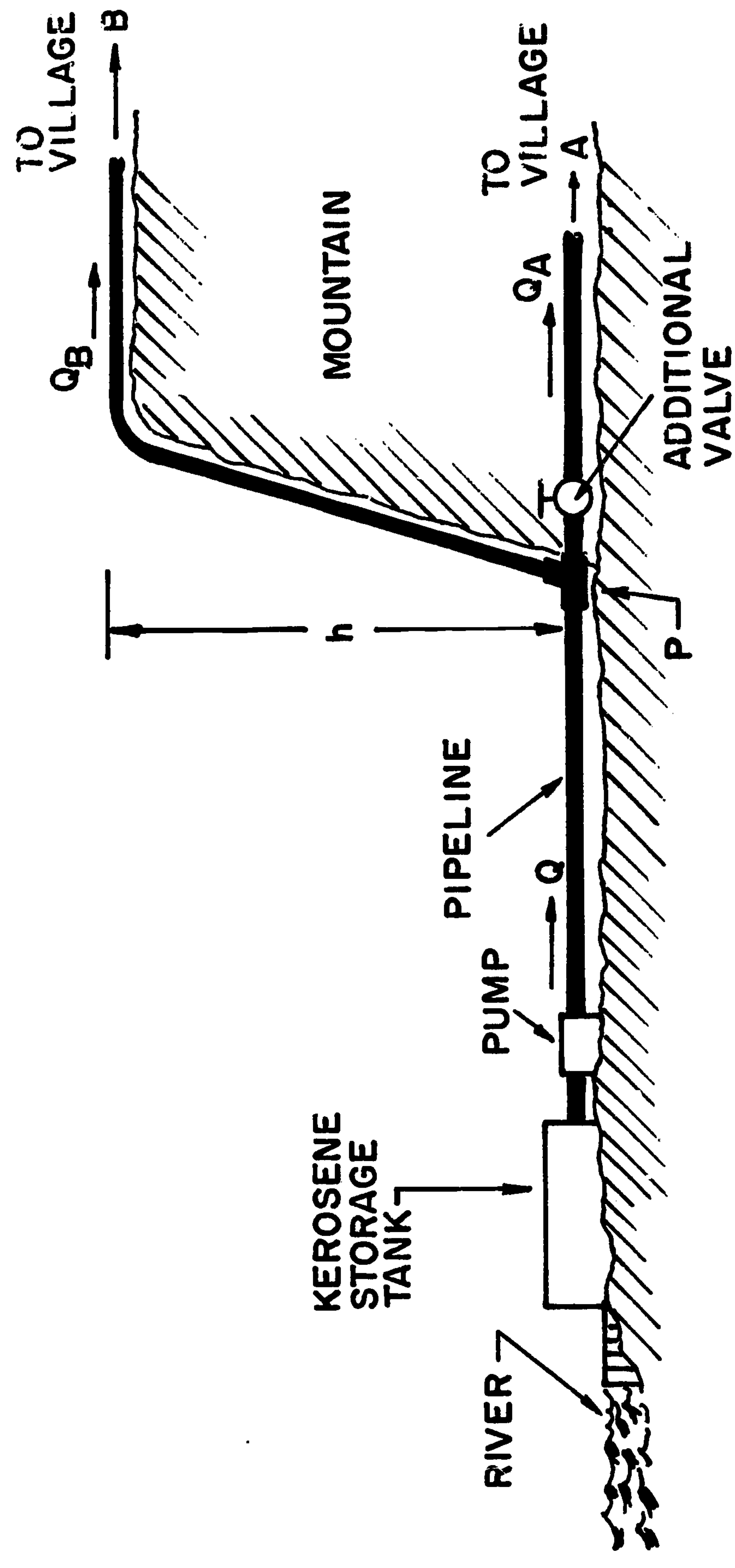


Fig. 1 Kerosene pipeline

Equations (1), (2) and (3) now form the mathematical model of the pipeline system. (Notice the similarity between these equations and the ones which were used as a mathematical model for an animal respiratory system in Chapter B-3 of the text.)

If $Q = 400$ gallons per minute
$h = 500$ feet
and $K = 1.0$

we can find the value of K_A which will make the flows to the villages equal by solving equations (1), (2), and (3) simultaneously. We can also find the pressure P. The magnitude of this pressure will let the engineer decide on how strong the pipe should be so that it won't burst under the pressure.

The simultaneous solution of these equations can be performed very easily on the Analog Computer.

Since the Analog is limited to signal amplitudes below 12 volts, let us multiply each equation by a factor of 1/100. We then obtain:

$$\frac{Q_B}{100} = K\left(\frac{P}{100} - \frac{h}{100}\right) \qquad (1')$$

$$\frac{Q_A}{100} = \frac{K\,K_A}{K + K_A} \cdot \frac{P}{100} \qquad (2')$$

$$\frac{Q}{100} = \frac{Q_A}{100} + \frac{Q_B}{100} \qquad (3')$$

Now the magnitude of the signals on the Analog will represent the flows and pressures divided by 100. To find the actual values we simply multiply the signal amplitudes.

We can simulate these three equations on the Analog in the following manner:

If we assume that a signal which represents $\frac{P}{100}$ will be available at the output of the first Summing-Scalor we can simulate the equation for $Q_A/100$ as shown in Fig. 2.

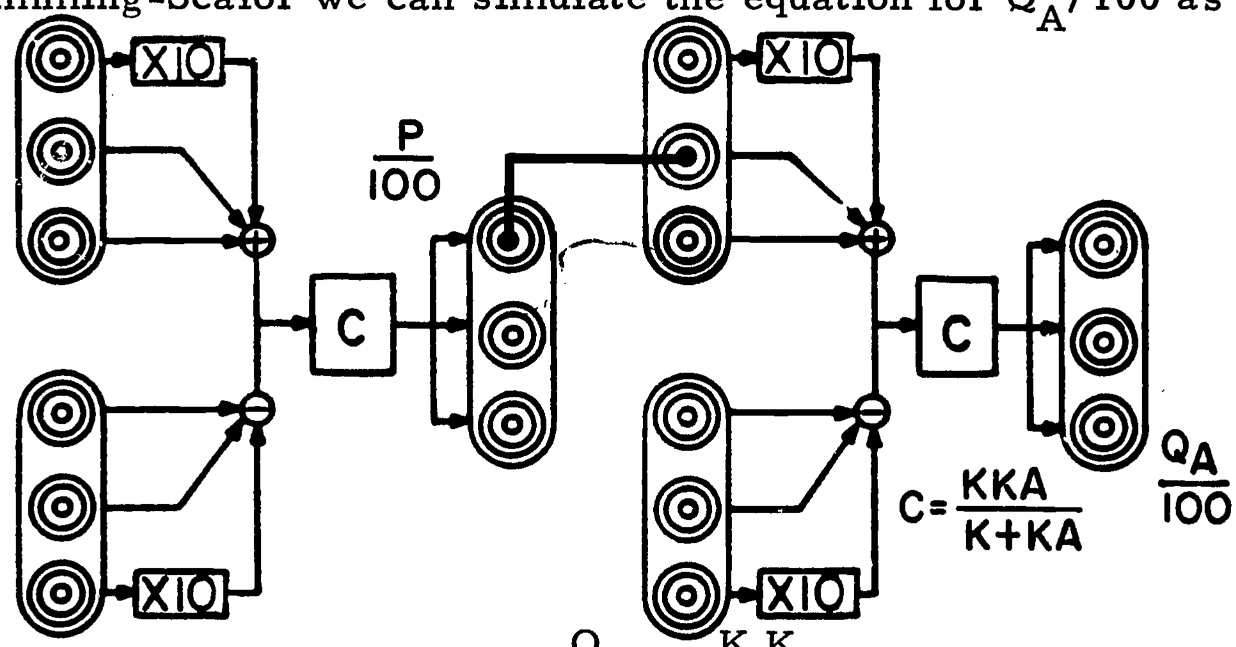


Fig. 2 Simulation of $\frac{Q_A}{100} = \left(\frac{K\,K_A}{K + K_A}\right)\frac{P}{100}$

We can obtain an equation for $Q_B/100$ from the third equation;

since $\frac{Q}{100} = \frac{Q_A}{100} + \frac{Q_B}{100}$

$$\frac{Q_B}{100} = \frac{Q}{100} - \frac{Q_A}{100}$$

This equation can be simulated as shown in Fig. 3. The known value of $\frac{Q}{100}$ is obtained from the CONSTANT terminal on the Analog.

We now use equation (1') to solve for $\frac{P}{100}$ as a function of $\frac{Q_B}{100}$

If we divide both sides of the equation by K and transfer the term $\frac{h}{100}$ we obtain:

$$\frac{P}{100} = \frac{1}{K} \frac{Q_B}{100} + \frac{h}{100}$$

This equation can also be written as:

$$\frac{P}{100} = \frac{1}{K} \left(\frac{Q_B}{100} + \frac{hK}{100} \right)$$

We see from this equation that the output of the first Summing-Scalor represents $\frac{P}{100}$ if $\frac{Q_B}{100}$ and $\frac{hK}{100}$ are the input signals and if the Scalor coefficient is set to $1/K$.

The signal $\frac{Q_B}{100}$ is available at the output of the last Summing-Scalor. We therefore just connect this output to the input of the first Summing-Scalor with a patch lead. The constant signal $\frac{hK}{100}$ can be obtained from an Initial Condition setting at one of the Integrator output terminals.

The final pipeline simulation is shown in Fig. 4.

Note that you can use the Integrator output as an additional constant signal source if no input is connected to the Integrator input terminal. Remember to depress the Set button while setting the Initial Condition.

<u>Procedure:</u>

1. Set the values of the CONSTANT signals and the Coefficients and wire up the pipeline simulation as indicated in Fig. 4.

2. Turn the coefficient knob on the middle Scalor all the way CCW. This will make $K_A = 0$, (the valve is completely closed). With this setting all the kerosene should be flowing to Village B.

*3. Check the simulation by measuring the values indicated and recording below. Before taking any recording it is good practice to depress the Set button for a few seconds to insure that the Initial Condition is at its proper value.

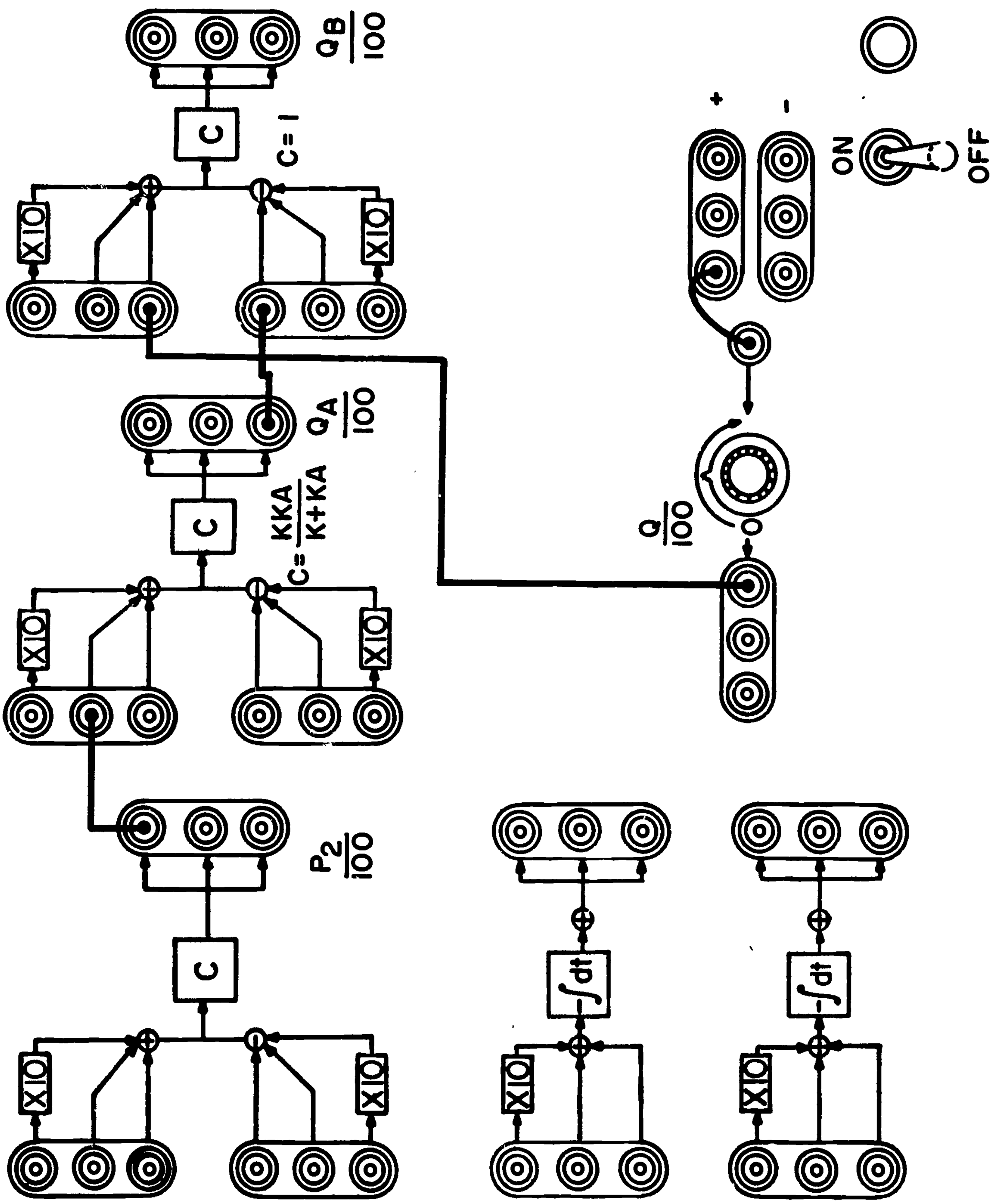


Fig. 3 Simulation of $\frac{Q_B}{100} = \frac{Q}{100} - \frac{Q_A}{100}$

For $K_A = 0$:

Q_B ____________________

Q_A ____________________

P ____________________

Q ____________________

*4. Slowly increase the coefficient $\frac{KK_A}{K+K_A}$ (increasing this coefficient has the same effect as increasing the opening of the valve in line A). Observe what happens to Q_A and then to Q_B. Do the changes you observe seem reasonable?

5. Increase the coefficient $\frac{K\,K_A}{K+K_A}$ until the flows to both villages are the same.

*6. What is the value of Q_A and Q_B? __________

*7. What is the resulting value of P? __________

*8. What is the value of the coefficient $\frac{K\,K_A}{K+K_A}$ when $Q_A = Q_B$? You can calculate this value by dividing the measured value of $\frac{QA}{100}$ by the measured value of $\frac{P}{100}$.

*9. What should be the value of the flow coefficient K_A for both villages to get equal amounts of Kerosene? (Note that K = 1).

*10. As $\frac{KK_A}{K+K_A}$ is increased, the flow to Village B decreases. Determine from the Analog the value of this coefficient at which the flow to village B stops.

*11. What is the corresponding value of K_A for this condition?

*12. Determine from the Analog the flow conditions which create the greatest pressure P in the pipeline.

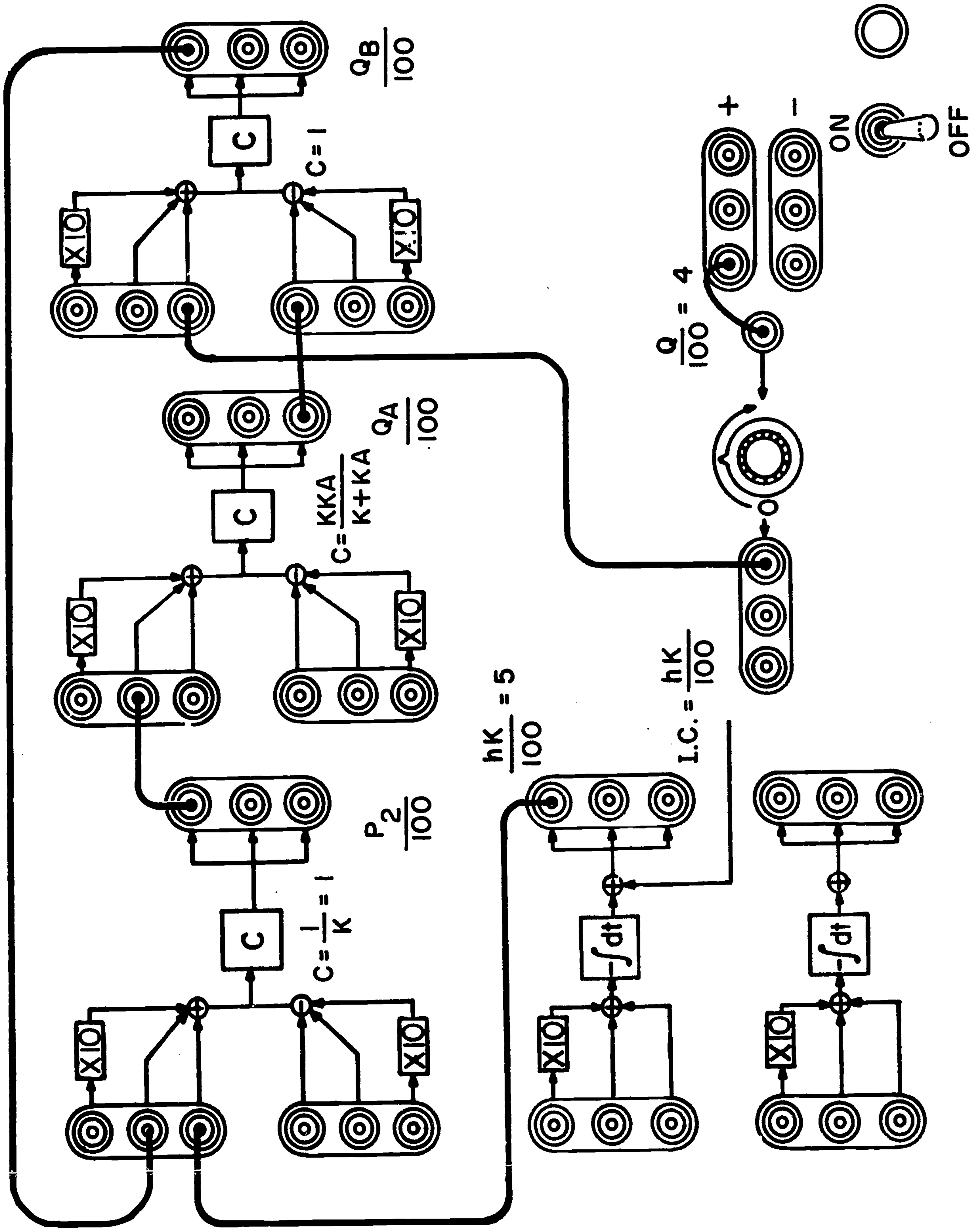


Fig. 4 Complete pipeline simulation.

EXPERIMENT XXI

Integrating on the Analog Computer

We now study the operation of the Analog Integrator. Before we begin we should turn on the Analog Computer so that it can warm up.

On the top panel of your Analog you will see that the Integrator, which is represented by the symbol

$$\longrightarrow \boxed{-\int dt} \longrightarrow$$

is combined with an Adder and a Ten Scalor. We call this combination, which is shown in Fig. 1, a Summing-Integrator. The terminals of this device have been given letter identification in Fig. 1 to facilitate the discussion which follows.

Recall from your study of "Man Made World" that an Integrator is a device which computes the area under a time-varying signal. Now look at your Analog and note the integral symbol $\int dt$ has a minus sign in front of it. This means that the integrator in the Analog computes the area under a time-varying signal and continually multiplies the value of this area by -1. This is an inherent characteristic of the electronic circuitry inside the analog. After you work with the analog for a while it will cause you no problem.

Recall also that the area under the integrator input signal represents the change in the output signal between the time that the integration is begun and the time that the integration is completed. It does not, however, take into account the fact that the output signal may have some significant magnitude when the area computation is started. Consider, for example, the situation where we wish to make a graph of the distance of a moving car from some fixed reference position. Now, if we can obtain a graph of the velocity of the car we can calculate the change in position of the car by measuring the area under the velocity-time curve. These results will represent the distance of the car from the fixed reference position, only if we started measuring the velocity at the reference. If, for example, we started measuring the velocity when the car was 20 feet from the reference, the distance of the car from the reference at any time would be the area under the velocity curve up to that time plus the initial distance of 20 feet. This initial distance is termed the Initial Condition, and it must always be added to the computed area. In some cases, of course, this initial condition may be zero. Notice that a separate input has been provided on the Analog after the Integrator for the addition of the initial condition.

From your previous work with the Summing-Scalor you can see that the signal at the output of the Summing-Integrators can be represented by the expression:

$$\text{Integrator Output} = \text{Initial condition} - \int (10S_a + S_b + S_c)\, dt$$

where S_a, S_b and S_c represent the amplitudes of the signals connected to terminals a, b and c as shown in Fig. 1.

Before we operate the Integrator, we will try to predict the output signal from the device for various input signals. (Don't forget, however, that the Integrator computes the negative of the area.)

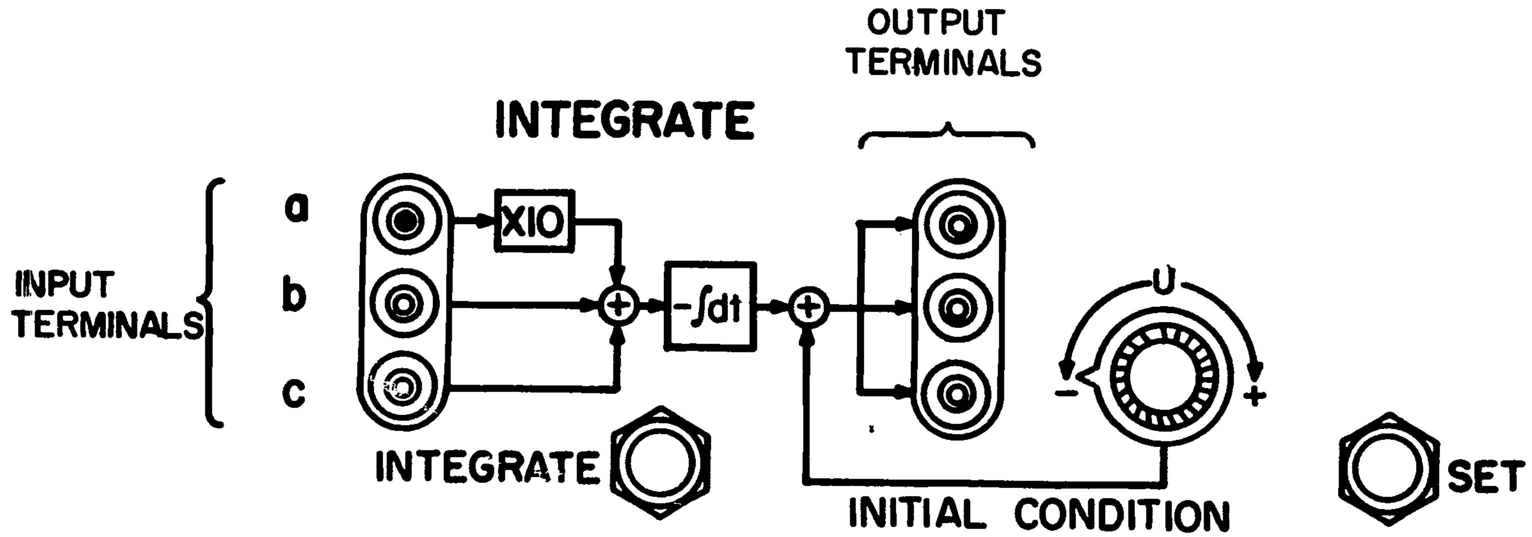


Fig. 1 The Summing-Integrator

Sketch in the spaces provided below the expected time variation in the output signal of the Summing-Integrator for the signle output signals shown. Assume that the initial value of the output signal is zero in all cases and that the input signal is connected to terminal "b" of Fig. 1.

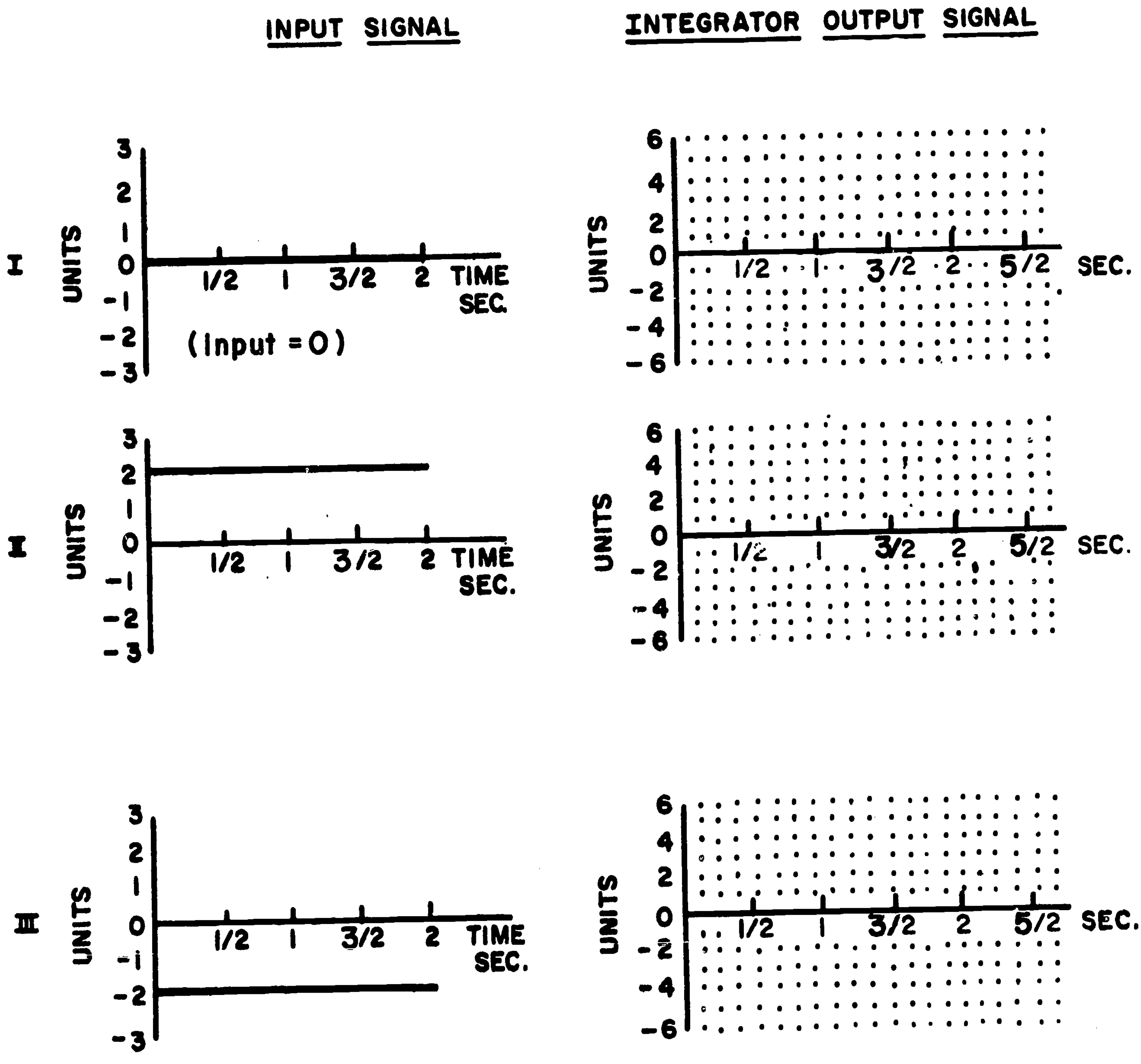


Fig. 2 Graphs of integrals of constant velocities

In each case, if the input signal represents a graph of the velocity of a car, the Integrator output signal would be a graph of -1 times the position of the car over the 2 second time interval. If the input signal represents the car velocity multiplied by -1, the graph again represents the change in position multiplied by -1.

From your prediction for Curve 1 you saw that the Summing-Integrator output signal should remain at zero when there is no signal connected to its input terminals. If the Integrator is not properly balanced, however, there will be a slowly increasing output signal. We check the balance on the two Summing-Integrators with the following procedure:

<u>Integrator balancing procedure</u>

(1) Zero the VOLTMETER.

(2) Set the voltmeter RANGE switch to 2.5 volts.

(3) Set TIMING selector switch on the Analog to the MAN (manual) position. (This makes the Integrator operate without pauses).

(4) Set the INTEGRATE lever straight up.

(5) Set INITIAL CONDITION knob to the 0 position.

(6) Connect the ground lead from a COM terminal on the Analog to GND on Poly-lab.

(7) Connect a lead from one of the output terminals of the Summing-Integrator to the INPUT terminal on the voltmeter. The voltmeter reads the magnitude of the integral (times -1) from moment to moment.

(8) Depress the red SET button on the Analog and slowly adjust INITIAL CONDITION knob until the meter reads zero. Release the SET button.

(9) Push the INTEGRATE lever to the right, to start the integration.

(10) Read the meter after one minute.

(11) If the Summing-Integrator is properly balanced, you should not detect any change in the meter reading.

Repeat the above procedure for the other Summing-Integrator.

From the prediction curves which you plotted, it can be observed that any input signal, other than zero, produces an output signal that will vary with time. It may, therefore, be difficult to read the signal amplitude on a meter if the amplitude is changing rapidly. In many applications, engineers use a "chart recorder" in which the signal magnitude is drawn with a pen on a strip of moving paper. This strip of paper then forms a direct graph of the signal output. An alternative, and the one which is used on this Analog, is to allow the computer to integrate for a fixed interval of time and to hold the value it has computed for this interval. A meter reading can then be taken while the signal amplitude does not change. The computer can then be switched on to integrate over the next time interval. If we continue taking readings in this manner, plot the results and then join all the data points by a smooth curve, the result will approximate the integral or area under the input signal curve. The Timing Selector Switch on the AMF Analog Computer has settings which will permit integrations in time intervals of 0.1, 0.25 and 1.0 seconds. In the MAN position the Summing-Integrator will "integrate" as long as the Integrate switch is to the right.

Let us now calculate with the Analog Computer the "integral" of the input signal shown in Curve II, Fig. 2.

(12) Set the INITIAL CONDITION on the lower Summing-Integrator to zero. Don' forget to raise the Integrate lever in its center position and to depress the SET button while you are making these adjustments.

(13) Wire up the Constant source on the Analog to give a signal of +2 volts (the input signal in Curve II). Use the meter to set the signal magnitude. You will have to set the RANGE switch to 2.5.

(14) Insert the meter lead into the output terminal of the lower Summing Integrator. Connect one of the yellow analog leads between the Constant terminal and one of the plain input terminals on the lower Summing-Integrator.

We will run the integration for 2 seconds. In order to obtain a sufficient number of points for our graph we "integrate" over 1/4 second intervals. In this manner we get an initial data point and 8 additional points. Put the Timing switch to the 0.25 position.

(15) Set the meter to the 2.5 volts range and check the zero. Depress the Set button and make sure that the Initial Condition is still zero. If it is not, readjust the Initial Condition knob. <u>The Set button should always be depressed for a few moments before you begin any integration.</u> This will ensure that the magnitude of the Integrator output signal begins at its prope initial value. In this case the initial value is zero.

(*16) Push the Integrate lever to the right. Observe that the voltmeter moves an then holds at a specific value. Read this value and plot it (at a time of 1/4 second) on the same axis on which you made your sketch of the integrator output. Identify the data point by an X.

Now return the Integrate lever to its central position and then push it back to the right. The voltmeter will again move and then hold at a new value. Plot this new value at a time of 1/2 second on your graph. Continue taking readings in this manner until you have a total integration time of two secon If you have made the proper prediction and have carefully operated the ana the X's from your data should lie exactly on top of the sketch which you pre viously made.

(*17) Repeat steps 13 through 16 for an input signal which has a magnitude of -2 units. Plot your results on the axes provided for Curve III.

Keep in mind that the Integrators have the same limitation on maximum signal amplitude as the Summing-Scalor.

This characteristic in the Scalor and in the Integrator is called Saturation. The electronic devices in the Analog reach a point where they are handling as large a signal as they can. You must avoid "saturating" these components, or your results will be incorrect. As already pointed out, the saturation level of the AMF Analog Computer is about 10-12 volts.

EXPERIMENT XXII

Integrating with Initial Conditions on the Analog Computer

We discussed previously the need for introducing initial conditions into an integrating operation. If for example we have a graph of the acceleration of a car we could, by the process of integration, obtain a graph of the velocity of the car, if we knew the velocity of the car at the time when the acceleration graph was started.

Assume that the graphs shown in Fig. 1 represent the acceleration of a car over a certain period of time and that the car starts with an initial velocity of two units.

If electric signals corresponding to these graphs are connected to the input of the Summing-Integrator, sketch on the axes provided how you expect the Integrator output signal to appear. The Analog Integrator computes the negative of the area. Thus, if the Integrator input signal represents acceleration, the output signal represents the velocity multiplied by (-1). You must be careful in dealing with the initial condition. If in this example, the initial car velocity is given as +2 units, an initial condition of (+2) x (-1) or -2 units must therefore be set into the Summing-Integrator.

(1) Turn on the Analog Computer and allow it to warm up for a few minutes.

(2) Connect a black "ground" lead from the Analog Computer to the GND terminal on the Polylab. Zero the meter.

Check the balance of the Summing-Integrator with the meter. (Put the Timing switch to MAN. Set the Initial Condition to about zero, and push the Integrate lever to the right). If the Analog needs to be balanced notify your teacher.

We now use the Analog to obtain the "integral" of the input signal shown in Curve II when the Initial Condition is + 2.

(3) Depress the Set button on the Analog and adjust the Initial Condition knob until the Voltmeter reads -2 volts.

(4) Now set the Constant supply to give a signal with a magnitude of +2 volts Connect the +2 Volt signal to one of the plain input terminals on the Summing-Integrator. Set the Timing switch to 0.25.

(*5) Depress the Set button and make sure that the Initial Condition is still -2 units. Plot this value (at a time of 0 seconds) on the axis on your sketch. Mark the data point by an X. Measure the magnitude of the Integrator output signal for each 1/4 second interval up to 2 seconds and plot these results.

Does the curve you have previously sketched agree with your data points

(*6) Now repeat steps (4) and (5) for an input signal of -2 units. The initial condition will still be -2 volts.

(*7) If the curves obtained in step 6 represent the velocity of a car, describe in words the motion of the car from the initial time when its velocity is +2 units to a time 2 seconds later.

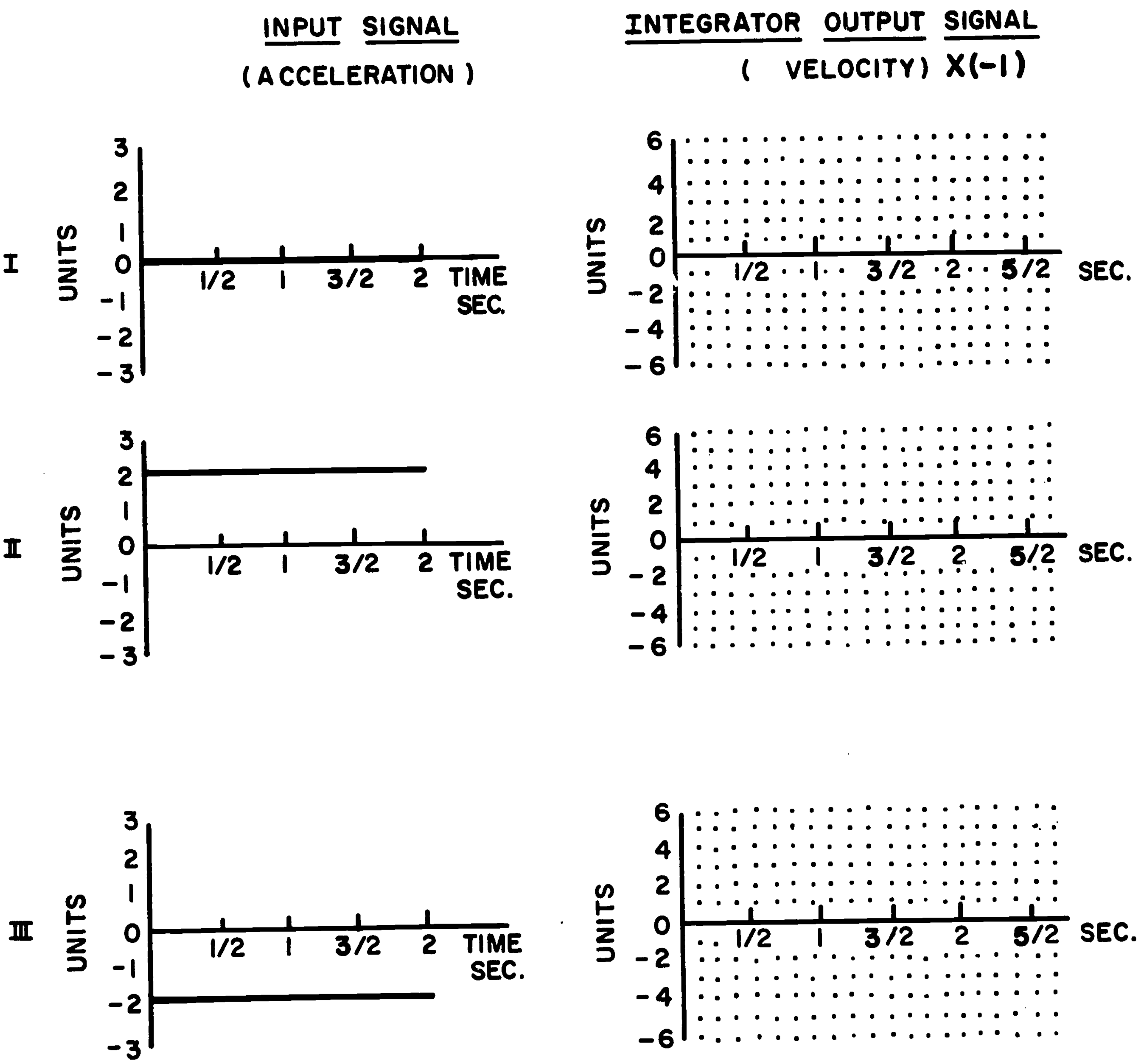


Fig. 1 Graphs of integrals of constant accelerations.

EXPERIMENT XXIII

The Cathode-Ray Oscilloscope (CRO)

Chapters B-3 and B-4 of the Man-Made World discuss a few of the many phenomena in the physical world which change with time. The world is continually in a state of change and engineers and scientists are interested in measuring and observing these changes. One instrument which is widely used in the study of changes which occur in electrical signals is the Cathode-Ray Oscilloscope.

The CRO is a special kind of TV set. Although it is not capable of showing the picture of a football game, it is capable of showing the picture of changing signals. The CRO is an automatic graph plotter that eliminates the time and effort required in the point-by-point plotting of changing signals. Moreover, the CRO shows the signal as it is generated, just as the TV set shows the ball game as it is being played. If the system generating the signal is changed in such a way that the shape of the signal changes, this change can be seen at once. Thus doctors sometimes use the CRO to observe the signals generated by a patient's heartbeat during an operation; changes in the shape of the signal indicate how the patient is reacting to the surgery. The CRO has countless important uses in the building and the control of the man-made world.

Part A

The heart of the CRO as of the TV set is the picture tube, or, as it is more commonly known, the cathode-ray tube. The basic features of this tube are shown in Fig. 1. It consists of an electron gun which emits a fine beam of high speed electrons (originally called a "cathode ray") at the narrow end of the tube. The wide end of the tube, called the screen, is coated on the inside with phosphorescent and fluorescent materials which produce a light spot at the point bombarded by the electron beam. This spot of light produces the picture seen on the screen.

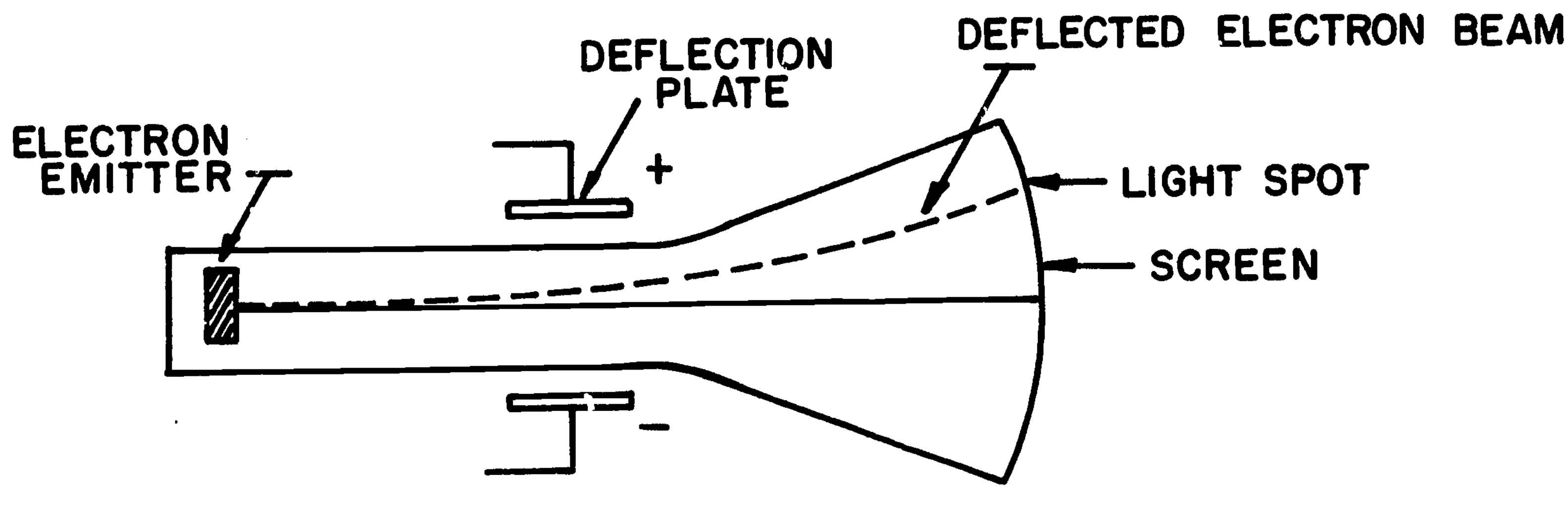


Fig. 1 The Cathode-Ray Tube.

The cathode-ray tube also contains provisions, not shown in Fig. 1, for bending, or deflecting, the electron beam. The beam can be deflected up or down as indicated by the dotted line in Fig. 1. It can also be deflected left or right. Thus, the beam can be made to strike any point on the screen by a proper combination of horizontal and vertical deflections. In the CRO, the horizontal deflection is used to sweep the beam across the screen while the vertical deflection depends upon the amplitude of the waveform at any instant of time.

The intensity of the light emitted by the screen as a result of bombardment by the electron beam depends on the strength of the beam. The strength of the beam, and thus the brightness of the picture, is controlled by the brightness control knob called the BEAM control.

In order for the cathode-ray tube to produce an image containing fine details, the electron beam must be concentrated into the smallest possible diameter, just as an artist must use a tiny brush to produce fine details. The concentration of the electron beam is controlled by the FOCUS knob. In some CRO's, changing the intensity of the picture defocuses the electron beam. In such cases the focus control should be readjusted whenever necessary to obtain a sharp picture.

Fig. 2 displays the control units for the CRO. We will study the function of each of the control elements in this experiment.

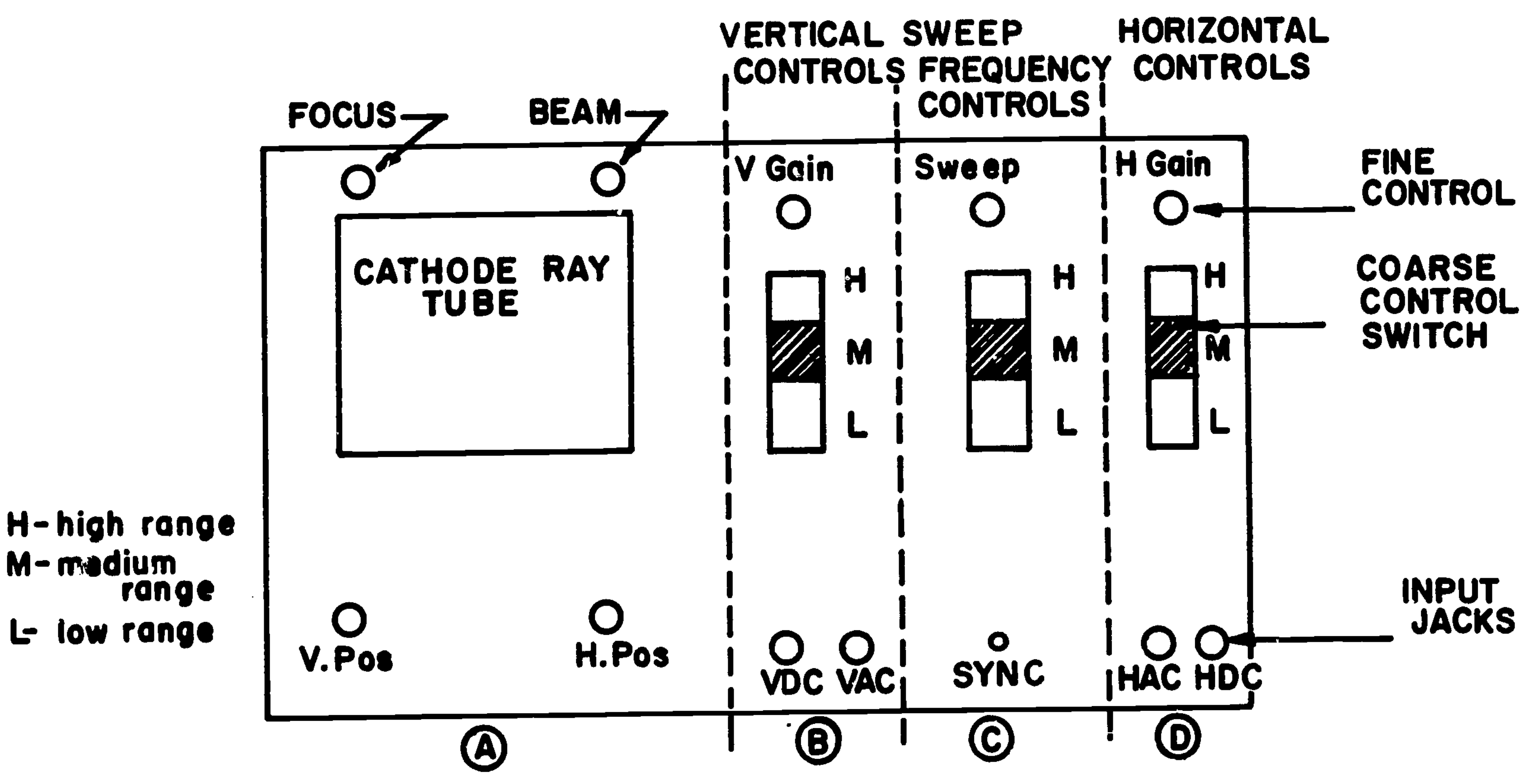


Fig. 2 The Cathode-Ray Oscilloscope (CRO) unit of the Polylab.

LM

In the section marked "A" in Fig. 2 the BEAM control adjusts the intensity of the spot or pattern on the screen and also acts as an ON-OFF switch for this section of the Polylab. When turned completely counter-clockwise (CCW) a "click" will be heard as the on-off switch removes all power from the CRO. All the other units in the Polylab will continue to operate normally until the main power switch, located in the power unit on the lower right hand panel, is turned off.

The FOCUS control permits the adjustment of the "sharpness" of the spot or pattern on the tube face.

The V POS or vertical position knob permits the beam to be moved up or down on the tube face and the H POS or horizontal position knob permits the trace to be shifted to the left or right.

A sweep generator is built into the unit so that the beam is kept moving automatically from left to right. This internal sweep can be varied in frequency and in amplitude. Section C in Fig. 2 controls the frequency of this internal sweep, while Section D permits the control of the amplitude of the sweep.

There are occasions when we may wish to use an external sweep generator rather than the internal sweep generator. This can be accomplished by connecting the leads from the external generator to the input jacks at the bottom of Section D. The insertion of a sweep frequency into either of these jacks will automatically disconnect the internal sweep generator, and permit the external generator to take control.

The V GAIN and H GAIN controls permit the picture on the CRO screen to be made larger or smaller.

In Sections B and C, coarse adjustments are first made with the slide switch (H-high, M-medium, L-low) and then a fine adjustment can be set with the small control knobs, immediately above each slide switch.

We can study the features of the CRO by following the experimental procedure outlined below:

1. Turn the V GAIN knob on the CRO clockwise (CW) as far as it will go and put the V GAIN switch in the H position.

2. Turn the H GAIN knob on the CRO CCW as far as it will go and put the H GAIN switch in the L position. (This is to cut both the frequency and the amplitude of the horizontal sweep to 0, as nearly as possible).

3. Set the V POS and H POS knobs in about the center of their range of rotation.

4. Turn the BEAM knob fully CW (for maximum brightness).

5. Turn on the power to the POLYLAB. The on-off switch is located in the lower right hand section of the front panel.

6. After a short wait a spot of light should appear on the screen. As soon as it appears reduce the intensity of the spot to a low value by turning the BEAM knob CCW. Note: The face of the tube will burn out if a

beam of high intensity is kept at one point on the screen for an extended period of time. If the beam is too bright you will see a faint "halo" around the spot. Reduce the intensity until the halo disappears and the spot is visible but not too bright.

7. Deflecting the beam: Rotate the V POS control knob and note the effect on the spot position. Center the spot and observe the effect of rotating the H POS knob. Note that you can move the spot to any position on the screen by properly adjusting these two knobs.

8. Focus and Beam Controls: Center the spot on the screen. Rotate the FOCUS knob through its entire range and note the effect on the spot. Adjust the FOCUS for the smallest spot. Turn the BEAM knob and notice the effects on brightness and focus. Refocus the beam whenever a change in brightness changes the focus.

Let us now look a little more closely at the method by which the electron beam is deflected. Refer again to Fig. 1. The electron emitter is designed so that under normal conditions the electron beam will travel straight and impinge at the center of the CRO screen. To deflect the beam upwards or downwards we place two parallel flat plates on either side of the tube as shown. We can then feed an electrical (voltage) signal into these plates by means of wires attached to them. The voltage signal causes the electron beam to be attracted to the deflection plate which has a positive polarity. The amount of the deflection depends on the amplitude of the electric signal. If the deflection signal increases, the electron beam moves closer to the positive plate. If the other plate then becomes positive the beam will be attracted to that plate. This alternating attraction causes the spot on the CRO screen to move up and down. A similar set of deflection plates placed at the sides of the tube deflect the beam to the right or to the left. The V POS and H POS controls work by feeding small but adjustable constant voltages to the deflecting plates.

We demonstrate the deflection of the electron beam by using the CONSTANT signal from the Analog Computer.

9. Wire the Analog Computer to provide a CONSTANT signal of positive sign as shown in Fig. 3.

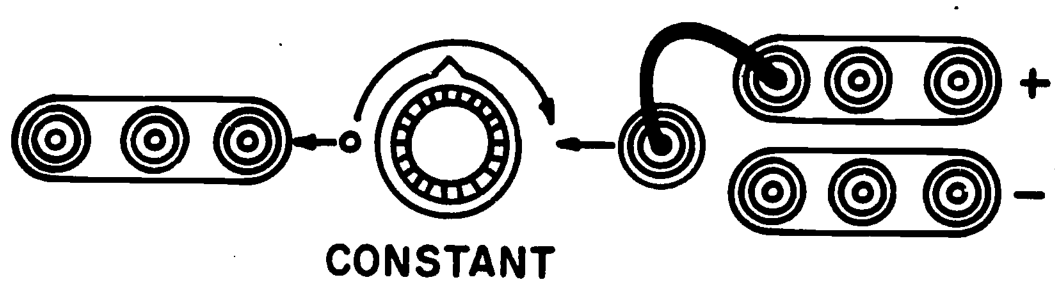


Fig. 3 Connection for positive signal

10. Adjust the V POS knob until the electron beam spot lies exactly on the middle horizontal dotted line on the CRO screen. Adjust the H POS knob to bring the spot to the middle vertical dotted line. These adjustments produce the ZERO position of the spot. The spot may drift away from this center position during about 20 minutes after the CRO is turned on. You can always reset the spot position by using the V POS and H POS controls.

11. Connect the constant terminal on the ANALOG to the V DC terminal on the CRO. Use one of the transfer leads, and don't forget to make the ground connection too.

12. Put the V GAIN SWITCH into the L position and turn the V GAIN KNOB completely CW.

13. Turn on the ANALOG COMPUTER and let it warm up for a few seconds.

14. Turn the CONSTANT KNOB on the ANALOG and observe that the spot on the CRO can be deflected upwards by increasing the signal magnitude on the ANALOG.

15. Move the patch lead on the ANALOG so that the signal at the CONSTANT terminals has a negative polarity.

16. Turn the CONSTANT knob on the ANALOG and observe how the spot on the CRO is deflected downward.

17. Remove the transfer lead from the V DC terminal on the CRO and place it into the H DC terminal.

18. Set the H GAIN switch to L and turn the H GAIN knob as far CW as it will go. (These directions are designed to make your control of the spot easier, and to prevent the sweep action from occurring.)

19. Observe how you can control the horizontal movement of the spot exactly as you controlled the vertical movement.

    The vertical (or horizontal) movement of the spot is always proportional to the magnitude of the signal which is connected to the vertical (horizontal) input terminal of the CRO. The distance which the spot moves for any given input signal can be adjusted by using the V GAIN and H GAIN controls on the CRO. The use of these controls is demonstrated in the next part of this experiment.

Part B

Use of the CRO Gain Controls

You observed in Part A of this experiment that the deflection of the electron beam is directly related to the amplitude of the signal which is connected to the CRO input terminals. A large signal will produce a large beam deflection and may in fact cause the beam to reach the limits of its deflection. A very small signal may produce such a small deflection that it is not visible to the viewer. The V (Vertical) GAIN and H (Horizontal) GAIN controls reduce or amplify the incoming electrical signal before it reaches the deflection plates of the CRO tube.

In this manner, the beam deflection can be kept within reasonable limits.

Recall that the L, M and H positions of the Gain Switch provide a coarse adjustment in gain, while the knob which is located directly above the switch provides a finer gain adjustment.

The following experimental procedure will demonstrate the use of the GAIN controls.

1. Prepare the Analog Computer to provide a signal with positive polarity at the CONSTANT terminals.

2. Turn on the CRO and adjust the controls so that a single spot appears exactly at the center of the screen. Keep the spot-intensity low to prevent damage to the CRO screen.

3. Put the V GAIN and H GAIN switches in the L position and the V GAIN and H GAIN knobs in their extreme CW positions.

4. Connect the CONSTANT terminal on the Analog to the V DC terminal on the CRO, and make the ground connection.

5. Set the CONSTANT knob so that the spot deflects 2 large scale divisions on the screen. (Note that the large scale division lines are spaced $\frac{1}{4}$" apart.)

6. Turn the V GAIN knob CCW and observe how the deflection of the spot decreases.

7. Return the H GAIN knob to its full CW position. Check the zero position of the spot (by pulling out the lead from the V DC terminal) and put in a constant signal which barely deflects the spot.

8. Increase the signal amplification by putting the V GAIN switch to the M and then H positions. Observe how the spot deflection increases.

9. Increase the CONSTANT signal amplitude and the V GAIN amplitude and note the position of the maximum possible beam deflection.

10. Repeat steps 4 through 9 with the CONSTANT signal connected to the H DC terminal and use the H GAIN controls.

    NOTE: In your future work with the CRO, you should never work with the vertical and horizontal gains so high that the beam reaches its extreme vertical or horizontal positions. You should also not keep the vertical gain so low that you can't observe the deflection of the beam.

Part C

The introduction to this experiment stated that the CRO could be used as an automatic graph plotter for a signal which changes with time. To do this we let the vertical deflection of the CRO beam represent the change in signal amplitude while the horizontal deflection of the beam represents the uniform passage of time. That is, we want the beam to move horizontally across the screen at a constant speed, at the same time that the signal to the vertical input terminal varies the vertical deflection The SWEEP (SWP) output of the SIGNAL GENERATOR and the SWEEP control on the CRO provide this uniform horizontal deflection. Let us first look at the sweep signal which is provided by the SIGNAL GENERATOR.

Fig. 4 shows the controls on the SIGNAL GENERATOR. For this experiment, we are interested only in the FREQUENCY dial, RANGE selector switch and SWEEP controls.

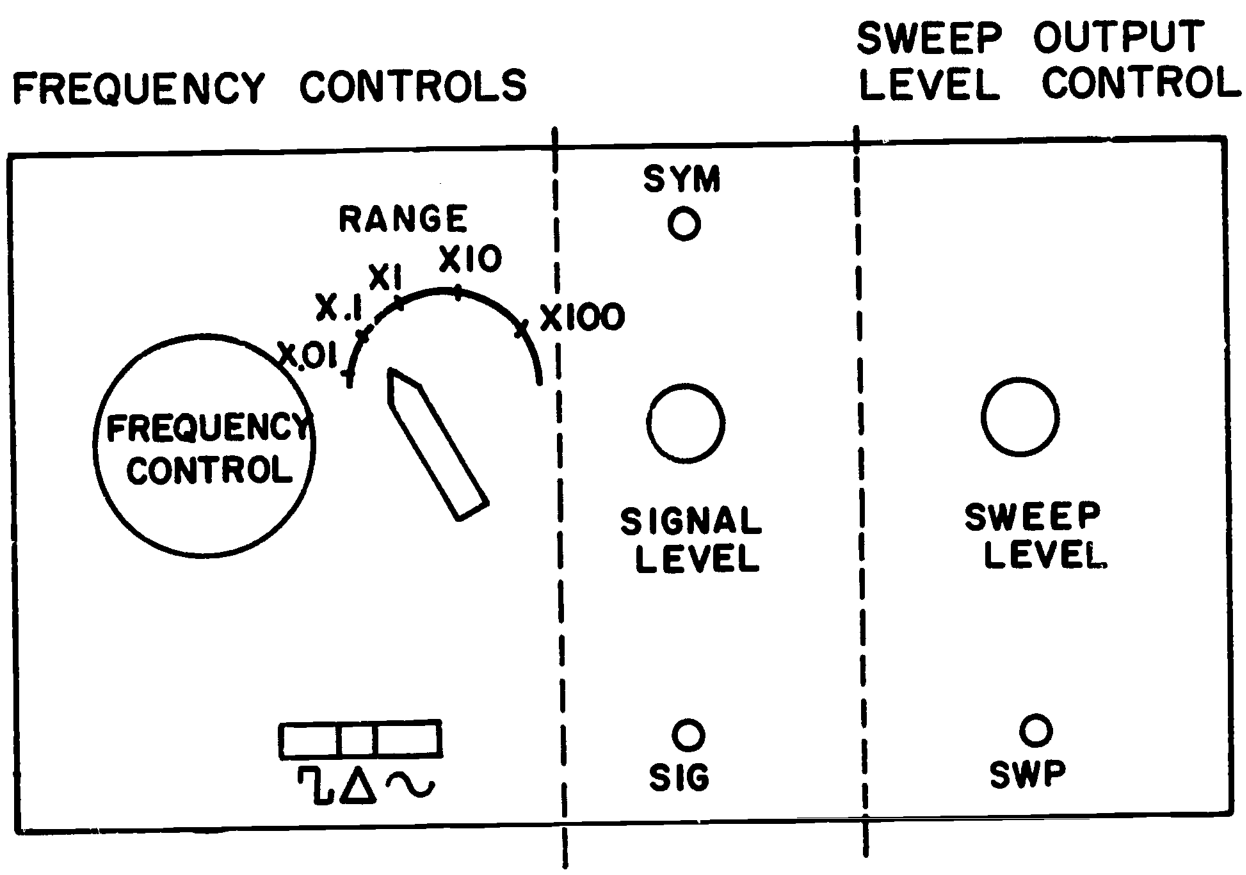


Fig. 4 Signal Generator unit.

The Polylab comes with several long gray leads which are to be used to transfer electrical signals between any of the terminals on the Polylab. You do not have to worry about connecting a separate ground lead when you are using the Polylab by itself. All the components in the Polylab are grounded together by internal wiring.

1. Put the H GAIN switch to L and the H GAIN knob to its extreme CW position.

2. Put the FREQUENCY dial on the SIGNAL GENERATOR on 20 and the RANGE switch to x. 1.

3. Center the spot on the CRO screen.

4. Connect the SWP terminal on the SIGNAL GENERATOR to the H DC terminal of the CRO. Turn the SWEEP control to its extreme CW position.

5. Observe the movement of the spot. Adjust the H GAIN controls (and the H POS control if necessary) so that the total deflection of the spot is 2" across the center of the screen. (Don't let the spot deflect to its maximum position).

6. Turn the SIGNAL LEVEL knob on the SIGNAL GENERATOR and observe how this control also varies the deflection of the spot.

Observe that the spot moves from left to right at a constant speed. When it reaches the right side of the screen, it abruptly jumps back to the left side and starts a new sweep. The retrace, however, occurs so quickly that you cannot see it under most conditions. This sweeping action repeats itself again and again. The number of sweeps that the beam makes in one second is called the sweep frequency and is usually expressed in cycles per second. One complete sweep and return is one cycle.

7. Turn the FREQUENCY knob and the RANGE switch on the SIGNAL GENERATOR and observe how the SWEEP frequency changes.

The frequency of the sweep on the SIGNAL GENERATOR is always one half of the value which is read on the frequency dial and the range switch. (You will see the reason for this in a later experiment.) Thus if the dial is set on 20 and the RANGE SWITCH is set on x. 1, the sweep frequency will be $\frac{1}{2}$ (20 x 0. 1) or 1 cycle per second. Observe that the RANGE switch can be set at positions of x. 01 to x 100 and the FREQUENCY dial can be varied from a value of 20 to 200. This means that the sweep frequency from the SIGNAL GENERATOR can be varied from a low value of $\frac{1}{2}$ (20 x 0. 01) or 0. 2 cycles per second to an upper value of $\frac{1}{2}$ (200 x 100) or 10, 000 cycles per second. The higher the frequency the faster the electron beam will sweep across the screen.

The internal sweep generator on the CRO performs the same function as the sweep generator on the SIGNAL GENERATOR. The sweep signal in this case is internally connected to the H DC terminal of the CRO. To use this internal sweep, the H GAIN switch should be in the H position and the horizontal input terminals on the CRO should be left open.

The sweep frequency is controlled by the three position switch and knob in the sweep section of the CRO control panel.

The internal sweep frequency can be varied from a low of about 20 cycles per second to a high of 20, 000 cycles per second.

8. Remove the lead between the CRO and the SIGNAL GENERATOR.

9. Put the H GAIN switch in the H position and adjust the CRO controls to to produce a sweep that travels across the center of the CRO screen.

Observe how the SWEEP control switch and knob control the sweep frequency. In the next experiment we use the CRO to produce a graph of the motion of a ball when it is dropped from a high window.

EXPERIMENT XXIV

Analog Simulation of a Freely Falling Object

In this experiment, we study the method by which an Analog Computer can simulate the behaviour of a simple physical system. We simulate the behaviour of a freely falling object.

Our physical system is a ball dropped from a window. We wish to simulate its motion so that we can determine how far it has fallen after any interval of time and how fast it is moving at any instant. To simplify our initial model of the system we assume that the ball encounters no air resistance (air resistance is included in Exp. XXV). We also assume that the speed of the ball is increasing smoothly at a rate of 9.8 meters per second in each second of flight. This value of acceleration is often accepted as the average acceleration due to the gravitational force.

A study of our text (Chapter B-4) reveals the relationship between acceleration, velocity and displacement for a moving object. We have already noted that an "integration" of acceleration with respect to time produces the value of the change in velocity and an "integration" of the velocity with respect to time produces a value for the change in the displacement of the moving object. If initial values for the velocity and for the displacement are added to the changes which are calculated by the integration, then the numerical value of the new velocity and the new displacement results. Thus, using the given value for the acceleration ($9.8 \frac{m}{sec^2}$) the velocity of the ball at any instant of time after the beginning of the drop is:

$$v = v_o + \int_o^t a\,dt$$

where v is the velocity at any particular instant, v_o is the initial velocity, and a is the value of the acceleration.

Also

$$s = s_o + \int_o^t v\,dt$$

where s is the displacement at any particular instant, s_o is the initial displacement and v is the value of the velocity.

Part A

With an initial velocity and initial displacement of zero, let us simulate the motion of a falling ball on the Analog and then display our results on the CRO.

The first step in the simulation is to check that the Summing-Scalors and integrators on the Analog Computer are balanced.

1. Set the Voltmeter to the 1 volt range. With the Voltmeter switch on zero, zero the meter.

2. Connect the ground lead between the Polylab and the Analog and a transfer lead between the output of the Summing-Scalor and the Voltmeter

input terminal.

With no input to the Summing-Scalor and with the coefficient set to 1, the output signal should be zero. If it is not zero, the Summing-Scalor requires balancing. Your teacher should be consulted if this is necessary.

3. Repeat step 2 for the other Summing-Scalors.

4. Set the initial conditions of each of the Integrators to zero, by using the Voltmeter. Note: You should first set the Voltmeter range switch to 25 so that you don't drive the meter needle off the scale if the present setting of the Initial Condition happens to be large. After you set the initial conditions to zero with the 25 volt Range, change the range to 1 volt and reset the initial conditions.

5. Release the Set button making sure that the Timing Switch is on Man and push the Integrate lever to the right so that the integration can begin.

With no input to the Integrator, the Integrator signal should remain zero. If the signal amplitude changes, the Integrator is unbalanced and your teacher should be consulted. Note: If you observe a change in the Voltmeter reading, check the zero adjustment to ascertain whether the change is due to the change in output signal amplitude or to a drift in the Voltmeter.

6. Repeat step 5 for the other Integrator.

The simulation of the falling ball problem proceeds as follows:

We assign a minus sign to the 9.8 meters per sec^2 gravitational acceleration to indicate that the direction of the acceleration is downward. With this assumption, the signals which represent the velocity in the downward direction and a displacement below the height at which the ball is dropped will also have negative polarities. (An upward velocity and an upward displacement would have positive polarities).

7. Let us develop a -9.8 volt signal to represent the numerical value of the gravitational acceleration. To accomplish this, connect a patch lead from one of the - terminals in the lower right hand corner of the Analog to a plain input terminal (not X 10) on the first Summing-Scalor. Put the Voltmeter on the 10 volt range. Adjust the coefficient knob of the first Scalor until you obtain an output signal of -9.8 volts on the Voltmeter. This acceleration can now be integrated by connecting the output of the Scalor to the input of the upper Summing-Integrator.

The output signal of the upper Summing-Integrator now represents the change in velocity (multiplied by -1). If this signal is then connected to the plain input terminal of the lower Summing-Integrator, the output of the second Integrator represents the change in displacement of the ball.

8. Wire the Analog as shown in Fig. 1.

9. Since the initial velocity and displacement are assumed to be zero, the initial conditions into the Integrators should remain zero.

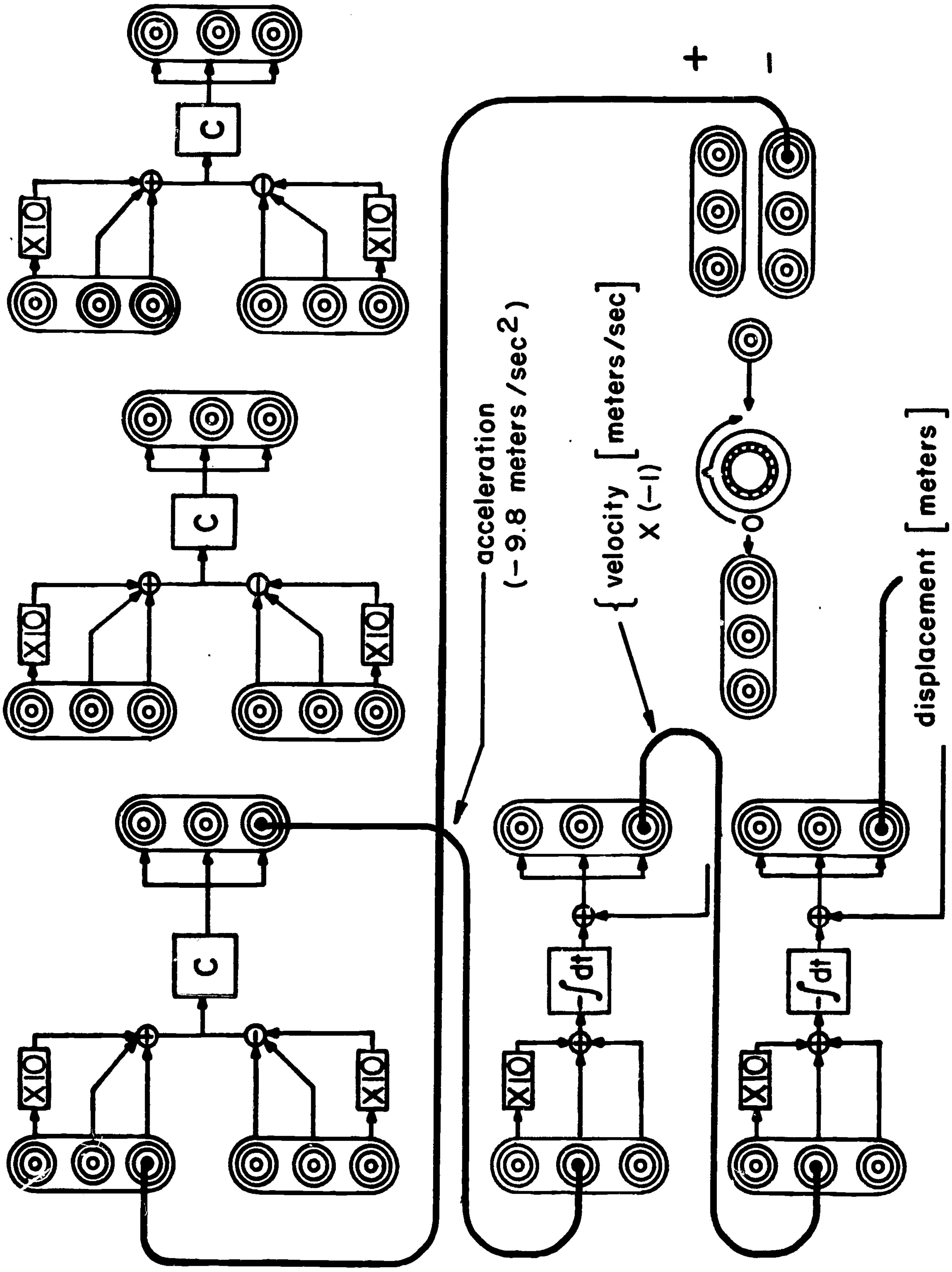


Fig. 1 Simulation of Freely Falling Ball.

10. Put the V Gain switch on the CRO to the M setting and position the beam spot in the upper center of the screen.

11. Connect the output of the lower Summing-Integrator to the V DC terminal of the CRO.

12. Start the integration and observe the motion of the falling ball. (Make any necessary adjustment in the V Gain controls so that the "fall" covers most of the screen.)

    Caution: When not using the scope turn the beam intensity down to prevent damage to the screen.

    You can "draw" a graph of this ball displacement by using the Signal Generator sweep signal for the time axis.

13. Connect the sweep (SWP) terminal on the Signal Generator to the H DC terminal on the CRO. Put the V Gain switch on the CRO to M. Set the sweep frequency to its lowest value and adjust the controls until the sweep covers most of the screen.

14. To make the "graph", push the Integrate lever just before the spot starts to sweep at the left hand side of the screen.

*15. Run the simulation, and sketch below the shape of the displacement versus time curve.

Engineers often use special cameras to photograph the waveforms which appear on the CRO screen. This gives them a very simple way of recording their observations.

16. Do the observed graphs have the shape that you would expect?

<u>Part B</u>

What would be the displacement and velocity of the ball at any instant if it were originally thrown downward with an initial velocity of 2 meters per second?

Since the upper Summing-Integrator always generates the velocity times (-1), we must first decide on the direction or polarity of the initial velocity signal (- down, + upward) and then set the <u>negative</u> of this initial velocity as our initial condition on the Analog.

The only difference between this problem and the Part A simulation is the presence of an initial velocity. We must integrate the gravitational acceleration and then add the initial velocity to the result to determine the velocity at any instant.

1. Generate the -9.8 volt acceleration signal as in Part A.

   Since the initial velocity is downward, it must have a negative sign, according to our assumptions in Part A. The initial condition (for velocity) on the Analog must therefore be (-2) x (-1) or +2 volts.

2. Use the Voltmeter to set the Initial Condition for velocity.

3. Remove any horizontal sweep from the CRO.

4. Observe the falling ball simulation on the CRO.

5. If the timing switch on the Analog is set to 1 second, you can observe how much farther the ball falls in 1 second when it is given an initial velocity of 2 m. per second as compared with an initial velocity of zero.

Part C

Now let us model another problem. We wish to determine the motion of the ball if we were to throw it straight up into the air. (We assume that we are standing at the edge of a steep cliff). We also assume that we throw the ball upward with a velocity of 6 meters per second.

The Analog model is exactly the same as the one for the falling ball except that now our initial velocity must have a positive sign.

1. Set the initial condition (v_o) on the Analog to (+6)x(-1) or -6 volts.

2. Set the timing knob to Man.

3. Push the Integrate switch and observe the movement of the "ball" on the CRO. Since the ball will finally be moving downward, you should set the zero position of the spot above the center of the screen.

*4. You can, if you wish, "draw" the graph of ball displacement versus time on the CRO by using the sweep signal from the Signal Generator.

*5. Optional experiment.

   Determine how much higher the ball would go if you were standing on the Moon and you threw it upwards with an initial velocity of 6 meters per second. The only difference in the simulation is that the gravitational acceleration on the Moon is 1/6 the acceleration on the earth.

EXPERIMENT XXV

Simulation of Falling Ball with Air Resistance

You recall that in the simulation of the falling ball in Experiment XXIV, we neglected air resistance. To make our simulation more accurate, however, this factor should be included in our analysis. The significance of air resistance can be experienced when one puts his hand out of the window of a moving car. Air resistance is also the reason why space vehicles and meteors which enter the earth's atmosphere heat up to extremely high temperatures.

When a ball is falling, air resistance opposes the acceleration of gravity. Thus the total downward acceleration will be somewhat less than 9.8 meters per second per second. When the ball is traveling upward the air resistance aids the gravitational acceleration in slowing down the ball. Thus the total downward acceleration will be greater then 9.8 meters per second per second.

We have found by experiment that (as an approximation) air resistance for a problem such as ours can be assumed to be proportional to the velocity at which the ball is traveling. The downward acceleration at any instant can therefore be represented by the expression:

$$\text{Acceleration} = -(9.8 + Bv)$$

where B is some constant value which depends on the properties of the air (its temperature for example) and on the size, shape and weight of the ball, and v is the velocity at any instant.

Recalling that an upward velocity has a positive polarity and that a downward velocity has a negative polarity, does this mathematical expression agree with the statements made above?

To simulate this new situation on the analog computer, we start as we did before. If we have an input signal which represents acceleration, we can put this signal through two Integrators to produce displacement. We can represent the acceleration of gravity by a constant input signal as we did before, but now we must add to this another signal which is proportional to velocity - and the velocity keeps changing.

If we look again at Fig. 1 in Experiment XXIV we see that the output signal from the first Integrator represents the negative of the velocity of the ball. There is no reason why we can't use this signal for our simulation. If this output is fed through a Scalor, changed in sign, and then added to the acceleration of 9.8, we obtain the desired value of acceleration. The resulting analog simulation is shown in Fig. 1 of this experiment.

Follow the flow of signals on the diagram and see if the output of the last Scalor (which is the acceleration signal) agrees with the equation:

$$\text{acceleration} = -(9.8 + Bv)$$

Let us determine how air resistance affects the height to which we can throw a ball if we again give it an initial velocity of 6 meters per second.

1. Assume that the air resistance coefficient is 0.2. Set the middle coefficient to 0.2 and the coefficient in the upper right hand corner of the Analog to 1.

Wire up the Analog as shown in Fig. 1.

Set the output of the first Scalor to 9.8, the initial condition for velocity to -6 and the initial displacement to zero.

*2. Set the timing switch to 0.1 sec., and plot below the ball displacement for thirteen 1/10 second intervals. Use the Voltmeter. How high does the ball go? ______________________.

3. To compare this to the situation with no air resistance, remove the lead that joins the output of the middle Scalor to the input of the right hand Summing-Scalor (the -Bv line).

*4. Plot a curve of ball displacement with no air resistance. Compare the two curves.

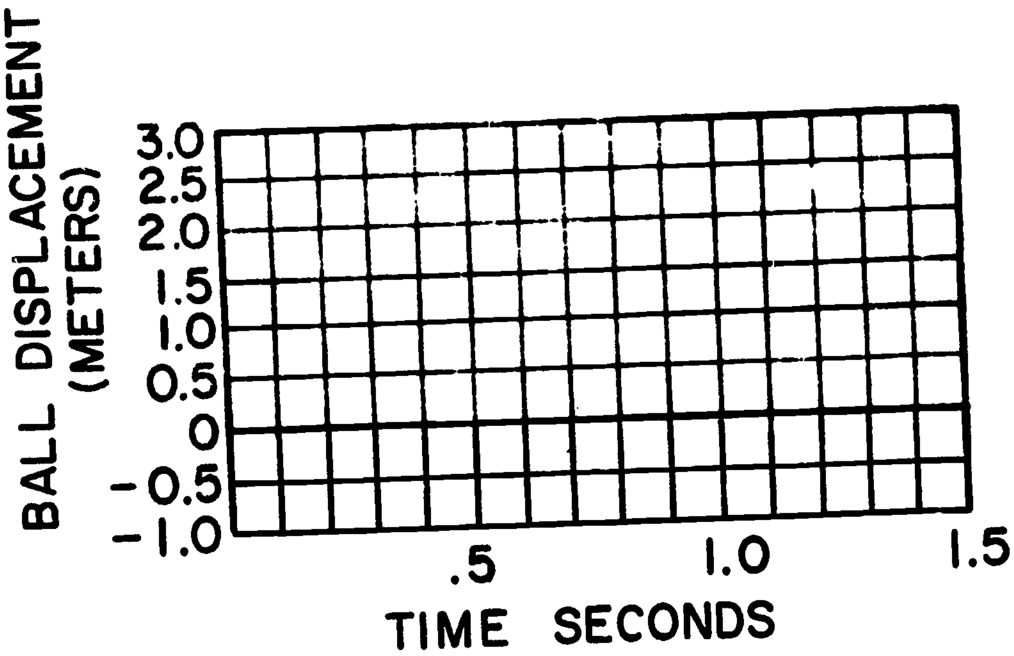


Fig. 2 Graphs of Displacement vs. Time for a Ball, with and without Air Resistance.

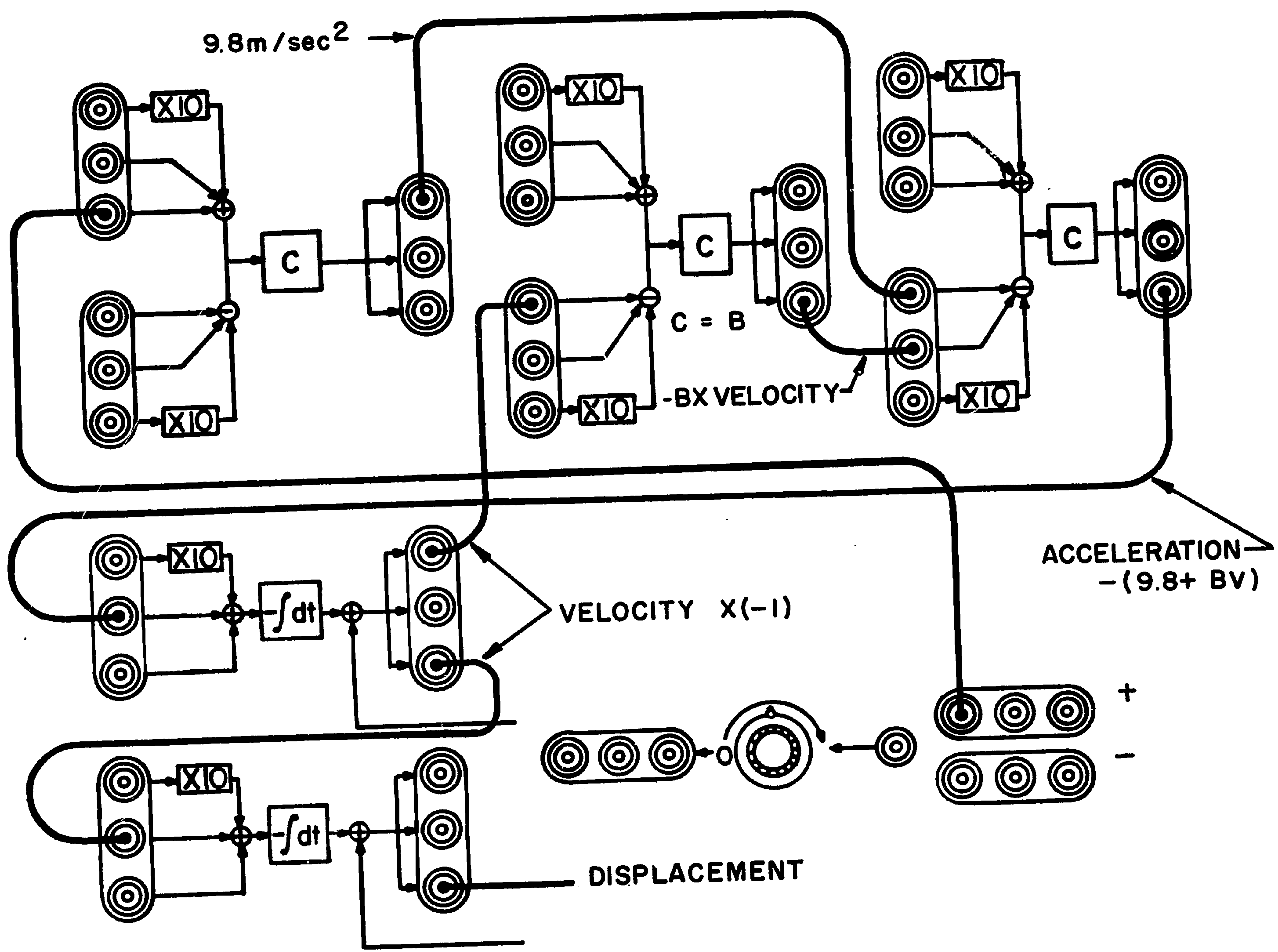


Fig. 1 Simulation of Falling Ball with Resistance.

EXPERIMENT XXVI

Boat Docking Simulation

Analog models are used to train airplane pilots and astronauts before they are allowed to "fly" the actual craft. If you consider the danger and expense involved in sending an astronaut into space you can see why all the astronaut's training must be accomplished on earth under simulated conditions. Thousands of airplace pilots have received their flying instruction on the famous "Link Trainer." This is an analog model which is made to look like the inside of an actual plane. When the pilot works the controls in the model cockpit an analog computer determines how the real plane would respond to the pilot's actions. Signals are then sent to a hydraulic mechanism which moves the trainer through the calculated motion. Pilots of the new jet airliners are trained in flight simulators.

We now set up a simplified analog trainer for handling small boats. We assume that our boat is the type in which the angle of the blades on the propeller can be adjusted. The acceleration of the boat for any engine speed is then controlled b adjusting the blade angle. Many commercial propeller driven aircraft also have this feature. It is used to aid in braking the plane on landing and aslo to reduce the propelling force when the engine is warmed up on the ground. In the former case the blade angle is reversed from the normal driving position and in the latter case the angle is set to zero. Navy minesweeping vessels also have this variable angle (variable pitch) feature. We assume that the acceleration of our boat is proportional to the speed of the boat. In an actual boat, there is some speed level above which this resistance increases very rapidly. We assume for our problem, however, that we are always operating below this level. Fig. 1 shows an analog simulation for the movement of the boat along a straight line.

With some analog computers we could set up a simulation to include the effect of the rudder position on the movement of the ship. For simplicity we assume that the rudder is fixed and that the boat moves in a straight line. The Constant knob on the Analog represents the blade angle control in which the blade can be positioned anywhere between zero and some maximum positive angle.

1. Study Fig. 1 and make sure you understand how the Analog simulation works.

2. Assume that the resistance coefficient for your particular boat is 0.7. Set the middle coefficient to 0.7 and the right hand coefficient to 1.

3. Wire up the simulation as shown in Fig. 1.

4. Set the initial conditions on both Integrators to zero. Put the timing switch to Man.

   The boat simulation is now ready for operation. By using the Constant knob to control the forward acceleration of the boat we will try to "pilot the boat from one boat landing to a second landing which is located directly across a lake. We assume however that we want to train the boat captains to pilot the boat under foggy conditions. In such weather it is

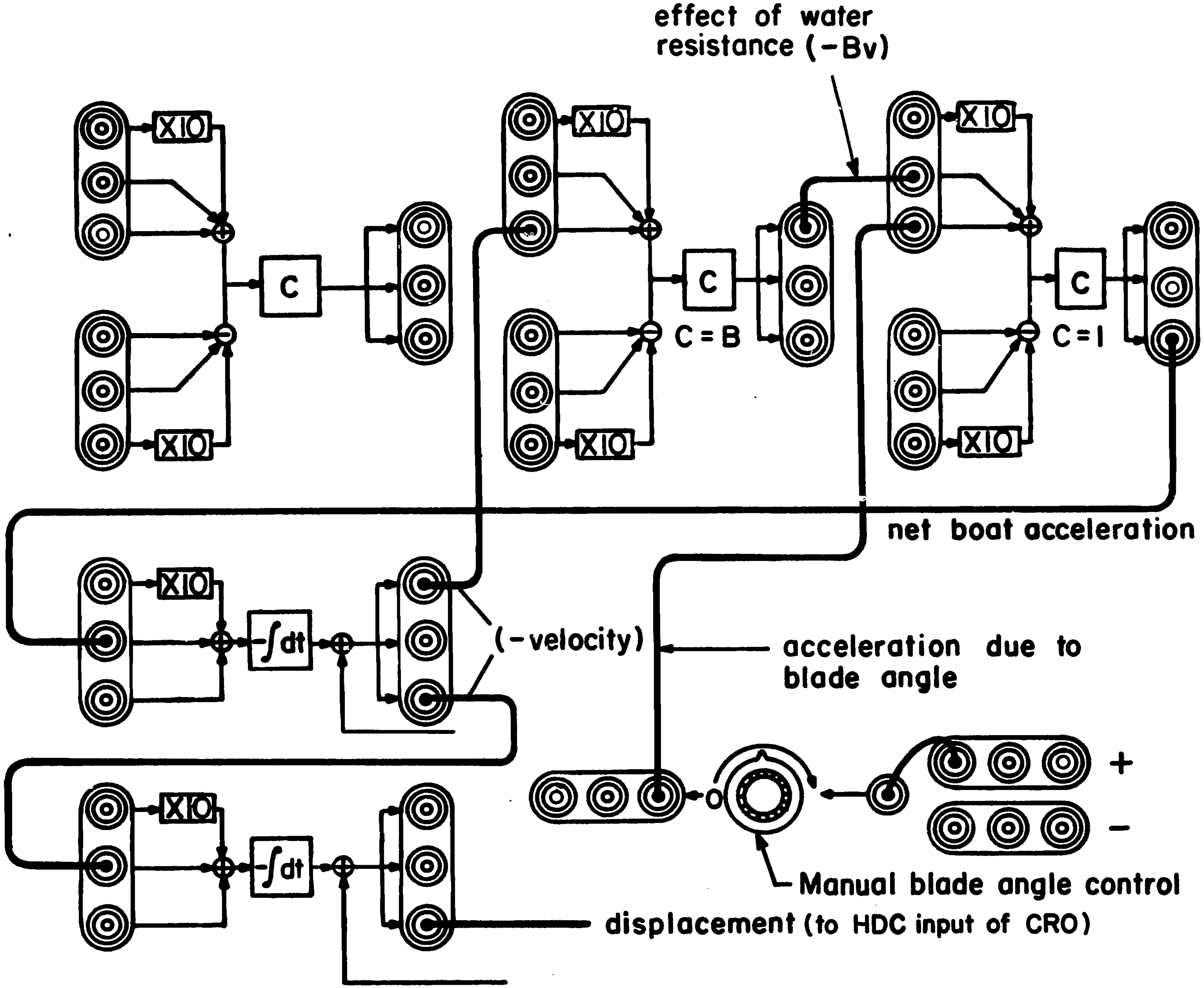


Fig. 1 Boat Simulation

not possible to see the opposite landing and we use a small sonar detector which is located on board the boat. The sonar detector is represented by the CRO. We shall imagine that the vertical grid line on the extreme left side of the CRO screen represents the starting point of the trip and that the docking position on the opposite side of the lake is represented by the vertical grid line at the right hand side of the screen. The horizontal displacement of the CRO beam indicates the position of the boat as it moves across the lake.

5. Use the Constant knob (the blade angle control) and try to pilot your boat to the dock across the lake. Control the boat carefully so that you do not strike the "dock". Repeat the "docking" maneuver by resetting the Analog, until you can make a smooth docking. You will have to push the Integrate lever to the right to "turn on" the boat engine.

6. This model could also be used to represent some of the new "ground effect" or "hover" vehicles. These vehicles which can ride over land or water have powerful blowers which force air out from underneath the body of the vehicle and thereby let the vehicle ride on a "cushion of air." This technique produces very little resistance to motion under normal circumstances. We assume here that our "ground effect" vehicle is driven by a propeller with controllable blade angles. Once again let the Constant knob on the Analog represent the blade angle control (and thereby the vehicle acceleration) and try to maneuver the craft without smashing the dock. For this vehicle, assume that the resistance coefficient is 0.2.

*7. What can you say about the effect of resistance to motion on the ease of controlling the position of a vehicle? This problem of low motion resistance is encountered in space craft and it is for this reason among many others that the changes in position of the craft must be carried out with the aid of high speed digital computers. The astronauts would find it difficult to control the firing of the propulsion rockets precisely enough to bring about a desired position change if they did not have some computer assistance.

EXPERIMENT XXVII

Coasting Car Simulation

We now study some characteristics of a moving automobile with an Analog simulation.

Visualize the following problem. You are traveling along a straight and level highway at 80 feet per second (approximately 55 miles per hour) and the car engine stalls. There is a gas station 900 feet further along the road; so that if you shift the transmission to neutral you may coast to the station.

The car will encounter wind resistance as well as the resistance of tires on the road, resistance in the wheel axles and in the drive mechanisms. Normally the acceleration of your car would be proportional to the distance which the accelerator pedal is depressed, decreased by the effect of frictional forces. However, you have no operating engine, so the acceleration due to the position of the accelerator pedal is zero. The total acceleration is then represented by the expression (0 - Bv) or just -Bv. The constant B is the coefficient which involves all the various resistances listed above. Actually some of the resistance terms vary as v^2 and others remain constant. As an approximation however, we assume all of these can be represented by the expression -Bv.

1. Verify that the Analog model of the above situation is represented by the simulation shown in Figure 1. Notice that the upper Integrator has been given an initial condition value of (-80) ft/sec.

2. Observe that the numbers you are working with here are too large to use in the Analog. (Recall that the saturation levels are about 10 volts.) We can overcome this difficulty by letting the electrical signal amplitudes represent 1/10 the magnitude of the true values. The situation is shown in Figure 2. There is actually no change in the simulation except for the value of the initial condition for velocity. Since the output of the upper Integrator now represents (velocity/10) x (-1) we must set the Initial Condition to (-80/10) ft/sec. or to -8 ft/sec. All other signals are then read as though they were 1/10 of the true values.

   We still, however, have one more problem. A displacement signal which is scaled down to 1/10 will still not enable us to read a distance of 900 feet. We must therefore scale down the displacement signal still further. We do this by placing a SCALOR between the two Integrators and set the COEFFICIENT of this SCALOR to 0.1. The input to the second Integrator is now $\frac{1}{10}\left(-\frac{v}{10}\right)$ or -v/100 and the resulting displacement is x/100. Now 10 volts on the meter represents 1000 feet. The final simulation is shown in Figure 3.

3. We will assume that the resistance coefficient for our car is 0.08. Set the COEFFICIENTS of the two VARIABLE SCALORS to values of 0.08 and 0.1 as shown. To do this, use the 1 volt range on the METER. Set the Analog CONSTANT for a signal of 1.0 volt and use this to set the COEFFICIENTS so as to give you outputs of 0.08 and 0.1. You can read these values easily on the 0-1 volt meter scale.

4. Wire up the ANALOG simulation as shown in Figure 3 and set the initial conditions to their proper values (assume that the INITIAL CONDITION for displacement is zero.) Set the TIMING switch to MAN.

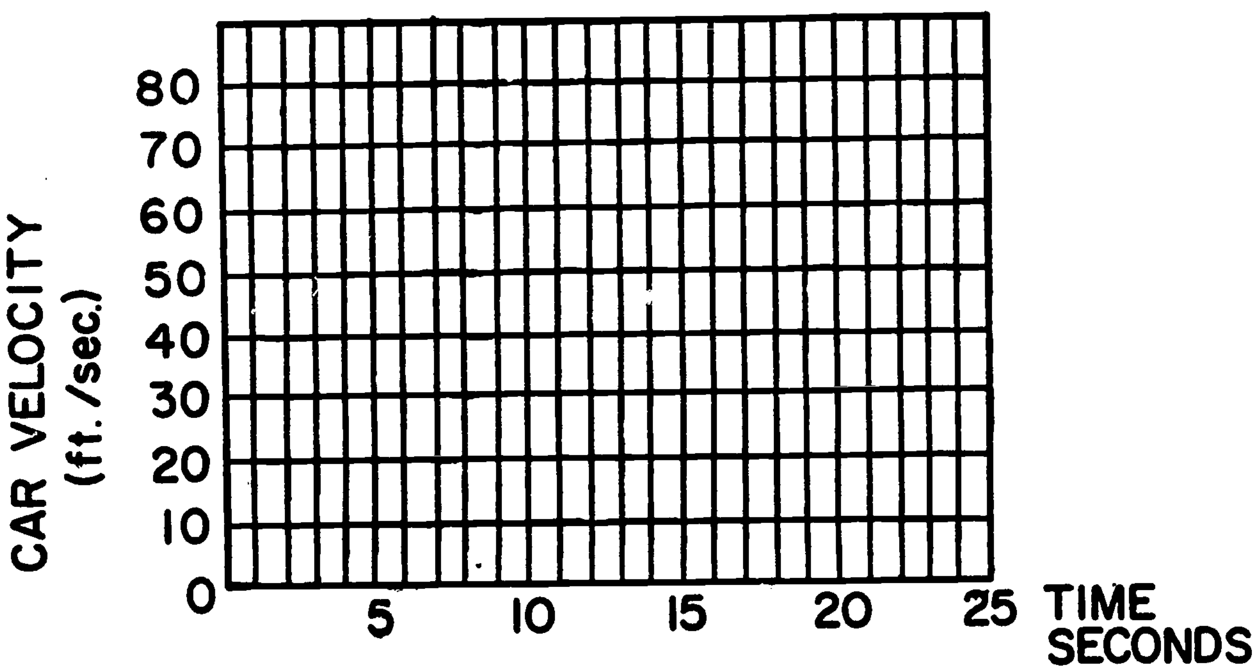
*5. Run the simulation and observe the car displacement with the METER. Will the car reach the gas station? (Since the output of the lower Integrator represents 1/100 displacement, the station is represented by a meter reading of 9 volts).

*6. If the car developed a flat tire on the way, do you think it would be able to coast to the station? Explain your answer.

*7. Reset the model to its initial conditions and plot a curve of car velocity for about 25 one-second intervals.

*8. What is the shape of the velocity curve? Why does it have this shape?

*9. How could you, with the help of the Analog, determine the actual value of the resistance COEFFICIENT for <u>your</u> car?



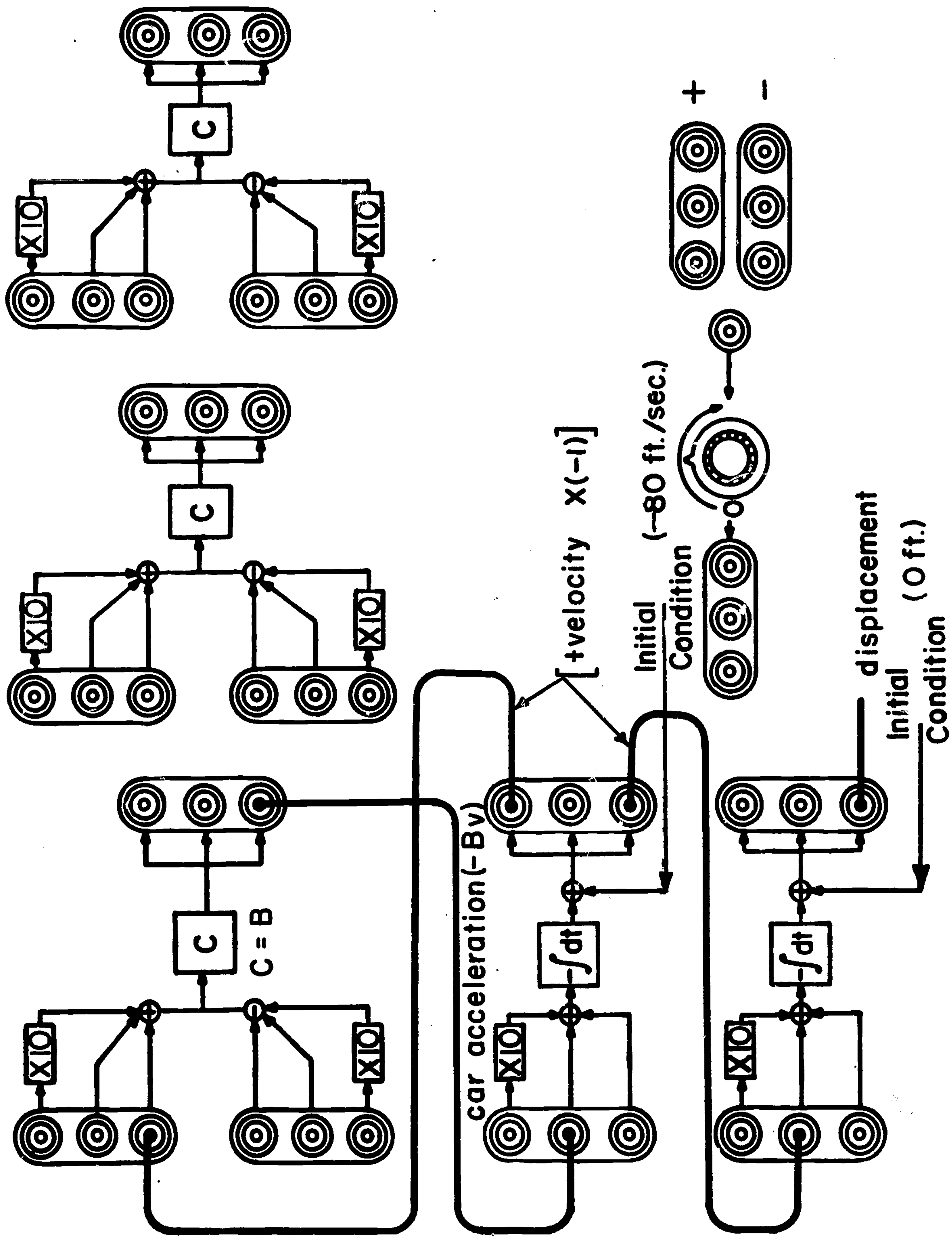
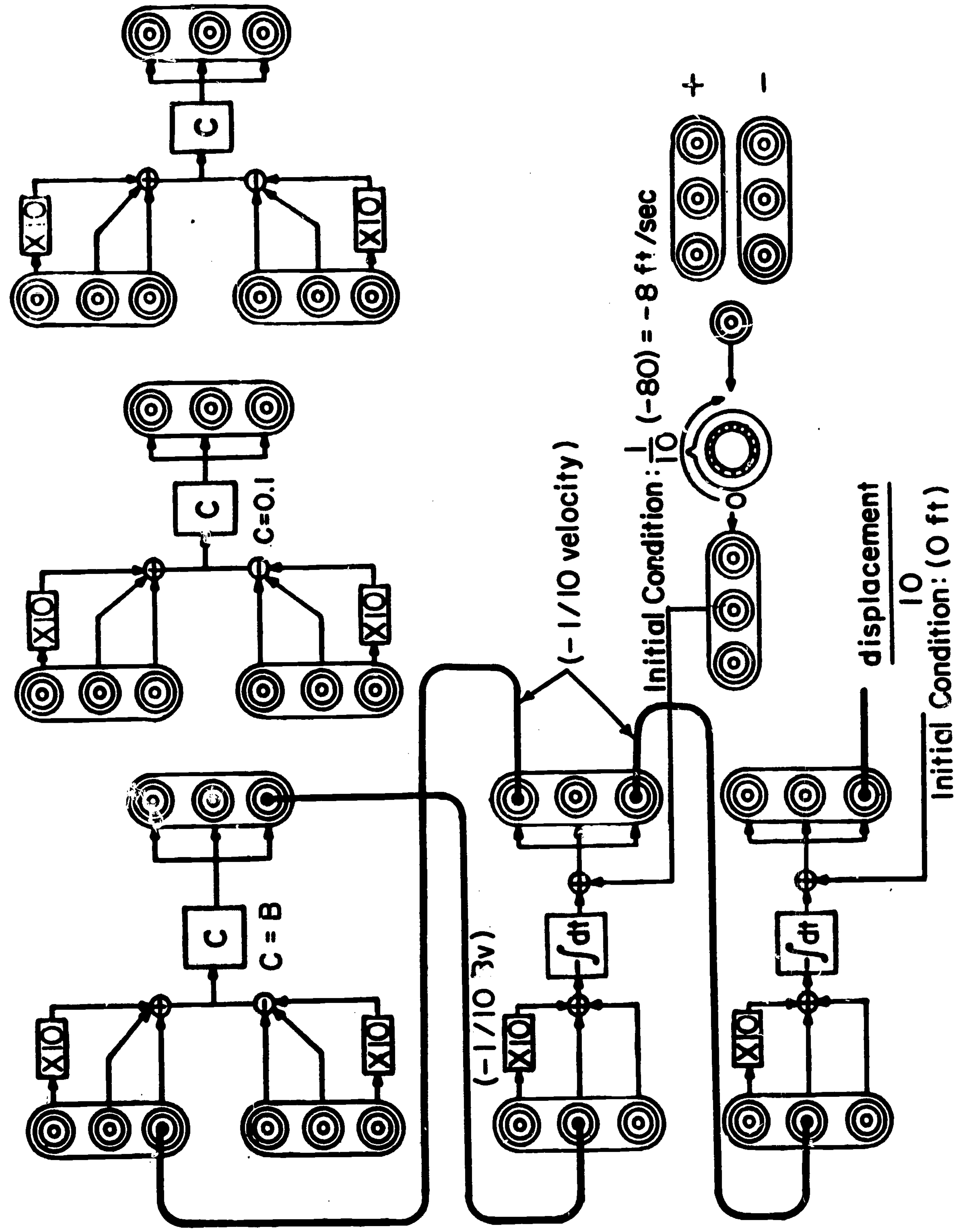


Fig. 1 Basic Simulation of Coasting Car


C
C=0.1
C = B
X10
∫dt
(−1/10 velocity)
Initial Condition: 1/10 (−80) = −8 ft/sec
+
−
displacement / 10
Initial Condition: (0 ft)

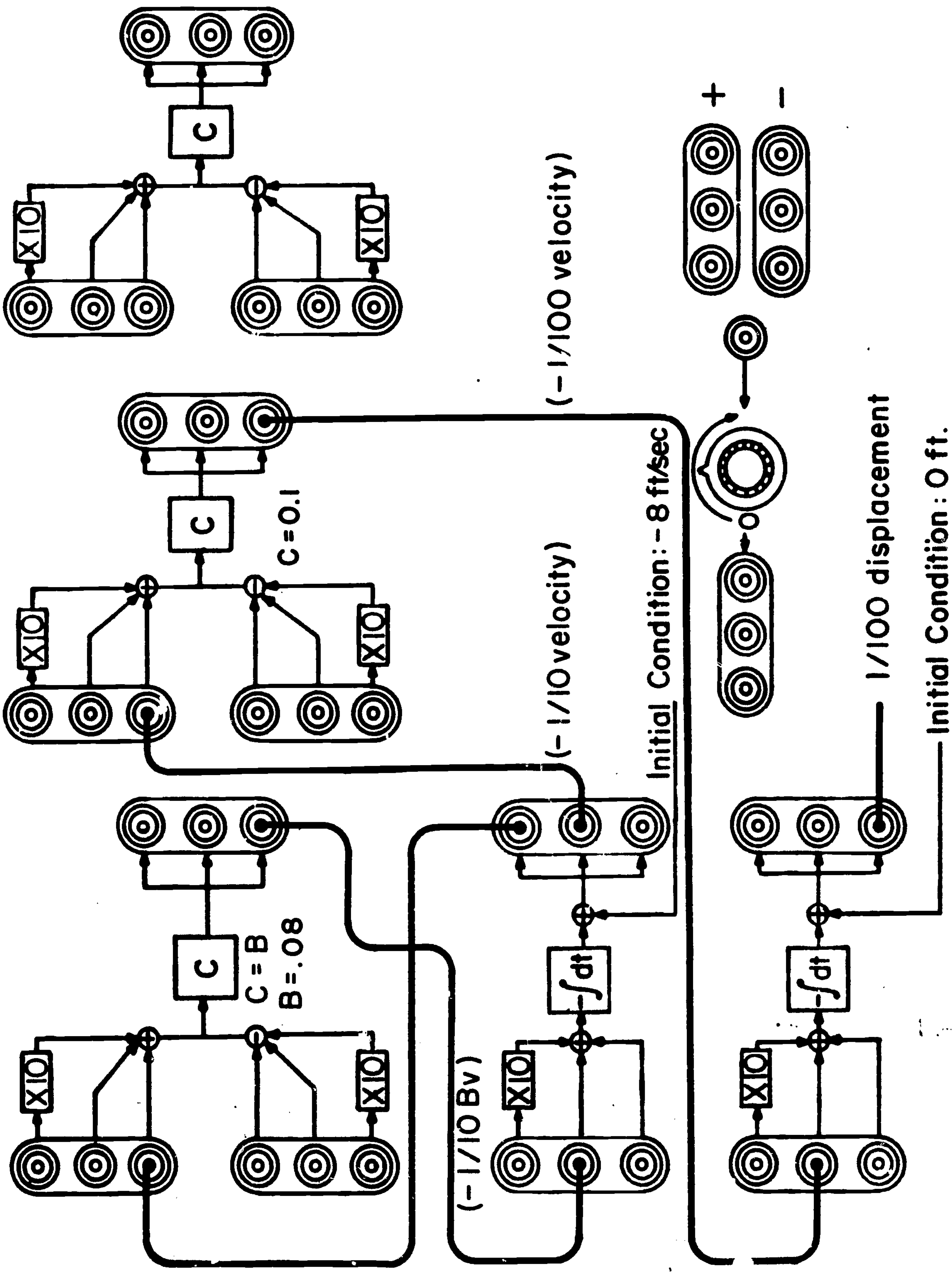


Fig. 3 Final Scaled Simulation of Coasting Vehicle

EXPERIMENT XXVIII

Periodic Signals and the Signal Generator

Part A

You have seen how the CRO can be used to produce "graphs" of electrical signals whose amplitudes change with time. In this experiment you will use the CRO once again, to look at electrical signals whose amplitudes change in a repetitive manner. We call these periodic signals. This type of signal occurs frequently in the natural and in the Man-Made World and in later experiments we study some physical systems which have periodic characteristics.

Let us first look at some simple and well known periodic signals. The Signal Generator which you have used as a Sweep Generator also supplies periodic electrical signals of different shapes. (You will soon see that the signal from the Sweep Generator is also periodic.)

Figure 1 shows the arrangement of the controls for the Signal Generator.

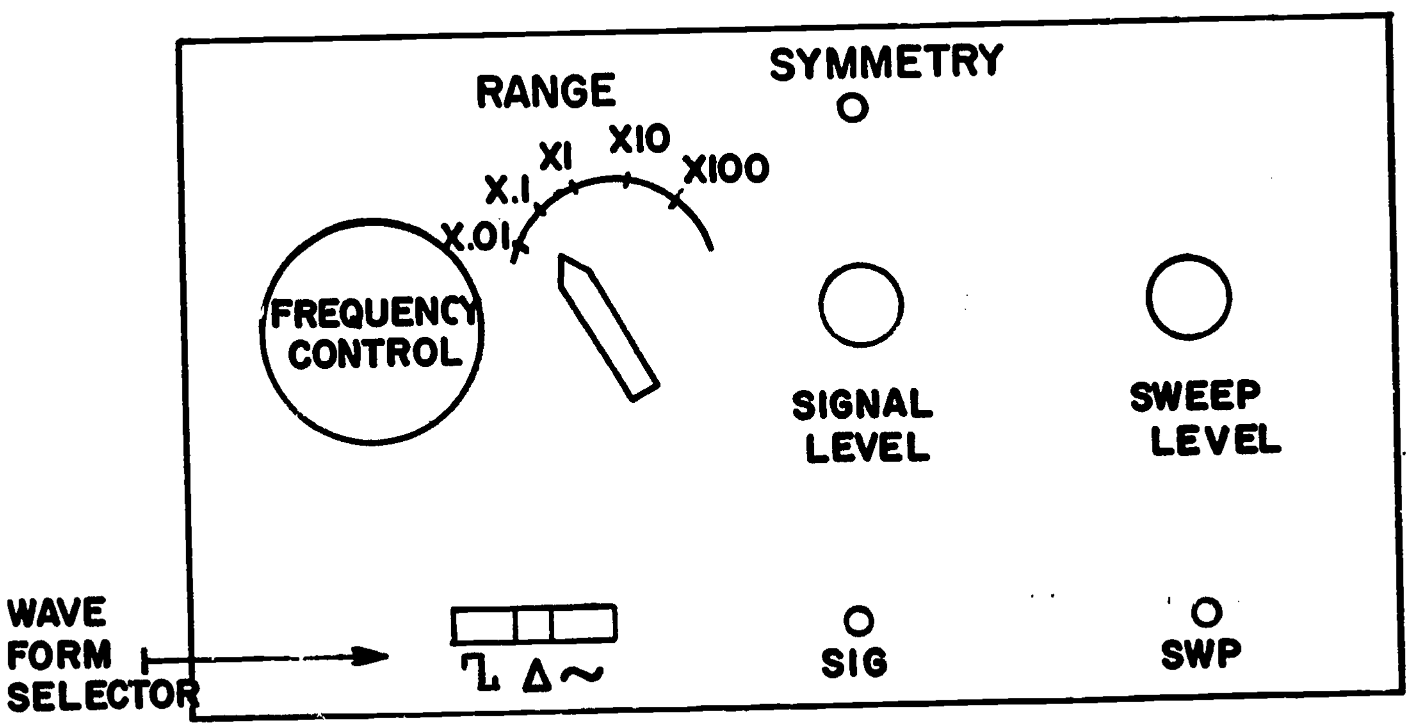


Fig. 1 Signal Generator

The Wave-Form Selector switch determines the shape of the signal (or wave form) which is available at the SIG (signal) terminal. Three signal shapes are available: a square wave, a triangle wave and a sine wave. The signal shape is selected by putting the Waveform Selector switch above the appropriate symbolic representation of the wave shape.

The frequency at which the change in signal amplitude repeats its pattern is controlled by the Frequency knob and Range switch. For the signals which are available at the SIG terminal the frequency can be read directly from the frequen dial and range. Thus the Signal Generator provides signals in a range of .2 cycles per second up to 20,000 cycles per second.

The Signal Level control determines the amplitude of the electrical signal.

The Symmetry control enables the operator to improve the shape and symmetry of the signal waveform.

You can observe the various periodic signals on the CRO by following the procedure given below. We first use the Sweep from the Signal Generator to drive the CRO beam across the screen.

1. Set the FREQUENCY dial to 20 and the RANGE switch to X.1. (This gives a sweep frequency of 1 cycle per second).
2. Put the H GAIN switch on the CRO to M and put the SWEEP LEVEL knob in the center of its range.
3. Connect a lead from the SWP terminal on the Signal Generator to the H DC terminal on the CRO.
4. Adjust the CRO controls to center the sweep and to make the sweep travel about 6 large divisions on the screen.
5. The CRO is now ready to produce a picture of a periodic waveform. Set the V GAIN knob on the CRO to a position midway between its extreme positions and put the V GAIN switch into the M position. Center the sweep with the V POS knob.

Observation of triangular signals:

6. Set the SYMMETRY knob near the center of its extreme positions and turn the SIGNAL LEVEL knob all the way to the left. Set the wave form selector switch to △ (Triangle). Connect a lead from SIG terminal on the SIGNAL GENERATOR to the V DC terminal on the CRO.
7. Turn the SIGNAL LEVEL knob a small amount to the right and observe that the spot is deflected up and down as it sweeps across the screen. The wavefrom which is traced by the spot should look like a series of triangles as shown in Figure 2 (a). If it does not, carefully adjust the SYM knob until it does. Now adjust the SIGNAL LEVEL knob until the total height or amplitude of the waveform is about 1 large division on the screen.
8. The V GAIN and H GAIN controls on the CRO can be used to control the vertical and horizontal size of the picture. Experiment with the GAIN controls until you feel you fully understand their use.

Note: If the Signal Level on the Signal Generator is set too high, you will not be able to obtain a good triangular or sinusoidal waveform. (The tops of the waveform will be flattened). Keep the Signal Level knob in the lower 2/3 of its range of motion.

Observation of sine wave:

9. Move the waveform selector switch on the FUNCTION GENERATOR to the (Sine) position. The waveform should look like the sine wave shown in Figure 2 (b). If it does not, obtain the proper waveform by adjusting the Symmetry knob. Make any other adjustments necessary to obtain a good picture on the CRO. Note: You can measure the peak voltage of a sine wave on the VOLTMETER by placing its three position switch to the AC position.

Observation of square wave:

10. Now put the function switch into the ⊓⊔ (Square Wave) position and adjust the height of the waveform to 2 large divisions in the screen. The picture should be similar to that in Figure 2 (c).

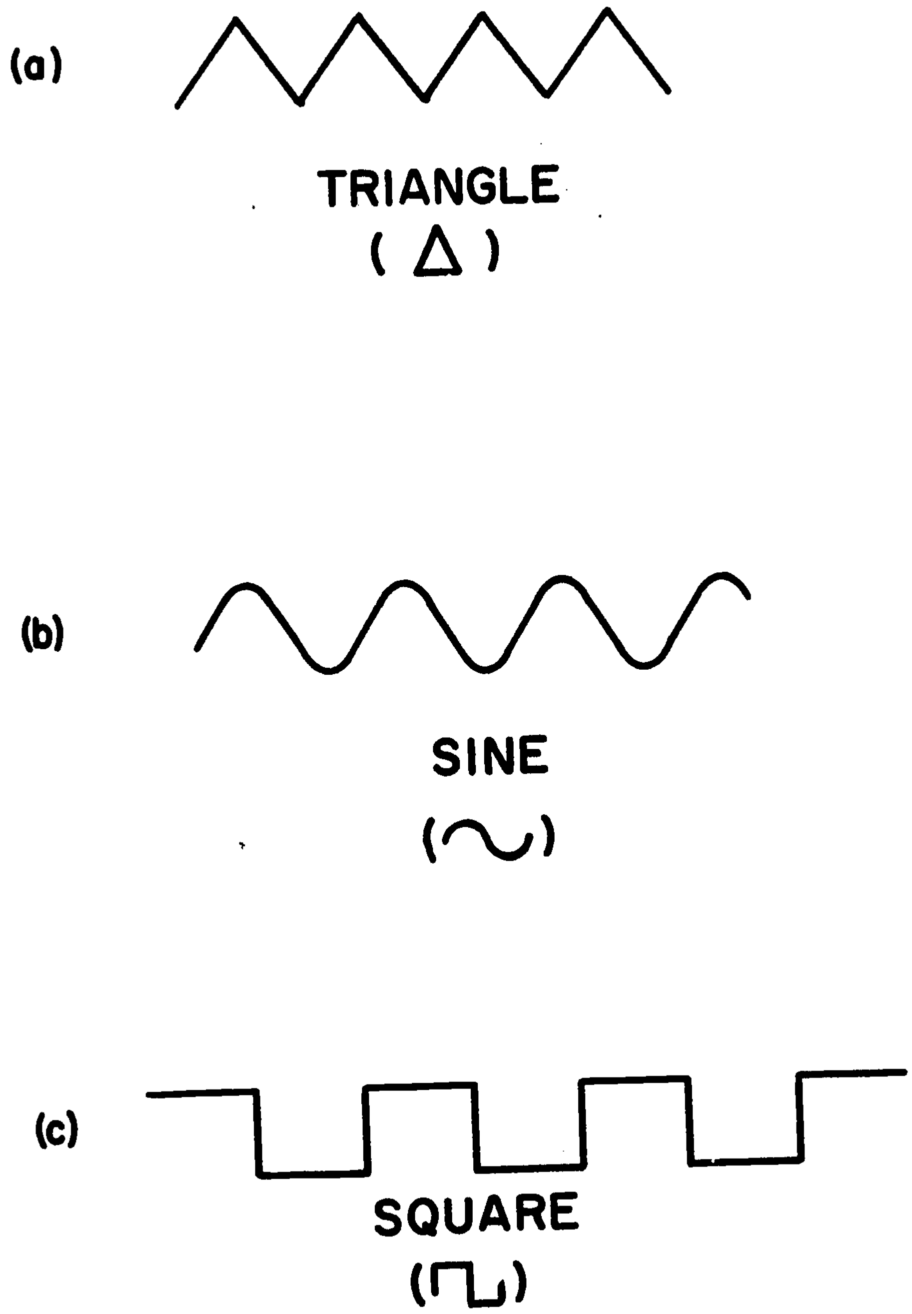


Fig. 2 Signal Generator waveforms.

11. Set the SIGNAL GENERATOR and the CRO to produce a good picture of a sinusoid waveform with a frequency of 2 cycles per second. Change the setting of the FREQUENCY dial and RANGE switch and observe the waveform on the CRO screen. You notice that the shape of the waveform does not change as you change the frequency. Also notice that in all cases you can observe the sine wave repeating itself twice. Each one of the repetitions of crest and trough is called a cycle. You observe two cycles of the waveform because the sweep frequency in the Signal Generator is half of the frequency of the output signal. Thus for every one cycle of horizontal sweep the vertical deflection of the CRO beam goes through two cycles. To observe one or more cycles of the Signal Generator signal on the CRO we need a sweep frequency control which is independent of the signal frequency control. In these cases we use the Internal sweep controls on the CRO.

Part B

1. With no inputs to the CRO put the H GAIN switch on H and adjust the H GAIN knob until the sweep covers about 6 large divisions across the center of the CRO screen.

2. Place the CRO SWEEP switch to the L position and the SWEEP knob to its extreme CCW position.

3. Set the SIGNAL GENERATOR to generate a sinewave of 400 cycles per second. Put the SIGNAL LEVEL control in the middle of its range.

4. Connect the SIG terminal on the signal generator to the V DC terminal on the CRO. The picture you observe may seem strange but adjust the V GAIN knob until the total height of the image is 2 large divisions.

5. Slowly turn the SWEEP knob on the CRO in a clockwise direction until you see a series of sinusoidal waveforms. Adjust the symmetry if necessary.

*6. Adjust the sweep until you see four cycles of the waveform. If the signal frequency is 400 cycles per second what must the sweep frequency be?

7. Experiment with the sweep frequency and observe how you can display any number of cycles of a periodic waveform on the CRO.

Note:

Whenever you want to look at periodic signals on the CRO, always keep the total height of the waveform greater than two small divisions. This will insure that the picture remains stationary on the CRO screen.

We now look at the shape of the sweep signal which is generated by the Signal Generator.

8. Connect the V DC terminal on the CRO to the SIG terminal on the SIGNAL GENERATOR. Make any needed adjustments so that you can clearly see the shape of the SWEEP waveform.

   The signal which you see should look like Fig. 3. This signal is called a saw-tooth waveform.

*9. Explain why the sweep signal must have this shape. (Refer to Experiment 20 if necessary to refresh your memory on the characteristics of the CRO sweep.)

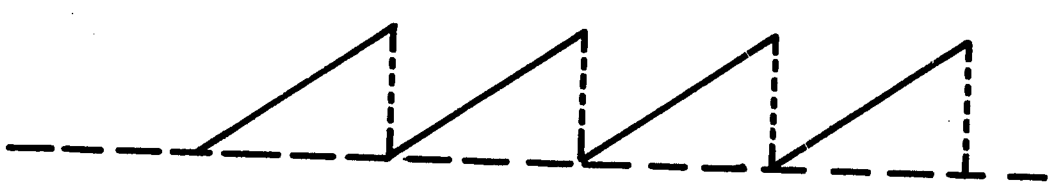


Fig. 3 A sawtooth wave.

EXPERIMENT XXIX

Pictures of Other Electrical Signals and Sound Waves on the CRO

In this experiment you will use the CRO to observe the periodic signals which occur in certain physical phenomena. One interesting waveform is that which is due to the electric lights and electric power lines in your classroom. The lights and lines generate electrical signals which travel through the air. You can see these signals on the CRO by using the following procedure.

1. Turn the power on and adjust the HORIZONTAL gain knob (with the HORIZONTAL switch in the H position) until the sweep covers about 6 large divisions at the center of the screen.

   Put the VERTICAL gain switch in the H position and put a lead into the V DC terminal of the CRO. Hold the plastic portion of the free end of thi lead in your hand and press a finger against the tip of the metal probe at the free end of the lead. Adjust the VERTICAL gain knob until the pictur is about two large scale divisions in height. Put the SWEEP switch in th L position and adjust the SWEEP frequency dial until you get a good picture of a periodic waveform that contains several cycles.

   You are now acting as an antenna and picking up the electrical signals which are present in the room. The frequency of this signal is 60 cycle per second and is generally called "60 cps pickup". You will see this pickup from time to time when you are changing the wires connected to the CRO.

   You can use the SWEEP signal from the SIGNAL GENERATOR to check if this signal has a frequency of 60 cycles per second.

2. Connect the SWP terminal on the SIGNAL GENERATOR to the H DC terminal on the CRO. Adjust the HORIZONTAL gain control or sweep leve until the sweep covers about 6 large divisions on the screen. Set the frequency RANGE switch on the SIGNAL GENERATOR to X1.

*3. Touch your finger again to the tip of the lead and carefully adjust the FREQ dial until you see one cycle of the waveform on the screen. Try to adjust the FREQUENCY dial so the waveform does not appear to mov The frequency of the vertical input waveform is now equal to the horizontal sweep frequency. Is the frequency of the "pickup" 60 cycles per second? (Don't forget that the sweep frequency is half the Frequency dial reading).

The problem which you experienced in getting the waveform to stand still is call synchronization. When you use the internal sweep on the CRO the synchronizati is done automatically. With external sweep, the waveform only appears to stan still when the signal frequency is some whole multiple of the sweep frequency. you want to learn more about synchronization you can do the Experiment on CR Synchronization.

The CRO can only produce pictures of waveforms of electrical signals. To produce a picture of a non-electrical signal such as sound, we must use an instrument called a transducer to convert the non-electrical signal into the electrical form. Transducers that convert sound waveforms into electrical waveforms are called microphones.

Pictures of sound waves can be obtained on the CRO by following the procedure given below.

4. Remove all leads to the CRO. Put the HORIZONTAL gain switch in the H position and adjust the CRO sweep so that it covers about 6 large scale divisions. Put the VERTICAL gain switch in the H position and the SWEEP switch in the M position.

5. Plug the microphone which is provided with your Polylab into the V DC terminal on the CRO. The microphone and the CRO are now ready to produce pictures of sound waves.

6. Whistle a soft long note into the microphone and adjust the VERTICAL gain knob to give a picture of suitable size. Adjust the SWEEP frequency knob on the CRO to obtain a good stationary picture of the periodic waveform (if possible). Change the loudness of your whistle and observe the change in the height of the waveform. Whistle a note of a different pitch, and observe that the frequency of the signal changes.

7. Speak various vowel sounds and adjust the SWEEP CONTROL until you get a good picture.

8. Observe the sound waveforms produced by a tuning fork, a harmonica, a whistle and other sound-producing instruments. In each case adjust the CRO SWEEP controls so that you get a good clear picture of the periodic waveform.

*9. In what ways do you observe the signals produced by these instruments to differ? (Careful observation will distinguish three).

EXPERIMENT XXX

Periodic Signals on The Analog Computer

In this experiment you see how the Analog Computer performs mathematical operations on periodic electrical signals.

In the first part of the experiment the Analog Computer is used to multiply a periodic signal from the Signal Generator by a constant, to add a constant signal to a periodic signal and to add two periodic signals together. In each case we observe the results on the CRO.

1. Check the balance of the Summing-Scalors and the Integrators on the Analog Computer.

2. Set the Signal Generator to produce a 300 cps sinewave.

   Set the V GAIN switch on the CRO to the M position, the SWEEP control switch to the L position and the H GAIN to the H position.

3. Connect a lead from the SIG terminal on the Signal Generator to the V DC terminal on the CRO. Adjust the controls to show 3 cycles of a sinewave with a total height of 4 large scale divisions on the CRO screen. Adjust the H GAIN knob so that the cycles cover the full gridded portion of the CRO screen.

4. Remove the lead between the CRO and the Signal Generator. Connect the SIG terminal on the Signal Generator to one of the Adder input terminals of the left hand Summing-Scalor.

   Ground the Analog to the Polylab.

   To see what happens as we change the value of the Coefficient, let us look at the output of the Summing-Scalor on the CRO.

5. Connect the output of the Summing-Scalor to the V DC terminal on the CRO.

6. Turn the COEFFICIENT knob on the Analog completely CW. This should make the coefficient equal to 1.0.

   Adjust the CRO if necessary so that you see the sinusoidal waveform which you obtained in step 3.

7. Observe what happens when a sinusoidal waveform is multiplied by a constant by slowly turning the COEFFICIENT knob on the Analog. You see that the signal still retains its form but its amplitude at each point is multiplied (in this case reduced) by the constant multiplier.

8. Move the FUNCTION switch on the Polylab to the triangular and the square wave positions and observe the effect of multiplying these signals by a constant coefficient.

Let us now see what happens when we add a constant signal to a sinusoidal waveform.

9. Return the FUNCTION switch on the Polylab to the sine position. Turn the scalor COEFFICIENT knob to its extreme CW position and adjust the SIGNAL LEVEL knob on the Polylab until the signal has a total height of about two large scale divisions.

   Center the waveform on the screen.

10. Connect a patch lead from one of the CONSTANT terminals on the Analog to the other Adder input terminal on the left hand Summing-Scalor.

    Turn the CONSTANT knob on the Analog to its full CCW position. Wire the Analog so that the Constant signal has a positive polarity.

11. Observe what happens to the picture on the CRO screen as the CONSTANT knob is slowly rotated. Notice that the signal waveform remains the same but is just displaced upward in proportion to the amplitude of the Constant signal. You can make this observation by looking at the pattern on the CRO with and without the constant signal.

12. Repeat step 11 for a triangular and for a square wave.

We now study the result of adding two sinusoidal signals which have different amplitudes.

13. We divide the signal from the Signal Generator between two leads and connect each lead to an individual Scalor. The outputs of the two Scalors are then added together in a third Summing-Scalor.

    The connections for this part are shown in Fig. 1. Study the figure to make sure you understand the reason for the connections shown.

14. Wire up the Analog and the Polylab as shown in Fig. 1.

15. Turn the COEFFICIENT knobs on the 1st Scalor and on the Summing-Scalor to their full CW position (1.0). Turn the COEFFICIENT knob on the 2nd scalor to its full CCW position (0).

16. Adjust the Signal Generator and the CRO controls to produce a sinewave with a total height of two large scale divisions on the CRO screen. Center the picture on the screen and adjust the SYMMETRY knob if necessary.

*17. Slowly increase the magnitude of the 2nd coefficient, C_2, and observe the shape of the resulting waveform. When the coefficient knob for C_2 is in its full CW position (i.e., with $C_2 = 1$), how does the amplitude of the waveform on the CRO compare with the amplitude of the signal from the Signal Generator?

18. Repeat step 16 for the triangular and square waveforms.

You should observe that in all cases the waveform retains its shape but increases in amplitude.

19. To subtract the two signals, connect the output from the second Scalor (the middle one) to the NEGATIVE ADDER of the Summing-Scalor on the right. Observe the resulting waveform as C_2 is varied from 0 to 1.0.

*20. What is the output signal from the Summing-Scalor when C_1 and C_2 are both equal to unity?

You should keep in mind that the results observed in steps 17, 18 and 19 were obtained by adding two periodic signals which differed only in amplitude. If we were to add periodic signals which were different in frequency, we should obtain entirely different results.

We can mathematically express the results of step 17 in the following way:

Let the signal from the Signal Generator be represented by the expression:

$$y = A \text{ sine } (at)$$

Since these are periodic signals, the symbol "t" represents time, and "a" is a constant which is related to the frequency of the periodic signal.

The signal from the 1st and 2nd scalors can then be represented by the expressions

$y_1 = A\, C_1 \text{ sine } (at)$ and $y_2 = A\, C_2 \text{ sine } (at)$ respectively.

The output signal from the Summing-Scalor is then:

$$Y = y_1 + y_2 = C_1 A \text{ sine } (at) + C_2 A \text{ sine } (at)$$

or by factoring:

$$Y = (C_1 + C_2)\, A \text{ sine } (at)$$

This is a sinewave whose amplitude A has been multiplied by the constant $(C_1 + C$ When the signals are subtracted the constant becomes $(C_1 - C_2)$. A similar analysis can be made for the triangular and square waveforms.

You have seen, in this experiment, how the analog can add and scale peri signals, and you have also seen some of the characteristics of those periodic si nals.

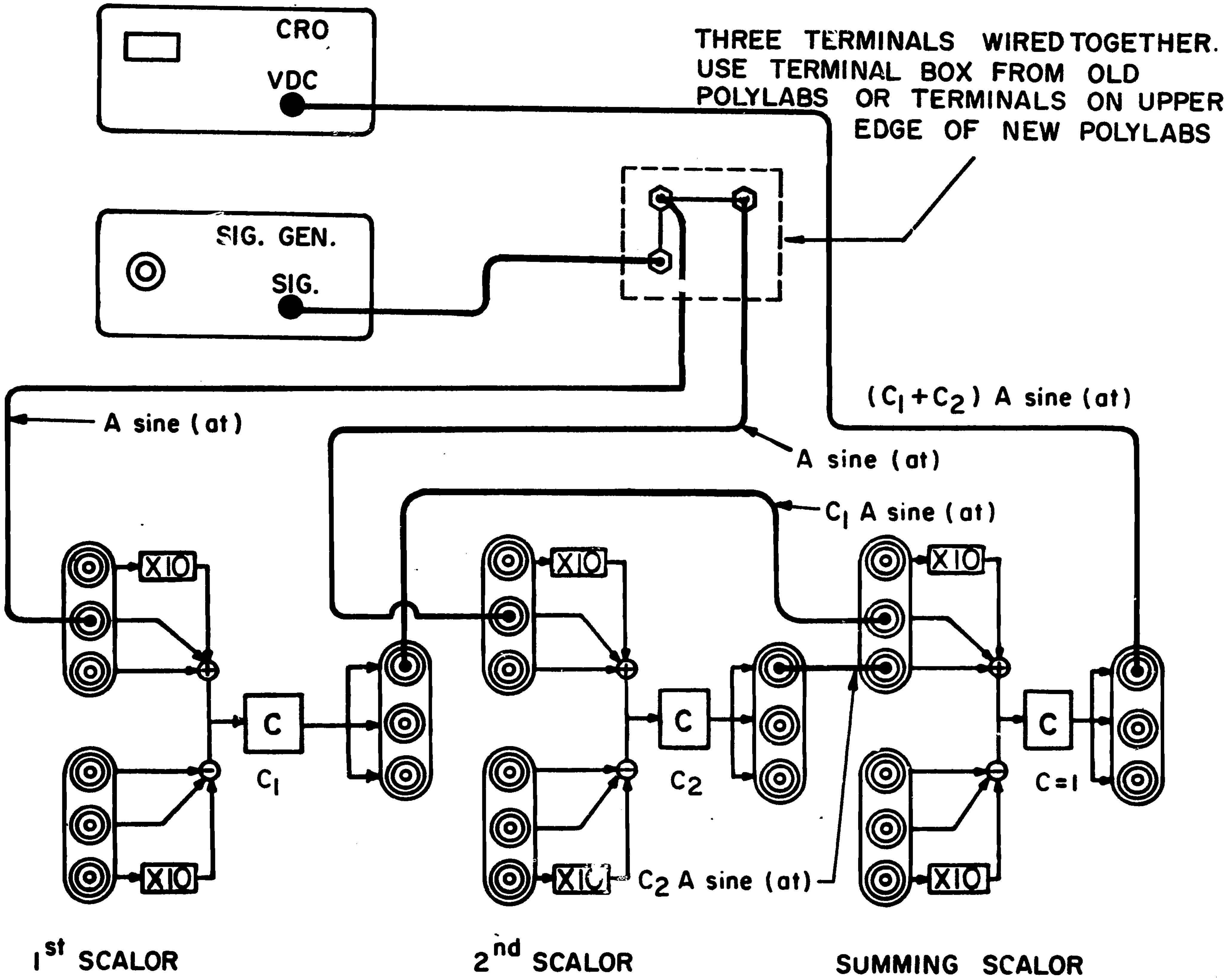


Fig. 1 Addition of Two Periodic Signals.

EXPERIMENT XXXI

Integration of Periodic Signals

In this experiment we study the effects of integration on periodic signals. We use the Integrator on the Analog Computer.

1. Put the V GAIN switch on the CRO to the M position, the SWEEP control to L, and the H GAIN switch to H.

   Adjust the beam sweep so that it is centered on the screen and covers the full width of the screen.

2. Set the Signal Generator for a 60 cycle sinusoidal waveform.

3. Connect the SIG terminal on the Signal Generator to the V DC terminal on the CRO.

   Adjust the Signal Generator and CRO controls so that you obtain a good pic ture of a sinusoidal waveform whose total height is three large scale divisions.

   Adjust the SWEEP control until you see three cycles of the waveform.

4. Remove the lead between the CRO and the Signal Generator. Do not chang(any of the Polylab settings.

   Connect the SIG terminal on the Signal Generator to one of the Adder input terminals on the upper Summing-Integrator.

   Connect the output of this Integrator to the V DC terminal on the CRO.

5. Depress the SET button on the Analog and observe how the CRO beam deflects as you rotate the Initial Condition knob. Set the INITIAL CONDITIO] to zero. (Remember that you can determine the zero position of the beam by removing the lead to the CRO).

6. Put the TIMING switch on the Analog to the MAN position.

7. Push the INTEGRATE lever and observe the CRO. The results are probably not what you expect. What do you think should have appeared?

   Let us analyze our observations in step 7 to learn why we obtained unexpected results.

   You probably did not observe any periodic signal but you did observe that the beam gradually deflected either upwards or downwards.

*8. Reset the Integrator and operate the Integrate lever again. This time observe that the beam deflects at a constant rate.

   If the output signal from an Integrator changes at a constant rate what type of signal must be at the Integrator input?

You know from step 3 that the Signal Generator is producing a sinusoidal signal. From your observations in step 5 you can conclude that the Signal Generator output is a sinewave which is added to a small constant signal. This constant signal is an error which is introduced in the Signal Generator if the signal is not adjusted for perfect symmetry.

If a periodic waveform is not symmetrical, the area under the curve on the positive side of the zero axis will differ from the area on the negative side. The positive areas (that portion above the zero reference) and the negative areas (that portion below the zero reference) will not, therefore, cancel each other and some net area will remain at the end of each cycle. This small area will accumulate as the areas under additional cycles of the waveform are measured. Since integration is an area-measuring operation the Integrator output signal will gradually move up or down as the integration progresses.

9. Readjust the SYMMETRY control, as follows:

   If the beam deflected downward during the integration in step 8 the SYMMETRY control should be rotated CCW to improve the symmetry of the sinewave. If the beam deflected upwards, the SYMMETRY control should be rotated CW.

   Reset the Integrator. Rotate the SYMMETRY control a small amount in the direction indicated in the above paragraph. Run the integration. If the beam still deflects rotate the symmetry control a bit further. Reset the Integrator and repeat the integration again.

   Continue this adjustment of the SYMMETRY control until the CRO beam remains stationary during the integration.

   As the symmetrical condition is approached the beam will deflect at a slower rate and you will be able to adjust the SYMMETRY control while the integration is being performed. Rotate the control until the beam stops moving. (Make sure however, that the beam has not reached its maximum deflection on the CRO screen).

We now must account for the absence of a periodic signal on the CRO. One possible explanation is that the amplitude of the integrated sine wave is much less than the amplitude of the original signal and cannot therefore be seen with the present vertical gain setting on the CRO.

10. Check this possibility by setting the V GAIN switch to the H position (for maximum sensitivity) and by turning the V GAIN knob to about halfway between its extreme positions.

*11. Reset the Integrator and run the integration again. Adjust the vertical gain control if the signal is too large. If the waveform still tends to drift during the integration (the input may still not be perfectly symmetrical) put the CRO input lead into the V AC terminal. This will prevent the error due to asymmetry from entering the beam control circuits in the CRO.

   What can you say about the shape of an integrated sinewave?

12. Reset the Integrator. Start the Integration again but this time slowly turn

the FREQUENCY knob on the Signal Generator to decrease the signal frequency as the integration proceeds.

*13. What happens to the amplitude of the Integrator output signal as you decrease the signal frequency? Can you explain why this happens? Does this explain why you had to increase the vertical gain on the CRO in order to see the integrated signal?

Note: The signal may suddenly become erratic if the integration is allowed to continue for a few minutes. The erratic behavior occurs when the accumulated error reaches the saturation level of the Integrator.

*14. Observe the shape of an integrated triangular waveform, and sketch it below. Before you run the integration make sure that the signal is not distorted and that it is symmetrical. You can accomplish this by repeating the adjustment procedures which are outlined in step 9.

*15. Put the CRO input lead into the V AC terminal (if it is not already there).

Set the Signal Generator for a square wave of 30 cycles.

Reset the Integrator. Run the Integrator and observe the shape of an integrated square wave. (Signal level can be increased without distortion.) Sketch it below.

Observe that of the three waveforms which were integrated, only the sinewave did not have its shape altered by the integration. This is why the sinewave is used so often in the analysis of dynamic systems. We know that no matter what mathematical operation we perform on the sinewave it will still remain a sinewave. We see later why this characteristic of the sinewave is so useful.