PRICE $1.00

# Electronic Analog Computer

# Heathkit

## OPERATIONAL MANUAL

HEATH COMPANY

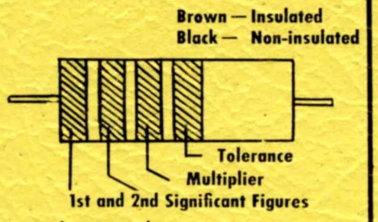
*A Subsidiary of Daystrom Inc.*

BENTON HARBOR, MICHIGAN

595-160

# STANDARD COLOR CODE — RESISTORS AND CAPACITORS

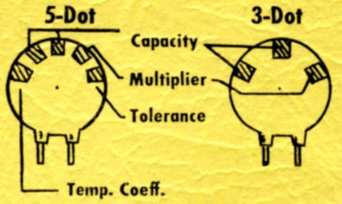
### AXIAL LEAD RESISTOR



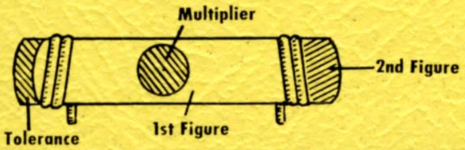

Wire wound resistors have 1st digit band double width

| INSULATED UNINSULATED Color | FIRST RING BODY COLOR First Figure | SECOND RING END COLOR Second Figure | THIRD RING DOT COLOR Multiplier |
|---|---|---|---|
| BLACK | 0 | 0 | None |
| BROWN | 1 | 1 | 0 |
| RED | 2 | 2 | 00 |
| ORANGE | 3 | 3 | ,000 |
| YELLOW | 4 | 4 | 0,000 |
| GREEN | 5 | 5 | 00,000 |
| BLUE | 6 | 6 | 000,000 |
| VIOLET | 7 | 7 | 0,000,000 |
| GRAY | 8 | 8 | 00,000,000 |
| WHITE | 9 | 9 | 000,000,000 |

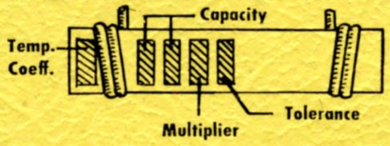
### DISC CERAMIC RMA CODE



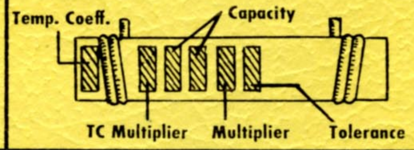

### RADIAL LEAD DOT RESISTOR



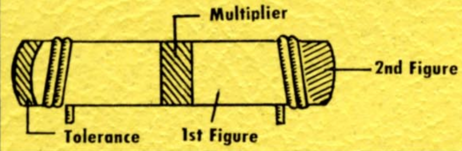

### 5-DOT RADIAL LEAD CERAMIC CAPACITOR



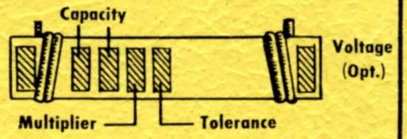

### EXTENDED RANGE TC CERAMIC HICAP



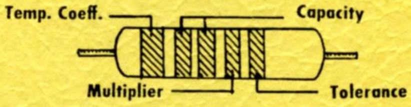

### RADIAL LEAD (BAND) RESISTOR




### BY-PASS COUPLING CERAMIC CAPACITOR




### AXIAL LEAD CERAMIC CAPACITOR

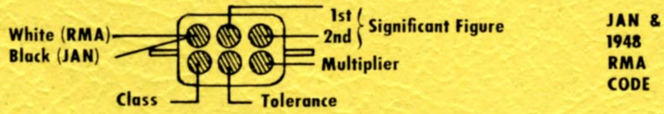



The standard color code provides all necessary information required to properly identify color coded resistors and capacitors. Refer to the color code for numerical values and the zeroes or multipliers assigned to the colors used. A fourth color band on resistors determines tolerance rating as follows: Gold = 5%, silver = 10%. Absence of the fourth band indicates a 20% tolerance rating.

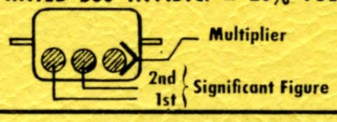
The physical size of carbon resistors is determined by their wattage rating. Carbon resistors most commonly used in *Heath*kits are ½ watt. Higher wattage rated resistors when specified are progressively larger in physical size. Small wire wound resistors ½ watt, 1 or 2 watt may be color coded but the first band will be double width.

# MOLDED MICA TYPE CAPACITORS

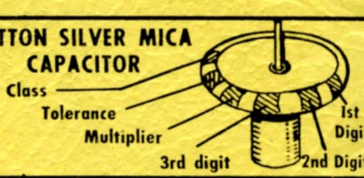
### CURRENT STANDARD CODE



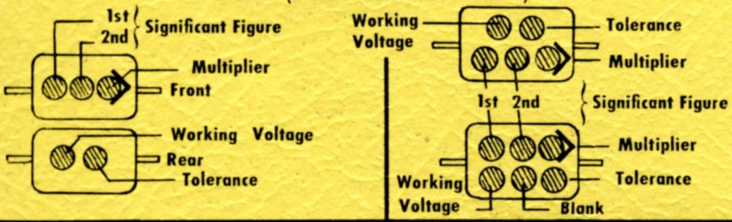

### RMA 3-DOT (OBSOLETE) RATED 500 W.V.D.C. ± 20% TOL.



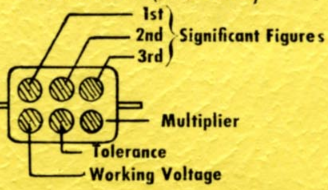

### BUTTON SILVER MICA CAPACITOR



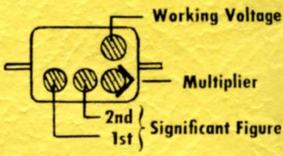

### RMA (5-DOT OBSOLETE CODE)




### RMA 6-DOT (OBSOLETE)

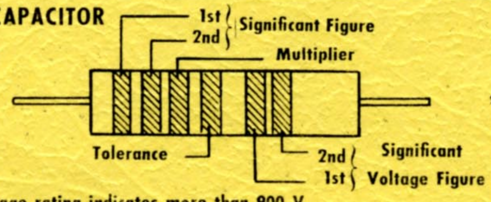



### RMA 4-DOT (OBSOLETE)




# MOLDED PAPER TYPE CAPACITORS

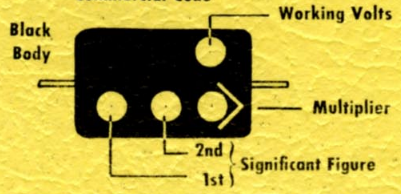
### TUBULAR CAPACITOR



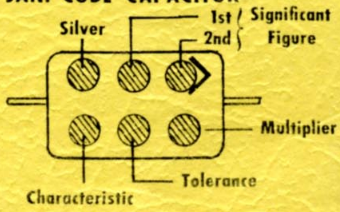

A 2 digit voltage rating indicates more than 900 V. Add 2 zeros to end of 2 digit number.

### MOLDED FLAT CAPACITOR

Commercial Code




### JAN. CODE CAPACITOR




The tolerance rating of capacitors is determined by the color code. For example: red = 2%, green = 5%, etc. The voltage rating of capacitors is obtained by multiplying the color value by 100. For example: orange = 3 × 100 or 300 volts. Blue = 6 × 100 or 600 volts.

In the design of Heathkits, the temperature coefficient of ceramic or mica capacitors is not generally a critical factor and therefore Heathkit manuals avoid reference to temperature coefficient specifications.

Courtesy of Centralab

# HEATH ELECTRONIC ANALOG COMPUTER OPERATIONAL MANUAL

**HEATH COMPANY**

A SUBSIDIARY OF DAYSTROM INC.

BENTON HARBOR, MICHIGAN

## INTRODUCTION

The Heath Electronic Analog Computer is designed to perform electronically several types of mathematical operations. Operations performed are addition of two or more variables, sign inversion, multiplication of a variable by a constant, integration of a variable with respect to time, and, with auxiliary equipment, the generation of functions of a variable. By combining and repeating several or all of these functions, complex problems can be solved.

The computer solves systems of algebraic or transcendental equations and many forms of differential equations, both linear and non-linear. It can also be used as a simulator of systems by solving the equations describing the system. It is, in fact, in simulation that the computer finds its widest application. Design parameters can be varied as the input limits are held constant, enabling arrival at proper component values.

Some typical problems which lend themselves to solution by the computer are mechanical vibration and oscillation, dynamic heat transfer problems, automatic control systems, transients and electrical circuits, automobile suspension systems, aircraft and missile stability and control, fluid flow, simulation of nuclear reactors, rigid body dynamics, and many types of mathematical problems.

The computer consists of D. C. operational amplifiers with suitable power supplies, control circuits and meter circuits. It is engineered to provide maximum flexibility and accuracy with a minimum of cost. Maximum efficiency of operation is gained by the functional layout of the panel with great flexibility obtained by bringing the connections from all components to jacks on the front panel.

## THEORY

In general, computers may be divided into two groups: digital and analog. The familiar desk calculator is of the digital type as are several of the well-known electronic computers. Essentially they operate in discrete steps. Generally the mathematical operations are performed by combinations of additions. Thus multiplication is performed by repeated additions and integration is performed by summation.

Digital computers are in general more accurate than analog computers. They are, however, more expensive and at the present time not practical in small sizes. They are valuable where high accuracies are needed and where large-scale computations are required.

Analog computers are typified by slide rules and differential analyzers. Physical quantities are made to obey mathematical relations comparable to those in the original problem. Analog computers are grouped according to the type of physical quantity used to represent the mathematical variable.

The Heath Analog Computer is a D. C. analog computer in which the variables are represented by D. C. voltages which may vary with time. Thus complicated mathematical problems can be solved by D. C. amplifiers and potentiometers. Such computers are relatively inexpensive, easy to operate and maintain, and flexible since they may be interconnected by simple patch cords.

Personnel with only routine training in engineering or physics can be rapidly trained to use electronic analog computers effectively. The programing of a digital computer can become, and generally is, a complex operation requiring extensive training and experience.

To solve a differential equation on an analog computer the procedure is generally as follows:

1. The computer is set up to solve the given problem and the voltages are set to the initial conditions given in the problem.

2. The computer is made operative and the voltages are forced to vary in the manner prescribed by the given differential equation. These voltage variations with time are recorded and they form the solution of the problem.

3. The machine is stopped and reset to its initial conditions and is then ready for another run with changed coefficients, initial conditions, etc.

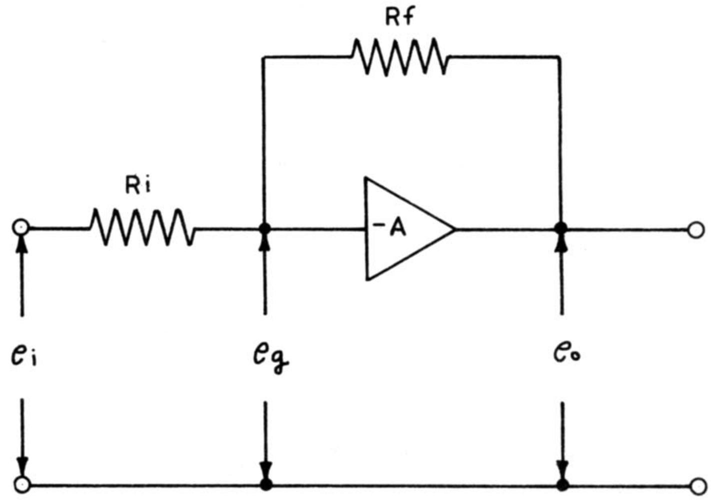



Figure 1

Linear mathematical operations are performed by using a high gain D. C. amplifier. Consider the circuit shown in Figure 1.

The forward gain of the amplifier is -A. Then

$$e_o = -A\, e_g \quad \text{or} \quad e_g = -\frac{e_o}{A}.$$

If -A approaches infinity, $e_g$ approaches zero. Therefore, if we make -A large, $e_g$ will be approximately zero. In practice this condition is realized by using high-gain amplifiers. In the Heath Analog computer, for example, the open loop gain is from 30,000 to 50,000. Since $e_o$ has a maximum value of 100 volts, $e_g$ will be at most two or three millivolts. Thus, considering

$$e_g = 0 \qquad \frac{e_i}{R_i} = -\frac{e_o}{R_f} \quad \text{or} \quad e_o = -\frac{R_f}{R_i} e_i$$

which can be written $e_o = -K e_i$ where $K = \frac{R_f}{R_i}$.

This amounts to multiplication by a constant coefficient.

Two voltages may be added as shown in Figure 2. Keeping in mind that $e_g$ is essentially at ground potential, $e_o = -\left(\frac{R_f}{R_1} e_1 + \frac{R_f}{R_2} e_2\right)$

or $e_o = -\left(K_1 e_1 + K_2 e_2\right)$ where $K_1 = \frac{R_f}{R_1}$

and $K_2 = \frac{R_f}{R_2}$.

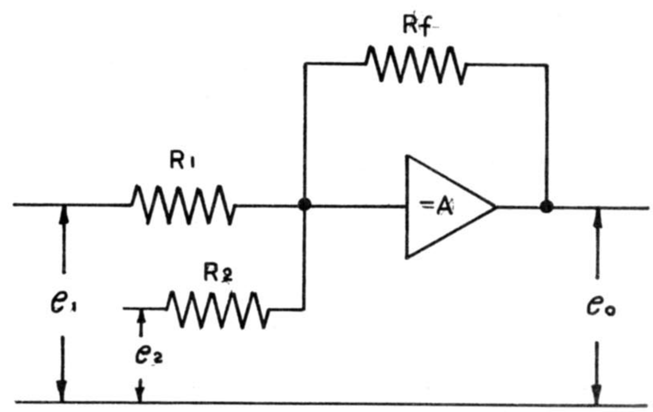



Figure 2

As long as $e_o$ does not exceed the range of the amplifier, any number of inputs may be used, in which case

$$e_o = -\left(\frac{R_f}{R_1} e_1 + \frac{R_f}{R_2} e_2 + \text{---} + \frac{R_f}{R_n} e_n\right)$$

or $e_o = -R_f \sum \frac{e_n}{R_n}$.

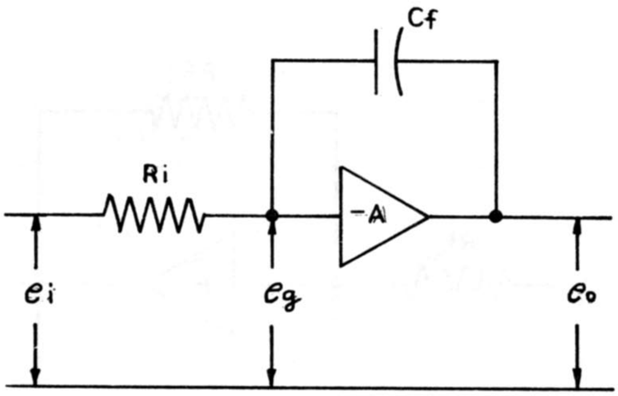



Figure 3

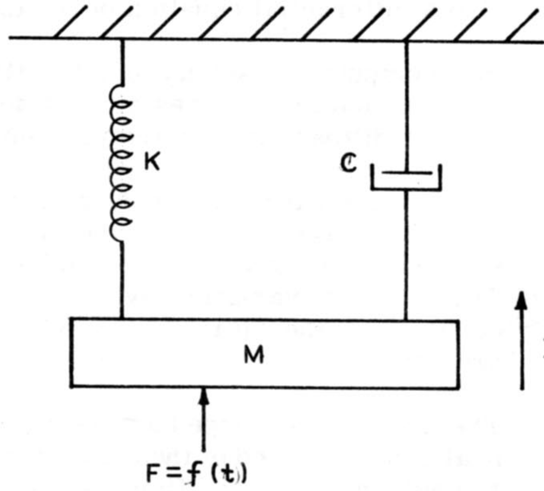



Figure 4

Integration is performed by replacing the feedback impedance $R_f$ with a capacitor $C_f$ as shown in Figure 3.

For this circuit since $e_g = 0$ $\quad i = \frac{dq}{dt} = \frac{e_i}{R_i}$ $\quad$ but $\quad q = C_f e_o$ $\quad$ so $\quad \frac{dq}{dt} = C_f \frac{de_o}{dt}$.

Therefore $\frac{e_i}{R_i} = C_f \frac{de_o}{dt}$ $\quad$ or $\quad de_o = \frac{1}{R_i C_f} e_i \, dt$ $\quad$ and $\quad e_o = \frac{1}{R_i C_f} \int e_i \, dt$.

By combining the above operations in various ways, problems of many kinds may be solved. As an example, consider a very simple physical problem, the mass-spring-damper shown in Figure 4.

The mass M is connected to the spring with elastic constant K. The viscous damping constant is C. Consider only vertical displacement y. The sum of the forces acting on mass M is then given by

$$M \frac{d^2y}{dt^2} + C \frac{dy}{dt} + Ky = f(t) \tag{1}$$

where f(t) is the applied force. The force f(t) is represented by a voltage supplied by a function generator or by amplifiers on the computer. This function f(t) is the forcing function. The problem is now to set up the computer circuit so as to obtain an output voltage which will be proportional to y for a given input voltage proportional to the force f(t). Equation (1) may be written in the form

$$M \frac{d^2y}{dt^2} = -C \frac{dy}{dt} - Ky + f(t) \tag{2}$$

If, in the circuit, there is a voltage equal to $M \frac{d^2y}{dt^2}$ it can be converted to $-\frac{dy}{dt_1}$ by passing it through an integrator with an RC time constant equal to m. This can then be passed through another integrator with unit time-constant which will then have output equal to y. The voltages representing $y, -\frac{dy}{dt}$, and f(t) can then be summed to give $-C\frac{dy}{dt} - Ky + f(t)$ which is the right hand side of the equation (2) and therefore equal to $M \frac{d^2y}{dt^2}$. Connecting the output of amplifier $A_3$ to the input of amplifier $A_1$ then satisfies the equation. This is shown in Figure 5.

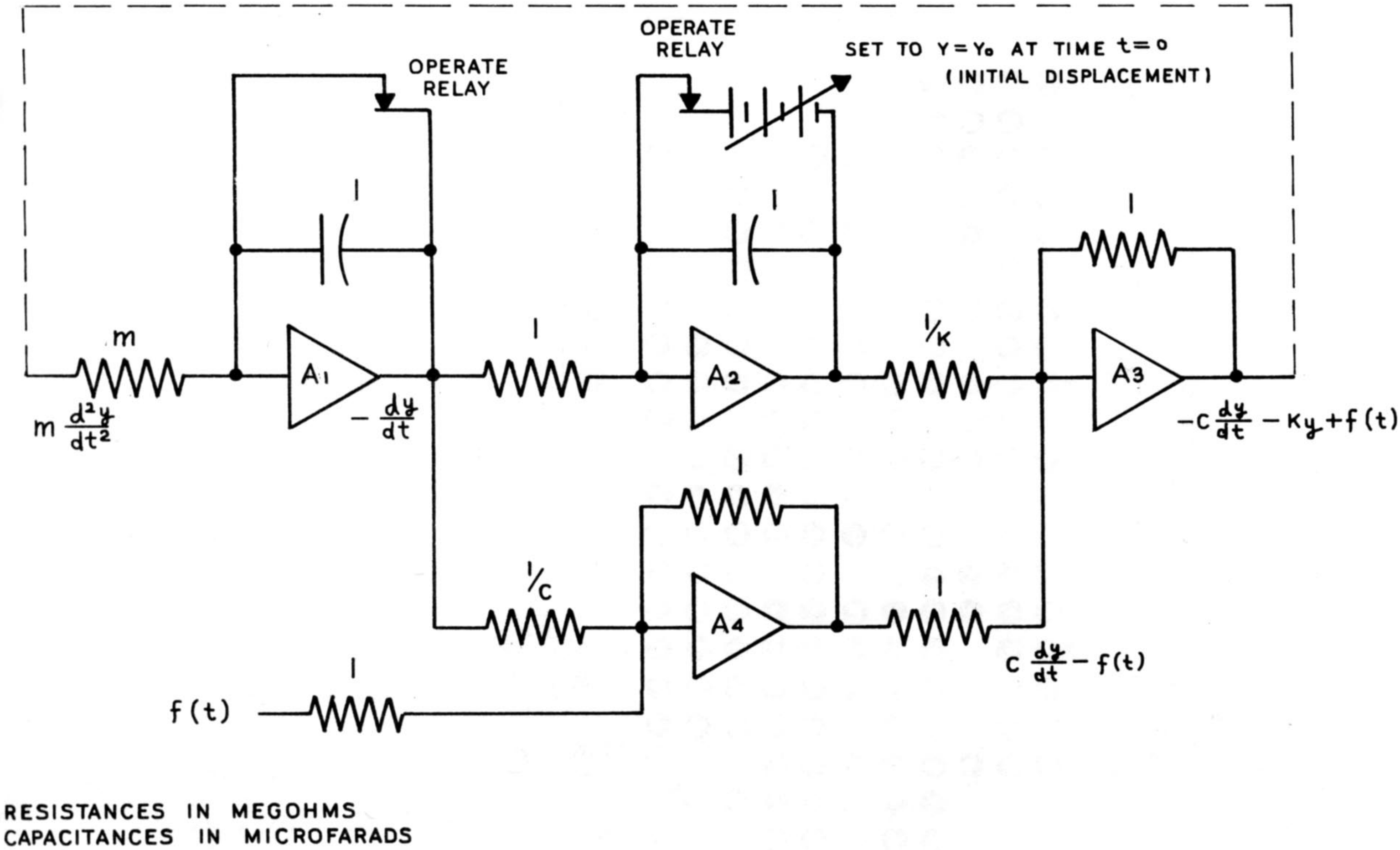



Figure 5

To obtain a solution to the problem, the initial displacement and velocity must be specified. This is done by charging the integrating capacitors to the proper voltages. Power supplies supplying variable voltages are provided for this purpose together with relays for applying the voltages to the integrating capacitors.

In order to avoid hum, it is necessary that the relay be connected to the input of the amplifier and the initial condition power supply be connected to the output of the amplifier as shown in Figure 5.

Many other illustrative problems are given in the general references in the bibliography as well as in the specific references given in Appendix A.

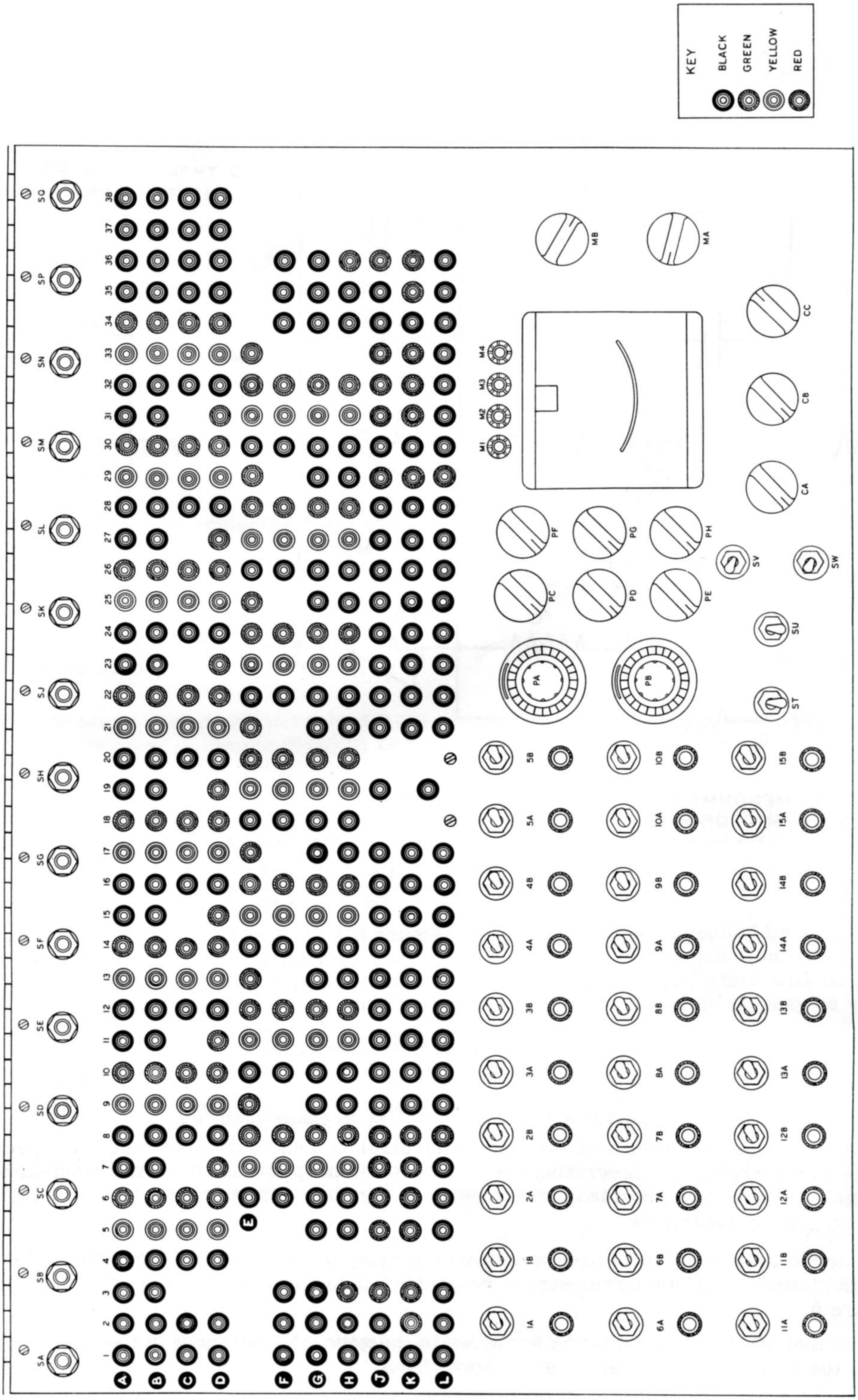

KEY
BLACK
GREEN
YELLOW
RED
SA SB SC SD SE SF SG SH SJ SK SL SM SN SP SQ
A B C D E F G H J K L
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
MA MB
CA CB CC
M1 M2 M3 M4
PA PB PC PD PE PF PG PH
ST SU SV SW
1A 1B 2A 2B 3A 3B 4A 4B 5A 5B
6A 6B 7A 7B 8A 8B 9A 9B 10A 10B
11A 11B 12A 12B 13A 13B 14A 14B 15A 15B

Figure 6

## PREPARATION OF COMPUTER FOR USE

After the Heath Analog Computer has been assembled it is ready for testing and use. Complete assembly instructions were supplied with each kit making up the computer. Carefully recheck the wiring and assembly of the various sub-assemblies. Plug the power cord of the completed computer into a 105-125 volt, 60 cycle AC outlet. CAUTION: Use of other voltages or frequencies will result in inoperation and damage to the computer.

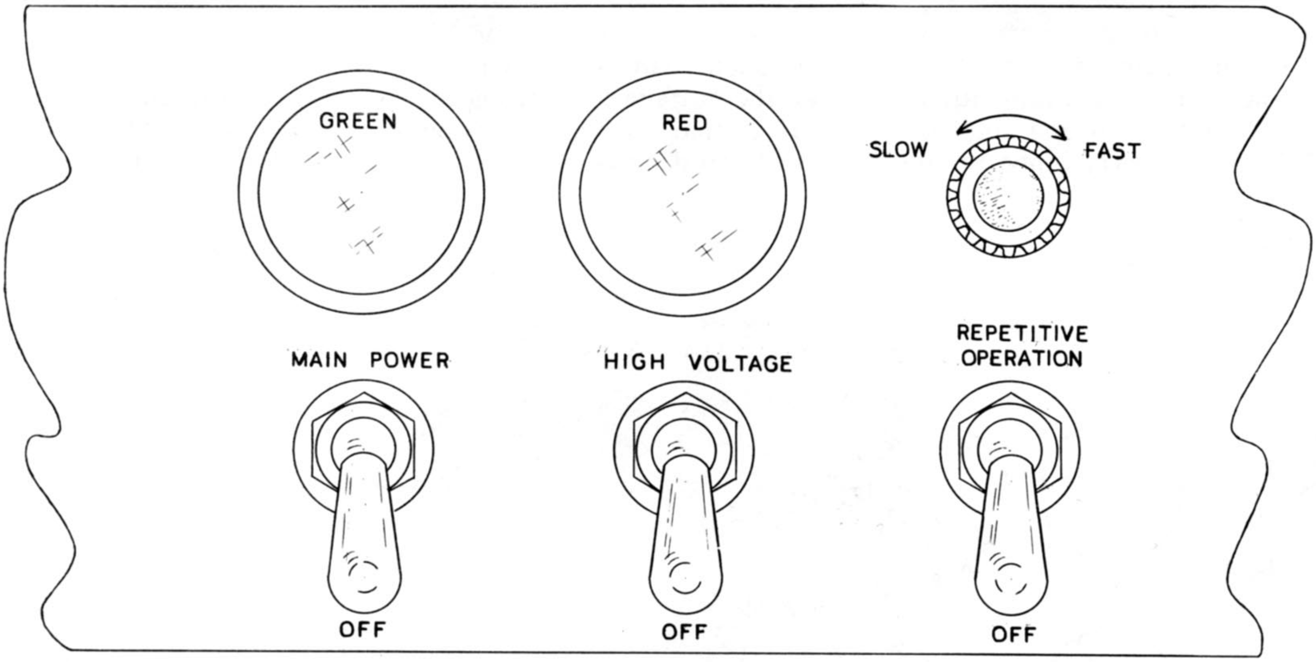



Figure 7

The front apron of the ES-400 cabinet is shown in Figure 7. The switch on the left is the main power switch. This should now be turned on. The filaments of all of the tubes should light up. Allow a few minutes for the tubes to warm up, then turn the high voltage switch on. This is the center switch. The switch on the right should be in the "off" position.

In use, the computer should be allowed to warm up for at least 30 minutes before solving problems. This will help to stabilize operation. If, in use, the computer is idle for short periods of time, only the center high voltage switch should be turned off. The main switch should be left on as this keeps the filaments on and makes unnecessary the "warming-up" period for the next operation. Actually, experience shows that for short "down" times the high voltage should also be left on.

## METER CIRCUIT

With the amplifier output switch in the "OFF" position and meter switch in "AMP. ZERO" position the amplifiers are connected directly to the meter by means of the push button switches at the top of the panel. With the switch in the output position (2-20-100 volts) the output of any amplifier may be connected directly to the meter by setting amplifier output switch to the number of the corresponding amplifier, 1 through 15. With the switches in these positions the output of the same amplifier is also connected to the binding posts above the meter marked "OUTPUT". A D. C. oscilloscope or a recorder may be connected to these terminals for read-out. With the amplifier output switch in the "EXT" position and the meter switch in one of the "OUTPUT" positions (2, 20 or 100 volts) the meter is used for measuring external voltages by use of the binding post above the meter, labeled "EXTERNAL". See Figure 8.

The coefficient potentiometers are set with the amplifier switch in any position and the meter switch in the "POT. SET" position. The actual voltage between the center tap of the potentiometer and the ground can be read on the meter by setting the meter switch in the "POT. READ" position, leaving the amplifier output switch in the "EXT" position.

At times it may be desirable to null the output of an amplifier. The voltage is applied to the input of an amplifier by the coefficient potentiometer which was previously set by use of the coefficient set switches under the meter. With unity gain on the amplifier the output of the amplifier should then also null against the same setting of the coefficient set switches. Set the meter switch to the "NULL" position and the amplifier output switch to the number of the amplifier being nulled. Set the invert toggle switch to the - position. Press the coefficient potentiometer spring return toggle switch to the left. The meter should read zero. If it does not, adjust the coefficient potentiometer until the meter does read zero. If it is desired to null the amplifier when the gain of the amplifier is 10, set the voltage potentiometer toggle switch to 10 V. This reduces the input to the amplifier by 1/10 so that the output may be nulled as before. The invert switch is necessary since the output of an amplifier is 180$^{\circ}$ out of phase with respect to the input.

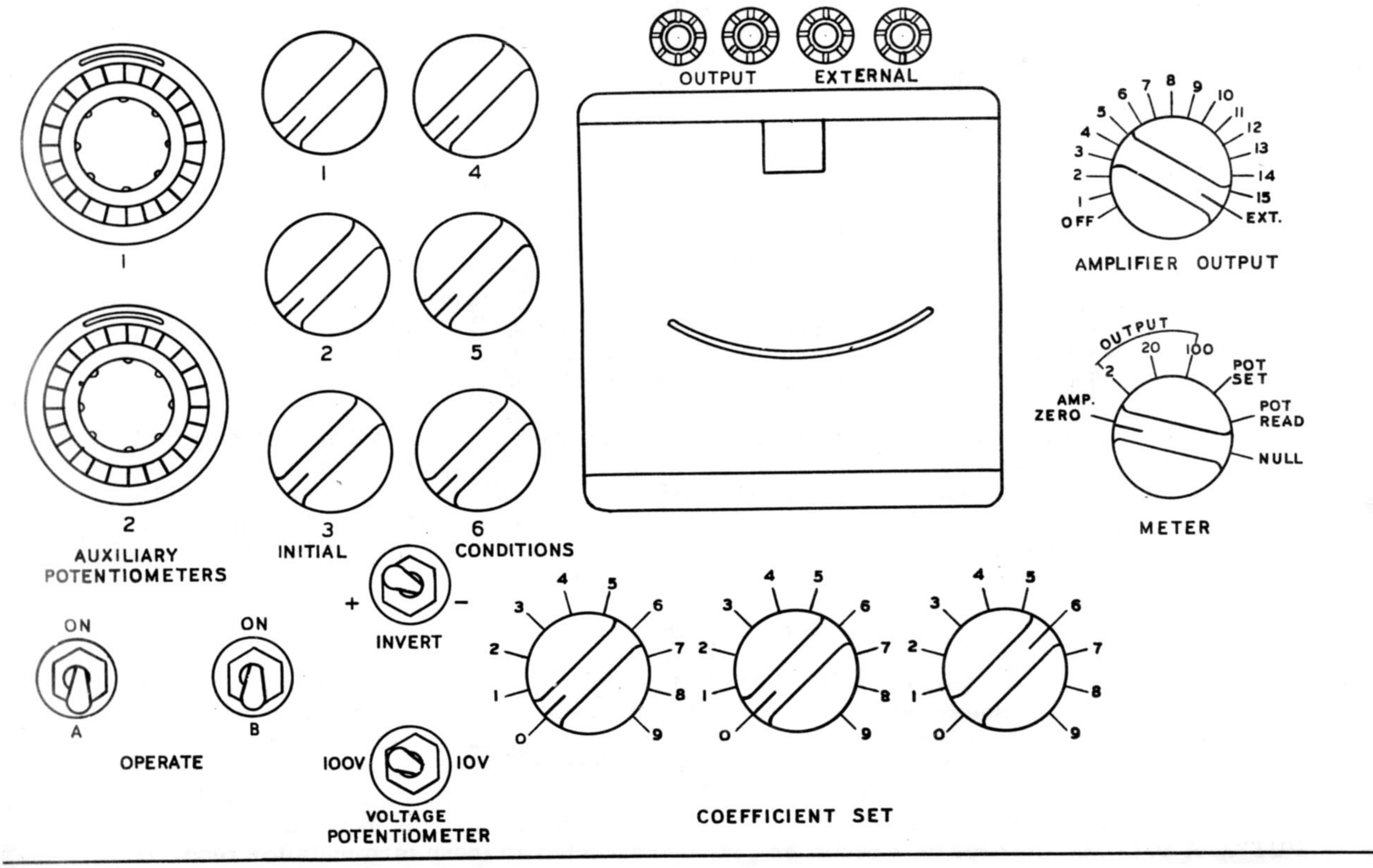



Figure 8

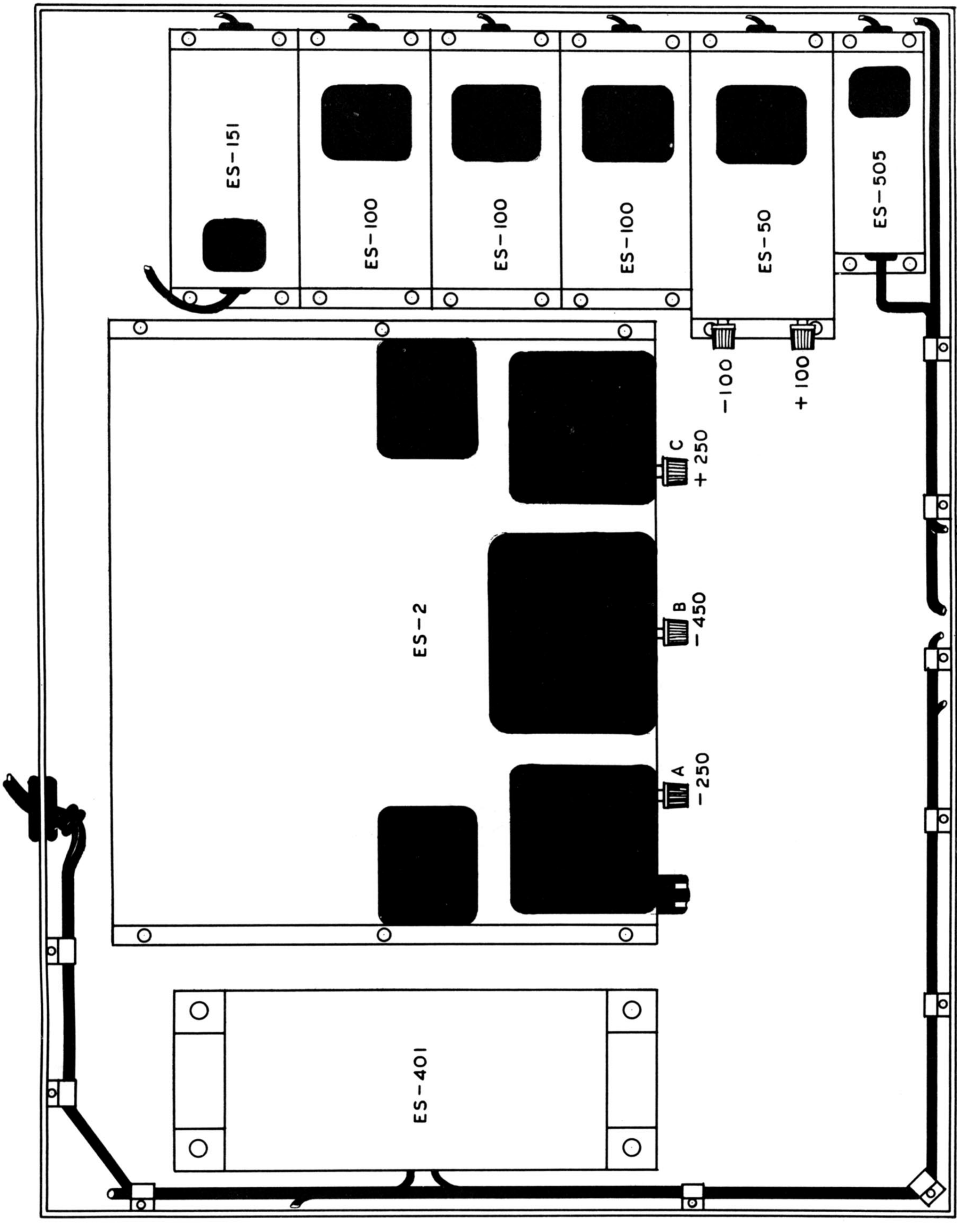

ES-151
ES-100
ES-100
ES-100
ES-50
ES-505
-100
+100
C
+250
B
-450
A
-250
ES-2
ES-401

Figure 9

## AMPLIFIER POWER SUPPLY ADJUSTMENT

The voltages of the amplifier power supply should be adjusted before adjusting the amplifiers. Use a VTVM or other good voltmeter. CAUTION: Turn the main power switch off while making connections to the power supply.

NOTE: It is important that the following adjustments be made in the proper order. Failure to follow this order will cause improper functioning of the regulator circuit since the -450 volt supply controls both the -250 and the 250 volt supply.

Remove any one of the D. C. amplifiers from the computer. Connect the negative lead of the voltmeter to pin 8 of the octal socket on the heat shield. This is the power socket which supplied the amplifier just removed. Connect the positive lead of the voltmeter to ground. Now turn on the power switch and adjust the -450 volt control B (see Figure 9) until the meter reads 450 volts.

Leaving the positive lead of the voltmeter connected to ground, move the negative lead from pin 8 to pin 7 of the octal socket. Again turn the power switch on and adjust the -250 volt control A until the voltmeter reads 250 volts.

To adjust the +250 volt supply connect the positive lead of the voltmeter to pin 5 of the octal socket and the negative lead to ground. Turn on the power switch and adjust control C until the meter reads 250 volts. Replace the amplifier which was removed while making these adjustments.

## AMPLIFIER ADJUSTMENT

On the front of each amplifier inside the cabinet is the gain control. Do not confuse this with the balance control on the top of the amplifier, outside the cabinet. The gain control is set by the following procedure. An oscilloscope and oscillator are connected to the amplifier as shown in Figure 10. An oscilloscope with a high gain vertical amplifier with good low frequency response is necessary for this adjustment. Adjust the gain control until the center portion of the trace is horizontal. The frequency of the oscillator should not exceed 60 cps. When the gain control is in full clockwise position, the open-loop gain of the amplifier is approximately 30,000. In full counterclockwise position, the gain is approximately 50,000. If an oscilloscope with a high gain amplifier is not available, it is best to set the gain control in full clockwise position. This will give enough gain for most problems.

On the panel are 15 pushbutton switches, one under each amplifier. Pushing one of these switches disconnects the amplifier immediately above it from the computer and connects it to the meter through the balancing circuit shown in Figure 11. The meter with associated switches and binding posts is shown in Figure 8.

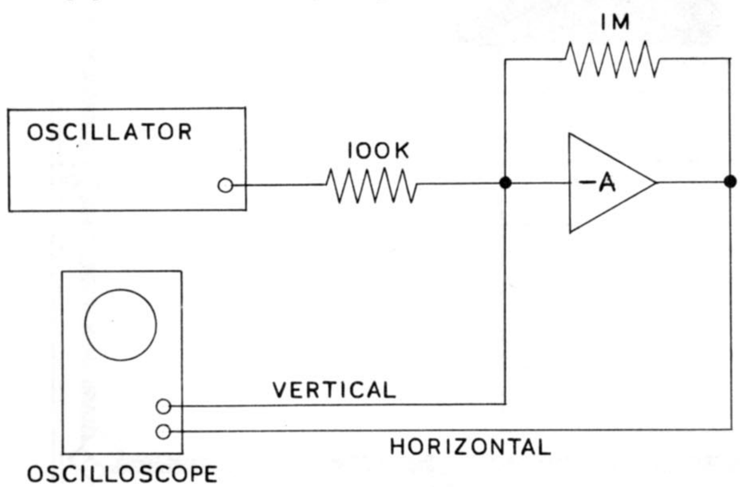



Figure 10

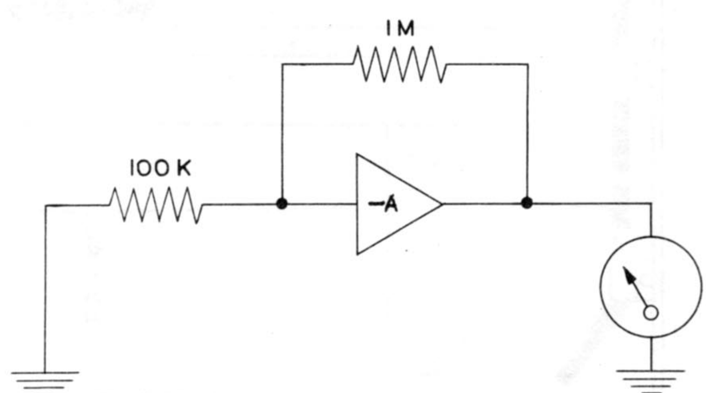



Figure 11

On the top of each amplifier is a balance control knob. To balance an amplifier, set the amplifier output switch at "off" and the meter switch at "amp. zero". Depress the push button switch on the panel below the amplifier. Turn the balance control until the meter reads zero. Starting at one end, zero each amplifier until all are balanced. This should be checked from time to time as amplifiers which are not "zeroed" will introduce errors in the solution.

## REFERENCE POWER SUPPLY

The output of the reference power supply is brought out to the panel on jacks. Use the following procedure for setting the output. Set the amplifier output switch to "EXT." and the meter switch to "100". The -100 volt supply must be adjusted first. Connect the negative output jack from the reference supply to the red binding post above the meter and marked "EXTERNAL" by use of a patch cord. It is not necessary to make the ground connection with a patch cord, as this is done internally in the computer. The control on the reference supply chassis nearer the rear of the cabinet is the negative control. Refer to Figure 8. Set this control for a meter reading of 100 volts. Leaving one end of the patch cord connected to the meter, change the other end from the negative jack of the reference supply to the positive jack. Set the positive output to 100 volts by use of the other control on the reference power supply chassis.

## SETTING COEFFICIENT POTENTIOMETERS

The coefficient potentiometers are on the front panel, each having a spring-loaded toggle switch and a control knob. To set a potentiometer set the voltage potentiometer toggle switch to the 100 V position and the invert toggle switch to the + position. Set the amplifier output switch to any position and the meter switch to "POT. SET". Under the meter are three coefficient set switches. Set these to the voltage desired. Select the coefficient potentiometer to be used. Press the toggle switch to the left and while holding it in that position, adjust the control knob just below until the meter reads zero. Release the switch.

The potentiometer is now set so that the coefficient set knobs show the voltage between the center tap of the coefficient potentiometer and ground as a fraction of the total voltage across the coefficient potentiometer. As an example, let the knobs read 3, 7 and 5 from left to right. Then the voltage between center tap and ground of the coefficient potentiometer is 37.5% of the total voltage across the potentiometer. Thus if 100 volts is applied to the potentiometer at V in Figure 12, the voltage $e_i$ will be 37.5 volts. If 50 volts is applied to V, the voltage at $e_i$ will be 18.75 volts, 10 volts at V will result in 3.75 volts at $e_i$ and so on.

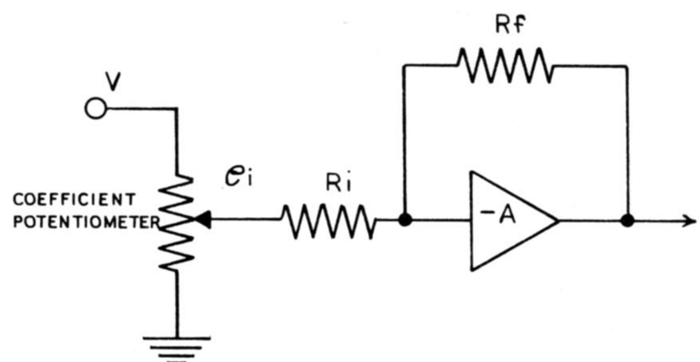



Figure 12

Auxiliary potentiometers of the 10-turn precision type are provided for special purposes where high precision is needed. Connections to these are brought to jacks on the panel.

## INITIAL CONDITION POWER SUPPLIES

The controls for the initial condition power supplies are at the left of the meter. The output jacks are at the right and left ends of the panel. Patch cords are used to connect the output of the supplies to the external terminals of the meter. With the amplifier output switch in "EXT" position and the meter switch in the 100 position the control is adjusted until the desired voltage is read on the meter. Either positive or negative voltages are available.

## OPERATION

Connections from each amplifier are brought out to the panel as shown in Figure 13.

The spacing between jacks is 3/4", so General Radio double plugs* or their equivalent may be used. A convenient method of mounting computing resistors is shown in Figure 14. The overall accuracy of the computer is dependent in part on the computing elements. For this reason, good quality resistors should be used, preferably precision resistors.

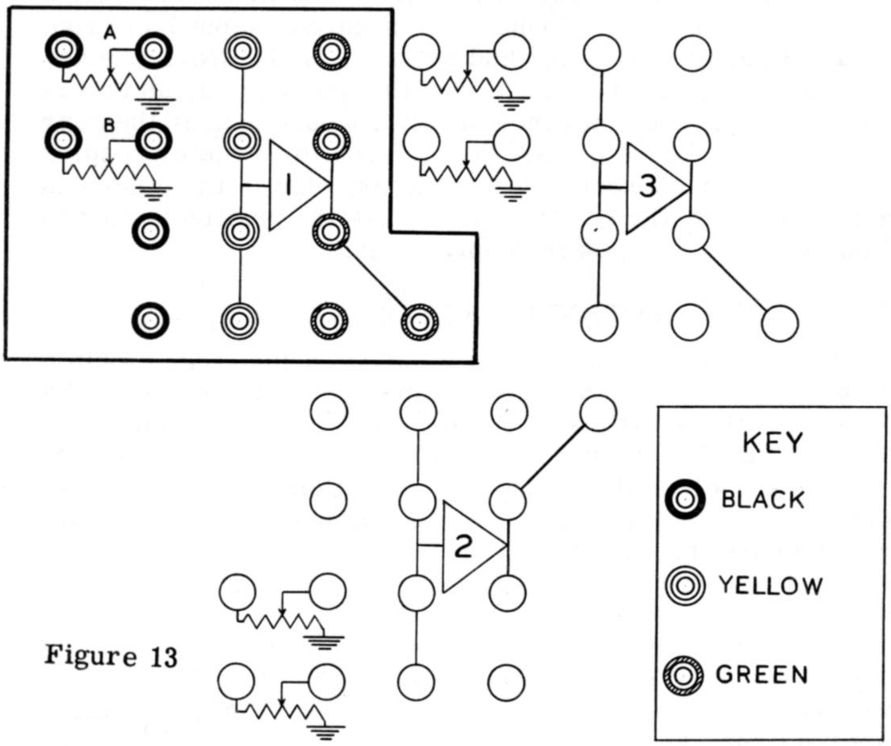



Figure 13

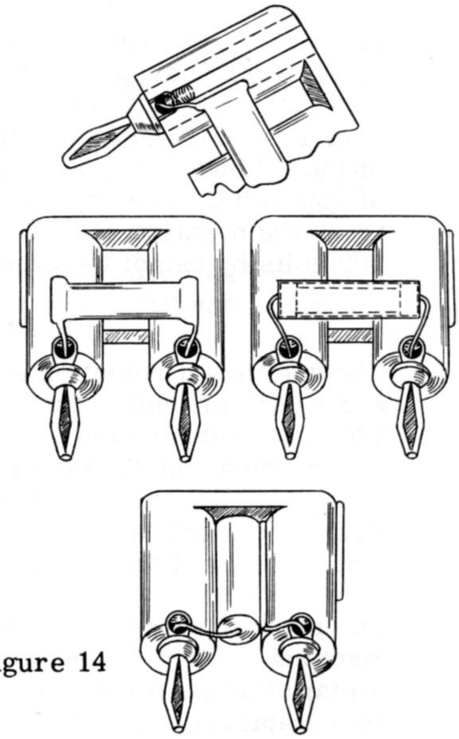


Figure 14

For satisfactory operation, capacitors used for integration must be of the highest quality. They should especially have very low leakage. The only satisfactory ones have polystyrene, polyethelyne, or equivalent dielectric.

The capacitors are generally too large and heavy to mount on the front of the panel. The best procedure is to solder flexible leads to the capacitor terminals. Banana plugs or GR plugs are attached to the free ends of the cords. The capacitors are then placed on the tray provided in the computer and the cords are plugged into the jacks from the underside of the panel. The cords should be long enough so that the capacitor will remain on the tray when the panel is fully opened.

Resistors and capacitors for problem set-up are not provided with the Heath Computer since the values used will depend on the problems to be solved. It is therefore more economical for the user to obtain those needed for the specific problems to be solved.

Patch cords for interconnecting amplifiers and for connecting relays and power supplies to the amplifier are available from the Heath Company.

## SETTING UP PROBLEMS ON THE COMPUTER

The general procedure for setting up a simple problem on the computer was described under Theory. For that purpose, block diagrams were used and exact values were not given. Now the actual set-up of a specific problem will be described.

*Available from General Radio Company, 275 Massachusetts Ave., Cambridge 39, Mass.

The first problem is a simple problem from elementary physics, that of a freely falling body. Disregarding air resistance, the body will fall, due to the force of gravity, with a constant acceleration. The equation describing this motion is as follows:

$F = ma = m\ddot{y} = mg$*

Acceleration $\underline{a}$ is equal to the second derivative of distance $\underline{y}$ with respect to time or $\ddot{y}$.

$\ddot{y} = g$ (a constant)

Integration of this equation once will give $\dot{y}$ which is velocity, and integration a second time will give y or displacement. For the computer, the block diagram is as shown in Figure 15.

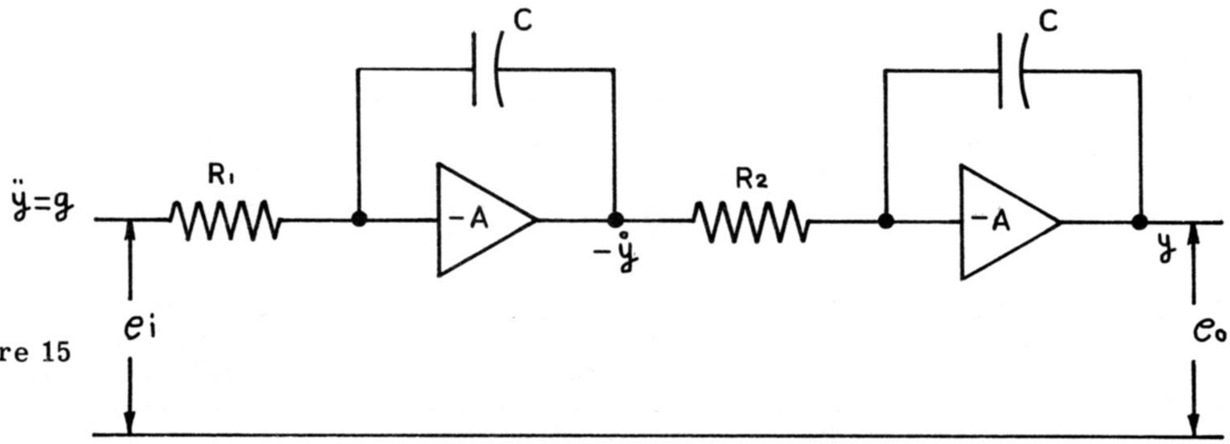



Figure 15

If we feed a voltage which is proportional to g and hence $\ddot{y}$ into the first amplifier, the output of that amplifier will be $-\dot{y}$ or velocity. That, in turn, will become y or distance at the output of the second amplifier.

Before the problem can be solved on the computer it is necessary to determine the time of solution desirable and the output amplitude of the solution. The time of solution is determined by the RC constant of the integrating amplifiers. If RC = 1, computer time is equal to real time. The computer time desirable is determined by the method of read-out. When using an oscilloscope for read-out, a short solution time is desirable. For a recorder, longer solution time is better.

Suppose, for example, in the problem of the falling body, the distance the body falls in 2.5 seconds is desired. Using an RC constant of 1 would give a solution time of 2.5 seconds. This would be acceptable for a recorder but is slow for an oscilloscope. A convenient time of solution would be 25 milliseconds. This is 1/100 of the real time so an RC constant of 0.01 is needed. This can be done by using C = 0.1 $\mu$fd and R = 100 K$\Omega$. Then RC = $(0.1 \times 10^{-6}$ farad) (100,000 $\Omega$) = 0.01 seconds.

It is now necessary to choose an input voltage which will not overdrive the amplifiers. The value of g is known to be approximately 32 ft/sec.$^2$. A quick check indicates that if we set g = 32 volts, the voltage representing the answer will exceed 100 volts. Since the linear response of the amplifiers is ±100 volts, this is undesirable. An input of 16 volts should permit satisfactory operation of the amplifiers.

The choice of amplitude-scale factor should be such that the output voltage does not exceed 100 volts. The normal operating range of the amplifiers in the Heath Analog Computer is ±100 volts. Beyond this range the amplifiers are subject to overloading. Neon lamps are connected in the circuit of each amplifier to indicate amplifier overloading. These light up when the output of the amplifier exceeds ±100 volts. Lighting of neon bulbs of amplifiers not being used is normal.

*$\dot{y}$ means the first derivative of y with respect to time, or $\frac{dy}{dt}$ and $\ddot{y}$ the second derivative of y with respect time or $\frac{d^2y}{dt^2}$. This notation is used only for time derivatives.

Maximum output voltages near zero should be avoided. Normally the peak voltage should be approximately ±50 volts. For best results, the amplifier gain should not exceed 50 with gains of 20 to 30 being preferable. Thus for this particular problem the time-scale factor and the amplitude-scale factor have been chosen. The problem now looks like Figure 16.

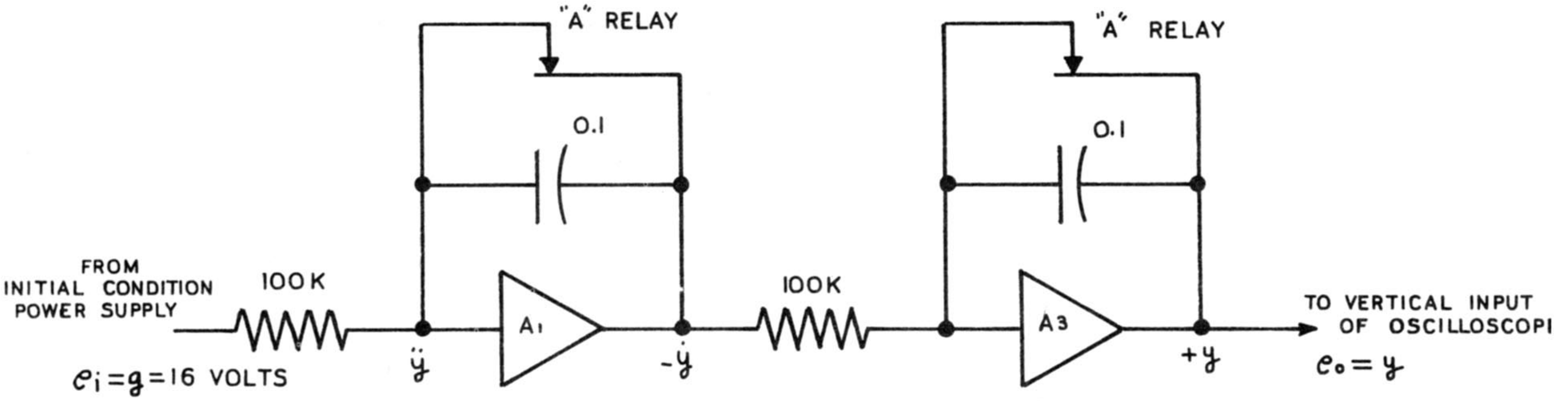



Figure 16

The solution of the problem leaves the integrating capacitors charged. It is necessary to remove this charge before the problem can be rerun. This is done by connecting relays across the capacitors. These are open during solution and closed to reset the problem. Relays are provided for this purpose. Jacks connected to these relays are provided on the panel. The arrows indicate the normally closed position.

The problem is set up on the problem board as shown in Figure 17 on Page 15. The output from amplifier 1 will give $\dot{y}$ which is the velocity of the object while the output from amplifier 3 will give y which is the distance through which the object has fallen.

The solution time for this problem was chosen for solution display on a cathode ray oscilloscope. When using the oscilloscope for read-out, it is convenient to use one of the DC amplifiers to provide the sweep generator for the oscilloscope. This may be done as shown in Figure 18.

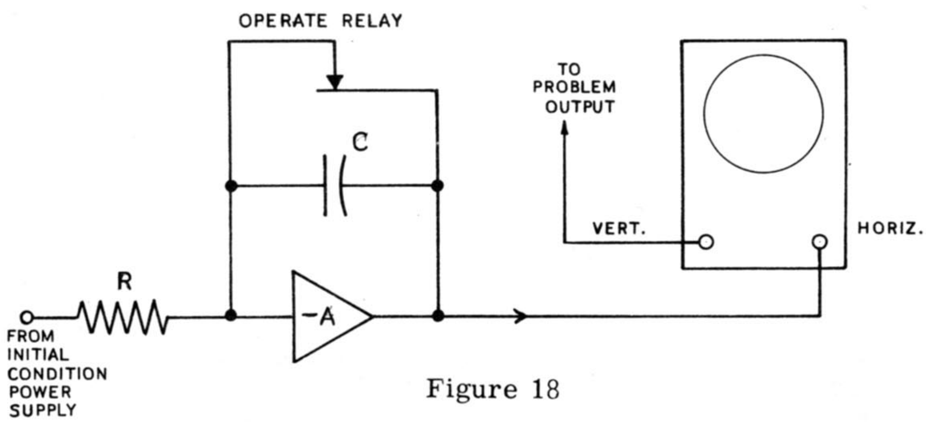



Figure 18

Ordinarily the value of RC is the same as for the integrating amplifiers. Repetitive operation is used with the repetitive oscillator reseting the problem and the horizontal sweep simultaneously providing a continuous trace of the solution on the oscilloscope. The knob on the front apron of the computer cabinet controls the rate of repetition. This control is adjusted to give a satisfactory pattern on the screen. The voltage, $e_{in}$, is obtained from one of the initial condition power supplies. Changing the voltage will change the sweep time.

On the front panel are two OPERATE toggle switches A and B. Switch A operates the A relays and switch B operates the B relays. The A relays will operate independently while the B relays will operate only if switch A is on.

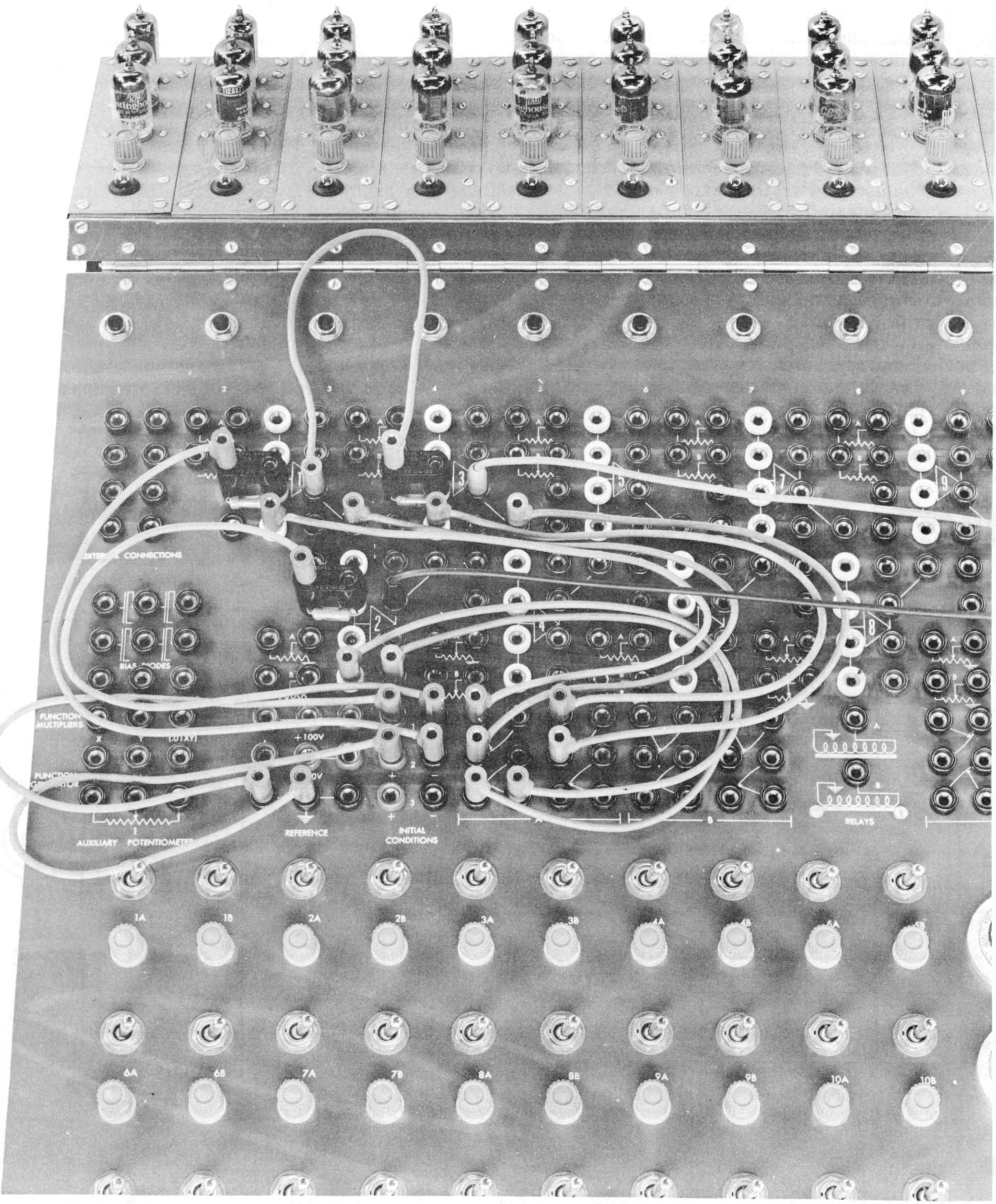

EXTERNAL CONNECTIONS
BIAS DIODES
FUNCTION MULTIPLIERS
FUNCTION GENERATOR
+100V
AUXILIARY POTENTIOMETER
REFERENCE
INITIAL CONDITIONS
RELAYS
1A
1B
2A
2B
3A
3B
4A
4B
5A
5B
6A
6B
7A
7B
8A
8B
9A
9B
10A
10B

Figure 17

To solve the problem, turn operate switch A on. The solution should now appear on the oscilloscope. If a permanent record is desired a photograph of the oscilloscope display can be made. In interpreting the answer, the time-scale and amplitude-scale factors must be kept in mind.

For a preliminary check of the solution the meter can be used. For this a time-scale factor of 1 is convenient for this particular problem. That is, computer time should equal real time. For this the input resistor for the integrating amplifiers should be 1 megohm and the feedback capacitor should be 1 $\mu$fd. The problem set-up is shown in Figure 19.

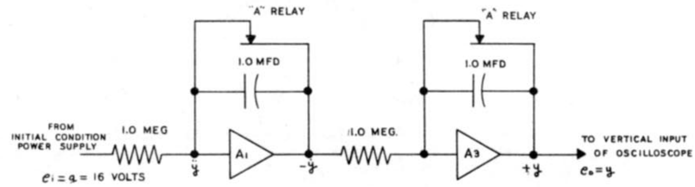



Figure 19

A permanent record of the solution can be made on a pen recorder. The time constant depends on the response of the recorder and the problem. For the falling body problem a time constant of 1 is suitable, the same as used for meter readout.

The solution to this problem of the freely falling body is shown in Figure 20. This is reproduced from an actual recording from a Heath Analog Computer.

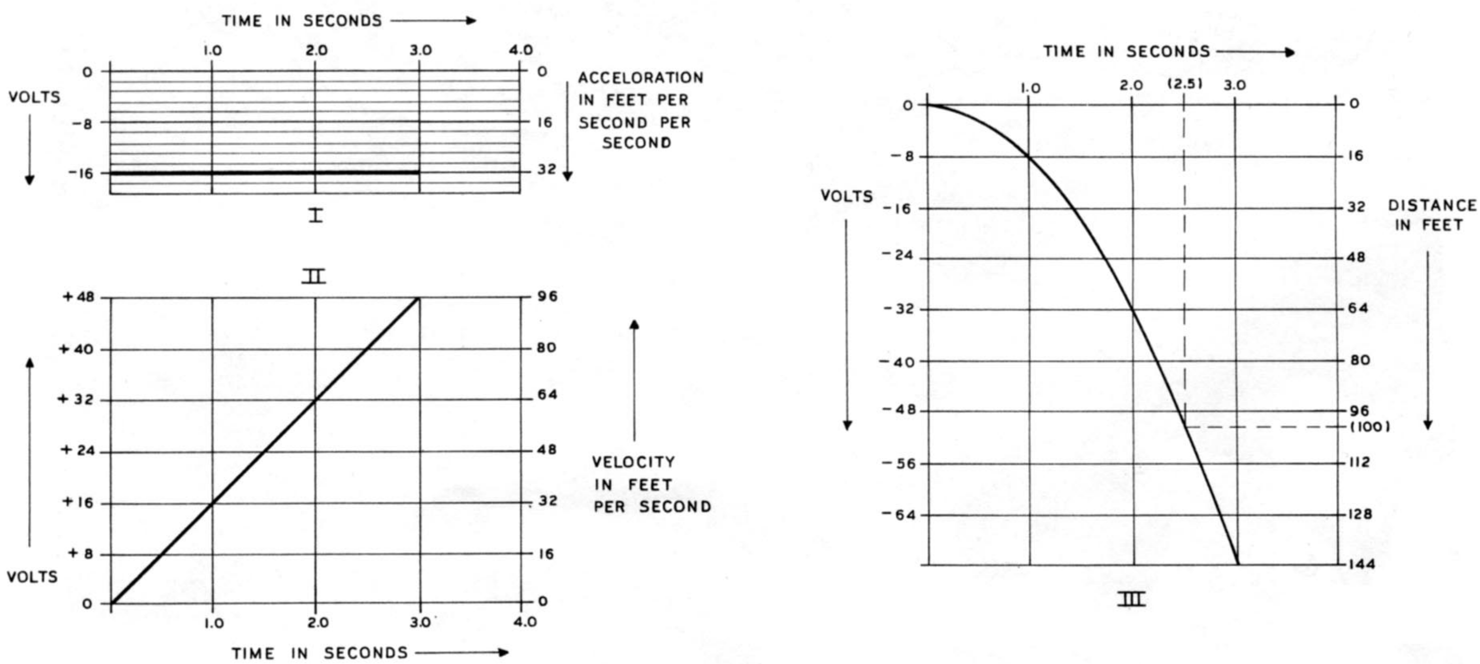



Figure 20

## DIODES

Problems are frequently encountered in which non-linear functions must be simulated. This may be done by means of the function generator which is described in the next section. For some cases either relays or diodes can be used. For general use diodes are generally superior to relays since suitable relays must be capable of very high-speed operation and have high sensitivity. There is also the problem of contact wear.

Crystal diodes can be used but are generally unsatisfactory because of finite back resistance. Fairly satisfactory crystal diodes are available at rather great cost. They have, of course, the advantages of requiring no filament supply and of having small physical size. In order to combine economy with satisfactory operation the Heath Analog Computer uses vacuum-tube diodes. The filament supply is wired in the computer while the anode and cathode connections are brought to jacks on the problem board as shown in Figure 21.

Four 6AL5 double diodes are used making available 8 diodes.

Diodes are used as limiters in problems in which a function is defined differently for different regions of the independent variable. Such a function might be defined as follows:

$$e_0 = -K_1 \qquad e_i < -K_1$$

$$e_0 = e_i \qquad -K_1 < e_i < K_2$$

$$e_0 = K_2 \qquad e_i > K_2$$

where $K_1$ and $K_2$ are constants.

Various limiting circuits can be used, one of which is shown in Figure 22. This is a series limiter circuit which is not the best as it does not provide as sharp limiting as some other circuits. It is, however, simple and does not require special components. Commonly encountered problems requiring these or similar techniques include hysteresis, backlash, certain types of friction and displacement limiting. A detailed discussion of non-linear operation will be found in the literature. *

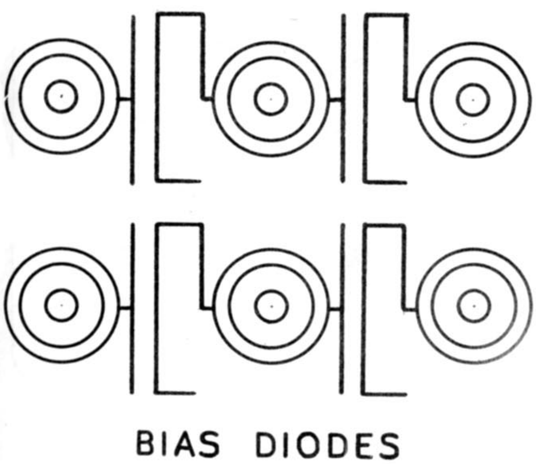



Figure 21

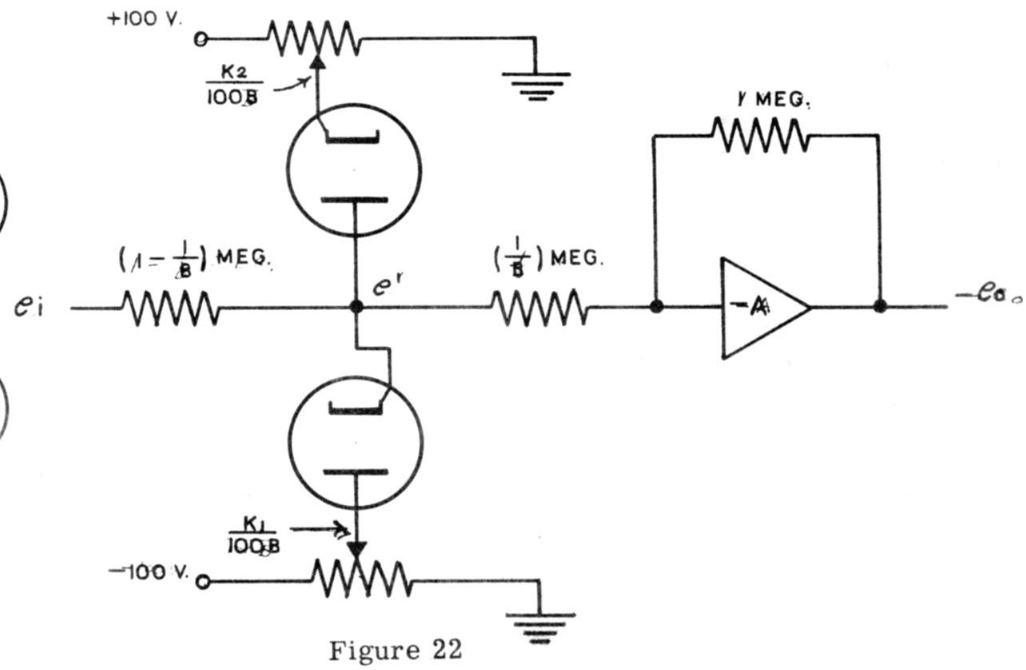



Figure 22

*See, for example: Morrill and Baum. Diode Limiters Simulate Mechanical Phenomena, ELECTRONICS, Vol. 25, No. 11, pp. 122 - 126.
Johnson: Analog Computer Techniques, Chapter 7, p. 107.

## FUNCTION GENERATOR

For general use a function generator is desirable. The Heath Function Generator may be used to generate almost any function. This is done by use of straight line segments which are combined to approximate curves such as are found in trigonometric functions as well as stepped functions. A total of ten segments is used, five in the plus x direction and five in the minus x direction. This is done by the use of ten diodes, each diode representing a line segment. Actually in the Heath Function Generator, five 6AL5 double diodes are used.

The break voltage and segment slopes are set by the controls on the panel of the generator. A drawing of the panel is shown in Figure 23.

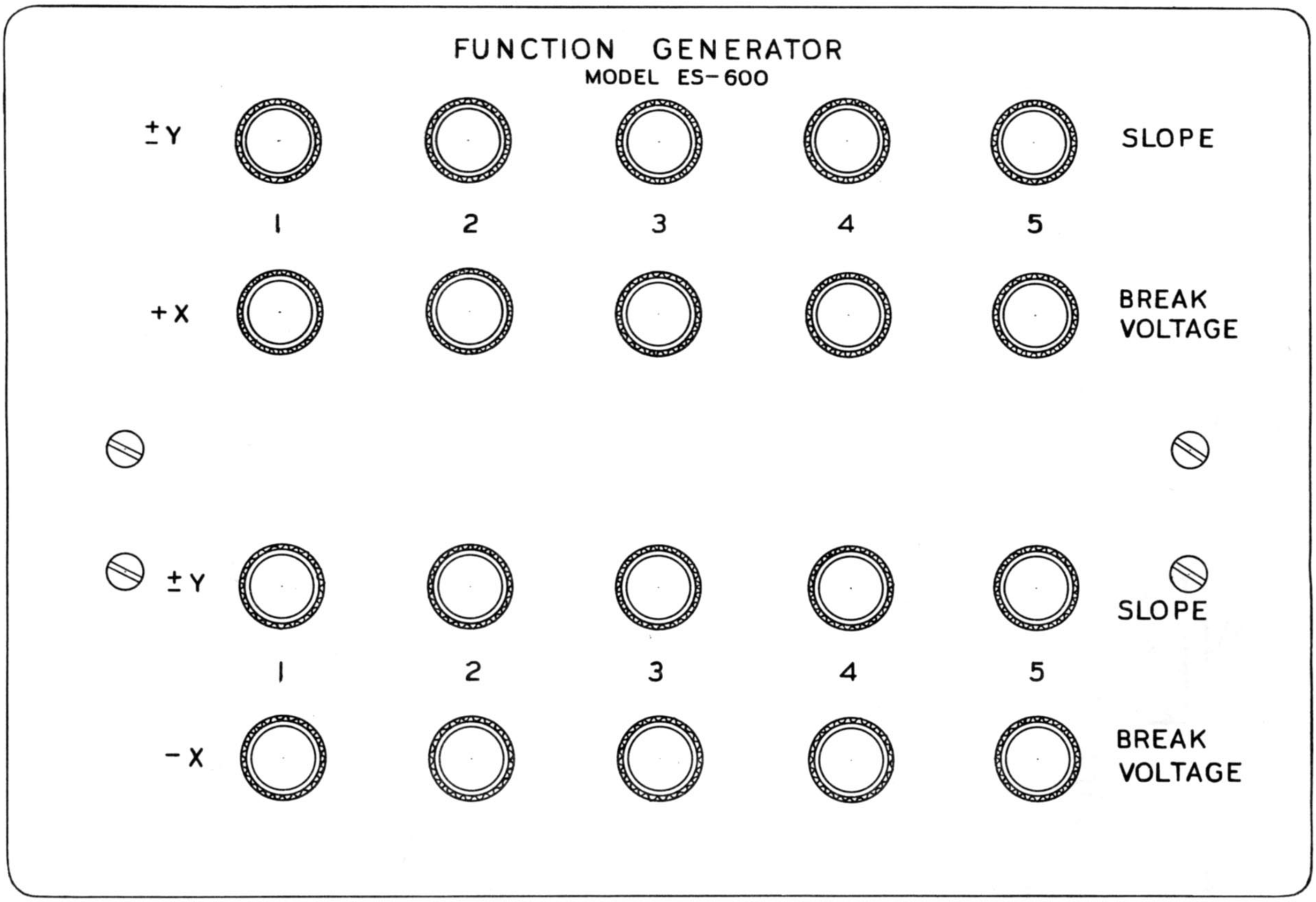



Figure 23

Each line segment is generated by a modified bridge circuit. Figure 24 shows a simplified version of this circuit.

A ramp function or voltage is fed into one arm of the bridge while the opposite arm is connected to a biased diode. The other two arms of the bridge combine to form the output. The voltage appearing at one of these arms is fed through a sign changing amplifier and then summed with the voltage appearing at the opposite arm. If the arm of potentiometer P (the slope control) is set in the center, the bridge will be balanced and the output of the summing amplifier will be zero. If, on the other hand, potentiometer P is adjusted one way or the other from center, the bridge will be unbalanced and the summing amplifier output will vary linearly with respect to the input in either a positive or negative y direction depending upon which side of center potentiometer P is set.

The break voltage, or value of x at which a straight line segment will begin, is set by biasing the diode to the particular voltage level or value of x desired.

The ramp-function generator has either a positive or negative input which because of the 180° phase shift in the amplifier, gives a minus or plus x output respectively.

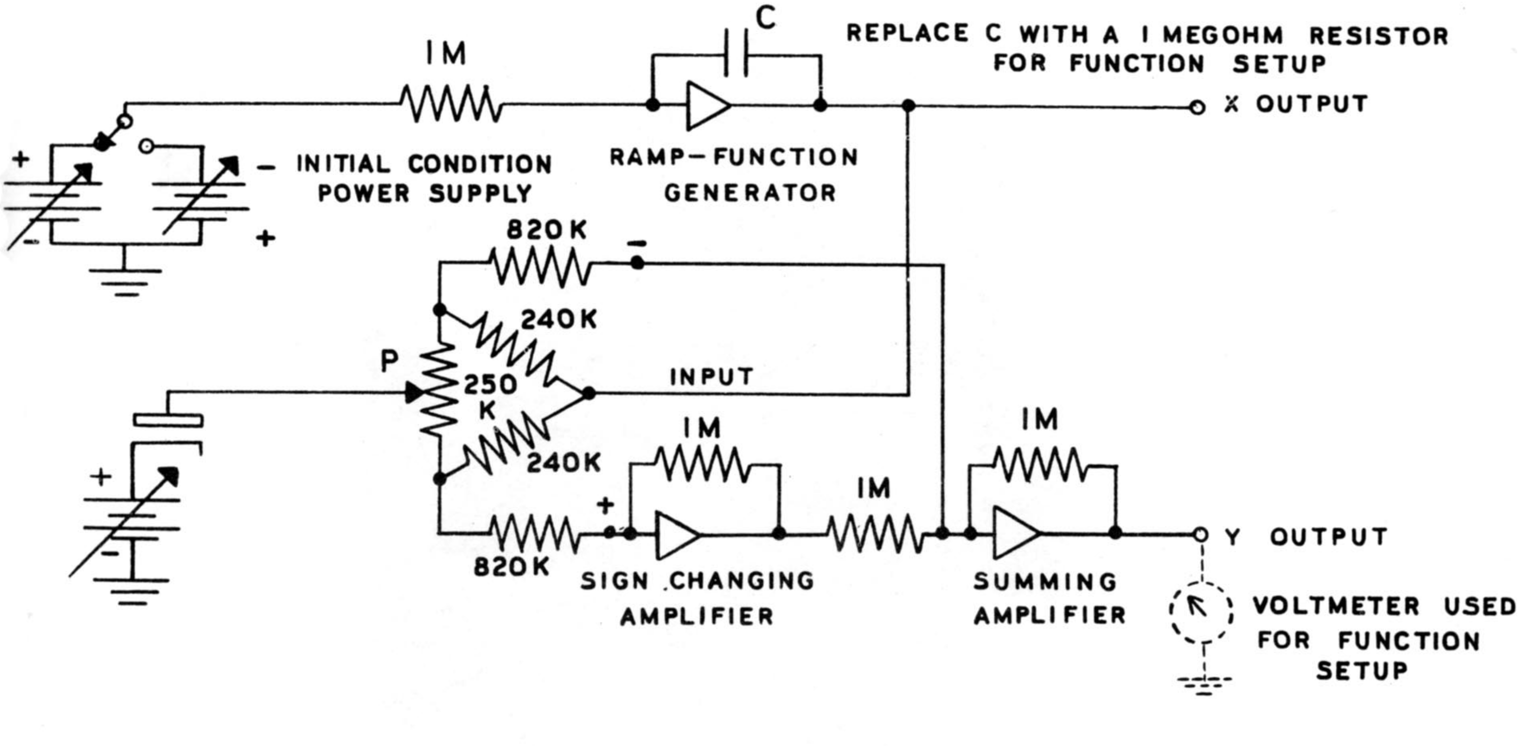



Figure 24

The following illustrates the interconnections and operation of the function generator in connection with the computer.

On the back of the computer cabinet is a strip containing Varicon sockets as shown in Figure 25.

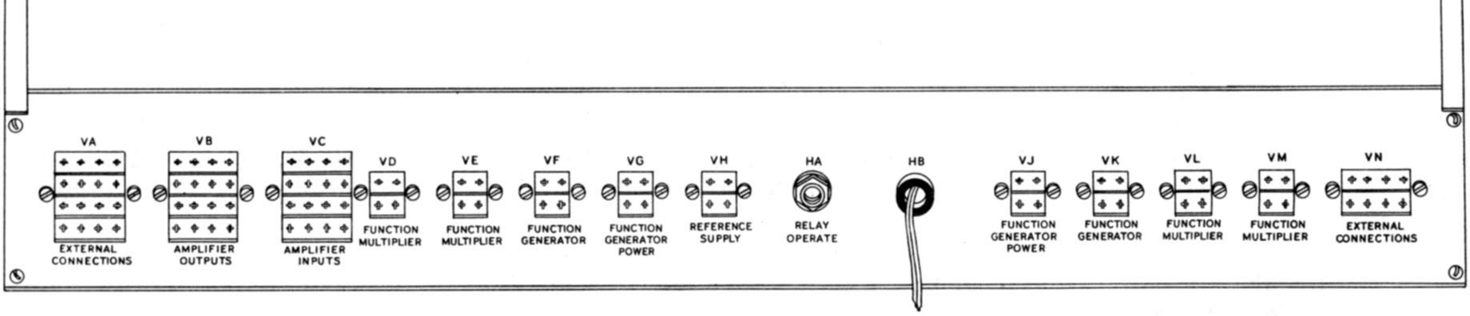



**Figure 25**

There are three cables on the back of the function generator. Plug the power cord into a 105-125 volt, 60 cycle outlet. Plug the 4-prong Varicon connector on the 4-conductor cable into either one of the Varicon sockets labeled FUNCTION GENERATOR POWER (VG or VJ). The 4-prong Varicon connector on the four shielded cables in the large sleeving is plugged into the Varicon socket labeled FUNCTION GENERATOR (VF or VK). If VF is used the Function Generator is now connected to the jacks on the righthand side of the panel. The power to the Function Generator is on when it is plugged in. When not in use it should be unplugged.

Connections to the function generator are made on the front panel as shown in Figure 26.

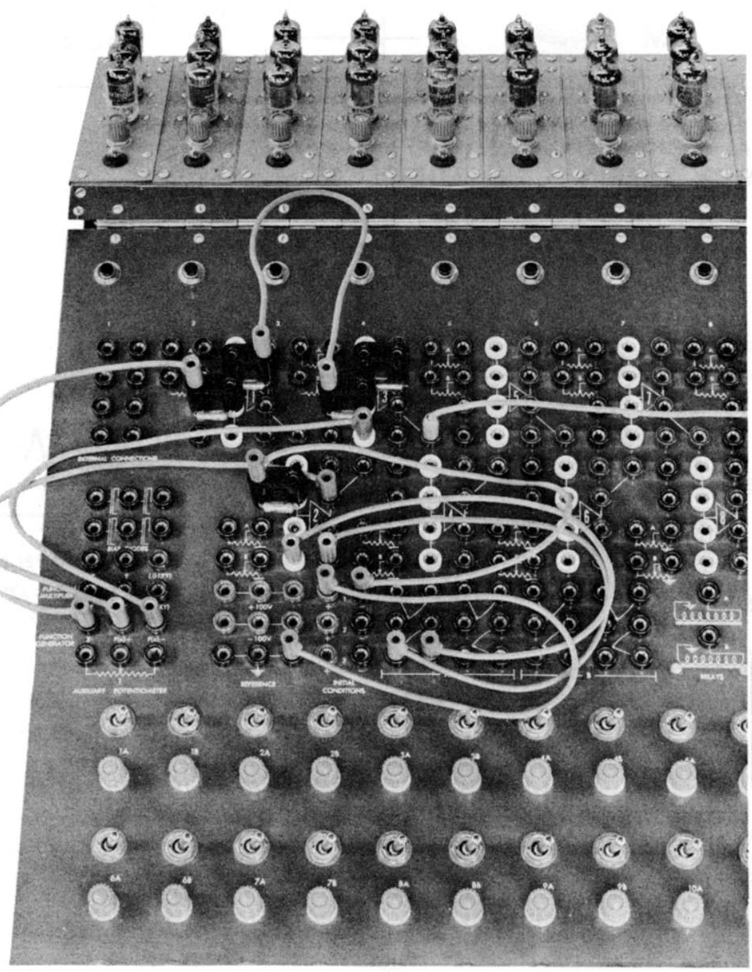


Figure 26

If more output is needed at the Y output a 10 megohm resistor may be used in the feedback of the summing amplifier instead of the 1 megohm resistor shown.

Connect the Y-output to a DC voltmeter as shown in Figure 24. Turn all of the slope and break voltage controls to the extreme clockwise position. Replace the feedback capacitor on the Ramp-Function Generator Amplifier with a 1 megohm resistor. This will apply a fixed DC voltage to the input of the function generator. For functions in the plus x-direction feed the ramp-function generator amplifier with a negative DC voltage from an initial condition power supply.

As an example, set up the function shown in Figure 27.

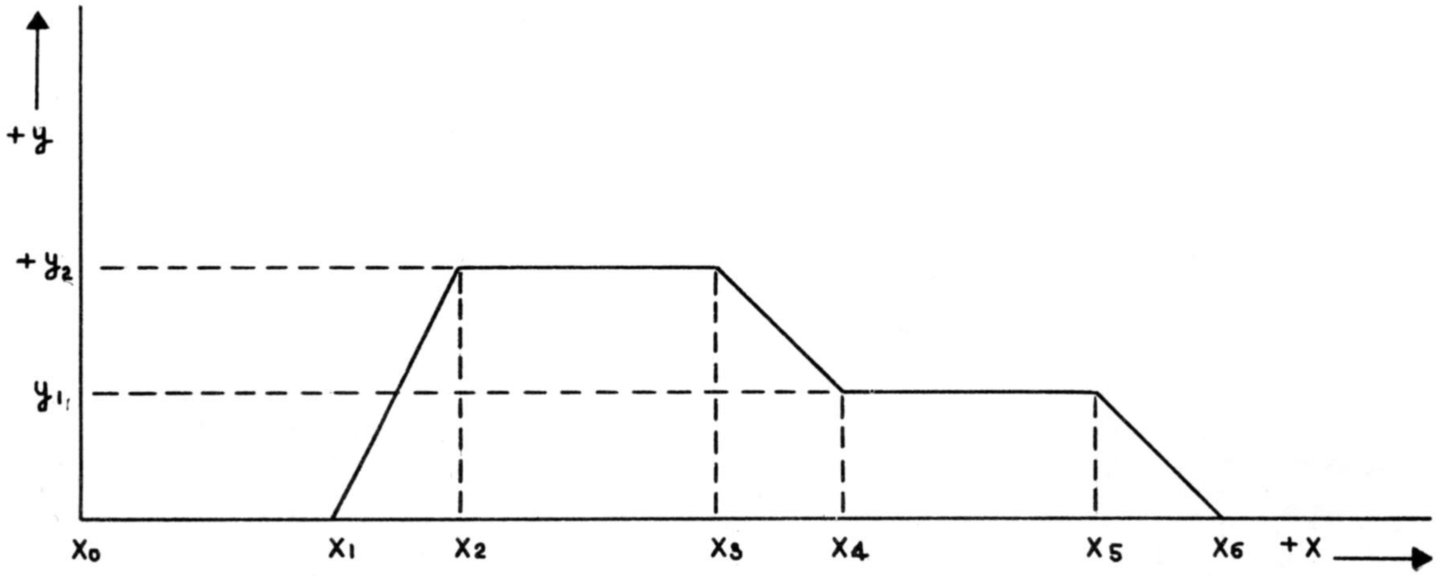



Figure 27

Set the initial condition voltage to the value $x_1$. Since this function is in the +x direction use the break voltage controls marked +x. Turn the break voltage control number 1 counterclockwise until the reading on the meter connected to the output of the summing amplifier changes abruptly. This indicates that diode number 1 has started conducting. Now set the input voltage from the initial condition power supply to the value $x_2$. Turn slope control number 1 immediately above break-voltage control number 1 until the meter on the output reads the value $+y_2$. Now turn break-voltage control number 2 counterclockwise until the meter reading changes abruptly. This indicates that diode number 2 is conducting. Now set the initial condition voltage to a value $x_3$. Turn slope control number 2 until the output meter reads $y_2$.

In the same manner set break voltage and slope controls 3, 4 and 5. After setting all controls replace the 1 megohm feedback resistor of the ramp-function generator amplifier with a 1 $\mu$fd capacitor.

When using an oscilloscope for read-out the x-output of the ramp-function generator amplifier may be used as the horizontal sweep for the oscilloscope. The y-output is fed into the computer problem set-up where indicated by the nature of the problem.

Provision is made on the computer panel for the use of two function generators.

## BIBLIOGRAPHY

### BOOKS - ANALOG COMPUTERS

Johnson, C. L.: Analog Computer Techniques. McGraw-Hill, 1956.

Korn, G. A. and Korn, T. M.: Electronic Analog Computers. McGraw-Hill, 1956 (2nd Ed.).

Paynter, H. M. (Editor): A Palimpsest on the Electronic Analog Art. George A Philbrick Researchers, Inc., 1955. (A collection of reprints of papers and other writings which have been in demand over the past several years.)

Soroka, W. W.: Analog Methods in Computation and Simulation. McGraw-Hill, 1954.

Wass, C. A. A.: Introduction to Electronic Analog Computers. McGraw-Hill, 1955.

### BOOKS - ANALOG AND DIGITAL COMPUTERS

Berkeley, E. C. and Wainwright, L.: Computers - Their Operation and Applications. Reinhold Publishing Corporation, 1956.

Staff: Engineering Research Associates, Inc.: High-Speed Computing Devices. McGraw-Hill, 1950.

Ivall, T. E.: Electronic Computers. Philosophical Library, Inc., New York, 1956.

### PAMPHLETS

Howe, C. E. and Howe, R. M.: A Tabletop Electronic Differential Analyzer. University of Michigan, Ann Arbor, 1953. Department of Aeronautical Engineering, Publication Air - 6.

Nichols, M. H. and Hagelbarger, D. W.: A Simple Differential Analyzer as a Demonstration and Laboratory Aid to Instruction in Engineering. University of Michigan, Ann Arbor, 1951. Department of Aeronautical Engineering.

Bibliographies in the above books will give references to many journal articles on specific applications of Analog Computers.

### APPENDIX A. REFERENCES TO SPECIFIC TYPES OF PROBLEMS

Han Chang, R. C. Lathrop and V. C. Rideout, "The Study of Oscillator Circuits by Analog Computer Methods." Proceedings of the National Electronics Conference - 1950.

Carl Heald, "Putting the Analog Computer to Work." ISA Journal, Vol. 3, No. 8, August, 1956. (Illustrates a bridge beam problem and a servomechanism generator control system problem.)

Vernon L. Larrowe, "Direct Simulation Bypasses Mathematics, Simplifies Analysis." Control Engineering, November, 1954. (Good.)

H. G. Markey and V. C. Rideout, "Analog Computer Solution of a Nonlinear Differential Equation." Palimpsest, pp. 177 - 183.

R. C. McMaster, R. L. Merrill, B. H. List, "Analogous Systems in Engineering Design." Product Engineering, January, 1953.

John E. Nolan, "Analog Computers and Their Application to Heat Transfer and Fluid Flow." Computers and Automation. Part 1 - November, 1954; Part 2 - December, 1954; Part 3, Bibliography - January, 1955.

James B. Reswick, "Scale Factors for Analog Computers." Product Engineering, March, 1954.

The Heath Electronic Analog Computer in use in an Engineering Laboratory. The engineer is setting up the computer to solve a problem involving bridge beam loading.

This is only one of many types of problems which can be solved on the Heath Computer.

This versatile and practical device is especially adaptable to industry* as well as in the College or University Laboratory.

* Thus freeing your engineers from the routine solving of mathematical equations.

# Lab Performance AT 1/2 THE PRICE YOU EXPECT TO PAY!

MODEL O-11

**Vertical Channel:**

| | |
|---|---|
| Sensitivity | 0.025 volts (RMS) per inch at 1 kc. |
| Frequency Response | Flat within ± 1 db from 8 cps, to 2.5 mc. Flat, + 1.5 to −5 db; 3 cps to 5 mc. Response at 3.58 mc, −2.2 db. (All response measurements referred to 1 kc) |

**Horizontal Channel:**

| | |
|---|---|
| Sensitivity | 0.6 volts (RMS) per inch at 1 kc. |
| Frequency Response | Flat within ± 1 db 1 cps to 200 kc. Flat within ± 3 db 1 cps to 400 kc. |
| Input Impedance | 30 megohms shunted by 31 mmf. (1 kc impedance, 4.9 megohms) |
| Attenuator | Low impedance type in cathode follower output. |

**Sweep Generator:**

| | |
|---|---|
| Range | 20 cps to 500 kc in five steps: 20 to 100 cps, 100 to 1000 cps, 1 to 10 kc, 10 to 100 kc, 100 to 500 kc. |
| Synchronizing | Selector switch permits synchronizing sweep generator with either positive or negative signal pulses internally, with external source through panel terminal or with line frequency. |

Push-Pull Amplifiers

Etched-Metal Circuit Boards

## Heathkit "Extra Duty" 5″ Oscilloscope Kit

This fine oscilloscope compares favorably to other scopes costing twice its price. It contains the extra performance so necessary for monochrome and color-TV servicing. Features push-pull horizontal and vertical output amplifiers, a 5UP1 CRT, built-in peak-to-peak calibration source, a fully compensated three-position step-type input attenuator, retrace blanking, phasing control, and provision for Z-axis modulation. Vertical amplifier frequency response is within +1.5 and −5 db from 3 CPS to 5 MC. Response at 3.58 MC down only 2.2 db. Sensitivity is 0.025 volts RMS/inch at 1 KC. Sweep generator covers 20 CPS to 500 KC in five steps. Etched-metal circuit boards reduce assembly time and minimize errors in assembly, and more importantly, permit a level of circuit stability never before achieved in an oscilloscope of this type. Shop and compare. You can't beat it!

# Easy Construction WITH CIRCUIT BOARDS

The V-7A will measure AC (RMS) and DC voltages in ranges of 0-1.5, 5, 15, 50, 150, 500 and 1500. It measures peak-to-peak AC voltage in ranges of 0-4, 14, 40, 140, 400, 1400 and 4000. Resistance ranges provide multiplying factors of X1, X10, X100, X1,000, X10K, X100K and X1 megohm. Center-scale resistance readings are 10, 100, 1,000, 10K, 100K, 1 megohm and 10 megohms. A db scale is also provided. The precision and quality of this VTVM cannot be duplicated at this price

## Heathkit Etched-Circuit VTVM Kit

MODEL V-7A

This multi-purpose VTVM is the world's largest selling instrument of its type—and is especially popular in laboratories, service shops, home workshops and schools. It employs a large 4½″ panel meter, precision 1% resistors, etched metal circuit boards, and many other "extras" to insure top quality and top performance. It's easy to build, and you may rely on its accuracy and dependability.


Function Generator Model ES-600 Now Available

HEATH COMPANY • BENTON HARBOR, MICHIGAN

*A Subsidiary of Daystrom, Inc.*

# HELPFUL KIT BUILDING INFORMATION

Before attempting actual kit construction read the construction manual through thoroughly to familiarize yourself with the general procedure. Note the relative location of pictorials and pictorial inserts in respect to the progress of the assembly procedure outlined.

This information is offered primarily for the convenience of novice kit builders and will be of definite assistance to those lacking thorough knowledge of good construction practices. Even the advanced electronics enthusiast may benefit by a brief review of this material before proceeding with kit construction. In the majority of cases, failure to observe basic instruction fundamentals is responsible for inability to obtain desired level of performance.

## RECOMMENDED TOOLS

The successful construction of Heathkits does not require the use of specialized equipment and only basic tools are required. A good quality electric soldering iron is essential. The preferred size would be a 100 watt iron with a small tip. The use of long nose pliers and diagonal or side cutting pliers is recommended. A small screw driver will prove adequate and several additional assorted screw drivers will be helpful. Be sure to obtain a good supply of rosin core type radio solder. Never use separate fluxes, paste or acid solder in electronic work.

## ASSEMBLY

In the actual mechanical assembly of components to the chassis and panel, it is important that the procedure shown in the manual be carefully followed. Make sure that tube sockets are properly mounted in respect to keyway or pin numbering location. The same applies to transformer mountings so that the correct transformer color coded wires will be available at the proper chassis opening.

Make it a standard practice to use lock washers under all 6-32 and 8-32 nuts. The only exception being in the use of solder lugs—the necessary locking feature is already incorporated in the design of the solder lugs. A control lock washer should always be used between the control and the chassis to prevent undesirable rotation in the panel. To improve instrument appearance and to prevent possible panel marring use a control flat nickel washer under each control nut.

When installing binding posts that require the use of fiber insulating washers, it is good practice to slip the shoulder washer over the binding post mounting stud before installing the mounting stud in the panel hole provided. Next, install a flat fiber washer and a solder lug under the mounting nut. Be sure that the shoulder washer is properly centered in the panel to prevent possible shorting of the binding post.

## WIRING

When following wiring procedure make the leads as short and direct as possible. In filament wiring requiring the use of a twisted pair of wires allow sufficient slack in the wiring that will permit the twisted pair to be pushed against the chassis as closely as possible thereby affording relative isolation from adjacent parts and wiring.

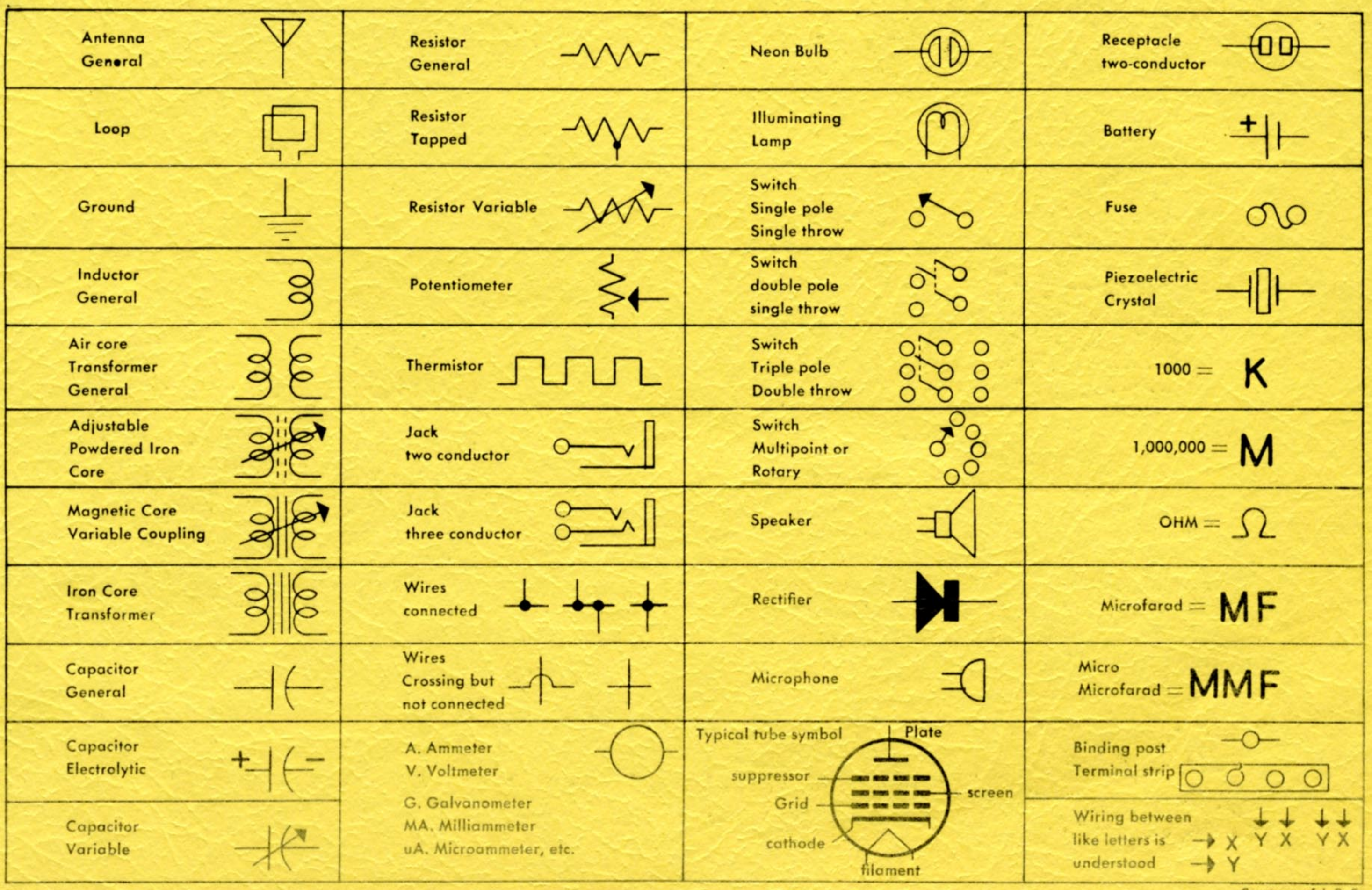
When removing insulation from the end of hookup wire, it is seldom necessary to expose more than a quarter inch of the wire. Excessive insulation removal may cause a short circuit condition in respect to nearby wiring or terminals. In some instances, transformer leads of solid copper will have a brown baked enamel coating. After the transformer leads have been trimmed to a suitable length, it is necessary to scrape the enamel coating in order to expose the bright copper wire before making a terminal or soldered connection.

In mounting parts such as resistors or condensers, trim off all excess lead lengths so that the parts may be installed in a direct point-to-point manner. When necessary use spaghetti or insulated sleeving over exposed wires that might short to nearby wiring.

It is urgently recommended that the wiring dress and parts layout as shown in the construction manual be faithfully followed. In every instance, the desirability of this arrangement was carefully determined through the construction of a series of laboratory models.

## SOLDERING

Much of the performance of the kit instrument, particularly in respect to accuracy and stability, depends upon the degree of workmanship used in making soldered connections. Proper soldered connections are not at all difficult to make but it would be advisable to observe a few precautions. First of all before a connection is to be soldered, the connection itself should be clean and mechanically strong. Do not depend on solder alone to hold a connection together. The tip of the soldering iron should be bright, clean and free of excess solder. Use enough heat to thoroughly flow the solder smoothly into the joint. Avoid excessive use of solder and do not allow a flux flooding condition to occur which could conceivably cause a leakage path between adjacent terminals on switch assemblies and tube sockets. This is particularly important in instruments such as the VTVM, oscilloscope and generator kits. Excessive heat will also burn or damage the insulating material used in the manufacture of switch assemblies. Be sure to use only good quality rosin core radio type solder.




Courtesy of I. R. E.

# HEATH COMPANY

*A Subsidiary of Daystrom Inc.*

***THE WORLD'S FINEST ELECTRONIC EQUIPMENT IN KIT FORM***

**BENTON HARBOR, MICHIGAN**

6-14-57



Litho in U. S. A.