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An Introduction to ANALOG COMPUTERS

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FOR CENTURIES man has been utilizing simple analog devices to solve mathematical problems by analogy. In other words, numbers are converted into something else which can be worked with more easily than the numbers themselves. One everyday example is the slide rule, which converts numbers into distances, then reconverts the summed distances into numbers, providing a solution. Anyone who has multiplied two numbers on a slide rule will testify to its operating ease, rapid solution, and remarkable accuracy.

This article will go one step beyond the slide rule and describe a direct-reading analog computer which will solve simple addition and multiplication problems, extract roots, and perform trigonometric operations. So simple is this computer that it could be called an "electronic slide rule."

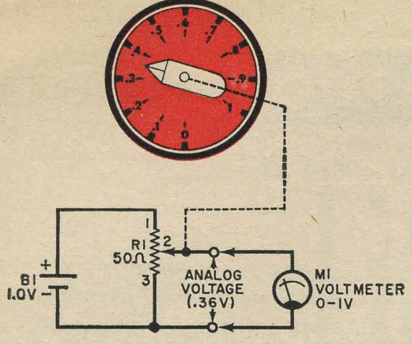

Fig. 1. A potentiometer can be used to convert dial settings to correspondingly equal voltages. When the dial is set at .36, the wiper picks off .36 volt d.c.

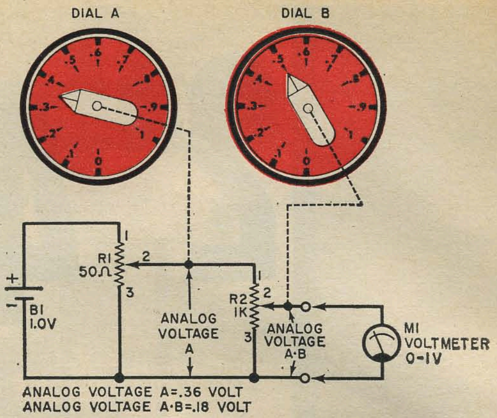

Fig. 2. Two cascaded potentiometers develop voltage analog equal to product of the dial settings.

Voltage Analog. An ordinary potentiometer will help us see how a number can be converted into a voltage analog. Figure 1 shows a simple circuit of a potentiometer, *R1,* connected in series with a battery, *B1.* Rotating the dial pointer on the shaft of *R1* causes the potentiometer wiper to "pick off" a voltage proportional to the dial setting.

In Fig. 1, the dial is calibrated from zero to one and the voltage supplied by the battery is 1.0 volt. Thus, in this particular instance, the dial setting indicates the voltage at the wiper of the potentiometer. A voltmeter connected at the output terminals of this circuit will indicate the setting of the dial—0.36 volt would mean that the dial is set at 0.36 unit. The voltage is an analog voltage, since it may represent a dial quantity of 0.36 acre, quart, or even light year.

Multiplying. In Fig. 1, a voltage analog for the number 0.36 was developed at the wiper of *R1.* It can also be said that the supply voltage across *R1* was multiplied by 0.36. Thus, 1.0 volt times 0.36 will be 0.36 volt. If a voltage other than 1.0 volt were supplied by *B1* in Fig. 1, we would be multiplying the supply voltage by the dial setting.

This apparent ability of potentiometers to multiply can best be seen in Fig. 2. Battery *B1* supplies 1.0 volt across potentiometer *R1.* Dial *A* is set at 0.36 so that analog voltage *A* developed at the wiper of *R1* (0.36 volt) is applied across potentiometer *R2.* Dial *B* is set at 0.50 so that the voltage at the wiper of *R2* will be only 0.50 times the voltage across *R2,* or simply 0.36 x 0.50. The voltage developed at the wiper of *R2* is appropriately called analog voltage A·B, and voltmeter *M1* will indicate this voltage to be 0.18—the product of 0.36 and 0.50.

Loading Error. Looking again at Fig. 2, you will note that the value of potentiometer *R1* is 50 ohms, whereas potentiometer *R2* is a 1000-ohm unit. The reason for this is quite simple, provided you down-gear your thinking from analog computers to simple d.c. networks. Figure 3(A) corresponds to Fig. 2 when the wiper of *R1* is set at 0.50 or mid-position. Hence, *R1a* in Fig. 3(A) represents the "top half" of *R1* in Fig. 2 (the portion between terminals 1 and 2). Likewise, *R1b* represents the "bottom half" of *R1* (the portion between terminals 2 and 3). We know from the dial setting that analog voltage *A should be* 0.50 volt. However, let's see what analog voltage *A* actually is in Fig. 3(A).

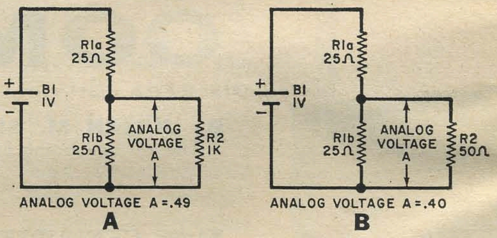

Fig. 3. Circuits showing cause for loading error (A) when R2 is 1000 ohms, (B) when R2 is 50 ohms.

First, since *R1b* and *R2* are in parallel, their combined resistance is approximately 24.4 ohms. Using Ohm's law, we find that the voltage drop across *R1b* (in parallel with *R2*) is approximately 0.49 volt. This means that *R2* in Fig. 2 will tend to lower the true value of analog voltage *A* and introduce a small error. In the case cited, the error is only 2%—not much for this simple computer circuit.

In Fig. 3(B), the value of *R2* was selected as 50 ohms solely to illustrate the loading effect of *R2* on *R1b*. In this instance, the combined resistance of *R1b* and *R2* is approximately 17 ohms. Again resorting to Ohm's law, we find analog voltage *A* developed across *R1b* and *R2* to be approximately 0.40 volt. Compared to the desired analog voltage of 0.50, the loading effect of a 50-ohm potentiometer will introduce an error of 20%—an excessive amount for most purposes.

It should be evident, then, that when two potentiometers are connected as shown in Fig. 2, the second one (*R2*) should be many times larger than the first one (*R1*). However, do not be tempted into believing a potentiometer with a very large resistance—one megohm, say—will completely solve our loading problem. Even if the resistance value of the second potentiometer is very large, a voltmeter connected across its wiper and bottom terminal will also cause a loading effect and hence introduce error. This is due to the resistance of the voltmeter itself—usually only several thousand ohms.

Galvanometer Indicator. One method of removing the loading effect of the voltmeter (*M1*) used in Fig. 2 is to replace it with an indicator that requires no current to indicate the analog voltage developed by a potentiometer. Such a device is the galvanometer indicator shown schematically in Fig. 4.

Close inspection of the circuit in Fig. 4 reveals that current will flow though galvanometer *M1* whenever the wipers of potentiometers *R2* and *R3* select voltages that are not equal. This condition causes the galvanometer pointer to deflect either to the left or right of its normal "center rest" or "zero deflection" position.

Since dial *B* is preset to "some number" input, as described earlier, it remains for dial *C* to be adjusted until the voltage at the wiper of *R3* equals the voltage at the wiper of *R2*. When this occurs, the voltage drop across the galvanometer is zero, resulting in zero current through the galvanometer and no deflection of the meter's pointer. Dial *C*, which is calibrated to convert the voltage picked off by *R3* to numbers, indicates the correct value of analog voltage A·B. Since the electrical components *M1* and *R3* draw no current from *R2*, there is no loading on the analog circuits and no errors are introduced into the electrical computations by the galvanometer.

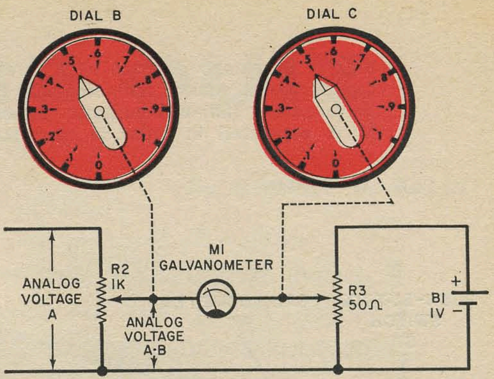

Fig. 4. No loading error occurs when voltage on wiper of R3 equals analog voltage A·B, or .5 volt.

An important fact to note in Fig. 4 is that potentiometer *R3* has a value of 50 ohms. This is permissible, since (1) *R3* does not load the computer circuits when the correct answer is set on dial *C* and (2) the lower value is desired so that when an incorrect answer is selected the deflection of *M1* will be large due to the large currents flowing through the galvanometer movement. This large deflection due to an incorrect answer enables the computer operator to adjust dial *C* accurately for a galvanometer null or zero deflection. In operation, of course, the galvanometer deflects either to the right or left of its center position, depending upon whether the wiper of *R3* is positive or negative with respect to the wiper of *R2*.

Complete Circuit. The simple analog computer circuit shown in Fig. 5 is identical to the one used in the analog computer kit made by the Edmund Scientific Co., Barrington, N. J. (see Fig. 6) and is the culmination of the circuits shown in Figs. 1 through 4.

Two interesting points should be noted:

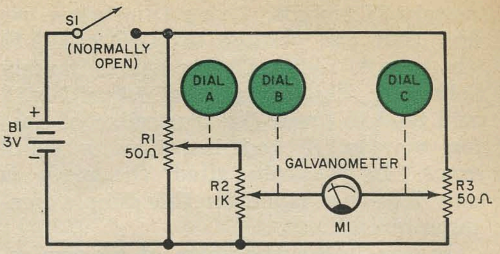

Fig. 5. Schematic diagram of a three-potentiometer analog computer with a galvanometer (MI) null indicator. Switch SI is depressed in order to read MI.

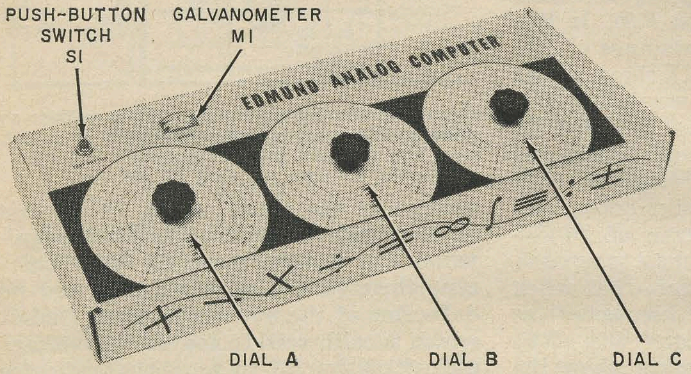

Fig. 6. Circuit components seen on front panel of Edmund Analog Computer are identified here. Each dial has four concentric scales.

the first one is that the battery voltage of *B1* is 3 volts. Previously in our discussion, we used a "1-volt" battery for *B1*. This variance in voltage suggests that the voltage of *B1* is not critical, as is actually the case.

Examine Fig. 5 carefully and note that *B1* is connected across two resistive legs: the summed resistances of *R1* and *R2*, and the resistance of *R3*. Galvanometer *M1* is used to detect a zero voltage difference between the resistive legs exactly like its counterpart in the Wheatstone bridge. Therefore, as long as the two resistive legs receive the same voltage, its value is unimportant.

The second point to be noted in Fig. 5 is that a switch (*S1*) has been added. This push-button switch is nothing more than an on/off switch for reducing battery drain. It is depressed only after dials *A* and *B* have been set to desired values and dial *C* is being adjusted so that the galvanometer indicates a null.

Sound Null. Another good way to determine when the analog computer is tuned to a null (correct answer), is to listen for it rather than look for it. In the Edmund computer, a null can be seen when the galvanometer is not deflected. In an analog computer kit made by General Electric (see cover photo), the galvanometer has been replaced with a headset; since the headset can only detect audio signals, the computer potentiometers are powered by an audio signal generator and not by dry cells. Except for these two changes, the General Electric analog computer kit is electrically identical to the Edmund kit.

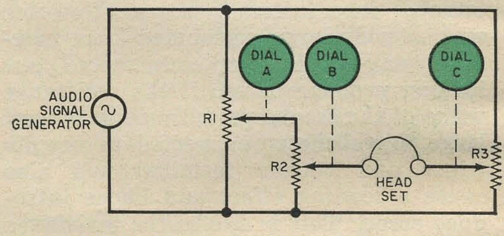

Fig. 7. Simplified schematic of G.E.'s "Project 4" computer. Headset is used to detect sound nulls.

Figure 7 is a simplified schematic drawing of the G.E. analog computer circuit. To operate, the computer potentiometers are preset to fixed input quantities and the "answer" potentiometer (connected to the *C* dial) is rotated until the audio sound is no longer heard in the headset.

Dials. The dials for both the Edmund and General Electric kits are accurately calibrated so that many complex prob-

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lems can be performed. The similarity of the dials found in each kit can be seen in Fig. 8.

The Edmund dials include a linear scale plus logarithmic and trigonometric scales, whereas the General Electric dials have in addition "squared" and reciprocal scales. Instruction manuals provided with both kits give detailed instructions on how to use these dials to solve many typical problems closely related to electrical technology and science.

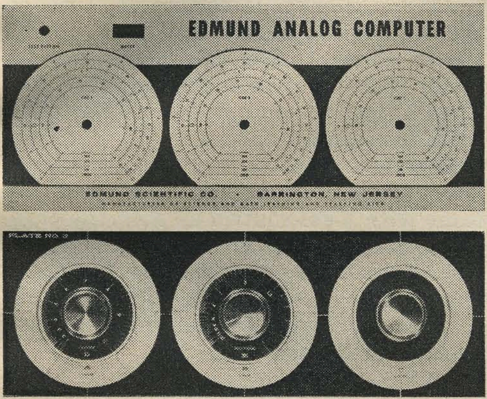

Fig. 8. Dials on Edmund Analog Computer have four scales each, while G.E.'s kit has more but unclutters scales by using removable dial scale plates.

A Fraction of the Field. The "ground floor" introduction to analog computers which you have just read naturally covers but a very small fraction of the total analog computer field. Besides potentiometers, meters, and switches, manufacturers of analog computers also use synchros, two and three-dimensional cams, linkages, gears, and complex electronic circuits to perform the countless specialized functions the human mind may require of a machine.

If you find the subject of analog computers interesting and this ground floor introduction just whets your appetite, you might want to visit your public or school library. Each day, more and more books on this timely subject are being placed on library shelves. Look for them, and be kind to that gent who beat you there—he may be the author of this article! —30—