ALL ABOUT

D/A Converter Applications

A fascinating device, there's more to the digital-to-analog converter than meets the eye. Here's a closer look at the device and its applications.

JOSEPH J. CARR

FOR DIGITAL CIRCUITS AND COMPUTERS TO communicate with the real (analog) world, digital-to-analog converts are necessary. Those converters, commonly available as single IC's, allow data and information to be transferred from one world to the other.

Digital-to-analog converters (DAC's) produce an analog output that is proportional to the product of two inputs. One of those inputs is an n-bit digital word. The other input is either a reference current or a reference voltage. If that input is a reference current, then the output of the DAC can be expressed mathematically by:

$$I_O = I_{REF} \times \left(\frac{A}{2^n}\right) \quad (1)$$

where A is the n-bit digital word. If the input is, instead, a reference voltage, then the DAC's output can be expressed by:

$$E_O = E_{REF} \times \left(\frac{A}{2^n}\right) \quad (2)$$

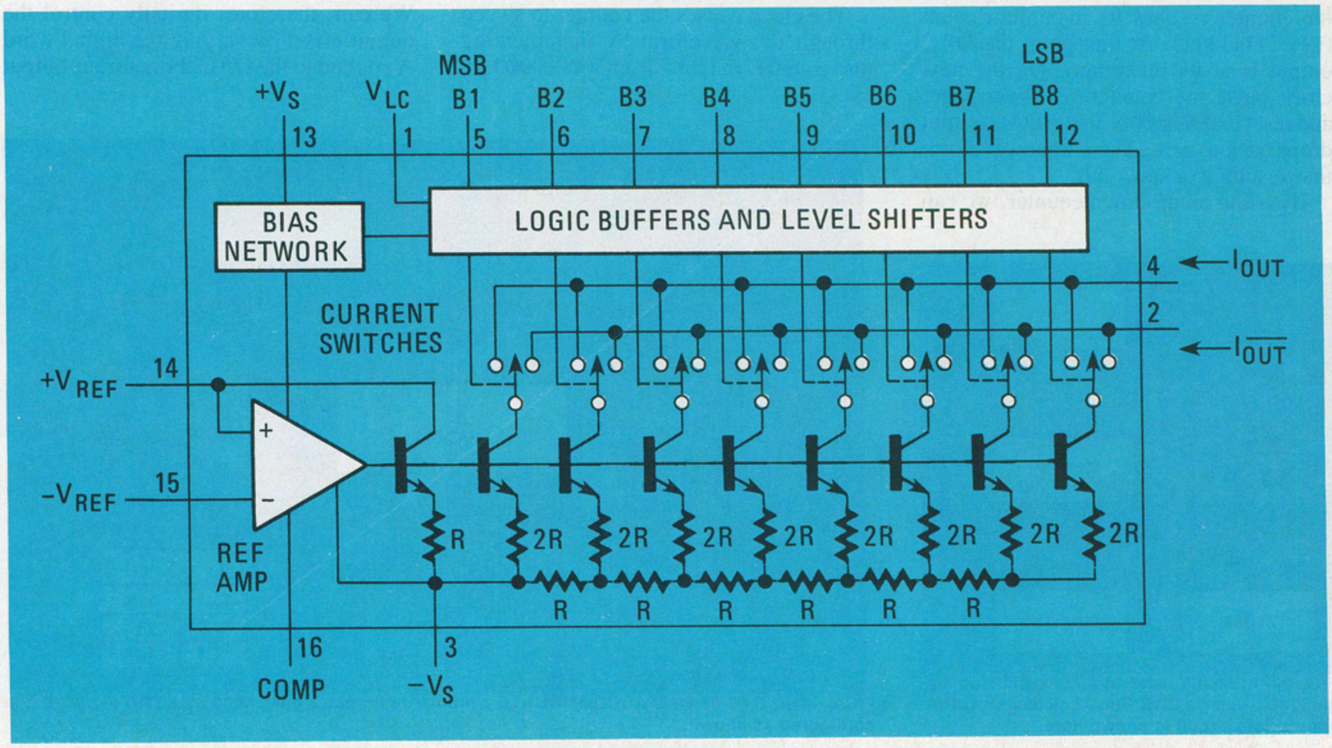
With only a little imagination we can make the DAC perform any number of functions in which equations 1 and 2 play a part. The most obvious function, and that for which the DAC was invented, is to create a DC voltage or current level proportional to the binary number applied to the digital inputs. We could, for example, connect those digital inputs to a computer's output port. The DAC's analog output then will be proportional to the digital value output from the computer. It will be in the form that we (in this analog word) will recognize, and it can be displayed on an oscilloscope or strip-chart recorder.

Figure 1 shows a typical 8-bit current-output multiplying DAC, the DAC-08 (Precision Monolithics, Inc., 1500 Space Park Dr., Santa Clara, CA 95050). Being a current-output device, the operation of the DAC-08 is described by equation 1. The device will produce an output current of (2 mA) × (A/256), where A is the digital word applied to the digital inputs. Amplifier IC2 converts the current output of the DAC-08 to a voltage output. The amplifier output E is given by the expression $I_O \times R3$, so with the component values shown E will range from 0 to 5 volts.

Operational amplifier IC3 is configured as a lowpass filter, and is optional. The output of a DAC is a step waveform, with each step being equal to the DAC's LSB (*L*east *S*ignificant *B*it) voltage. The values shown in Fig. 1 will produce a gain of 2, so the output will be 10 volts for a 5-volt input. The cut-off frequency will be 1000 Hz, but circuit values can be changed to accommodate other frequencies.

Waveform generator

A DAC can be used to generate a sawtooth output waveform by connecting its digital inputs to the output terminals of an ordinary binary counter circuit (see Fig. 2). A 7-bit CMOS 4024 counter can be used with an 8-bit DAC if the clock terminal is used as the LSB input.



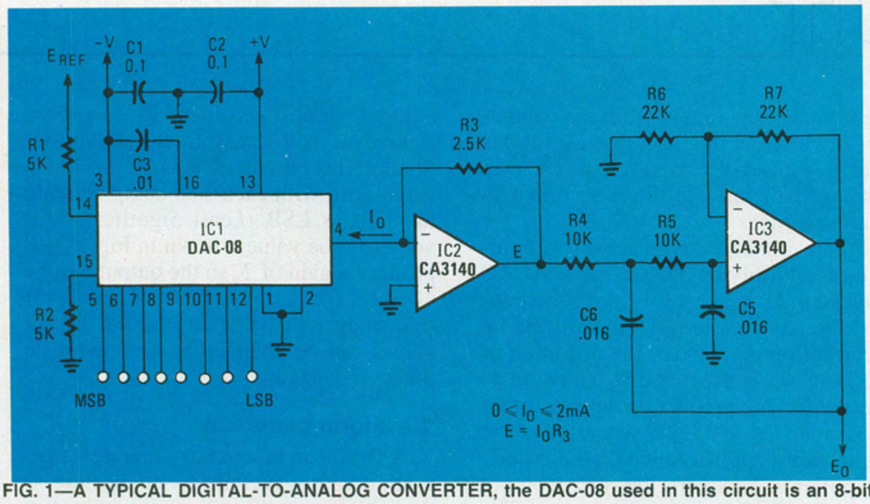


FIG. 1—A TYPICAL DIGITAL-TO-ANALOG CONVERTER, the DAC-08 used in this circuit is an 8-bit current-output multiplying device.

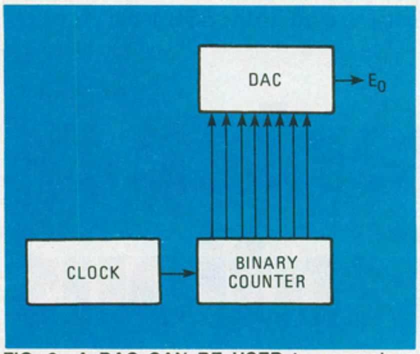


FIG. 2—A DAC CAN BE USED to generate a sawtooth waveform by connecting its input terminals to the outputs of a binary counter.

Let's see what happens. When the counter output is 00000000, the DAC output is zero. As the counter output increments, the DAC output is rising, until the counter reaches its maximum count (i.e. 11111111). At that point the DAC output is at its maximum. On the next clock pulse the counter will overrange, and reset to 00000000, so the DAC output drops back to zero. The output waveform that results is a sawtooth.

By using an up-down counter, we can generate a positive-going (as was done above) or negative-going sawtooth. The latter requires that we count down from the counter's maximum, rather than up from zero.

A triangular waveform can also be generated using an up-down counter. If we count up from 00000000 to 1111111, and then reverse the order and count back down to 00000000 (instead of merely resetting the counter), the output waveform will be a triangle function.

We actually can generate almost any function or waveform that we desire if a circuit such as the one shown in Fig. 3 is used. The bit pattern corresponding to the points on the desired curve are stored in sequential addresses in a ROM. Those bit patterns will be applied sequentially to the digital inputs of the DAC, and cause the instantaneous value of the output voltage to change accordingly.

The clock causes the counter to sweep through the waveform by incrementing the counter outputs from 00000000 to 11111111. The frequency of the generated waveform is controlled by varying the clock speed. That type of circuit, incidentally, is used in electronic music-generation.

Digitally controlled attenuator

Equations 1 and 2 show that a multiplying DAC produces an output proportional to two different factors; i.e. an analog reference and a digital word. Figure 4 shows how to connect the DAC-08 to accommodate a bipolar reference such as an AC signal. Current I_{REF} is equal to E_{REF}/R_{REF}, and should be 2 mA under normal operating conditions. Furthermore, E_{REF} must be greater than the peak AC value of the input signal E_{IN}.

The compensation capacitor, C_C, between the −V supply and pin 16 affects the frequency response of the DAC. The RC time constant, $R_{REF} \times C_C$, determines the maximum slew rate of the DAC-08. With component values of 1000 ohms and 15 pF, the slew rate will be 4 mA/µS.

That same circuit can be used for on-off keying of a reference signal. That is done by tying all of the digital inputs together to form a single keying terminal. When the keying terminal is low, the AC output is cut off, but when it is brought high the AC reference is passed to the output at its full amplitude.

Op-amp offset control

A DAC can be used to control the output offset of an operational amplifier by using a circuit such as the one shown in Fig. 5. The output voltage can be expressed by:

$$E_O = \frac{-E_{IN}R_F}{R_{IN}} + \left(\frac{-AE_{REF}}{256} \times \frac{R_F}{R1}\right)$$

We can, therefore, digitally control the output offset by varying the digital word A applied to the DAC. For current-output

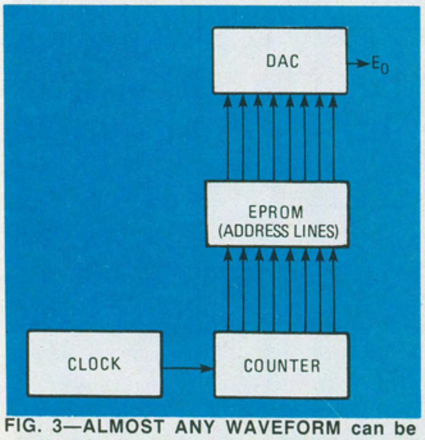


FIG. 3—ALMOST ANY WAVEFORM can be generated using a DAC. The block diagram of an appropriate circuit is shown here.

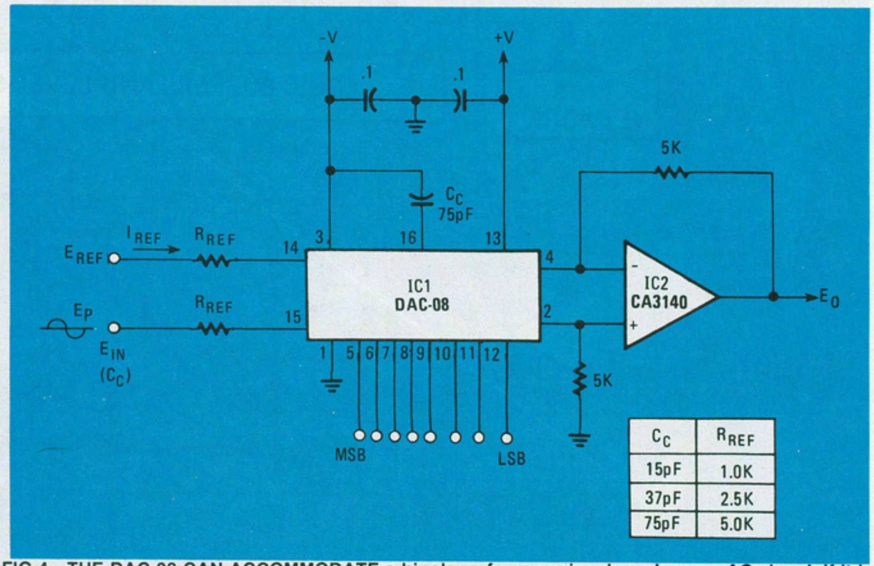


FIG 4—THE DAC-08 CAN ACCOMMODATE a bipolar reference signal, such as an AC signal, if it is configured as shown.

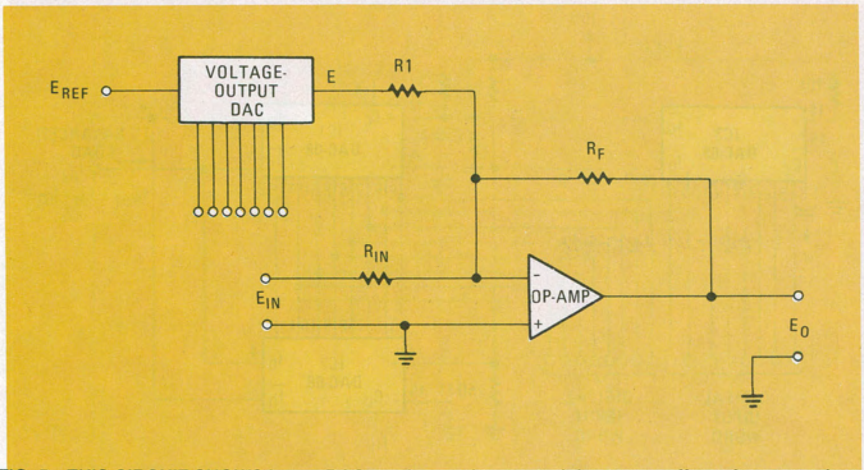


FIG. 5—THIS CIRCUIT SHOWS how a DAC can be used to control the output offset of an operational amplifier.

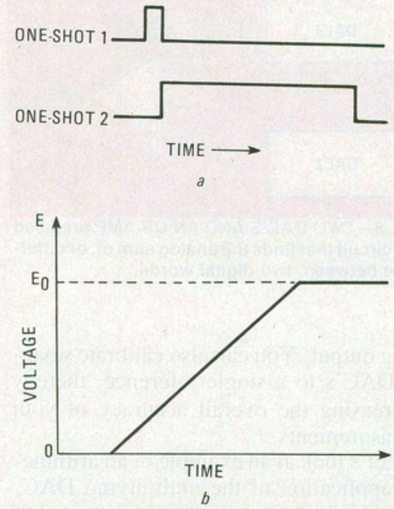


FIG. 7—TIMING DIAGRAMS for the one-shots used in Fig. 6 are shown in *a*; the resulting output, E_O, is shown in *b*.

DAC's eliminate R1.

Automatic zeroing circuits

Many circuits have an offset that must be nulled before proper operation is possible. Medical, scientific, and industrial instruments, for example, use transducers to acquire data and convert it to an electrical signal. Unfortunately, almost all transducers have a certain offset voltage. That is, they will produce an output voltage even when whatever it is they're supposed to measure (blood pressure, vibration, etc.) is not present. Consider arterial blood-pressure transducers used in medical electronics. Those instruments use Wheatstone-bridge transducers to sense the blood pressure. Theoretically, the output should be zero when the transducer is open to atmosphere. But transducer imperfections and hydrostatic pressure in the lines to the patient creates an offset in the amplifier output that must be nulled. Figure 6 shows a representative auto-zero circuit that will automatically null a circuit at the push of a button.

When power is first applied, the power-on reset circuit will reset the DAC to 00000000. When the transducer is opened to the atmosphere, a voltage will appear at the output (E_O). That voltage represents the sum of all of the offsets in the circuit preceding that stage. When the zero button is pressed, one-shot 1 fires a brief pulse that ensures that the counter and DAC are reset to zero, while also triggering one-shot 2. (The timing diagrams are shown in Fig. 7). The time period of one-shot 2 is very long relative to the time period of one-shot 1 (and might actually approach one second or more). When the output of one-shot 2 is high, clock pulses are gated into the counter causing the counter and DAC to increment. The comparator will have a high output as long as E_O is not zero. Voltage E, the DAC output, will rise in ramp-like fashion as the DAC digital inputs increment (see Fig. 7). It is summed with input voltage $-E_{IN}$ at the inverting input of the op-amp (that op-amp should be a low- or unity-gain device), so the output voltage, E_O, will drop. When E_O has dropped to zero, the output of the comparator drops low, shutting off the flow of clock pulses to the counter. The digital inputs of the DAC, therefore, remain at the last count that occurred before the comparator output dropped low. Unless the transducer offset changes, the output voltage E_O will represent only the true value of the signal, less any offset.

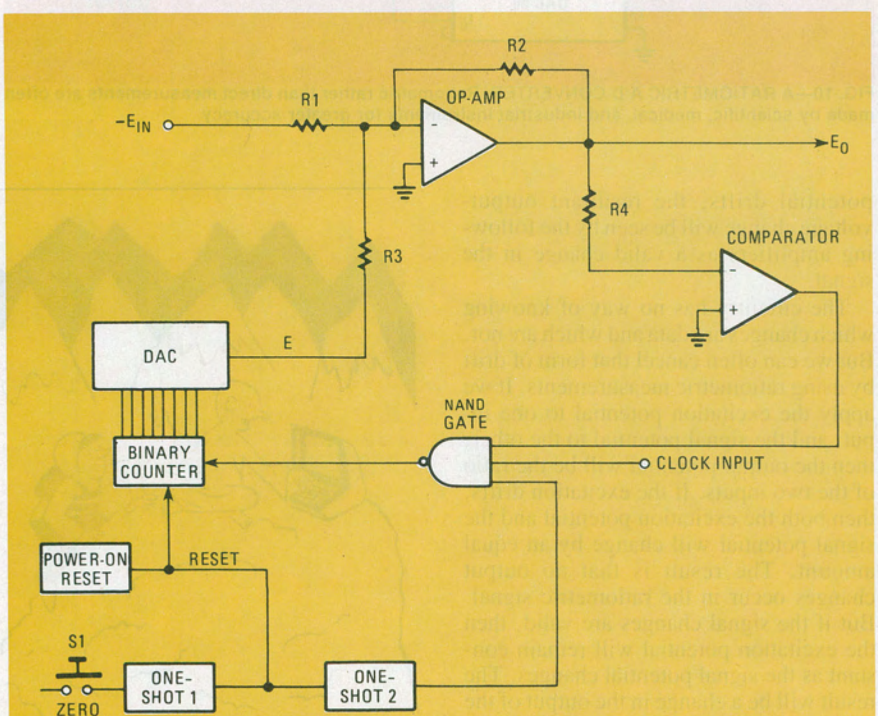


FIG. 6—A DAC CAN BE USEFUL in a circuit designed to null out any offsets in sensitive measuring equipment. Such a circuit is shown here.

Making use of a multiplying DAC

What is a multiplying DAC? All DAC's are multiplying circuits (see equations 1 and 2): they produce an output that is the product of an analog reference and a digital word applied to the digital inputs. But in manufacturers' catalogues we note that only some DAC's are referred to as "multiplying" devices. The reason for that is that a multiplying DAC is commonly defined as a DAC that operates from an external analog reference, while one that operates only from its own internal reference is a non-multiplying DAC.

A little cleverness counts for a lot in using a multiplying DAC. You can, for example, design circuits that perform arithmetic operations and produce an an-

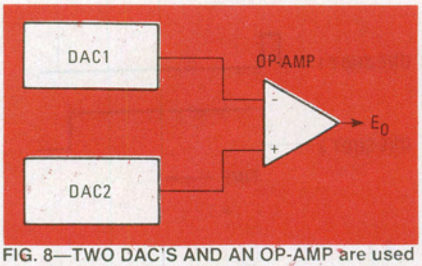


FIG. 8—TWO DAC'S AND AN OP-AMP are used in a circuit that finds the analog sum of, or difference between, two digital words.

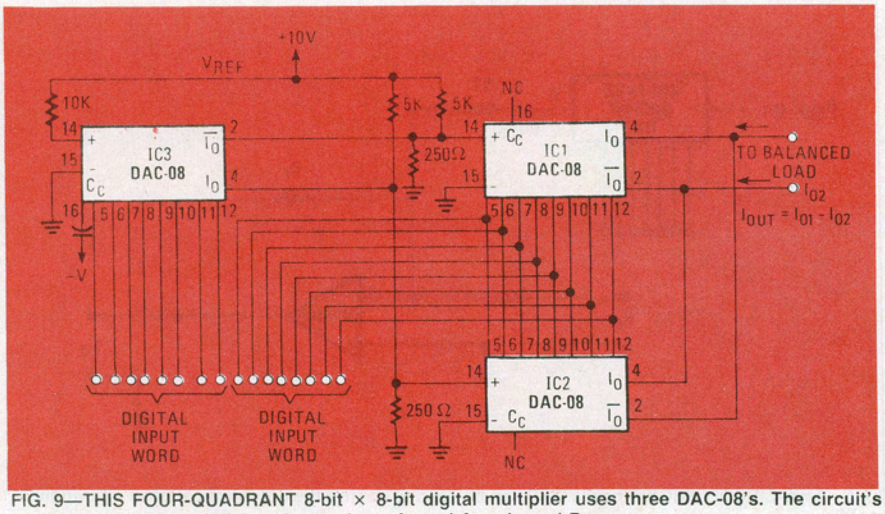


FIG. 9—THIS FOUR-QUADRANT 8-bit × 8-bit digital multiplier uses three DAC-08's. The circuit's output will be proportional to the product of word A and word B.

alog output. You can also calibrate several DAC's to a single reference, thereby increasing the overall accuracy of your measurements.

Let's look at an example of an arithmetic application of the multiplying DAC, one in which it is used in a circuit that produces the analog sum or difference between two digital words. That requires two DAC's and an operational amplifier as shown in Fig. 8. Apply one digital word to each DAC. Their respective outputs are fed to the input(s) of the operational amplifier. (If the sum of the two is required, then connect both DAC outputs to the same op-amp input. But if the difference is required, connect the subtrahend—the number you wish to subtract—DAC output to the inverting input, and the minuend—the number from which it is subtracted—DAC output to the noninverting input.) The gain of the op-amp allows us to set the scaling factor (if needed), so that the op-amp output correctly represents the sum or difference between the two words.

Figures 9 and 10 show two more ways that DAC's can be used. Figure 9 shows a four-quadrant 8-bit by 8-bit digital multiplier based on the DAC-08. Two of the devices, IC1 and IC2, are connected together to make an extended range circuit, while IC3 is used to supply the analog reference for IC1 and IC2. Since the digital word applied to IC3 sets the analog reference-current applied to the other two DAC's, which are multiplying DAC's, the output will be proportional to the product of word A and word B.

Figure 10 shows a pair of DAC-08 devices connected into a ratiometric A/D converter circuit. That is the same basic circuit that is used in many A/D converters (i.e. successive approximation or binary ramp types), but with two DAC's instead of one. The resulting output word is proportional to the ratio of the two input voltages, V_X and V_Y.

Ratiometric measurements are often performed by scientific, medical, and industrial instruments because they are often more reliable than actual value measurements. It seems that factors that create drift problems often affect two or more parameters, so they will cancel out if ratios are used. Take, for example transducer measurements (as previously discussed). If the transducer's excitation

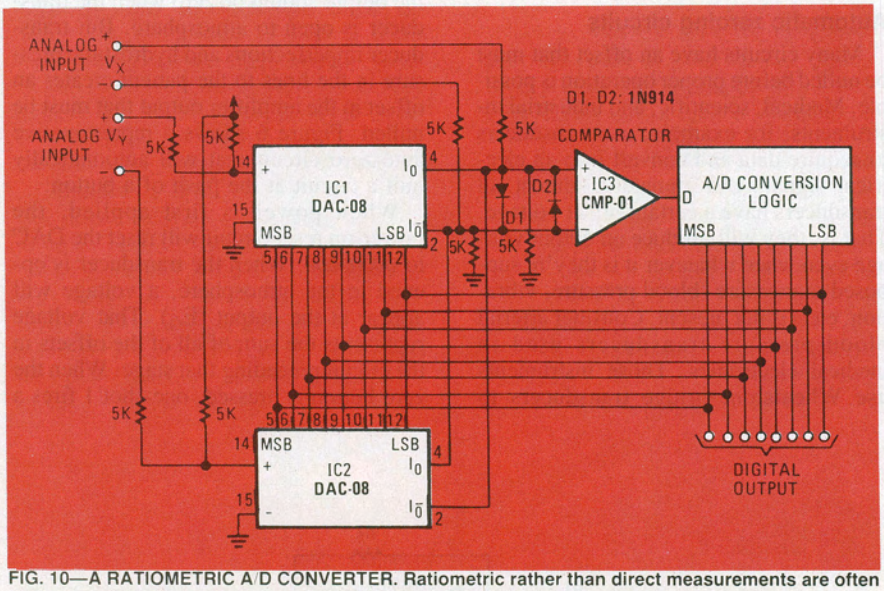


FIG. 10—A RATIOMETRIC A/D CONVERTER. Ratiometric rather than direct measurements are often made by scientific, medical, and industrial instruments for greater accuracy.

potential drifts, the resultant output-voltage change will be seen by the following amplifiers as a valid change in the signal.

The circuitry has no way of knowing which changes are data and which are not. But we can often cancel that form of drift by using ratiometric measurements. If we apply the excitation potential to one input, and the signal potential to the other, then the output potential will be the ratio of the two inputs. If the excitation drifts, then both the excitation potential and the signal potential will change by an equal amount. The result is that no output changes occur in the ratiometric signal. But if the signal changes are valid, then the excitation potential will remain constant as the signal potential changes. The result will be a change in the output of the ratiometric circuit. The output from a ratiometric circuit is called a "normalized" output. **R-E**

"The meaning of life? Just a second..."