Experimenter's Corner

By Forrest M. Mims

ANALOG TO DIGITAL CONVERTERS, PART 1

IN JULY and August we examined some of the basic characteristics of digital-to-analog (D/A) converters. Now we're going to devote equal time to analog-to-digital (A/D) converters.

Both D/A and A/D converters play key roles in such applications as digital multimeters, solid-state data loggers, speech synthesizers, digital communications devices, motor speed controllers and many others. In all these applications the converter interfaces the analog world of continuously variable information and signals such as temperature, voltage, velocity, force and light intensity with the two-state binary operation of digital circuits.

We've already seen how a simple D/A converter can convert a four-bit binary code into a voltage to vary the brightness of a lamp or the speed of a motor, generate waveforms, etc. An A/D converter performs the mirror image task of transforming a variable signal like the voltage from a pressure transducer into the binary format that a digital circuit can process. Probably the best-known application for the A/D converter is the digital multimeter, but such converters can be found in other applications working with a variety of digital circuits.

The digital circuit associated with the A/D converter can be as simple as a RAM and a counter that together store a series of analog measurements for later retrieval (a data logger). Alternatively, it might be a sophisticated flat-screen, solid-state oscilloscope that uses an array of hundreds of LED's in place of a bulky cathode ray tube. It could just as well be a microcomputer programmed to monitor and make decisions about various analog signals, trends or events.

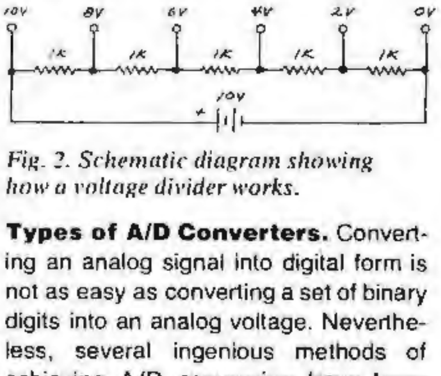

Fig. 2. Schematic diagram showing how a voltage divider works.

Types of A/D Converters. Converting an analog signal into digital form is not as easy as converting a set of binary digits into an analog voltage. Nevertheless, several ingenious methods of achieving A/D conversion have been

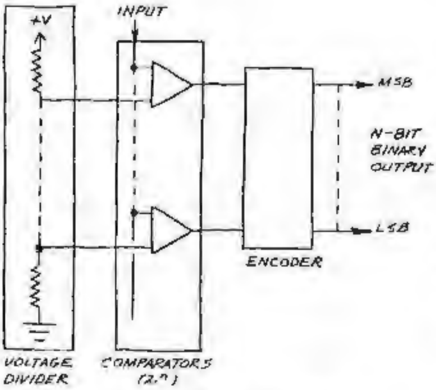

Fig. 1. Block diagram of parallel or flash A/D converter.

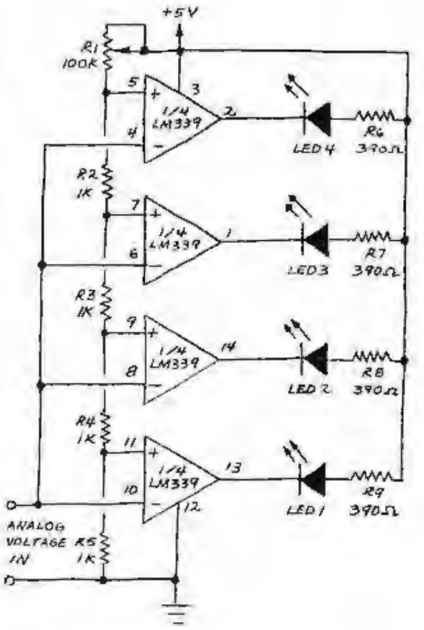

Fig. 3. LED thermometer-style bargraph readout.

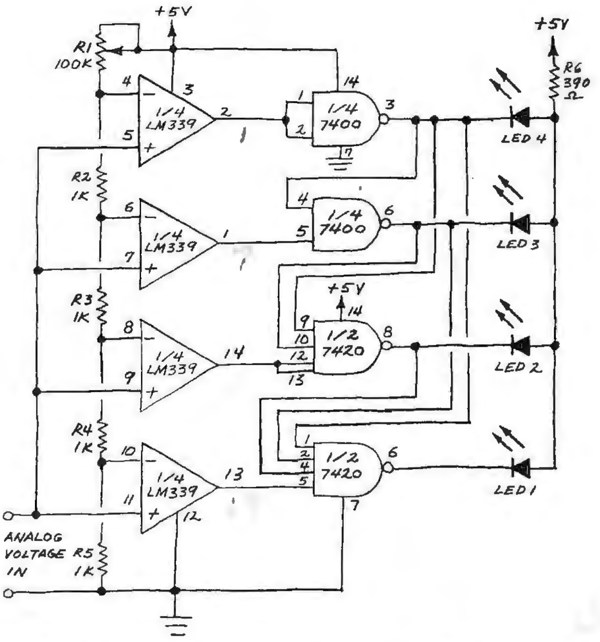

Fig. 4. A NAND gate decoder converts 4-element bargraph output into 1-of-4 moving dot readout.

developed. One of the simplest of these employs a D/A converter and a counter. The counter is initially cleared so that all its outputs are at logic zero. A clock increments the counter, and each successive count is converted into an analog voltage by the D/A converter and applied to an op amp comparator along with the incoming analog signal. When the two analog signals are equal, the comparator changes states and inhibits the clock. The binary word stored in the counter is the digital equivalent of the analog input signal.

Although this method of conversion is simple, it's very slow. The time for a conversion can range from no clock period (0 volts in) to 2^N clock periods where N is the counter's capacity in bits. Thus, an 8-bit counter would require between 0 and 256 clock periods for a single data conversion.

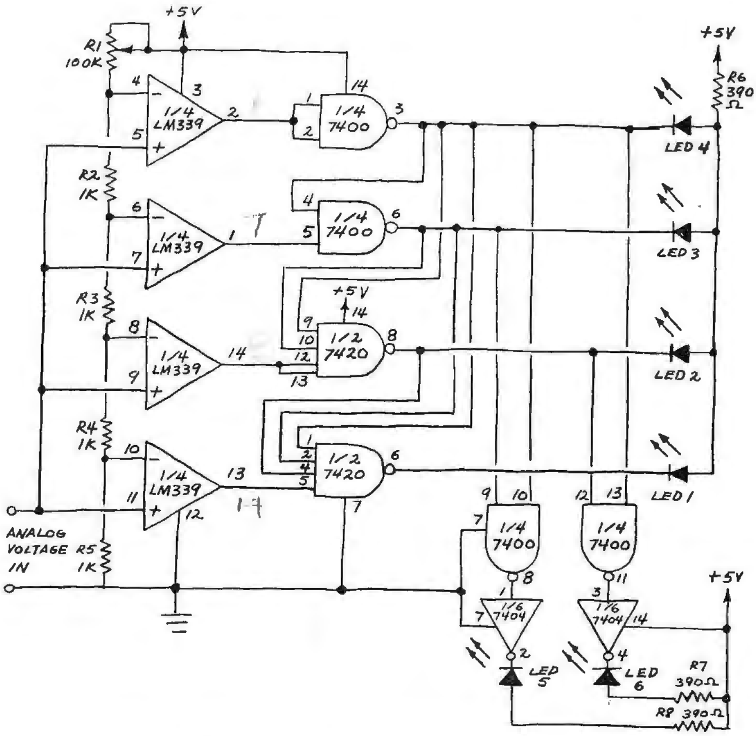

Fig. 5. An A/D converter with binary output is made by adding a 2-bit encoder as shown here.

A method called *successive approximation* can reduce the conversion time to only *N* clock periods. Briefly, this method employs a D/A converter connected to a "successive approximation" register that stores a binary number equivalent to half the full-scale output of the converter. Both the output from the converter and the incoming analog signal are fed into a comparator. If the D/A converter's output is *less* than the input signal, the most significant bit (MSB) in the data register remains high. The next-most significant bit goes high when the next clock pulse arrives. The updated output from the D/A converter is then compared with the input signal. If it is greater than the input, the second-most significant bit goes low and the third-most significant bit goes high.

The conversion process continues bit by bit until the least significant bit (LSB) is reached. The data register then contains the binary word that corresponds to the analog input.

Another popular method of A/D conversion is called dual-slope conversion. Like the two previous methods, dual-slope conversion requires a clock and various control circuits. In other words, it's both complicated and slow.

The fastest A/D converter is also the simplest. It's called the *parallel* or *flash* converter, and is made from a voltage divider connected to a series of comparators and an encoder. Figure 1 shows how the components in a flash converter are organized. As you can see, the flash converter doesn't require a clock. Data conversion takes place as fast as the comparators can change state and the encoder encode.

Commercial flash converters are very expensive because converting an analog signal into an N-bit word requires 2^N comparators. This means that an 8-bit output word requires 256 comparators!

Fortunately for us experimenters, low-resolution (anything less than 4 bits) A/D flash converters are easy to design and build. Therefore, the remainder of this installment of "Experimenter's Corner" will be devoted to the step-by-step design and assembly of the various sections of a flash converter. As you'll soon realize, there are many applications for both the completed converter and the various stages that make it up.

The Voltage Divider. The first stage of a flash A/D converter is a standard voltage divider. In case you're relatively new to electronics, voltage dividers are more common than you might think. An

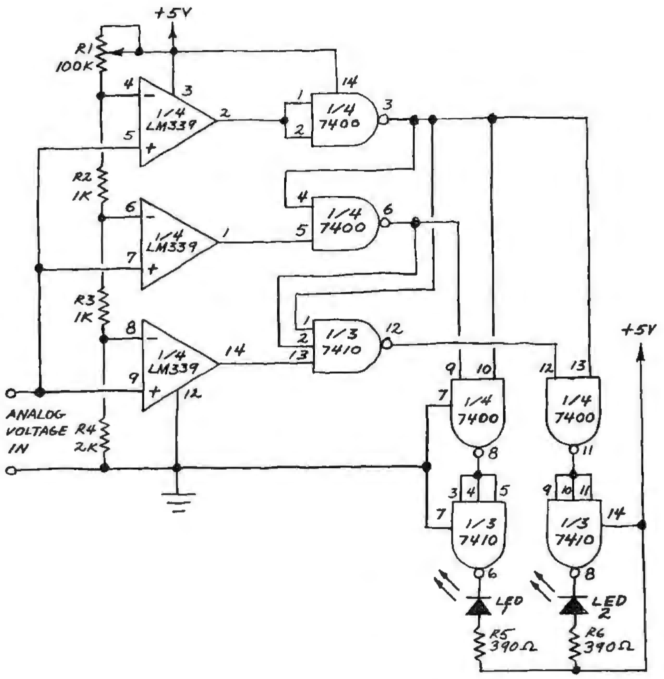

Fig. 6. Simplification of A/D converter by elimination of one NAND gate in Fig. 5

ordinary potentiometer is actually a variable voltage divider. If the end terminals of a linear potentiometer are connected across a 10-volt supply, 5 volts will appear between the wiper and ground when the wiper has been rotated to its mid-point.

You can begin assembly of the flash A/D converter *and* see how a voltage divider works by building the circuit in Fig. 2 on a solderless breadboard. The accuracy of the divider is determined by the tolerances of the resistors. Five or 10-percent resistors will work, but 1-percent resistors are much better. If you can't find 1-percent components, use a multimeter to select five resistors having values as close to 1000 ohms as possible. After you connect power to the divider, use a multimeter to measure the voltages between ground and the junctions of the resistors. The voltage across each resistor will be 20 percent of the input voltage.

Comparators and a Bargraph Readout. A comparator is an op amp designed to provide very high gain. The result is a stage whose output rapidly changes state when the voltage at one input exceeds the second input.

Figure 3 shows how to connect the four comparators in an LM339 quad comparator to a slightly modified version of the voltage divider of Fig. 2. The modification consists of substituting a 100,000-ohm or higher potentiometer for the uppermost fixed resistor to permit the range of voltages available from the points in the divider to be adjusted. The output of each comparator is connected to an LED, and the result is a bargraph or thermometer-style readout.

Since the inputs of each comparator are connected to both the incoming analog voltage and the resistor junctions in the divider, the comparators switch on one after another in succession, from the lowest to the highest, as the incoming voltage is increased. The circuit can be easily adjusted to light up successive LED's in increments of as little as one millivolt per LED if the potentiometer has a resistance of several megohms. If you calibrate the circuit with a known input voltage you can use it for a voltmeter.

The circuit can also be used as both a resistance indicator and timer. In the resistance mode, the potentiometer can be adjusted to indicate up to 10 megohms per LED. To use the circuit as a timer, connect a capacitor directly across the input leads. Depending on the value of the capacitor, the LED's will turn on in succession at intervals ranging from less than a second to a few minutes.

You can even use the circuit as a light meter by connecting a cadmium-sulfide photocell across the inputs. Because the readout is luminescent you can use the meter in very dim light—but you'll have to optically isolate the photocell from the display to prevent false readings.

Moving Dot Readout. A bargraph

readout is preferred for some applications, but for others only a single LED need glow at any one instant. I've not discovered a preferred name for this kind of readout, but *moving dot display* seems as good as any.

Figure 4 shows how to make a NAND gate decoder to convert the 4-element bargraph output into a 1-of-4 moving dot readout. Study the decoder to see how it works. In particular, notice how the outputs of the top three gates are coupled down to the inputs of the lower gates.

The circuit shown in Fig. 4 can be used in most if not all applications of the bargraph readout. It's even possible to keep the bargraph readout by adding a four-pole switch to connect either the bargraph or the moving dot display to the circuit.

Completing the A/D Converter. The transformation of the moving dot readout into an A/D converter with a binary output is completed by adding a 2-bit encoder comprising two previously unused 7400 NAND gates in the moving dot display's decoder (Fig. 5). Notice the two inverters at the output of the encoder. These inverters could be eliminated by using AND gates for the encoder, but the 7404 hex inverter is more readily available than the 7408 quad AND gate. Besides, the two NAND gates were already available.

If you've built the circuits described so far, you're probably wondering if it's worth four chips, a handful of resistors and a bird's nest of wires to obtain a mere 2 bits of data conversion. First, it's important to note that only 2 bits are available because only four comparators are used. This gives a 1, 2, 3, 4 count in decimal or a 00, 01, 10, 11 count in binary. As was mentioned earlier, it takes 2^N comparators to give N bits of data conversion.

Next month, we'll expand the basic A/D converter to provide a 4-bit BCD output. Meanwhile, let's conclude this column by simplifying the 2-bit circuit as shown in Fig. 6.

As you can see, the simplified circuit eliminates the moving dot LED's. Since an LED is not needed for the 00 position, the bottom 7420 NAND gate in Fig. 5 can be eliminated. This means one 3-input NAND gate in a 7410 can be substituted for the 7420 dual 4-input NAND gate used originally.

On page 98, is the first of what is planned as a regular monthly addition to this column—the "Project of the Month." Try your hand at it. ◇