Experimenter's Corner

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DIGITAL TO ANALOG CONVERTERS, PART 1

ALMOST any electronic circuit can be classified as either analog or digital. Analog circuits are those in which the signal voltages present may be at any level between low and high extremes determined by the power supply. Many analog circuits are known as linear circuits since they produce an output directly proportional to an input signal over a limited range of amplitude and frequency. Digital circuits are, on the other hand, those in which signals can assume only one of two distinct levels. Typically, one is at or near ground potential and the other near the power-supply voltage. In TTL digital integrated circuits, the two voltage levels are a low of a few tenths of a volt and a high of about 3.3 to 5.0 volts.

Although an amazing variety of circuit functions can be performed using only analog or digital techniques, some applications can only be accomplished by combining the two methods. Some examples of combining analog and digital techniques are the digital voltmeter, speech recognition circuitry, sophisticated motor-speed controllers, digital data transmission and many kinds of computer output circuits for controlling electromechanical devices like solenoids.

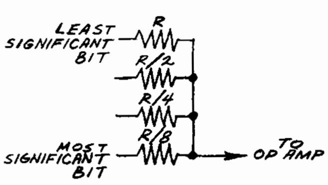

Fig. 2. Simple 4-bit D/A converter using resistor ladder.

D/A Conversion. Let's suppose that you've built a simple digital controller circuit that will turn individual lamps in an array on and off in any pattern you specify. The brain of the controller is a semiconductor memory that you can program with the desired information. How would you use your controller to adjust the *brightness* of a single lamp without modifying the controller circuitry?

The solution to this problem is a digital-to-analog (D/A) converter. The D/A converter is connected directly to the controller's output and adjusted to produce an output voltage proportional to the controller's binary output. Figure 1 shows how the controller is connected to the D/A converter.

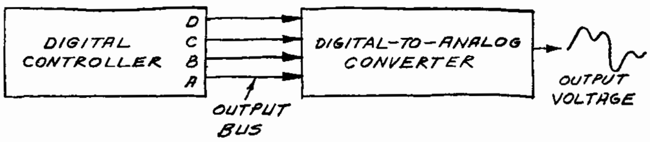

Fig. 1. Connecting digital controller to D/A converter.

There are several ways to design a D/A converter circuit, but the most common uses a resistor network followed by one or more operational amplifiers. Figure 2 shows a simple, 4-bit D/A converter that uses a ladder-like network of parallel input resistors. The values of the resistors are determined by their binary weighting factors. A 4-bit input has binary weighting factors of 2^3 (8_{10}), 2^2 (4_{10}), 2^1 (2_{10}) and 2^0 (1_{10}). If the lowest order (2^0) resistance is R, then the values are R, R/2, R/4 and R/8.

Though the circuit shown in Fig. 2 is very simple, it has two major drawbacks. First, it's difficult (at the hobbyist level) to find resistors having the precise resistances that are required. Second, the resistance values become spread over a very wide range for a relatively small number of input bits. Thus, for a 10-bit D/A converter, the input resistors must range from R to R/1024. The digital circuit connected to the D/A converter, often a chain of flip-flops or gates, must be able to supply a wide range of currents (high currents for low resistances and low currents for high resistances).

The problems of the D/A converter in Fig. 2 can be solved by increasing the number of resistors in the ladder network. The result is the *R-2R* ladder network shown in Fig. 3. As you can see, the ladder resistors have values of *R*

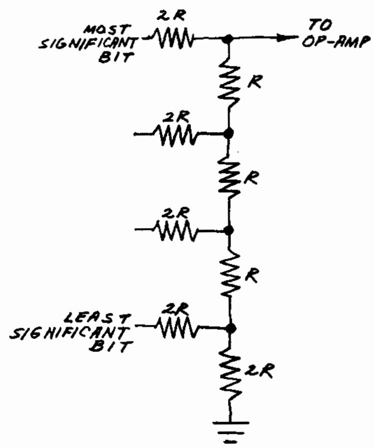

Fig. 3. R-2R resistor ladder network for D/A converter.

and *2R*. This means only two readily available resistance values are required. It's possible to use a single value if you're willing to connect two *R* resistors in series to obtain the *2R* values.

D/A Conversion Demonstrator. If you're serious about electronics experimentation and want to stay abreast of the latest developments, you should assemble a D/A demonstration circuit like the one shown in Fig. 4. This circuit is the basis for the practical D/A converter we'll discuss later.

The demonstrator circuit uses four spdt switches to achieve a 4-bit input. There's nothing improper about a mechanically switched binary output. Many real-world circuits use them. Most D/A converters, however, are connected directly to a digital circuit that provides a binary output.

You can test the operation of the D/A converter by connecting a voltmeter across its output while switching in various binary outputs. Since we're using a 9-volt battery as a reference voltage and since there are sixteen possible input combinations, the output voltage should range from 0 volts to slightly under 9 volts in increments of 9/16 volt.

Here are the actual voltages measured with the demonstrator circuit:

Binary In	Voltage Out
0000	.00
0001	.57
0010	1.12
0011	1.69
0100	2.19
0101	2.76
0110	3.32
0111	3.89
1000	4.50
1001	5.06
1010	5.60
1011	6.15
1100	6.69
1101	7.78
1110	7.82
1111	8.40

The output of the circuit is plotted on a graph in Fig. 5. As you can see, the response of the circuit is reasonably linear, even though I used 10% tolerance resistors. Commercial D/A converters are made with resistors having tolerances of 1% or better. When very close tolerances are necessary for super-accurate D/A converters, a pulsed laser is used to vaporize minute portions of the carbon or metal-film resistive elements until the exact values required are obtained.

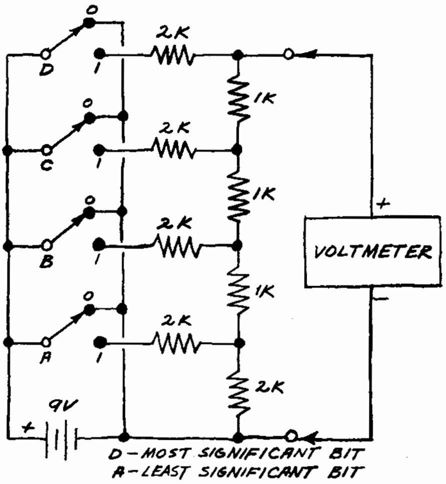

Fig. 4. D/A demonstrator circuit.

It's handy to be able to predict in advance the analog voltage output for a specific input bit pattern. The weighting factors for our 4-bit network are:

Most Significant Bit—
$2^3 = 1/2$ Reference Voltage
$2^2 = 1/4$ " "
$2^1 = 1/8$ " "

Least Significant Bit—
$2^0 = 1/16$ Reference Voltage

To calculate the analog output, simply multiply the reference voltage by the weighting factor for each bit portion with a 1 and sum the products. Thus 1100 is:

1—$1/2 \times 9 = 4.50$
1—$1/4 \times 9 = 2.25$
0— 0 0
0— 0 0
6.75 volts

The calculated analog output, 6.75 volts, is only 0.06 volt higher than the value measured with the prototype circuit. That's an error of less than 1%! ◇

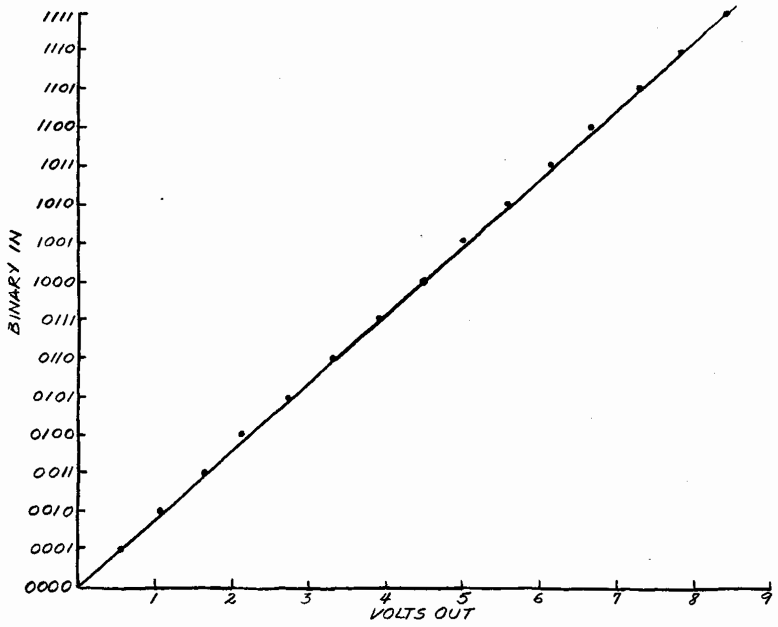

Fig. 5. Voltage output vs. binary input for Fig. 4.