Know your converter codes. When you work with a/d and d/a converters, there are many input and output codes to choose from. Here are some characteristics of each.

The right digital code can help simplify system design when analog-to-digital and digital-to-analog converters are used in the system.

While some custom a/d and d/a converters use special codes, off-the-shelf units employ one of a few common codes adopted by the industry as "standard" (Table 1). Understanding which code to use, and where, is the key to a simpler system design. And the added benefits with a standard code include lower cost of the converter and a wider choice of vendors.

Many designers are perplexed about application. There are unipolar codes—straight binary, complementary binary and binary coded decimal (BCD). There are bipolar codes—sign-magnitude binary, sign-magnitude BCD, offset binary, one's complement and two's complement. Other decimal codes include excess-three, 2421, 5421, 5311 and 74-2-1. And there are also reflective codes—such as the Grey code; and error-detecting codes—like the Hamming.

All codes used in converters are based on the binary numbering system. Any number can be represented in binary by the following

$$N = a_n 2^n + a_{n-1} 2^{n-1} + \ldots + a_2 2^2 + a_1 2^1 + a_0 2^0,$$

where each coefficient a assumes a value of one or zero. A fractional binary number can be represented as

$$N = a_1 2^{-1} + a_2 2^{-2} + a_3 2^{-3} + \ldots + a_n 2^{-n}.$$

A specific binary fraction is then written, for example, as 0.101101. In most converters it is this fractional binary number that is used for the basic converter code. Conventionally the fractional notation is assumed and the decimal point dropped.

The left-most digit has the most weight, 0.5, and is commonly known as the most-significant-bit (MSB). Thus the right-most digit would have the least weight, $1/2^n$, and is called the least-significant-bit (LSB).

This coding scheme is convenient for converters, since the full-scale range used is simply interpreted in terms of a fraction of full scale. For instance, the fractional code word 101101 has a value of $(1 \times 0.5) + (0 \times 0.25) + (1 \times 0.125) + (1 \times 0.0625) + (0 \times 0.03125) + (1 \times 0.015625)$, or 0.703125 of full-scale value. If all the bits are ONEs, the result is not full scale but rather $(1 - 2^{-n}) \times$ full scale. Thus a 10-bit d/a converter with all bits ON has an input code of 1111 1111 11. If the unit has a +10-V full-scale output range, the actual analog output value is

$$(1 - 2^{-10}) \times 10\ \text{V} = +9.990235\ \text{V}.$$

The quantization size, or LSB size, is full scale divided by 2^n—which in this case is 9.77 mV.

Table 1. Summary of coding for a/d and d/a converters

	D/a converters	A/d converters
Unipolar	Straight binary	Straight binary
	BCD	BCD
	Complementary binary	Straight bin. invert. analog
	Complementary BCD	BCD, inverted analog
Bipolar	Offset binary	Offset binary
	Complementary off. binary	Two's complement
	Two's complement	Offset bin. invert. analog
		Two's compl. invert. analog
		Sign + mag. binary
		Sign + mag. BCD

Analyzing digital codes

The four most common unipolar codes are straight binary, complementary binary, binary-coded decimal (BCD) and complementary BCD. Of these four, the most popular is straight-binary, positive-true. Positive-true coding means that a logic ONE is defined as the more positive of the two voltage levels for the logic family.

Negative-true logic defines things the other way—the more negative logic level is called ONE and the other level ZERO. Thus, for standard TTL, positive true logic makes the +5-V output logic ONE and 0 V a ZERO. In negative true logic the +5 V is ZERO and 0 V is ONE.

All four of the codes are defined (Table 2) in terms of the fraction of their full-scale values. Full-scale ranges of +5 and +10 V are shown. with 12-bit codes.

Table 2. Unipolar codes—12 bit converter

Straight binary and complementary binary

Scale	+10 V FS	+5 V FS	Straight binary	Complementary binary
+FS −1 LSB	+9.9976	+4.9988	1111 1111 1111	0000 0000 0000
+7/8 FS	+8.7500	+4.3750	1110 0000 0000	0001 1111 1111
+3/4 FS	+7.5000	+3.7500	1100 0000 0000	0011 1111 1111
+5/8 FS	+6.2500	+3.1250	1010 0000 0000	0101 1111 1111
+1/2 FS	+5.0000	+2.5000	1000 0000 0000	0111 1111 1111
+3/8 FS	+3.7500	+1.8750	0110 0000 0000	1001 1111 1111
+1/4 FS	+2.5000	+1.2500	0100 0000 0000	1011 1111 1111
+1/8 FS	+1.2500	+0.6250	0010 0000 0000	1101 1111 1111
0+1 LSB	+0.0024	+0.0012	0000 0000 0001	1111 1111 1110
0	0.0000	0.0000	0000 0000 0000	1111 1111 1111

BCD and complementary BCD

Scale	+10 V FS	+5 V FS	Binary coded decimal	Complementary BCD
+FS−1 LSB	+9.99	+4.95	1001 1001 1001	0110 0110 0110
+7/8 FS	+8.75	+4.37	1000 0111 0101	0111 1000 1010
+3/4 FS	+7.50	+3.75	0111 0101 0000	1000 1010 1111
+5/8 FS	+6.25	+3.12	0110 0010 0101	1001 1101 1010
+1/2 FS	+5.00	+2.50	0101 0000 0000	1010 1111 1111
+3/8 FS	+3.75	+1.87	0011 0111 0101	1100 1000 1010
+1/4 FS	+2.50	+1.25	0010 0101 0000	1101 1010 1111
+1/8 FS	+1.25	+0.62	0001 0010 0101	1110 1101 1010
0+1 LSB	+0.01	+0.00	0000 0000 0001	1111 1111 1110
0	0.00	0.00	0000 0000 0000	1111 1111 1111

D/a and a/d converters: The operating basics

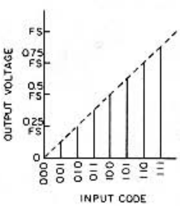
The basic transfer characteristic of an ideal d/a converter forms the plot shown in Fig. A. The d/a takes an input digital code and converts it to an analog output voltage or current. This form of discrete input and discrete output (quantized) gives the transfer function a straight line through the tops of the vertical bars. In general the analog values are completely arbitrary and a large number of binary digital codes can be used. Analog full-scale can be defined as −25.2 to 85.7 V as easily as 0 to 10 V.

In practice, though, the industry has settled on several codes and very simple ranges for most major applications. For instance, the transfer characteristics in Fig. A are for a d/a converter that uses a 3-bit unipolar binary code and an output defined only in terms of its full-scale value.

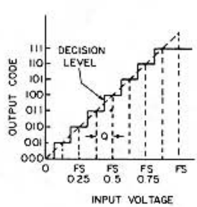
The ideal a/d converter (Fig. B) has a staircase transfer characteristic. Here an analog input voltage or current is converted into a digital word. The analog input is quantized into n levels for a converter with n bits resolution. For the ideal converter, the true analog value corresponding to a given output code word is centered between two decision levels. There are 2^N-1 analog decision levels. The quantitization size, Q, is equal to the full-scale range of the converter divided by 2^n.

For the ideal d/a converter, there is a one-to-one correspondence between input and output, but for the a/d there is not, because any analog input within a range of Q will give the same output code word. Thus, for a given code word, the corresponding input analog value could have errors of from 0 to $\pm Q/2$. This quantization error can be reduced only by an increase in converter resolution.

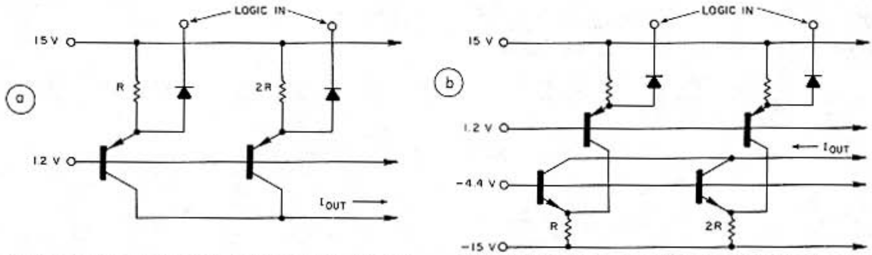
Although the analog input or output ranges are arbitrary, some of the standardized ranges include 0 to +5, 0 to +10, 0 to −5 and 0 to −10 V for unipolar converters, and −2.5 to +2.5, −5 to 5 and −10 to +10 V for bipolar units. Many units on the market are programmable types in which external pin connections determine the range of operation.



A



B



1. **Weighted current-source configurations** for straight binary (a) and complementary binary (b) coding generate output current in different directions. The resistor weighting determines the output code.

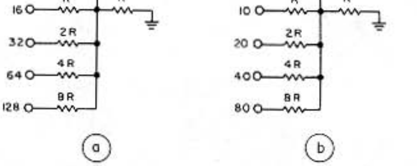
Complementary-binary, positive-true coding is also used in d/a converters. This scheme is used because of the weighted current source configuration employed in many converter designs.

Fig. 1 shows two commonly used weighted-current-source designs. The pnp version (Fig. 1a) delivers a positive output current with straight binary positive-true coding. When the logic input is ONE, or +5 V, the current source is on, since the input diode is back-biased. Thus the current from each ON weighted current source is summed at the common-collector connection and flows to the output. A ZERO input holds the cathode of the input diode at ground and steals the emitter current from the transistor, keeping it off.

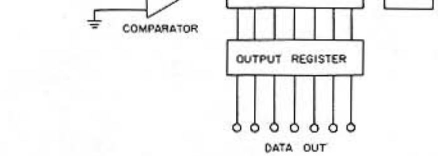
The use of an npn current source (Fig. 1b) produces a negative output current with complementary binary positive-true coding. The pnp transistors operate in the same way as before, but each collector is connected to the emitter of an npn weighted current source, which is turned on or off by the pnp transistor. This basic method finds common use in IC quad current-source circuits.

Complementary binary, positive-true, coding is identical to straight binary negative true; these are just two definitions of the same code. Straight-binary, negative-true, coding is commonly used to interface equipment with many minicomputer input/output busses. Unipolar a/d converters most frequently use the straight binary positive-true coding. They also use straight-binary inverted-analog where the full-scale code word corresponds to the negative full scale analog value.

Another popular code used in many converters is BCD. Table 2 shows three-decade BCD and complementary BCD codes used with converters that have full-scale ranges of +5 or +10 V. BCD is an 8421 weighted code, with four bits used to code each decimal digit. This code is relatively inefficient, since only 10 of the 16 code states for each decade are used. It is, however, a very useful code for interfacing decimal displays and switches with digital systems.



2. **Binary (a) and BCD (b) ladder networks** in d/a converters use the same weighting in the resistor quads but different divider ratios.



3. **Most a/d converters for bipolar operation** are offset by a current equal to the value of the MSB. The half-scale then becomes 100 . . . 0.

With d/a converters, it is especially convenient to have input decimal codes for use with such equipment as digitally programmed power supplies. And, with a/d converters, BCD is particularly popular for the dual-slope type for direct connection to numeric displays.

BCD coding in converters can be achieved in two ways: binary-to-BCD code conversion or direct weighting of internal resistor ladders and current sources. Today it is almost always done by resistor weighting schemes (Fig. 2). Each of the weighted resistors gets switched to a voltage source and thus generates the weighted current for the amplifier. Fig. 2a shows an 8-bit binary ladder network. Due to temperature-tracking constraints, groups of four resistors are used. Then the total resistance variation won't exceed 8-to-1.

In between the groups of four resistors is a current divider composed of two resistors that give a division ratio of 16 to 1 between resistor quads. The BCD ladder configuration is similar, with the same values in each of the groups of four resistors. In this case, however, the current divider has a ratio of 10 to 1 between resistor quads. Thus, because of the difference in internal weighting, BCD-coded converters cannot be pin-strapped for another code; they must be ordered only for BCD use.

Codes can be made bipolar

Most converters have provision for both unipolar and bipolar operation by external pin connection. The unipolar analog range is offset by one-half of full scale, or by the value of MSB current source, to get bipolar operation (Fig. 3). The current source, equal to the MSB current, is derived from the internal voltage reference, so it will track the other weighted current sources with temperature.

For bipolar operation, this current source is connected to the converter's comparator input. Since the current flows in a direction opposite from that of the other weighted sources, its value is subtracted from the input range. With the weighted currents flowing away from the comparator input, the normal input voltage range is positive. Thus the offsetting can change a 0 to +10-V input range into a −5 to +5-V bipolar range.

If the analog range is offset for a converter with straight binary coding, the new coding becomes offset binary. This is the simplest code for a converter to implement, since no change in the coding is required. Table 3 shows offset binary coding for a bipolar converter with a ±5-V input range. All ZEROs in the code correspond to minus full scale. The code word that was originally half-scale becomes the analog zero, 1000 0000 0000. And all ONEs correspond to +5 V less one LSB. Successive-approximation a/d converters also have a serial, straight-binary output. This serial output is the result of the sequential conversion process, and it also becomes offset binary when the converter is connected for bipolar operation.

Three other types of binary codes are shown in Table 3, along with the offset binary. Of all four, the two most commonly used are offset binary and two's complement. Some converters use the sign-magnitude binary, but the one's complement is rarely used.

The two's complement code is the most popular because most digital arithmetic is performed in it; thus most interfacing problems are elim-

Table 3. Bipolar codes—12 bit converter

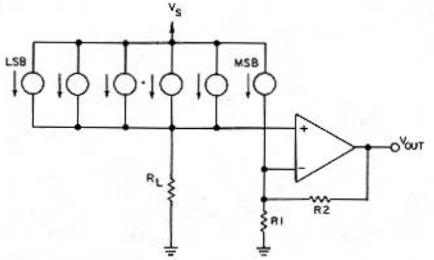
Scale	±5 V FS	Offset binary	Two's complement	One's complement	Sign-mag binary
+FS−1 LSB	+4.9976	1111 1111 1111	0111 1111 1111	0111 1111 1111	1111 1111 1111
+3/4 FS	+3.7500	1110 0000 0000	0110 0000 0000	0110 0000 0000	1110 0000 0000
+1/2 FS	+2.5000	1100 0000 0000	0100 0000 0000	0100 0000 0000	1100 0000 0000
+1/4 FS	+1.2500	1010 0000 0000	0010 0000 0000	0010 0000 0000	1010 0000 0000
0	0.0000	1000 0000 0000	0000 0000 0000	0000 0000 0000*	1000 0000 0000*
−1/4 FS	−1.2500	0110 0000 0000	1110 0000 0000	1101 1111 1111	0010 0000 0000
−1/2 FS	−2.5000	0100 0000 0000	1100 0000 0000	1011 1111 1111	0100 0000 0000
−3/4 FS	−3.7500	0010 0000 0000	1010 0000 0000	1001 1111 1111	0110 0000 0000
−FS+1 LSB	−4.9976	0000 0000 0001	1000 0000 0001	1000 0000 0000	0111 1111 1111
−FS	−5.0000	0000 0000 0000	1000 0000 0000	—	—

*Note: One's complement and sign magnitude binary have two code words for zero as given below; these are designated zero plus and zero minus:

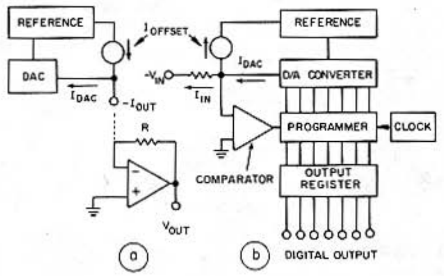
	One's complement	Sign-mag binary
0+	0000 0000 0000	1000 0000 0000
0−	1111 1111 1111	0000 0000 0000

Table 4. Inverted analog offset binary coding comparison

Scale	Normal analog offset binary	Inverted analog offset binary	Normal analog comp. offset binary
+FS		0000 0000 0000	
+FS − 1 LSB	1111 1111 1111	0000 0000 0001	0000 0000 0000
+1/2 FS	1100 0000 0000	0100 0000 0000	0011 1111 1111
0	1000 0000 0000	1000 0000 0000	0111 1111 1111
−1/2 FS	0100 0000 0000	1100 0000 0000	1011 1111 1111
−FS +1 LSB	0000 0000 0001	1111 1111 1111	1111 1111 1110
−FS	0000 0000 0000		1111 1111 1111



4. **For two's complement coding** in a d/a, the MSB current-source must go to the opposite terminal from the other weighted sources to avoid output glitches.



5. **The inverted-analog d/a converter** (a) and the inverted-analog a/d converter (b) have negative-going analog output and input values, respectively.

inated. The easiest way to characterize the two's-complement code is to look at the sum of a positive and negative number of the same magnitude; the result is all ZEROs plus a carry.

Visually the only difference between two's complement and offset binary is the left-most bit. In two's complement code it is the complement of the left-most bit in offset binary.

This left-most bit is normally called the MSB; in offset binary it is, in effect, the sign bit, and is so called in the other codes. Thus two's-complement coding is derived from offset binary when the sign bit is complemented and brought out as an additional output.

Coding has its limitations

Both two's-complement and offset-binary codes have magnitudes (if we temporarily forget about the sign bit) that increase from minus full scale to zero, and, with a sign change, from zero to plus full scale. Both codes have a single definition of zero. On the other hand, one's-complement and sign-magnitude codes have magnitudes that increase from zero to plus full scale and from zero to minus full scale. Both of these codes have two code words for zero, as shown in Table 3. Because of the extra code word used for zero, the range of these codes is one LSB less than for offset-binary and two's-complement coding.

For positive numbers, one's-complement is the same as two's-complement. The negative number in one's-complement is obtained when the positive number is complemented. Sign-magnitude coding is identical to offset binary for positive numbers; negative numbers are obtained by use of the positive number with a complemented sign bit.

D/a converters don't usually use two's complement coding. This is because it's hard to invert the MSB weighted current source. If the logic input is inverted, there is an extra digital delay in switching the current source, and this causes large output transients when the current is switched on and off.

The other alternative is to change the direction of the MSB current instead of inverting the digital input. This is also difficult to do and can introduce switching delays.

One satisfactory way of inverting the MSB is shown in Fig. 4. Here a voltage output d/a converter that uses two's-complement coding has the MSB current switched into the negative amplifier input terminal, while the other weighted currents are switched into the load resistor and positive input terminal. Thus opposite-polarity output voltages are produced, and there are no additional switching delays in the MSB.

One other code in Table 1 is the sign-magnitude BCD. This code, used mostly in dual-slope a/d converters, usually requires 13 bits for a three-decade digital display. Of the 13 bits, 12 are for the BCD code and one for the sign bit. An additional output bit for an overrange indication is generally supplied.

Another scheme in Table 1 is inverted analog code. This is also called negative reference coding. While most converters use zero to plus full scale as analog values; the inverted configuration uses zero to minus full scale values. The coding then increases in magnitude when the analog level increases in magnitude from zero to minus full scale. For bipolar coding, normal analog has an increasing code as the analog value goes from minus full scale to plus full scale; inverted analog coding does the opposite—the code increases as the analog value goes from plus full scale to minus.

Why the need for this code? Fig. 5a shows a d/a converter that delivers a negative output current. With bipolar operation and use of the offset current source, the converter provides a code ZERO that corresponds to plus full scale output current. However, if a current-to-voltage converter is used at the output, an inversion takes place, and a normal analog output voltage results.

In Fig. 6b, a d/a converter with positive output current is used in an a/d converter. Since the d/a output current is summed with the offset and input current at the comparator input, a negative input voltage is needed to balance these currents. The analog input thus goes from plus full scale to minus full scale for an increasing output code. Normal analog coding is achieved by use of an inverting amplifier ahead of the analog input terminal.

Inverted analog coding is compared with the normal offset binary coding in Table 4. This comparison shows that if the inverted analog offset binary code is rotated around the zero of the analog voltage, a normal analog offset binary output results. If inverted analog offset binary is compared with normal analog complementary offset binary, the two codes will appear identical except for an offset of one LSB. The relationship between these two codes can be expressed as:

Normal analog complementary binary + 1 LSB = Inverted analog offset binary.

Therefore a converter that uses one of these codes can also be used for the other with an external offset adjustment of 1 LSB. ■■