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CODING SCHEMES USED WITH DATA CONVERTERS

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With the recent proliferation of analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), and the variety of digital coding schemes which they use, has come a need to understand these different coding schemes which converters use to talk to the "digital world". The purpose of this article is to describe the individual coding schemes used with ADCs and DACs manufactured by Burr-Brown, and explain their relationships.

Following this text is a list of abbreviations and definitions intended to clarify any questions regarding the nomenclature which has been used.

Throughout this guide, examples and tables given are for a 4-bit data converter. In unipolar and bipolar examples alike, the Full Scale Range (FSR) is 10V creating a V_{LSB} of 0.625V. For unipolar examples, minus full scale (–FS) is 0V and plus full scale (+FS) is 10V; for bipolar examples, –FS is –5V and +FS is +5V.

USB — UNIPOLAR STRAIGHT BINARY

The Unipolar Straight Binary coding is perhaps the simplest coding scheme to understand. As the name implies, it is a coding scheme which is used only for unipolar voltages.

When using USB coding, the digital count begins at all zeros (0000) at a V_{CODE} of 0V (V_{t+} = 0V + 1/2V_{LSB} and there is no V_{t-}). As the digital code increments, the analog voltage increases one V_{LSB} at a time, and the digital count ends (1111) at the positive full scale value. Table I shows how the USB codes correspond to analog voltages for a 4-bit digital system.

MNEMONIC	DIGITAL CODE	V_{t-}	V_{CODE}	V_{t+}
Zero	0000		0.000	0.3125
+1 V_{LSB}	0001	0.3125	0.625	0.9375
	0010	0.9375	1.250	1.5625
	0011	1.5625	1.875	2.1875
1/4 FSR	0100	2.1875	2.500	2.8125
	0101	2.8125	3.125	3.4375
	0110	3.4375	3.750	4.0625
	0111	4.0625	4.375	4.6875
1/2 FSR	1000	4.6875	5.000	5.3125
	1001	5.3125	5.625	5.9375
	1010	5.9375	6.250	6.5625
	1011	6.5625	6.875	7.1875
3/4 FSR	1100	7.1875	7.500	7.8125
	1101	7.8125	8.125	8.4375
	1110	8.4375	8.750	9.0625
+FS	1111	9.0625	9.375	

TABLE I. USB Coding Scheme.

Unipolar Straight Binary is the coding scheme used by the ADC7802 and ADS7803.

CSB — COMPLEMENTARY STRAIGHT BINARY

The Complementary Straight Binary coding scheme is the exact digital opposite (one's complement) of Unipolar Straight Binary. CSB coding, like its counterpart USB, is also restricted to unipolar systems.

When using CSB coding with a digital system, the digital count begins at all zeros (0000) at the positive full scale value. As the digital code increments, the analog voltage decreases one V_{LSB} at at time, until 0V is reached at a digital code of 1111. The relationship between CSB coding and its corresponding analog voltages can be seen in Table II.

MNEMONIC	DIGITAL CODE	V_{t-}	V_{CODE}	V_{t+}
Zero	1111		0.000	0.3125
+1V_{LSB}	1110	0.3125	0.625	0.9375
	1101	0.9375	1.250	1.5625
	1100	1.5625	1.875	2.1875
1/4 FSR	1011	2.1875	2.500	2.8125
	1010	2.8125	3.125	3.4375
	1001	3.4375	3.750	4.0625
	1000	4.0625	4.375	4.6875
1/2 FSR	0111	4.6875	5.000	5.3125
	0110	5.3125	5.625	5.9375
	0101	5.9375	6.250	6.5625
	0100	6.5625	6.875	7.1875
3/4 FSR	0011	7.1875	7.500	7.8125
	0010	7.8125	8.125	8.4375
	0001	8.4375	8.750	9.0625
+FS	0000	9.0625	9.375	

TABLE II. CSB Coding Scheme.

BOB — BIPOLAR OFFSET BINARY

Bipolar Offset Binary coding, as the name implies, is for use in bipolar systems (where the analog voltage can be positive and negative). This coding scheme is very similar to USB coding since, as the analog voltage increases, the digital count also increases.

BOB coding begins with digital zero (0000) at the negative full scale. By incrementing the digital count, the corresponding analog value will approach the positive full scale in 1V_{LSB} steps, passing through bipolar zero on the way. This "zero crossing" occurs at a digital code of 1000 (see Table

Printed in U.S.A. March, 1991

SBAA042

III). The digital count continues to increase proportionally to the analog input until the positive full scale is reached at a full digital count (1111) as shown by Table III.

With BOB coding, the MSB can be considered a sign indicator whereas a logic "0" indicates a negative analog value, and a logic "1" indicates an analog value greater than or equal to BPZ.(1)

MNEMONIC	DIGITAL CODE	V_{t-}	V_{CODE}	V_{t+}
–FS	0000		–5.000	–4.6875
	0001	–4.6875	–4.375	–4.0625
	0010	–4.0625	–3.750	–3.4375
	0011	–3.4375	–3.125	–2.8125
1/2 –FS	0100	–2.8125	–2.500	–2.1875
	0101	–2.1875	–1.875	–1.5625
	0110	–1.5625	–1.250	–0.9375
BPZ – $1V_{LSB}$	0111	–0.9375	–0.625	–0.3125
BPZ	1000	–0.3125	0.000	+0.3125
BPZ + $1V_{LSB}$	1001	+0.3125	+0.625	+0.9375
	1010	+0.9375	+1.250	+1.5625
	1011	+1.5625	+1.875	+2.1875
1/2 +FS	1100	+2.1875	+2.500	+2.8125
	1101	+2.8125	+3.125	+3.4375
	1110	+3.4375	+3.750	+4.0625
+FS	1111	+4.0625	+4.375	

TABLE III. BOB Coding Scheme.

The ADS7800, a 12-bit, 333kHz, sampling analog-to-digital converter, utilizes the Bipolar Offset Binary output code to implement its ±5 and ±10V input ranges. The DAC780x series of digital-to-analog converters also use this scheme in each of their three different interface formats (serial, 8-bits + 4-bits parallel, and 12-bit parallel).

COB — COMPLEMENTARY OFFSET BINARY

Complementary Offset Binary coding, like its counterpart BOB, is also for use in systems where the analog signal is bipolar. The relationship between COB and BOB is that each coding scheme is the one's complement (all bits inverted) of the other.

COB coding begins with digital zero (0000) at the positive full scale. By incrementing the digital count, the corresponding analog value will approach the negative full scale in $-1V_{LSB}$ steps, passing through bipolar zero on the way. This "zero crossing" occurs at a digital code of 0111 (see Table IV). As the digital count continues to increase, the analog signal goes more negative until the negative full scale is reached at a full digital count (1111) as shown by Table IV.

With COB coding, like BOB coding, the MSB can also be considered a sign indicator whereas a logic "1" indicates a negative analog value, and a logic "0" indicates an analog value greater than or equal to BPZ.(2)

MNEMONIC	DIGITAL CODE	V_{t-}	V_{CODE}	V_{t+}
–FS	1111		–5.000	–4.6875
	1110	–4.6875	–4.375	–4.0625
	1101	–4.0625	–3.750	–3.4375
	1100	–3.4375	–3.125	–2.8125
1/2 –FS	1011	–2.8125	–2.500	–2.1875
	1010	–2.1875	–1.875	–1.5625
	1001	–1.5625	–1.250	–0.9375
BPZ – $1V_{LSB}$	1000	–0.9375	–0.625	–0.3125
BPZ	0111	–0.3125	0.000	+0.3125
BPZ + $1V_{LSB}$	0110	+0.3125	+0.625	+0.9375
	0101	+0.9375	+1.250	+1.5625
	0100	+1.5625	+1.875	+2.1875
1/2 +FS	0011	+2.1875	+2.500	+2.8125
	0010	+2.8125	+3.125	+3.4375
	0001	+3.4375	+3.750	+4.0625
+FS	0000	+4.0625	+4.375	

TABLE IV. COB Coding Scheme.

BTC — BINARY TWO'S COMPLEMENT

Binary Two's Complement coding is the type of coding used by most microprocessor or math processor based systems for mathematical algorithms, and is also the coding scheme which the digital audio industry has decided to use as its standard.

Binary Two's Complement coding is also a scheme designed for bipolar analog signals. It is very similar to BOB, but does not appear so. The only difference between BOB and BTC is that the MSB has been inverted.

Unfortunately, BTC is not as straightforward as the schemes previously mentioned. The codes are not continuous from one end of the analog "spectrum" to the other due to a discontinuity which occurs at BPZ.

Digital zero (0000) corresponds to BPZ, and the digital count increments to its maximum positive code of 0111 as the analog voltage approaches and reaches its positive full scale value. The code then resumes at the negative full scale value at a digital code of 1000, and then approaches BPZ until a digital value of 1111 is reached at one LSB value below BPZ.

With the BTC coding scheme, the MSB can also be considered a sign indicator. When the MSB is a logic "0" a positive value is indicated, and when the MSB is a logic "1" a negative value is indicated.(3)

This is the coding scheme which is used with Burr-Brown's DSP interface chips (DSP101/DSP102 analog input and DSP201/DSP202 analog output) designed for "zero chip interface" to most of the popular digital signal processors available today. Binary Two's Complement is also one of the codes utilized by the ADC603 and ADC614 high speed analog-to-digital converters, and, of course, all of Burr-Brown's PCM digital audio converters.

NOTE: (1) The V_{t+} transition to BPZ from a negative value (0111 to 1000) actually occurs at –0.3125V causing the MSB to go "positive" at a negative value. (2) The V_{t+} transition to BPZ from a negative value (1000 to 0111) actually occurs at –0.3125V causing the MSB to go "positive" at a negative value. (3) The V_{t+} transition to BPZ from a negative value (1111 to 0000) actually occurs at –0.3125V causing the MSB to go "positive" at a negative value.

MNEMONIC	DIGITAL CODE	V_{t-}	V_{CODE}	V_{t+}
–FS	1000		–5.000	–4.6875
	1001	–4.6875	–4.375	–4.0625
	1010	–4.0625	–3.750	–3.4375
	1011	–3.4375	–3.125	–2.8125
1/2 –FS	1100	–2.8125	–2.500	–2.1875
	1101	–2.1875	–1.875	–1.5625
	1110	–1.5625	–1.250	–0.9375
BPZ – $1V_{LSB}$	1111	–0.9375	–0.625	–0.3125
BPZ	0000	–0.3125	0.000	+0.3125
BPZ + $1V_{LSB}$	0001	+0.3125	+0.625	+0.9375
	0010	+0.9375	+1.250	+1.5625
	0011	+1.5625	+1.875	+2.1875
1/2 +FS	0100	+2.1875	+2.500	+2.8125
	0101	+2.8125	+3.125	+3.4375
	0110	+3.4375	+3.750	+4.0625
+FS	0111	+4.0625	+4.375	

TABLE V. BTC Coding Scheme.

MNEMONIC	DIGITAL CODE	V_{t-}	V_{CODE}	V_{t+}
–FS	0111		–5.000	–4.6875
	0110	–4.6875	–4.375	–4.0625
	0101	–4.0625	–3.750	–3.4375
	0100	–3.4375	–3.125	–2.8125
1/2 –FS	0011	–2.8125	–2.500	–2.1875
	0010	–2.1875	–1.875	–1.5625
	0001	–1.5625	–1.250	–0.9375
BPZ – $1V_{LSB}$	0000	–0.9375	–0.625	–0.3125
BPZ	1111	–0.3125	0.000	+0.3125
BPZ + $1V_{LSB}$	1110	+0.3125	+0.625	+0.9375
	1101	+0.9375	+1.250	+1.5625
	1100	+1.5625	+1.875	+2.1875
1/2 +FS	1011	+2.1875	+2.500	+2.8125
	1010	+2.8125	+3.125	+3.4375
	1001	+3.4375	+3.750	+4.0625
+FS	1000	+4.0625	+4.375	

TABLE VI. CTC Coding Scheme.

CTC — COMPLEMENTARY TWO'S COMPLEMENT

Complementary Two's Complement coding is also a scheme designed for bipolar analog signals. It is the one's complement of its counterpart BTC, and is also very similar to COB, although this relationship is not immediately obvious. The only difference between COB and CTC is that the MSB has been inverted.

With CTC coding, digital "zero" is at an analog voltage which is slightly less (1 LSB) than analog bipolar zero. As the digital count increments, the analog voltage becomes more negative until all of the bits are high except for the MSB (0111). At this point, the digital code corresponds to the analog negative full scale. The next step in incrementing the digital code would be to have the MSB a logic "1", and the rest of the bits as logic "0"s (1000), and this code represents the analog positive full scale value. As the digital codes continue to increment, the corresponding analog voltage decreases until BPZ is obtained. Table VI demonstrates this analog/digital relationship.

With Complementary Two's Complement coding, the MSB is also a sign indicator with its states of "0" and "1" representing negative and positive voltages, respectively.

This code is also used by Burr-Brown's high speed ADC603 and ADC614. These converters accomplish this dual code task by providing an input for code selection.

MANIPULATING BETWEEN VARIOUS CODES

The input and output codings used with ADCs and DACs is varied, and an individual converter may be capable of utilizing one or more coding scheme. However, with all of these schemes available, the desired scheme is not always readily available with the particular converter of interest. Do not fear, because converting one coding scheme to another, to match a particular system, is very easy as long as you wish to convert a bipolar scheme to another bipolar scheme; or a unipolar scheme into another unipolar scheme. The only devices required for any transformation are digital logic "inverters", however, some of the transformations can be achieved by using analog components.(4) The following section will be divided into sections depending on how the transformation is to be accomplished.

Inversion of all Bits

USB to CSB and CSB to USB
BOB to COB and COB to BOB
BTC to CTC and CTC to BTC

The CSB scheme is simply the USB code with all of the bits inverted (one's complement). This is also how to perform most of the transformation of BOB to COB, and BTC to CTC. For conversion of unipolar schemes, there is only a digital "solution", and conversion of bipolar schemes may be done with analog or digital components.

Converting between the bipolar codes in an analog fashion, all that's needed is one op amp configured for a gain of –1V/V (see Figure 2). This op amp can be used on the input stage of an ADC or the output stage of a DAC. Some sample and hold amplifiers, such as the SHC5320, are configurable for a gain of –1V/V, providing very easy conversion between these codes in an analog-to-digital system. Remember that either $+1V_{LSB}$ or $-1V_{LSB}$ must be summed in with the analog value.

The bipolar transformations may be quite straightforward when done in the analog domain; however, to convert digitally, an individual logic "inverter" must be used on every data line, input or output (see Figure 1), as with the unipolar schemes.

The ADC603 and ADC614 allow both BTC and CTC coding schemes by providing an "Output Logic Invert" input pin. This flexibility allows these converters to be used in even more applications easier than if just one scheme had been implemented.

NOTE: (4) When converting bipolar digital schemes, regardless of whether the transformation is done digitally or in an analog fashion, a value of either $+1V_{LSB}$ or $-1V_{LSB}$ must be summed in with the analog value. This is due to the assymetric nature of the codes around bipolar zero (see definition of V_t). This addition of one V_{LSB} is relatively simple, since most data converters allow for an offset adjustment which can accomodate this.

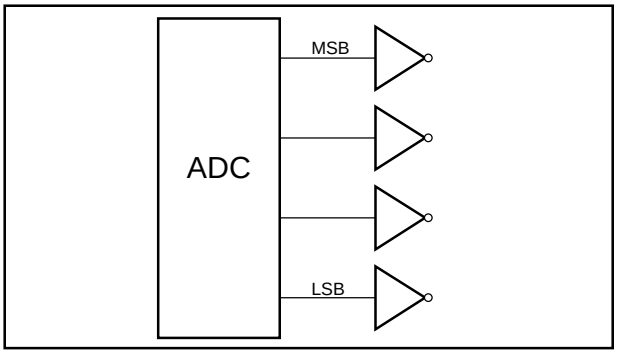

FIGURE 1. Digital Inversion of All Bits.

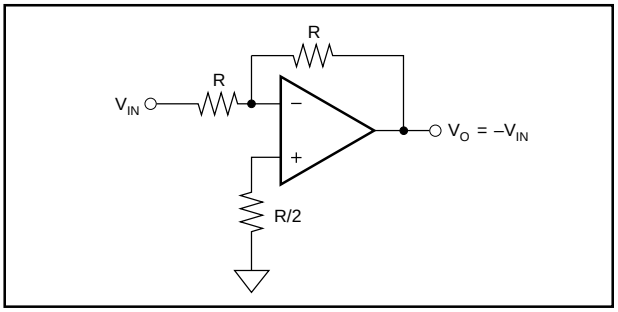

FIGURE 2. Analog Signal Inversion.

Inversion of the MSB

BOB to BTC and BTC to BOB
COB to CTC and CTC to COB

Manipulating the BOB scheme into BTC and manipulating COB into CTC requires much less hardware. To go from BOB to BTC, or COB to CTC (or vice versa) it is only necessary to invert the MSB (see Figure 3).

Burr-Brown's PCM78, a 16-bit ADC developed for digital audio applications allows BOB or BTC output schemes by providing a "BOB/BTC select" input. Open circuit or grounding of this pin provides for BTC and BOB respectively by controlling an internal inverter for the most significant bit.

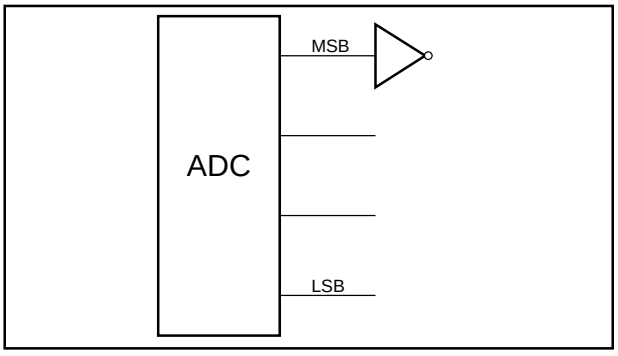

FIGURE 3. Inversion of the MSB.

Inversion of all bits except the MSB

BOB to CTC and CTC to BOB
BTC to COB and COB to BTC

Manipulation of BOB into CTC and BTC into COB requires inverting all bits except the MSB. This is also a difficult transformation to accomplish, since it would require a digital inverter for every bit except the most significant bit (see Figure 4).

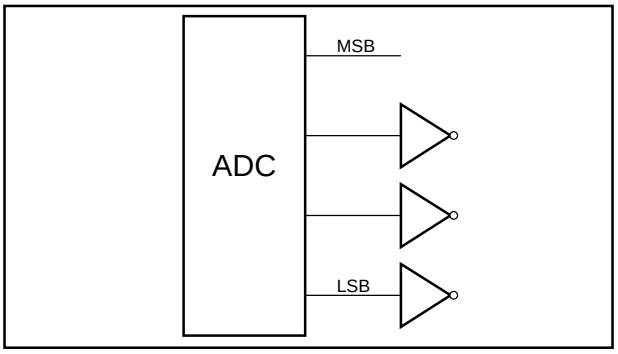

FIGURE 4. Inversion of All Bits Except the MSB.

DEFINITIONS

n	=	Number of bits in a particular digital system.
LSB	=	Least Significant Bit — The digital bit with the least analog "weight".
MSB	=	Most Significant Bit — The digital bit with the greatest analog "weight".
Increment	=	To increase a digital "count", or to count up, as in a code changing from 0000 to 0001.
Decrement	=	To decrease a digital "count", or to count down, as in a code changing from 0001 to 0000.
USB	=	Unipolar Straight Binary coding.
CSB	=	Complementary Straight Binary coding.
BOB	=	Bipolar Offset Binary coding.
COB	=	Complementary Offset Binary coding.
BTC	=	Binary Two's Complement coding.
CTC	=	Complementary Two's Complement coding.
FSR	=	Full Scale Range — The dynamic range of an analog signal.
BPZ	=	Bipolar Zero — An analog voltage of 0V.
V_{LSB}	=	Least Significant Bit Voltage — The value of voltage represented by one LSB. For digital-to-analog converters which provide a current output mode of operation, V_{LSB} actually refers to a voltage after a current-to-voltage conversion. Throughout the text, it is presumed that this current to voltage conversion has taken place. $V_{LSB} = FSR/2^n$ **(Equation 1)**

DEFINITIONS (CONT)

V_{CODE} = Code Voltage —The voltage corresponding to a particular digital code in an ideal converter. For digital-to-analog converters which provide a current output mode of operation, V_{CODE} actually referes to a voltage after a current-to-voltage conversion. Throughout the text, it is presumed that this current-to-voltage conversion has occurred.

$V_{CODE} = (digital\ code)_{10} * V_{LSB}$ **(Equation 2)**

For analog-to-digital converters, the code voltage is actually an analog range of voltages encompassed by $V_{CODE} \pm 1/2V_{LSB}$. This is due to the inherent quantization error of $\pm 1/2V_{LSB}$ that is present in the finite digital output of the ADC.

The value of $(digital\ code)_{10} * V_{LSB}$ will be used throughout this text to represent V_{CODE} unless otherwise stated.

+FS = Positive Full Scale —The most positive end of an analog signal's range which is represented by a digital code. A V_{CODE} equal to the positive full range (+FS) does not exist. The industry standard is that the most positive voltage corresponding to a digital code (maximum V_{CODE}) is the positive full scale voltage minus the voltage associated with one LSB ($+FS - 1V_{LSB}$). The text "positive full scale" (or +FS) refers to this lesser, industry standard value. This +FS industry standard is primarily due to another industry standard in which 0V is a code voltage (see Equation 3) bounded by the absolute value of $\pm 1/2V_{LSB}$. In a unipolar system, this means that the analog voltage range represented by a digital code corresponding to BPZ is only $1/2V_{LSB}$. In bipolar systems, all digital codes have analog ranges of $1V_{LSB}$, and a digital code representing 0V is 0V $\pm 1/2V_{LSB}$ (see Equation 3 and Equation 4).

–FS = Negative Full Scale — The most negative end of an analog signal's range which is represented by a digital code.

V_t = Transition voltage — The voltage which corresponds to the actual change of a digital code in an ideal analog-to-digital converter. These voltages are the voltages at each end of the range of $V_{CODE} \pm 1/2V_{LSB}$.

$V_{t+} = V_{CODE} + 1/2V_{LSB}$ **(Equation 3)**

$V_{t-} = V_{CODE} - 1/2V_{LSB}$ **(Equation 4)**

For an ideal digital-to-analog converter, the output would be exactly V_{CODE}, and the transition voltage can be ignored.

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