Basic DAC Architectures I: String DACs and Thermometer (Fully Decoded) DACs

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INTRODUCTION

Rather than simply treating DACs as black boxes having a digital input and an analog output, it is much more useful to understand the fundamental DAC architectures in use today. This can also aid in the selection process which can be somewhat daunting considering the sheer number of DACs currently on the market.

This tutorial examines the most fundamental DAC architectures, the "string" DAC and the "thermometer" DAC. String DACs had their origin with Lord Kelvin, who invented the Kelvin divider in the mid-1800s. String DACs are popular today, especially in applications such as digital potentiometers where resolutions of 6 to 8 bits are typical. Because of their relative freedom from code-dependent switching glitches, thermometer DACs are popular building blocks in low distortion segmented DACs as well as in pipelined ADCs.

THE SWITCH: A SIMPLE 1-BIT DAC

It is reasonable to consider a changeover switch (a single-pole, double-throw, SPDT switch), switching an output between a reference and ground or between equal positive and negative reference voltages, as a 1-bit DAC as shown in Figure 1. Such a simple device is a component of many more complex DAC structures, and is used, with oversampling, as the basic analog component in many of the sigma-delta DACs we shall discuss later. The simple switch is also very easy to implement in standard CMOS processes. Nevertheless it is a little too simple to require detailed discussion, and it is more rewarding to consider more complex structures.


V_{REF}

OUTPUT
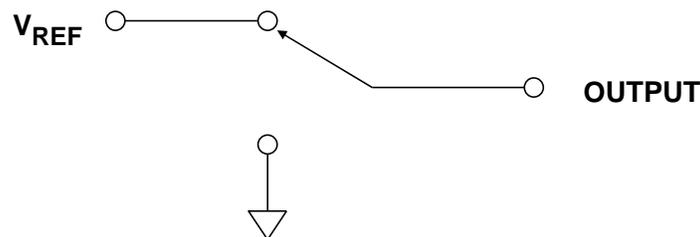
Figure 1: 1-Bit DAC: Changeover Switch (Single-Pole, Double Throw, SPDT)

THE KELVIN DIVIDER (STRING DAC)

The simplest DAC structure of all, after the changeover switch mentioned above, is the Kelvin divider or *string DAC* as shown in Figure 2. An N-bit version of this DAC simply consists of 2^N equal resistors in series and 2^N switches (usually CMOS), one between each node of the chain

and the output. The output is taken from the appropriate tap by closing just one of the switches (there is some slight digital complexity involved in decoding to 1 of 2^N switches from N-bit data, but digital circuitry is cheap). The origins of this DAC date back to Lord Kelvin in the mid-1800s, and it was first implemented using resistors and relays, and later with vacuum tubes in the 1920s (See References 1, 2, 3).
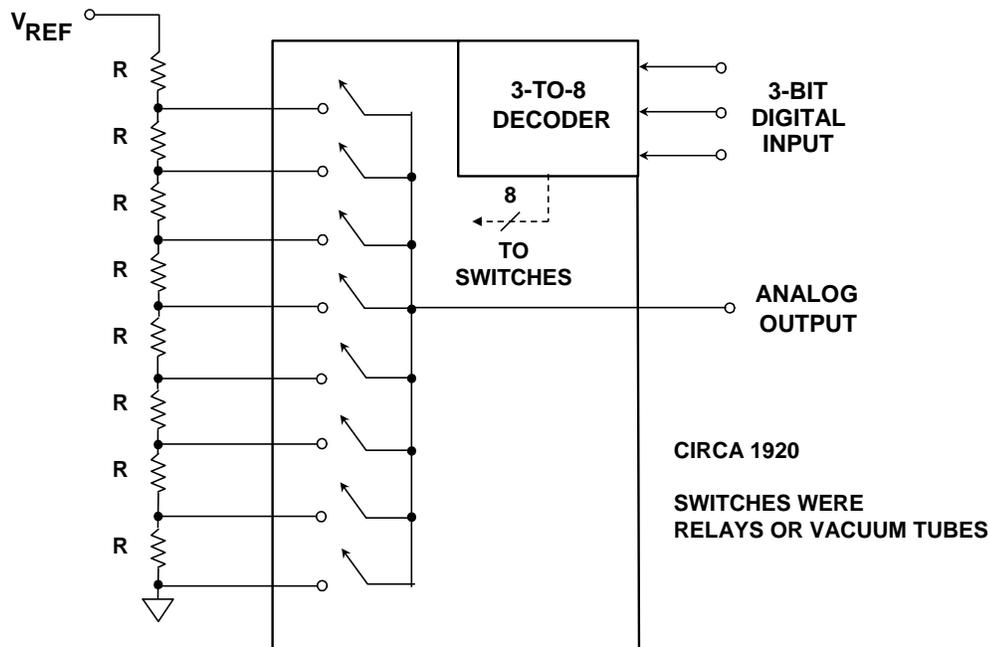

Figure 2: Simplest Voltage-Output Thermometer DAC:
The Kelvin Divider ("String DAC")

This architecture is simple, has a voltage output (but a code-dependent output impedance) and is inherently monotonic—even if a resistor is accidentally short-circuited, output n cannot exceed output n + 1. It is linear if all the resistors are equal, but may be made deliberately nonlinear if a nonlinear DAC is required. Since only two switches operate during a transition, it is a low-glitch architecture. Also, the switching glitch is not code-dependent, making it ideal for low distortion applications. Because the glitch is relatively constant regardless of the code transition, the frequency content of the glitch is at the DAC update rate and its harmonics—not at the harmonics of the fundamental DAC output frequency. The major drawback of the string DAC is the large number of resistors and switches required for high resolution, and as a result it was not commonly used as a simple DAC architecture until the recent advent of very small IC feature sizes made it very practical for low and medium resolution DACs. Today the architecture is quite widely used in simple DACs, such as digital potentiometers and, as we shall see later, its current-output version, the thermometer DAC, is also used as a component in more complex high resolution segmented DAC structures.

The output of a DAC for an all "1"s code is 1 LSB below the reference, so a string DAC intended for use as a general purpose DAC has a resistor between the reference terminal and the first switch as shown in Figure 2.

In an ideal potentiometer, on the other hand, all "0"s and all "1"s codes should connect the variable tap to one or other end of the string of resistors. So a digital potentiometer, while basically the same as a general purpose string DAC, has one fewer resistor, and neither end of the string has any other internal connection. A simple digital potentiometer is shown in Figure 3.
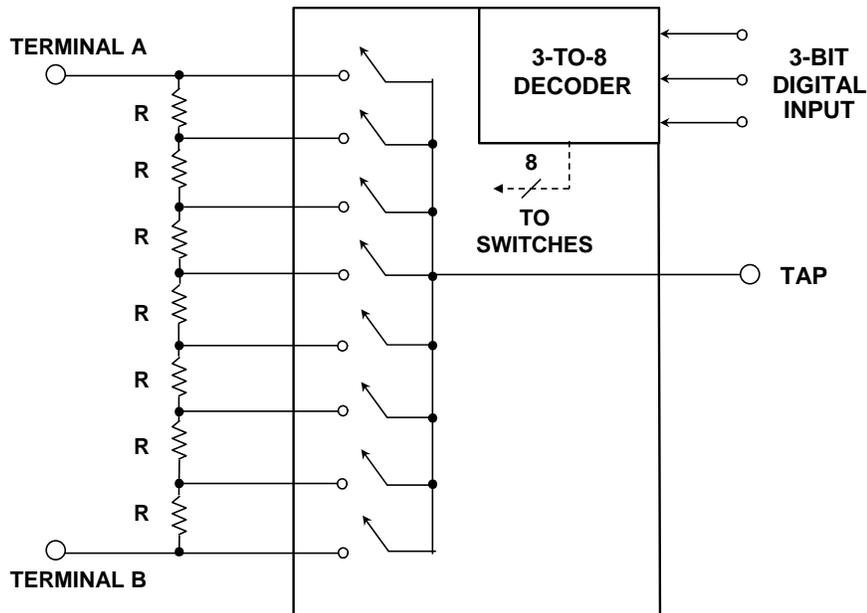

Figure 3: A Slight Modification to a String DAC Yields a "Digital Potentiometer"

The simplest digital potentiometers are no more complex than this, and none of the potentiometer terminals may be at a potential outside the 5-V or 3-V logic supply. But others have more complex decoders with level shifters and additional high voltage supply terminals, so that while the logic control levels are low (3 V or 5 V), the potentiometer terminals have a much greater range—up to ±15 V in some cases. Digital potentiometers frequently incorporate nonvolatile logic so that their settings are retained when they are turned off.

It is evident that string DACs have a large number of resistors (2^N for an N-bit DAC as we have already seen). It is not practical to trim every resistor in a string DAC to obtain perfect DNL and INL, partly because they are too many, and partly because they are too small to trim, and mainly because it's too costly. Because of the physical size, pure string DACs are primarily limited to resolutions of 8 to 10 bits.

CURRENT OUTPUT THERMOMETER (FULLY DECODED) DACs

There is a current-output DAC analogous to a string DAC that consists of 2^N-1 switchable current sources (which may be resistors and a voltage reference or may be active current sources) connected to an output terminal, which must be at, or close to, ground. This architecture is commonly referred to as a "thermometer" or "fully decoded" DAC. Figure 4 shows such a thermometer DAC which uses resistors connected to a reference voltage to generate the currents.
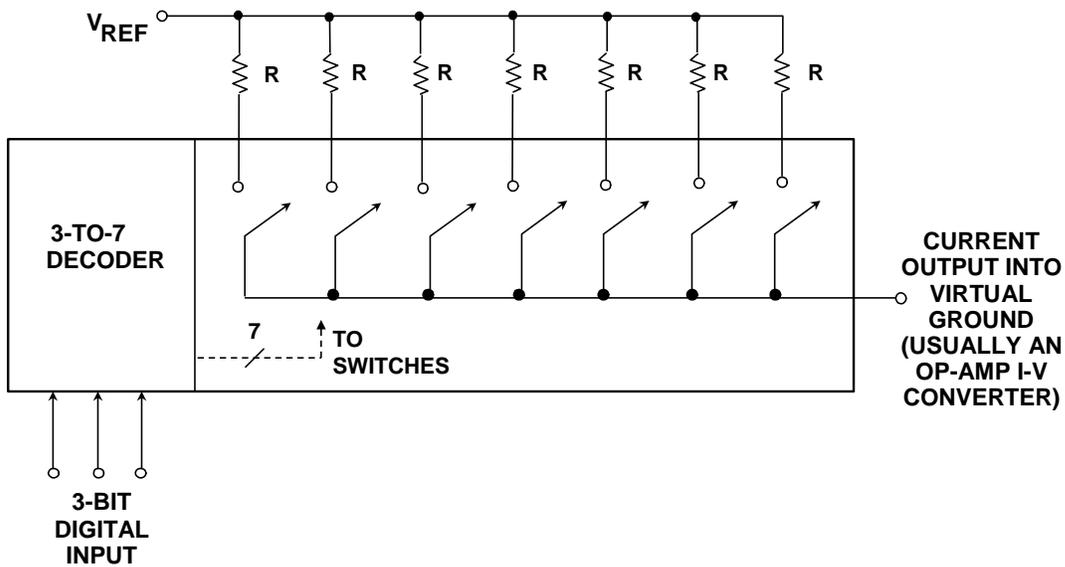
Figure 4: The Simplest Current-Output Thermometer (Fully-Decoded) DAC

If active current sources are used as shown in Figure 5, the output may have more compliance, and a resistive load used to develop an output voltage. The load resistor must be chosen so that at maximum output current the output terminal remains within its rated compliance voltage.
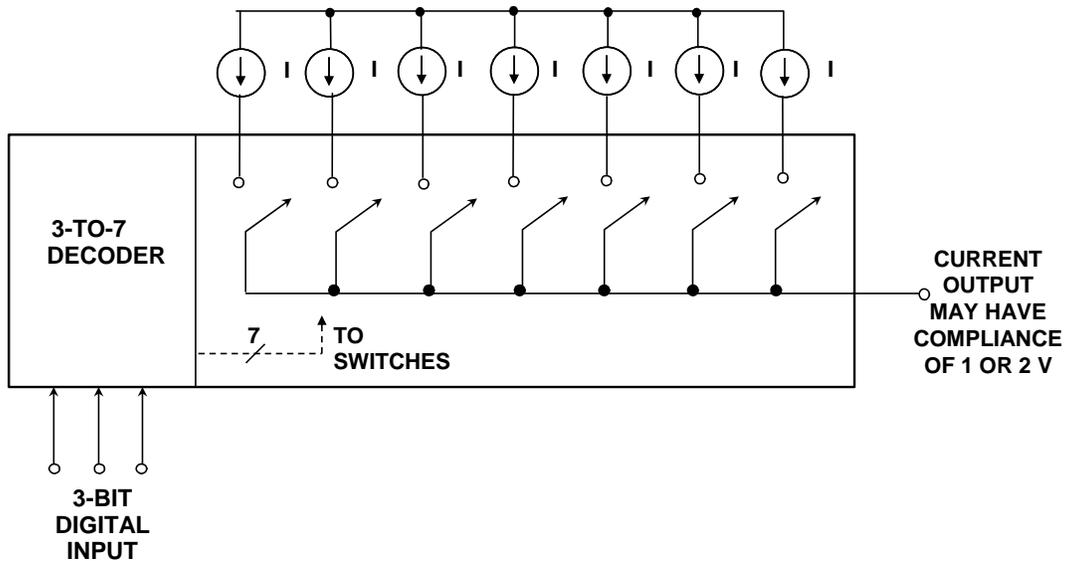

Figure 5: Current Sources Improve the Basic
Current-Output Thermometer DAC

Once a current in a thermometer DAC is switched into the circuit by increasing the digital code, any further increases do not switch it out again. The structure is thus inherently monotonic, irrespective of inaccuracies in the currents. Again, like the Kelvin divider, only the advent of high density IC processes has made this architecture practical for general purpose medium

resolution DACs, although a slightly more complex version—shown in the next diagram—is quite widely used in high speed applications. Unlike the Kelvin divider, this type of current-mode DAC does not have a unique name, although both types may be referred to as *thermometer* DACs or *fully-decoded* DACs.

A DAC where the currents are switched between two output lines—one of which is often grounded, but may, in the more general case, be used as the inverted output—is more suitable for high speed applications because switching a current between two outputs is far less disruptive, and so causes a far lower glitch than simply switching a current on and off. This architecture is shown in Figure 6.
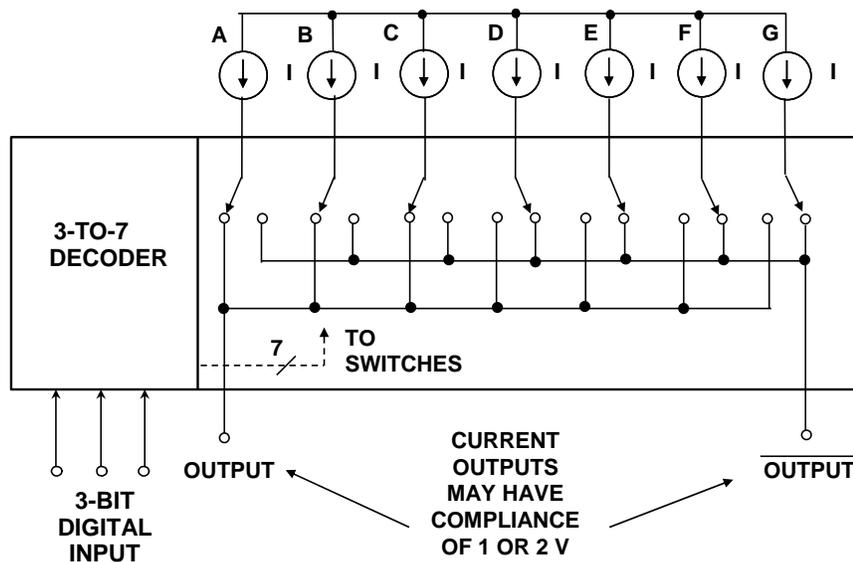
Figure 6: High Speed Thermometer DAC with Complementary Current Outputs

But the settling time of this DAC still varies with initial and final code, giving rise to *intersymbol interference* (ISI). This can be addressed with even more complex switching where the output current is returned to zero before going to its next value. Note that although the current in the output is returned to zero it is not "turned off"—the current is dumped when it is not being used, rather than being switched on and off. The techniques involved are too complex to discuss in detail here but can be found in Reference 4.

In the normal (linear) version of this DAC, all the currents are nominally equal. Where it is used for high speed reconstruction, its linearity can be improved by dynamically changing the order in which the currents are switched by ascending code. Instead of code 001 always turning on current A; code 010 always turning on currents A & B, code 011 always turning on currents A, B & C; etc., the order of turn-on relative to ascending code changes for each new data point. This can be done quite easily with a little extra logic in the decoder. The simplest way of achieving it is with a counter which increments with each clock cycle so that the order advances: ABCDEFG, BCDEFGA, CDEFGAB, etc., but this algorithm may give rise to spurious tones in the DAC output. A better approach is to set a new pseudo-random order on each clock cycle—this requires

a little more logic, but, as we have pointed out, even complex logic is now very cheap and easily implemented on CMOS processes. There are other, even more complex, techniques which involve using the data itself to select bits and thus turn current mismatch into shaped noise. Again they are too complex for a tutorial of this sort. (See References 4 and 5 for a more detailed discussion).

REFERENCES:

1. Peter I. Wold, "Signal-Receiving System," *U.S. Patent 1,514,753*, filed November 19, 1920, issued November 11, 1924. *(thermometer DAC using relays and vacuum tubes).*

2. Clarence A. Sprague, "Selective System," *U.S. Patent 1,593,993*, filed November 10, 1921, issued July 27, 1926. *(thermometer DAC using relays and vacuum tubes).*

3. Leland K. Swart, "Gas-Filled Tube and Circuit Therefor," *U.S. Patent 2,032,514*, filed June 1, 1935, issued March 3, 1936. *(a thermometer DAC based on vacuum tube switches).*

4. Robert Adams, Khiem Nguyen, and Karl Sweetland, "A 113 dB SNR Oversampling DAC with Segmented Noise-Shaped Scrambling," *ISSCC Digest of Technical Papers*, vol. 41, 1998, pp. 62, 63, 413. *(describes a segmented audio DAC with data scrambling).*

5. Robert W. Adams and Tom W. Kwan, "Data-directed Scrambler for Multi-bit Noise-shaping D/A Converters," *U.S. Patent 5,404,142*, filed August 5, 1993, issued April 4, 1995. *(describes a segmented audio DAC with data scrambling).*

6. Walt Kester, *Analog-Digital Conversion*, Analog Devices, 2004, ISBN 0-916550-27-3, Chapter 3. Also available as *The Data Conversion Handbook*, Elsevier/Newnes, 2005, ISBN 0-7506-7841-0, Chapter 3.