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# 6. Reflections of a Dinosaur

Sixty five million years ago, at the end of the Cretaceous period, the dinosaur vanished from the earth. Some scientist believe that the disappearance was due to the cataclysmic collision of a large body with Earth.

The explosive growth of digital technology is the cataclysmic event that has threatened the analog designer with extinction. The linear circuit engineer has been added to the list of endangered species. For the past twenty years the focus of the engineering curriculum has shifted priority from analog to digital technology. The result of this shift is that only a small fraction of recently trained engineers have the analog design skills necessary to attack "real world" problems. The microprocessor has revolutionized the area of measurement and control, but the transducers used to measure and control temperature, pressure, and displacement are analog instruments. Until sensors and actuators are available that can convert a physical parameter such as temperature directly to digital information, the analog designer will still be in demand.

Analog design is a challenging field because most projects require the designer to optimize a circuit by surrendering one performance parameter to enhance another. As an old analog guru once said when comparing the analog and digital disciplines, "Any idiot can count to one, but analog design requires the engineer to make intelligent trade-offs to optimize a circuit." Analog design is not black or white as in "ones" and "zeros"; analog design is shades of gray.

This essay contains the reflections, thoughts, and design philosophies of a nearly extinct species of electrical engineer, the analog circuit designer. Digital technology has reduced our population to a small fraction of those that existed twenty or thirty years ago. This is unfortunate since the need for, and the challenge of, analog design is still with us. This chapter relates experiences I have had as an electrical engineer since I received my degree in June 1959. I hope these reflections will in some way encourage and help the recently initiated and entertain those of you who remember filament transformers and $B^+$ power supplies.

My undergraduate electrical engineering education covered mainly vacuum tube technology, but there were two "new" areas that the department felt were of significant enough importance to include in the curriculum. As a result, we received a one-hour lecture on transistors and a one-hour lecture on crysistors. For those of you who are unfamiliar with the crysistor, it is a superconducting magnetic memory element that showed promise of revolutionizing the computer world.

It would have been difficult to predict in 1960 that the vacuum tube would become a relic of the past, transistor technology would rule, and the crysistor would completely disappear from the scene. Although the crysistors never made it, the discovery of new low-temperature superconductors may give it a second chance.

It amazes me that most of the technology I work with today did not even exist in

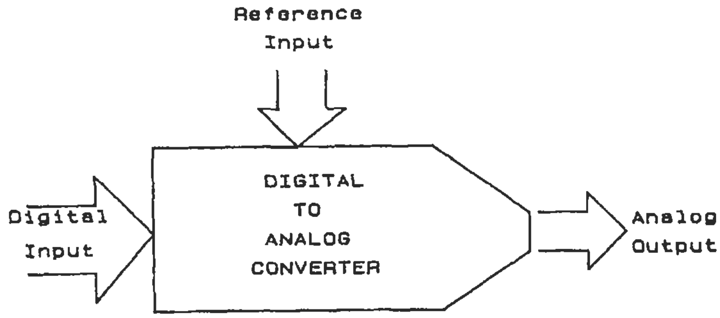


**Figure 6-1.** Basic digital to analog converter (DAC).

the late '50s and early '60s. I mention this to emphasize that a firm understanding of fundamental principles is much more important to one's long-term success in engineering, or any field for that matter, than the learning of some specific skill. For example, without a thorough understanding of Maxwell's equations and Ohm's law and how they are applied, it would be difficult, if not impossible, to progress with new technologies. My approach to troubleshooting circuits is, "The circuit will not violate Ohm's law." If I make measurements that suggest the opposite, I look for oscillations. But I digress—back to the "early years."

The late 1950s were the times of vacuum tube digital computers with 16 K of memory. Computing power that today fits on a desktop occupied hundreds of square feet of space. The mechanical desktop calculators we used required several seconds to multiply two 10-digit numbers. They were not portable, so everyone carried slide rules that were quicker to use, easier to carry around, and didn't need 110 V electrical power. The slide rule only produced an answer to three or four significant digits, but this was not a real limitation since electrical engineering was only a 1% or at best a 0.1% science. Measuring instruments were all analog and even a General Radio meter with the black crinkle finish and a mirrored scale (now that shows my age) would only yield a voltage measurement of three significant digits at best.

During the mid 1950s a 12-ounce container of Coke (which at that time referred to a soft drink) cost a dime. The top-of-the-line Chevrolet and a year at a private university cost about the same—$2,000. As an economist friend of mine once pointed out, inflation is a relative thing, since the price of the Chevrolet and a year's tuition for a private university have remained constant over the years.

The thirty or so years between the late 1950s and the present have brought many changes. The vacuum tube digital computer which once occupied a room is now fabricated on a silicon chip the size of your thumbnail. The mechanical calculator and slide rule have disappeared and been replaced by the solar powered scientific calculator. Electrical measurements are made with digital instruments that are accurate to six or seven significant digits, and Coke is no longer just a soft drink. To those of us in the analog world, digital technology is a two-edged sword. Digital technology has created powerful tools for the analog designer to use, but it has also depleted our ranks by attracting some of the most promising students. This is unfortunate since some of the most challenging problems are analog in nature, and fewer and fewer graduating engineers are equipped to solve them.

I classify analog designers into one of two categories. There are those who do truly original work, and these I consider the artists of our profession. These individuals, as in most fields, are very rare. Then there are the rest of us, who are indeed

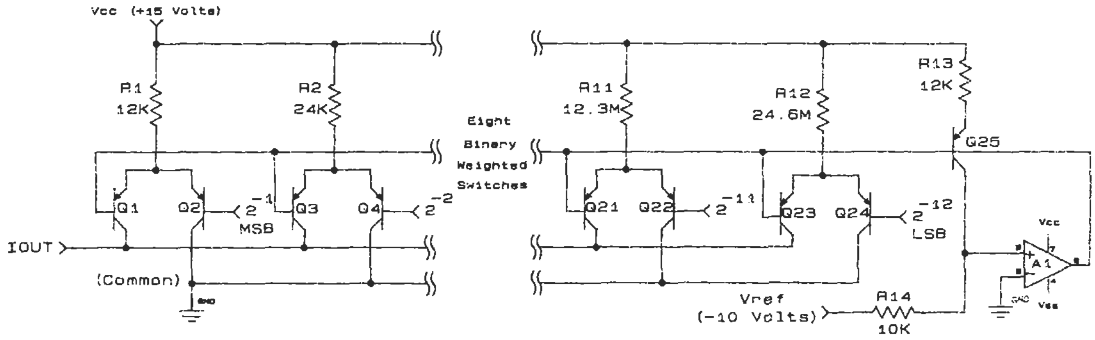


Figure 6-2. Transistor–transistor switched binary weighted 12-bit DAC.

creative, but do it by building on the present base of knowledge. A quote from Sir Isaac Newton beautifully describes how this design process works:

> If I have seen farther than others
> it is by standing on the shoulders of giants.
> —Sir Isaac Newton to Robert Hooke, February 5, 1675

A less tasteful, but some would say more honest, illustration of how electronic circuits are designed is contained in a humorous 1950s song by Tom Lehrer:

> Plagiarize, Plagiarize,
> Let no one else's work evade your eyes.
> Remember why the good Lord made your eyes.
> So don't shade your eyes but,
> Plagiarize, Plagiarize.
> Only be sure always to call it please,
> Research.
> —Song by Tom Lehrer

I quoted the lyrics of the Lehrer song tongue-in-cheek, but circuit design is an evolutionary process where one must draw on past developments. The digital-to-analog converter (DAC) of the early 1960s is a classic example of how a circuit develops, changes, and improves as it moves through the hands of different designers.

For those of you not familiar with DACs a quick explanation is in order. The DAC is a device whose input is a digital number, usually in a binary format, and whose output is an analog signal. The analog output is usually a voltage or a current whose value is a function of the digital input and a reference voltage (see Figure 6-1). The DAC was one of the first circuits developed for linking the analog and digital domains, and even today the DAC plays a large role in computer graphic terminals, music synthesizers, and the many other applications in which a digital processor must communicate with the analog world.

During the early 1960s transistors were replacing vacuum tubes, and digital integrated circuits were just becoming available. Analog integrated circuits were not widely available, and those that were available were expensive. Almost all analog circuit design was carried out with discrete components and an occasional integrated amplifier. The transistor was becoming available, and since it closely approximates an ideal current source, it was an excellent candidate for the switch in a current output DAC. The first DACs built with transistors used emitter coupled current

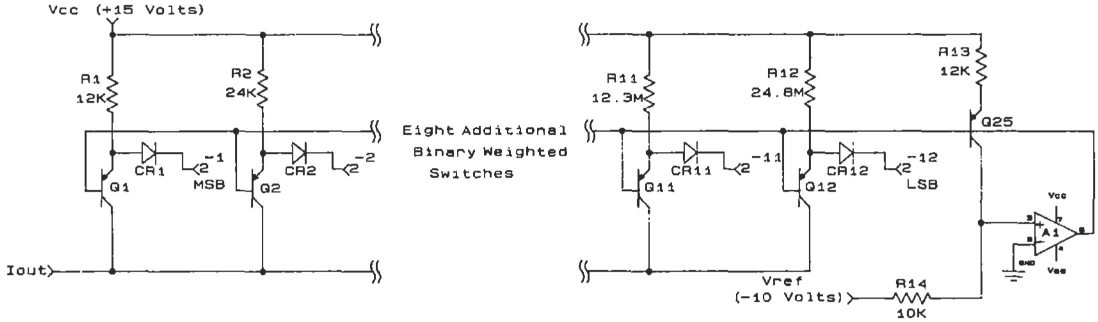


**Figure 6-3.** Transistor-diode switched binary 12-bit weighted DAC.

sources. The emitter coupled transistors (see Figure 6-2) steered the current to the output bus ($I_{out}$) or common (GND), depending on the level of the digital input.

The most significant bit (MSB)[1] current source consist of a resistor (R1) and two pnp transistors (Q1, Q2). The servo amplifier (A1) biases the base of Q1 to approximately 1.4 V. When the base of Q2 is above 2.0 V (a digital logic "1"), all current through R1 is steered to $I_{out}$ through Q1, since Q2 is cutoff. Conversely, when the base of Q2 is lower than 0.8 V (a digital logic "0"), all the current is steered to GND through Q2, since Q1 is cutoff.

The reference loop Q25,A1,R13, and R14 biases the bases of the transistors (Q1, Q2, . . . , Q21, Q23) connected to $I_{out}$, maintaining a constant voltage across the current setting resistors R1 through R12. The values of the components are selected for a nominal base bias voltage of 1.4 V. It will be left as an exercise for the student to show that when the digital input bit is a logic "1" the servo amplifier (A1) will maintain the same voltage across resistors R1 through R12 by adjusting the base voltages of all the transistors connected to $I_{out}$. The magnitude of the constant voltage across the resistors will be $V_{ref} \times$ (R13/R14). Since each current setting resistor is twice the value of the resistor to its left, the currents from each switch will be binary weighted. That is, the current of each switch will be ½ the current of the switch to its left.

If the operation of the reference loop is not clear, don't spend serious time trying to understand it, as it is not necessary for the discussion that follows. A detailed discussion of DAC reference loops can be found in one of the data conversion handbooks that are available from converter manufacturers.

The analog output of this DAC is a current that can be converted to a voltage by connecting a resistor from the $I_{out}$ terminal to ground. To ensure that the transistors remain biased in the correct operating range, the $I_{out}$ terminal should not exceed +1 V. For a DAC that produced a 2 mA full scale output current, a 500 Ω resistor connected from $I_{out}$ to ground would produce a 0 to +1 V output swing. A −1 V to +1 V output swing could be obtained by terminating the $I_{out}$ terminal with a 1000 Ω resistor to −1 V source instead of ground.

As stated before, the current setting resistors of each switch pair increases in a binary sequence. The current from each transistor pair is twice that of the transistor pair on its right and half of the current of the transistor pair on its left. If the MSB

1. Bit is an acronym for a digit of a binary number. It is derived from *B*inary *I*n*T*eger. The highest order digit of the binary number is usually called the MSB or *M*ost *S*ignificant *B*it. The Bit's are also labeled to indicate their relative weight in the binary number. For example the MSB is also called the $2^{-1}$ bit because it contributes ½ of the full scale output current the next lower order bit is labeled $2^{-2}$ since it contributes ¼ of the full scale output current. The lowest order bit of a binary number is called the LSB or Least Significant Bit.

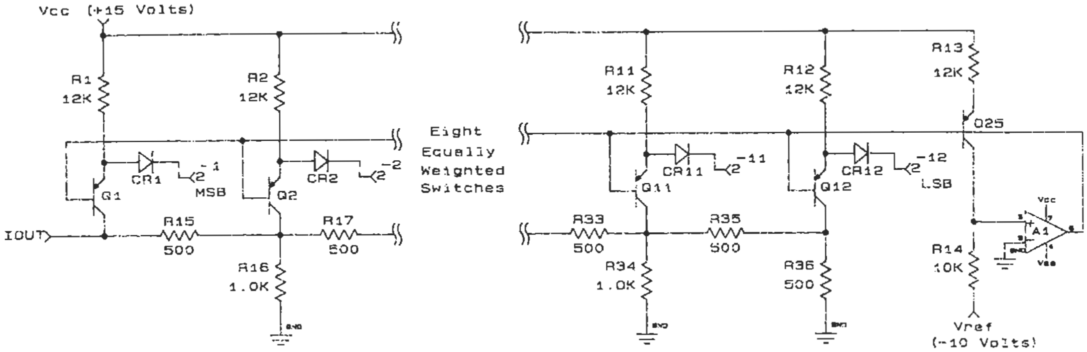


**Figure 6-4.** Transistor–diode switched R-2R current division 12-bit DAC.

of the digital input is a logic "1" and all the other digital inputs are "0," the output current would be $\frac{1}{2}$ its full scale value. If the MSB-1 ($2^{-2}$) is a logic "1" and all the other digital inputs are "0," the output current would be $\frac{1}{4}$ of full scale. If both the MSB and the MSB-1 are logic "1"s and all the other digital inputs are "0," the output current would be $\frac{3}{4}$ ($\frac{1}{2}+\frac{1}{4}$) of full scale. In this manner any combination of digital "1"s and "0"s can be converted to a current.

This circuit topology functioned fine but used two transistors per switch. In the late 1960s transistors were expensive and occupied significant space on the printed circuit board. In an effort to reduce cost and size, an imaginative engineer realized that the transistors that steered the current to ground could be replaced with simple diodes (see Figure 6-3). The substitution was possible because converters were usually driven with digital logic capable of sinking several milliamps of current to ground.

The diode is smaller and less expensive than a transistor, reducing the cost and size of the converter with no degradation in performance. The trade-off that the designer made to obtain a decrease in cost and size was the requirement that the converter's digital drive sink several milliamps of current to ground. At the time this did not represent a serious compromise, because digital CMOS logic was not widely used. The most popular logic used bipolar transistors and could easily sink the necessary several milliamps of current.

The circuits of Figures 6-2 and 6-3, although very simple, possessed one major drawback, that of speed. The currents of the LSBs are so much less that the currents of the MSBs, that the switching times of the LSBs are significantly slower than the MSBs. This difference in switching time results in large switching transients or "glitches." In the case of a 12-bit converter the ratio of the MSB current to the LSB current is 2048 to 1. For a 12-bit converter with a 1 mA MSB, the LSB would only switch 500 nA and the LSB switching time would be at least an order of magnitude slower than the MSB. In many slow speed applications the switching transients are not important, but for high speed applications, such as drivers for graphic terminals, glitch-free operation is essential.

I don't know who first had the idea, but someone formulated the concept of operating all the switches at the same current and performing the binary division of each bit at the output of the appropriate current source (see Figure 6-4).

The binary current division is accomplished with the R-2R[2] ladder connected to

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2. The current divider of Figure 6-4 is called an R-2R ladder because of the similarity of the resistor configuration to a ladder laid on its side. the rungs of the ladder are the even numbered resistors R16 through R32. The top side of the ladder is formed by the odd numbered resistors R15 throught R35. The bottom side of the ladder is Common (GND). The ratio of the values of the even numbered resistors to the odd numbered resistors is 2:1. Thus the current divider is called and R-2R ladder. The termination resistor is a special case and has a value of R since the ladder is finite in length.

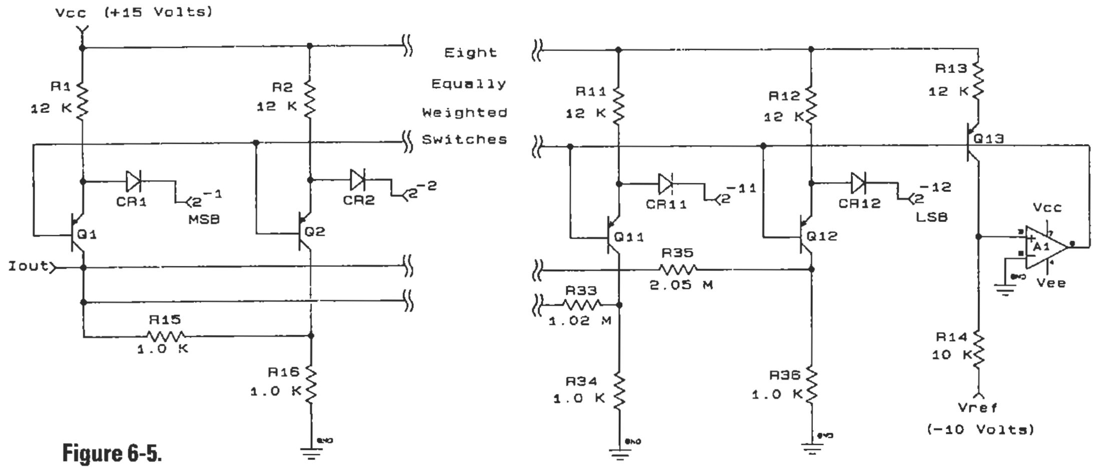


**Figure 6-5.** Transistor–diode switched individual current division 12-bit DAC.

the outputs of the current steering switches. For those unfamiliar with the R-2R ladder, it is an interesting exercise to calculate what fraction of current introduced into the nth R-2R-R node will reach a load resistor $R_L$ connected from the $I_{out}$ node to ground. A little mathematical manipulation will show that the current introduced at any node of the R-2R ladder is attenuated by

$$2^{-n} \times (2R/(R_L+2R))$$

when it reaches the load resistor $R_L$; where $n$ = the number of stages between the node where the current is introduced and the $I_{out}$ node.

$n = 0$ for the MSB
$n = 1$ for the MSB-1
$n = 2$ for the MSB-2

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.

$n = n - 2$ for the LSB+1
$n = n - 1$ for the LSB

An interesting property of the R-2R ladder is that the resistance of the ladder at any R-2R node looking to the right is always 2R. Using Figure 6-4 as an example, the resistance looking into R35 is 1000 Ω, R35 + R36. The resistance looking into R33 is also 1000 Ω, (R33 added to the parallel combination of R34 with the sum of R35 and R36). This calculation can be repeated at each node, and you will find that the resistance looking into $I_{out}$ is also 2R.

When all the current sources are made equal and the current division is done with the R-2R ladder, the switching times of each bit are matched. The physical length of the R-2R ladder will introduce a differential delay from each bit to the $I_{out}$ node, but this is a very small effect and turns out not to be important if the resistance of the R-2R ladder is low. Even the small delay due to the propagation time through the R-2R ladder can be reduced by providing a separate divider for each bit (see Figure 6-5). This scheme has been tried, and the results are almost identical to the dynamic performance of the R-2R divider.

The use of equal current sources and a resistive divider, either the R-2R or the individual, improves the dynamic performance. The improved performance is gained at the expense of complexity and power consumption. The R-2R and the individual divider circuits use three resistors per bit instead of the one resistor per bit of the

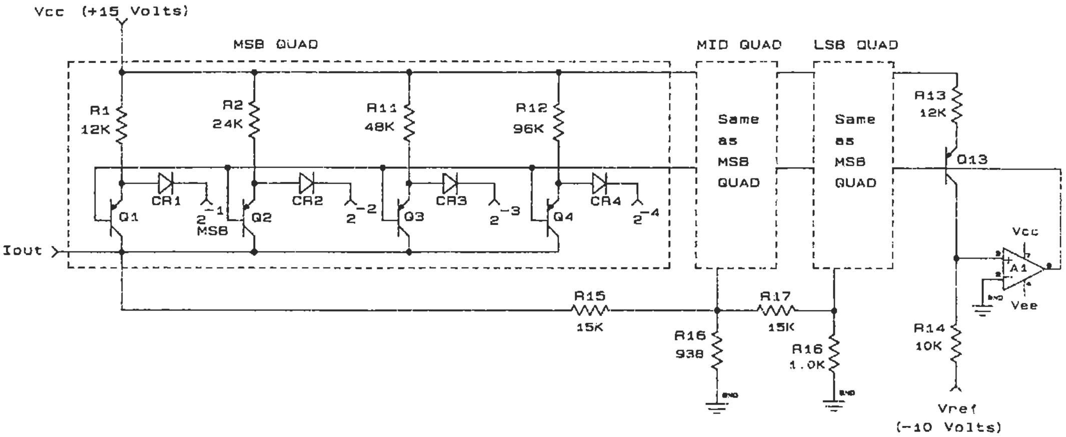


Figure 6-6. Transistor–diode switched binary weighted quad current division 12-bit DAC.

binary weighted converters. The total current switched in the binary converters is the full scale output current of the converter. The total current switched by the resistive divider converters is ½ the full scale output current of the converter multiplied by the number of bits, since each bit switches ½ of the full scale current. A 12-bit binary weighted converter with a 2 mA full scale output current would switch 2 mA. A 12-bit resistive divider converter with a 2 mA full scale output current would switch 12 mA. The dynamic performance of the slower binary weighted circuit is improved by increasing its complexity and power consumption.

The binary weighted configuration and the current division configuration can be combined to form a converter that is faster and slightly more complex than the binary weighted scheme but less complex and only slightly slower than current division. The two combined topologies, binary weighting and current division, are shown in Figure 6-6.

The first four bits of this hybrid converter are binary weighted. The four-bit configuration is repeated two more times to obtain 12 bits. The four-bit sections are coupled with a 16 to 1 divider so that the proper fraction of current from each bit will appear at the $I_{out}$ node. Using this scheme, the ratio of the highest to lowest switched current is now 8 to 1 instead of the 2048 to 1 ratio of the binary weighted converter. The 8 to 1 ratio is not as ideal as the 1 to 1 ratio of current division scheme, but the total switched current is halved from 12 mA, for the current division to 6 mA for the hybrid configuration. The 8 to 1 current ratio yields switching times that are matched closely enough for all but the most demanding applications.

The hybrid configuration averages 4/3 resistors per switch, which is slightly more

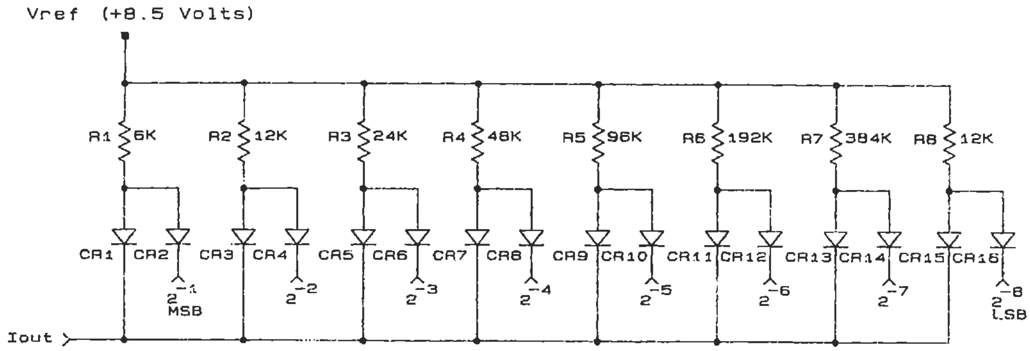


Figure 6-7. Diode–diode switched binary weighted 8-bit DAC.

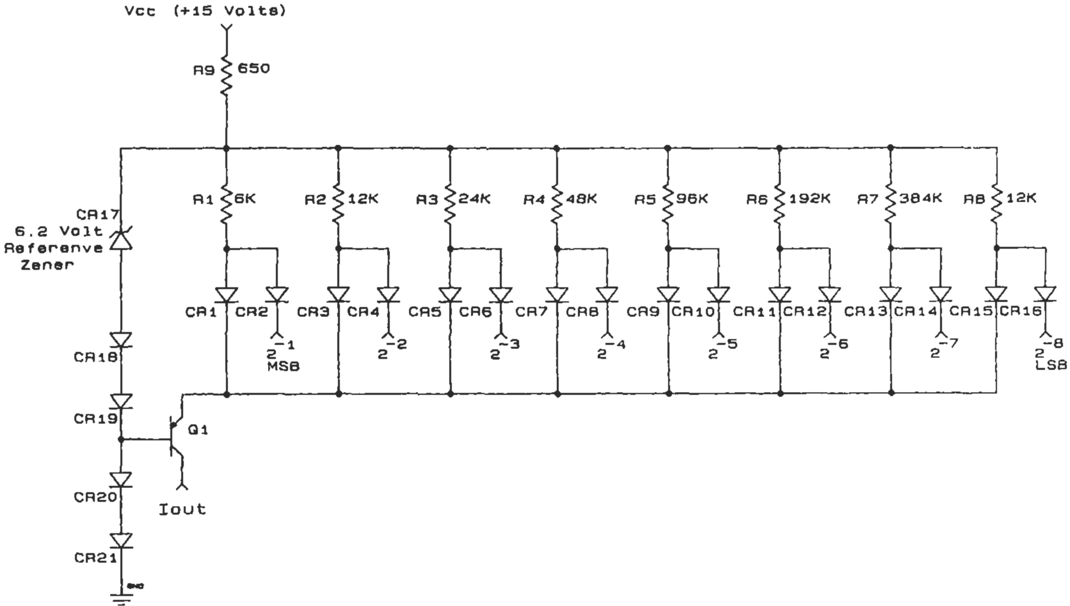


**Figure 6-8.** Hybrid Systems' DAC 371-8 8-bit DAC.

than the binary weighted converter (one resistor per switch) and significantly less than the current division configuration (three resistors per switch).

By combining and modifying existing circuits, new circuits can be created that are better suited for a particular application than the circuits from which they were derived.

Performance is not the only parameter that can be optimized by modifying existing circuits. Performance can sometimes be traded off for other variables such as cost and size.

In the early 1970s Hybrid Systems (now Sipex) was looking for a technique to build a "cheap and dirty" digital-to-analog converter that could be given away as a promotional item. At the time, the circuit of Figure 6-6, or some slight variation, was the configuration used by most converter manufacturers. This circuit was too expensive to give away, so a modification was in order. We modified the circuit of Figure 6-2 by replacing all the switching transistors with diodes (see Figure 6-7).

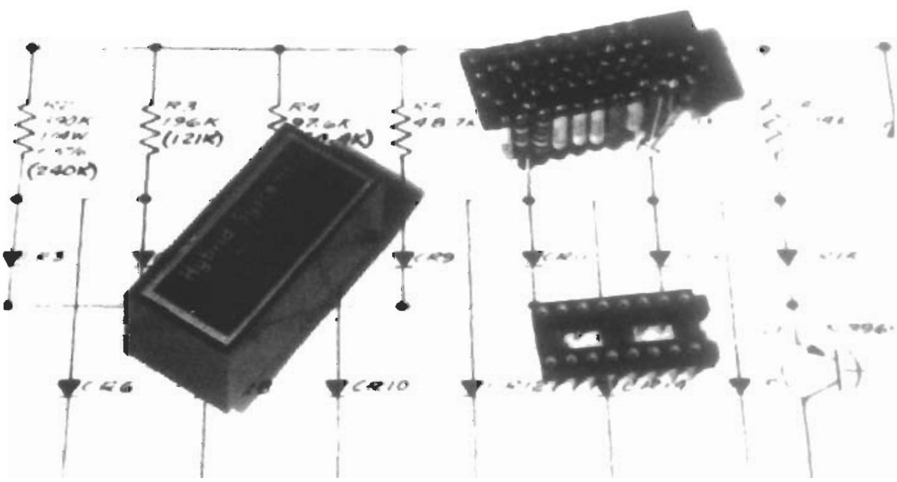

**Figure 6-9.** Internals of Hybrid Systems's DAC 371-8.

This design works as long the $I_{out}$ is maintained at 2 V. The current from each bit would flow to either the right- or left-hand diode, depending on the state of the digital input. To maintain the proper digital switching level and to keep the current through each bit constant, it is necessary to hold the $I_{out}$ node at 2 V. This is accomplished by using a transistor (Q1) as a constant voltage node to sum the currents from each bit. The reference loop of Figure 6-2 is replaced by four diodes (CR18,CR19,CR20,CR21), a zener reference (CR17), and a resistor (R9) (see Figure 6-8). The reference circuit depends on the forward voltage across a diode (CR19) tracking the $V_{be}$ of the transistor (Q1). This circuit compensates for $V_{be}$ changes of the transistor with temperature, but it does not compensate for changes in transistor beta. The reference circuit does not adjust as well as the servo loop, but it is good enough. The reference circuit maintains a constant voltage across the resistors (R1,R2, . . ., R8), and the transistor sums the bit currents to the $I_{out}$ node. Since the emitter-to-base voltage of the transistor varies with emitter current, the linearity of the circuit was limited to slightly better than 8 bits (0.2%).

A schematic of the design of what became Hybrid Systems' DAC 371-8 is shown in Figure 6-8. The mechanical construction of the DAC 371-8 was also distinctive. The diodes and resistors were mounted on end, resulting in a DAC footprint only slightly larger than a 16 pin dual in-line integrated circuit package. The pins for the unit were configured to plug into a 16 pin DIP socket (see Figure 6-9).

The HS 371-8, an 8-bit current output converter, was used as a promotional give-away, but the demand was so great we added it to our catalog as a standard product. It ultimately became our best-selling product of the early 70s, averaging about 40,000 units a year for 10 years. The product was developed as a gimmick and turned out to be a real winner. Even today, 20 years later, units are still being sold.

This trip through DAC history is an example of how a circuit evolves by modifying and improving an old design. One does not have to reinvent the wheel with each new project. You should keep up to date on recent developments and not be afraid to research how a particular function was implemented in the past. You can benefit from the accomplishments and the mistakes of others. Fight the NIH (*N*ot *I*nvented *H*ere) attitude and improve on the work of others with your own original ideas.

Manufacturing technology is also an area that gives the designer an opportunity to exercise innovation and creativity. The early DACs (vintage 1960s) were all built on printed circuit boards with discrete components. To keep the DAC as small as possible, designers used the fewest number of the smallest components. This meant, as we have seen, that diodes were substituted for transistors whenever possible. The two-terminal diode occupies less space than a three-terminal transistor. The modifi-

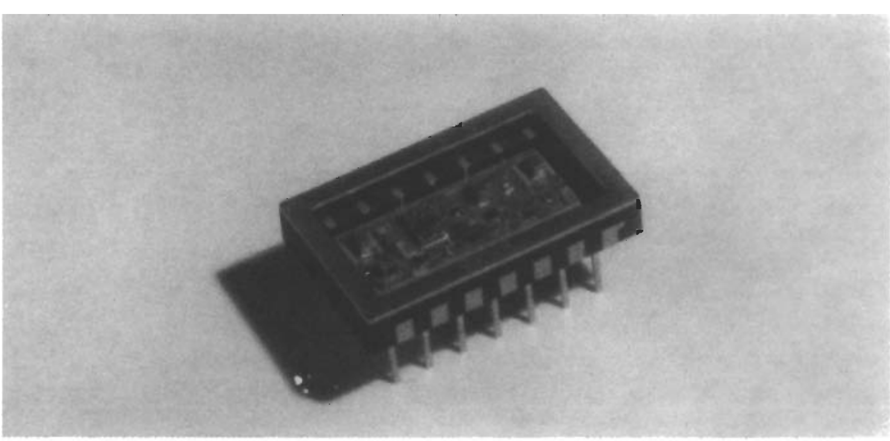

**Figure 6-10.** Chip and wire hybrid construction.

cation of the transistor–transistor switch (Figure 6-2) to the transistor–diode switch (Figure 6-3) is an illustration of replacing a transistor with a diode to reduce cost and save space. If switching time is not a consideration, one would choose a binary weighted DAC (Figures 6-2 and 6-3) over the current divider configuration (Figures 6-4 and 6-5) since fewer resistors are required. The value of the resistors is not important when working with discrete components since all resistors of the same power rating are the same physical size. A 1/4 W 10 Ω resistor is the same size as a 1/4 W 100 MΩ resistor. Since the least number of components minimizes size, the circuit with the least number of resistors is preferred. The "minimum component count" strategy is the one to use when the assembly is discrete components on a printed circuit board, but when chip and wire hybrid construction is used, a different approach is necessary.

Chip and wire hybrid assemblies are constructed by attaching individual semiconductor dice to a ceramic substrate. The surface of the ceramic substrate contains a gold conductor pattern that interconnects the semiconductor dice attached to the substrate. Electrical connections are made from the pads of the semiconductor dice to the gold conductors on the substrate with gold wire (see Figure 6-10).

Precision resistors for the hybrid are made by depositing a thin film of resistive material such as nickel-chromium on a silicon wafer. Using standard semiconductor technology, the unwanted resistive film is etched away, leaving the desired resistor geometries on the silicon wafer. The wafer, with many identical circuits on it, is cut into individual dice. Each resistor die contains from one to several dozen resistors, depending on the design. The resistance value of the thin film resistor is determined by its geometry. The larger the value of the resistor the more area it occupies on the silicon die. Therefore, the area occupied by resistors in a chip and wire hybrid is determined by the total resistance and not by the number of resistors. In a chip and wire hybrid, the total resistance should be minimized to keep the unit as small as possible.

The size advantage gained with discrete components by using a diode instead of a transistor is lost in a chip and wire hybrid assembly. A transistor die is approximately the same size and cost as a diode die. In fact, when the circuit requires a diode, it can be obtained by using a transistor connected as a diode. The base and collector of the transistor are connected together to form one terminal of the diode, and the emitter of the transistor is the other terminal of the diode. Using a transistor to replace the diode can also help your purchasing department by reducing the number of different components it has to buy.

It can be concluded from the last two paragraphs that the circuit topology used for printed circuit construction is not optimum for a chip and wire hybrid. Printed circuit construction places a high priority on minimizing the number of resistors to reduce the size of the unit. The total value of the resistance is the parameter that determines the size of a thin film resistor die used in a hybrid. For example, five 10 KΩ resistors on a thin film die occupy less than 1/10th the area that one 500 KΩ thin film resistor die will occupy. But five 10 KΩ discrete resistors on a printed circuit board will occupy five times the space of one 500 KΩ discrete resistor. To minimize the size of a chip and wire hybrid, one must minimize the total resistance, even though a greater number of resistors is used.

The optimum topology for a 12-bit chip and wire hybrid DAC is different from the optimum topology for a discrete component version of a 12-bit DAC. Table 6-1 shows the number of resistors required in the switching section for both the binary weighted and the current division DACs constructed using discrete components on a printed circuit board and the total resistance for both versions constructed using chip and wire hybrid technology.

**Table 6-1**

| Construction Technology | Binary Weighted | Current Division |
|---|---|---|
| Printed circuit | 12 resistors | 36 resistors |
| Chip and wire | 20 megohms | 0.15 megohms |

If size were the only consideration, the binary weighting would be selected for the printed circuit assembly and the current division would be the selected for the hybrid. Since current division is faster than the binary weighted design, one might think that the hybrid possesses the best of both worlds—small size and good performance. But alas, the First Law of Engineering[3] has not been repealed. The hybrid is smaller and has better performance than the discrete component model, but to obtain these improvements the designer must compromise on cost. A precision chip and wire hybrid is always more expensive than an equivalent printed circuit design. If size is important, the user must be willing to pay for the decrease in size with an increase in price.

A designer will usually have several circuit configurations from which to choose to perform a desired function. The designer should evaluate all circuit possibilities and select the configuration best suited for the job. To make the proper selection, a designer must evaluate every component of the circuit and be able to integrate these components into an optimum system.

The paper design of the circuit is only one aspect of product development. Packaging, assembly, documentation, repair, trimming, testing, and last but not least, helping the end user with application problems are all important parts of producing a usable product. A good designer becomes involved in every aspect of product development. The designers name is on the product, and a good designer should do everything possible to assure its success. The designer should feel personally responsible when the product develops a problem.

At some point in the product development process, hardware, in the form of a breadboard, will appear. This is a decisive moment. One now has a circuit to which power can be applied. Before the breadboard was available, the design only existed on paper. You now find out if your theoretical design performs as you predicted. A word of advice: if the breadboard is completed on Friday afternoon, don't power it up until Monday morning. Enjoy the weekend.

The breadboard evaluation is a time to compare the actual performance to the predicted performance. If the predicted and actual results do not agree, *beware*. Don't casually dismiss the difference. Investigate thoroughly until you find the discrepancy between the paper design and the breadboard. I cannot emphasize enough the importance of attaining agreement between the paper design and actual circuit operation.

Occasionally during a breadboard evaluation, even though everything seems to be operating properly, I will get a second sense that something is not right. It's hard to describe, but the feeling is there. It might be a wave form that has an insignificant wiggle or a voltage that is close to the proper value but not exact. When I get this feeling, I investigate the circuit more thoroughly than I normally would. More times than not I find a hidden problem. If the problem is not solved then, it will appear at a later time and really bite me in the rear end. If you sense a circuit is not operating properly, take heed; it probably isn't. Place your trust in the "Force" and investigate.

Working with customers on application problems is challenging and can be

3. The First Law of Engineering, "You don't get something for nothing," is a result of the First Law of Thermodynamics. The First Law of Engineering also has applications in economics, business, and politics.

rewarding. Your interface with the customer is usually over the phone, so you have to develop a technique for trouble shooting at a distance. The person on the other end of the phone line usually performs the measurements you request and verbally communicates the results. In these situations take nothing for granted. What is obvious to you is probably not obvious to the person on the other end of the line, or you would not be on the phone in the first place. All the questions should be asked, no matter how mundane they may be. "Did you by-pass the power supplies with both ceramic and tantalum capacitors to ground?" Answers to such questions as this will give you a better feel for the level of expertise at the other end of the line. Customer interface can be rewarding, as you can sometimes solve a problem that the customer has struggled with for some time. Occasionally a situation will arise that can make you a legend in your own time.

Several years ago I was testing a 12-bit DAC in the lab and obtaining some very strange results. After performing the usual checks I found the –15 V supply had become disconnected. The loss of the negative supply voltage resulted in the strange behavior of the DAC. I reconnected the supply and the unit worked fine. The next day I was sitting in our application engineer's office when he received a call from a customer who was having a problem. The customer was testing the same model DAC that had given me the strange problem the previous day. As luck would have it, the problem he described was exactly the strange behavior I had witnessed the day before. I played a hunch and told our application engineer to have the customer check for a cold solder joint on the –15 V supply. The application engineer, looking a little skeptical, conveyed the information. About 15 minutes later the customer called back, verifying that his technician did find a bad connection on the –15 V supply. He fixed the cold solder joint and the unit worked fine. I never told our application engineer the whole story. Situations like that happen very seldom, so when they do, milk them for all they are worth. That is how legends are born.

Even though digital technology has become the glamor segment of the electronics industry, analog design still provides excitement and challenge for those of us who enjoy the color gray. Integrated circuit technology has allowed the development of complex analog circuits on a single silicon die. It is ironic that digital technology has played a major role in making the new innovations in analog design possible. Without simulators for design, CAD systems for layout, and digital measurement systems for testing, analog technology could not have advanced to its present state. The design process has been highly automated, but a creative and innovative mind is still a requirement for good circuit design. It was once said that, "Anyone who can be replaced by a computer should be." The number of analog designers is fewer, but until the world is quantized into "ones" and "zeros," the analog circuit designer still has a place in the electronic industry.

I will close with an old story I first heard from Don Bruck, one of the founders of Hybrid Systems. The story defines the difference between an analog and a digital engineer. In keeping with contemporary demands, the story can be made less gender specific by switching the male and female roles.

Two male engineers, one specializing in digital design and the other in analog, are working together in the laboratory. A nude female appears at the door, attracting the attention of both men. The vision of beauty announces that every 10 seconds she will reduce the distance between herself and the engineers by one half. The digital engineer looks disappointed and states, "That's terrible, she will never get here." The analog engineer smiles and then replies, "That's okay, she will get close enough."

That is the essence of analog design—all else is explanation.