CHAPTER 10
DATA CONVERSION/ ACQUISITION

10.0 INTRODUCTION

All of the preceding chapters have dealt with digital circuitry and it's applications. In this chapter you will study methods for converting between analog and digital signals. These techniques are important since many of the quantities measured and manipulated are analog quantities.

10.1 OBJECTIVES

Upon completion of this chapter you should be able to:

- Explain the basic operation of a digital to analog converter.

- Understand the operation of an analog to digital converter.

- Name two types of analog to digital converter.

- Understand the basic operation of sample and hold circuits.

10.2 DISCUSSION

The focus of this chapter will be data conversion. Data may be encountered in either analog or digital form. Devices which convert from analog to digital data are called analog to digital or A/D converters. Devices which convert from digital to analog data are called digital to analog or D/A converters or DACs.

The need to convert between data types often arises since many data to be manipulated are analog such, as temperature or wind velocity, and the computing machines which are commonly used to manipulate these data are digital. Further, many of the devices which are driven need analog inputs yet the machinery best suited to solving the equations for driving the device are digital.

Data conversion allows switching data from one data type to another to best suit the needs of the people using the system.

10.2.0 D/A Conversion

You will study digital to analog conversion first since the circuitry for this conversion is simpler than the circuits used for A/D conversion. A variety of methods of implementing D/A converters have been devised. Many of these methods share some common circuit elements. Figure 10-1 shows the general block diagram for all D/A converters.

FIGURE 10-1. Basic D/A Converter Block Diagram.
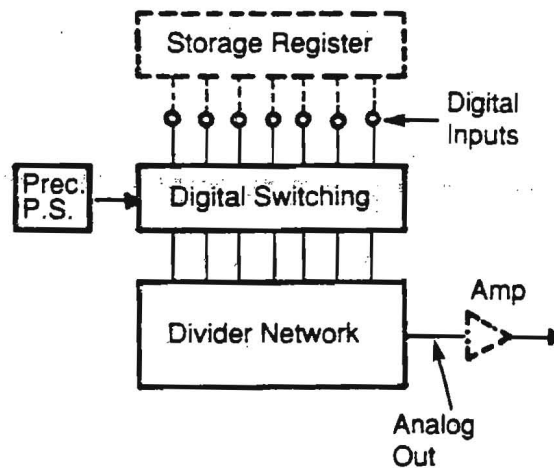
Notice that the three basic elements are a divider network, a set of bit switches, and a precision power supply. Frequently, D/As contain registers to store the binary data while it is being converted. An output amplifier is often included with the D/A to provide buffering and amplification of the results. A simple D/A converter is shown in Figure 10-2.

$V = 15\,V$

2^0, 2^1, 2^2, 2^3

$\dfrac{R_0}{8}$ $\dfrac{R_0}{4}$ $\dfrac{R_0}{2}$ R_0 V_A

$R_L \gg R_0$

FIGURE 10-2. Simple D/A Converter.
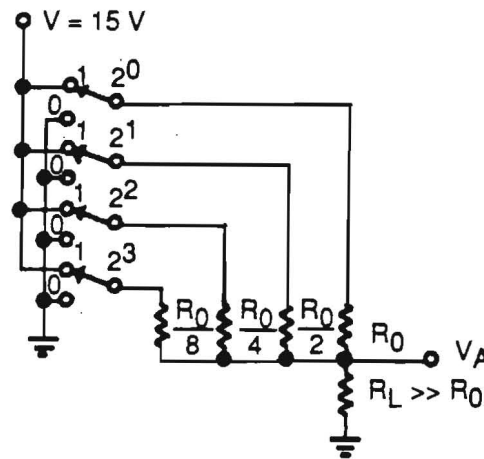
In most practical circuits, the switches will be replaced with electronic switches controlled by the outputs of a register or counter.

The value of the resistor connected in series with each switch is equal to the value of the resistor connected to the 20 bit divided by the decimal equivalent of the bit weight. Hence the second resistor is R/2 and if you were to add a fifth switch the value of the resistor would be R/16.

The resistors of all switches in the HI state are connected in parallel between V, the supply voltage, and the output. The resistors of all switches in the LO state form a parallel network between the output and ground.

The voltage on the output is a function of the voltage divider produced by the number entered on the switches. If the number six is entered, then the voltage divider would consist of R/2 and R/4 paralleled between the supply voltage and the output and R/8 and R paralleled between the output and ground. This assumes that R_L is many times greater than R_O and little current flows through it. The voltage output under these conditions can be calculated from the resistance of the parallel networks. The R/2 and R/4 combination has an equivalent resistance of R/6. The R/8 and R combination has an equivalent resistance of R/9. The voltage divider output is equal to (R/9)/(R/9 + R/6), or 2/5, of the supply voltage. When the supply voltage is fifteen volts as chosen, the output is 6V. In general for the circuit shown with a 15V supply, Vout = 1V x (number set on the switches). This network is capable of fifteen steps; for a supply of any voltage, V, the output is: Vout = V/15
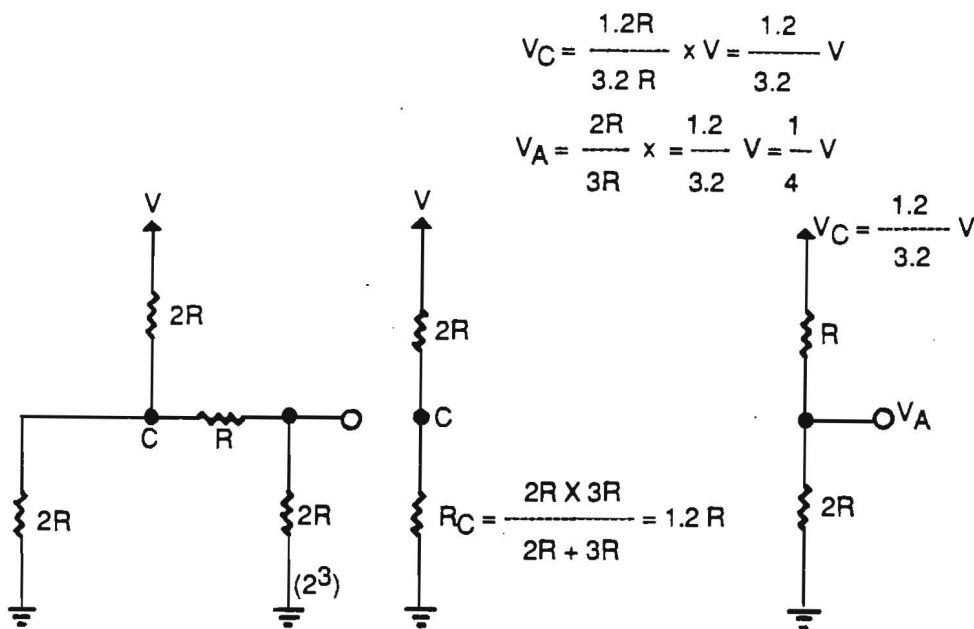
x (number of switches set).

      This type of circuit will work, but has several drawbacks. One is that resistors of the correct size may not be commonly available in standard sizes. Another is that the current loading varies radically from one switch to another. For large networks this can result in switching problems when electronic switches are used. Another type of circuit, the binary ladder, solves these problems. Figure 10-3 shows the circuit diagram for a ladder type D/A converter.
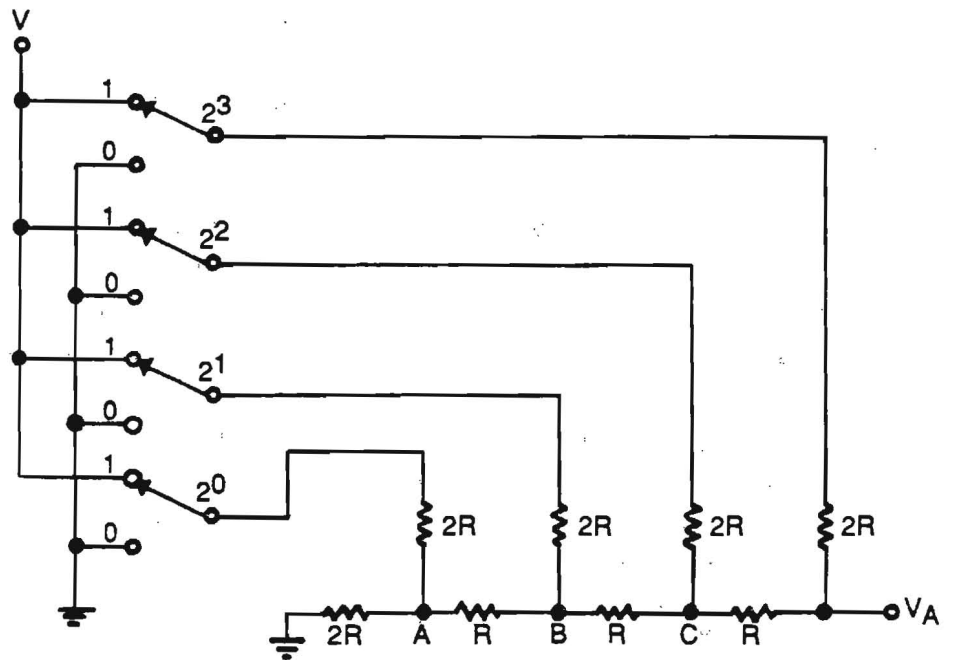
      Notice that this circuit can be fabricated to any size with only two sizes of resistors. An equivalent divider network is easily determined for the binary ladder. Assume that all switches except for the MSB are grounded. When this set of conditions exists, the value of the resistance between any node (except the MSB node) and ground is R. The MSB node, which is the circuit output, has a resistance of 2R to ground and to the supply voltage. This means that the output is at a voltage level of $V/2$. For a sixteen volt supply this translates to 8V. Other input combinations are more complex to analyze. When the input is a 4, all switches are grounded except for the 4 switch. This situation is shown in Figure 10-4.

$$V_C = \frac{1.2R}{3.2R} \times V = \frac{1.2}{3.2} V$$

$$V_A = \frac{2R}{3R} \times = \frac{1.2}{3.2} V = \frac{1}{4} V$$

FIGURE 10-4. Ladder Analysis for A4.

$$V_C = \frac{1.2}{3.2} V$$

$$R_C = \frac{2R \times 3R}{2R + 3R} = 1.2R$$

(Circuit diagrams with resistors labeled 2R, R, and nodes C, V, V_A, (2^3))

To calculate the output voltage, the voltage at the 4 node must be calculated first. The resistance to ground is 2R going through the lesser order switches and 3R going through the higher order switch. The resistance to the power supply is 2R through the 4 switch. The voltage at the 4 node is: 1.2R/(1.2R + 2R) x V or 1.2/3.2 x V. The output is 2/3 of the voltage of the 4 node so: 1.2/3.2 x V x 2/3 = 2.4/9.6 x V = V/4. For a sixteen volt supply this means a 4V output. Considering the result obtained when only the MSB was selected this should not be surprising. Notice that the sixteen volt value was chosen so that the output is one volt per count.

10.2.1 D/A Specifications

Fortunately D/A converters are available as ICs. In order to properly select the correct D/A converter for a particular application, some knowledge of D/A specifications is required. A large number of performance specifications are available from device manufacturers. The specifications that are most commonly available and pertinent are the resolution, accuracy, and speed.

The resolution is the smallest standard incremental change in output voltage of a D/A converter. A converter with n switches can resolve 1 part in 2n. Resolution may be expressed as a percentage of full scale or as a number of bits.

Accuracy is a somewhat indefinite term which describes the maximum deviation of the D/A output from an ideal straight line drawn from zero to full-scale voltage. An accuracy specification includes all types of errors and is not usually found on a data sheet since the individual errors are specified. The errors included in accuracy are: scale error, offset error, linearity, and differential non-linearity.

Scale error is the departure of a DAC from the theoretical voltage output. This parameter is normally measured at full scale input. Offset error is the output voltage of the DAC with zero input. Offset error can be expressed as a number of bits or a percentage of full scale. Many data conversion circuits have external resistors that allow the user to adjust offset to zero.

Linearity describes the departure of the data conversion circuit from an ideal output curve when other error sources are ignored. Linearity errors are a major concern in data conversion circuits and are expressed in percent of full scale or number of bits.

Differential non-linearity indicates the difference between the actual analog voltage change and the ideal voltage change. For example, a DAC with a 1.5 LSB step in response to a code change would have a 1/2 LSB differential non-linearity. Differential non-linearity can be at most twice the linearity. Differential non-linearity is a measure of how smooth and even the output curve of a DAC is.

The speed of a device is not given as a number but can be typified by several performance specifications. The primary parameters which affect device speed are settling time, slew rate, and conversion rate. The settling time is the amount of time required for the DAC to reach a stable output after a code transition. Slew rate is the rate at which the output amplifier can make voltage changes and is usually specified in V/time. Conversion rate is a measure of how rapidly the device can perform repetitive data conversions. Conversion rate includes and allows for all internal delays and is given as either number of conversions/second or as the amount of time to perform one conversion.

10.2.2 D/A Applications

The most obvious use of a digital to analog converter is to convert data to the analog domain after data processing. Many A/D converters use an internal DAC as part of the circuitry used in the conversion system.

Two broad classes of A/D converters exist, simultaneous or flash converters which operate in parallel and sequential converters which operate serially. The parallel converter is a straight forward device which operates more quickly than a sequential converter. Unfortunately, flash converters are also more complex circuits and expensive to construct. Both types of A/D converters employ comparators as the basic means of conversion. Flash converters use a voltage divider as a reference input to a bank of comparators. 2^n-1 comparators are required to produce a converter with 2^n equally spaced output steps.

Each of the comparators in the bank has one input from the divided voltage reference and the other input is the voltage being converted. The output of the comparator bank must be encoded to form a binary output word. Figure 10-5 show a typical flash A/D converter.
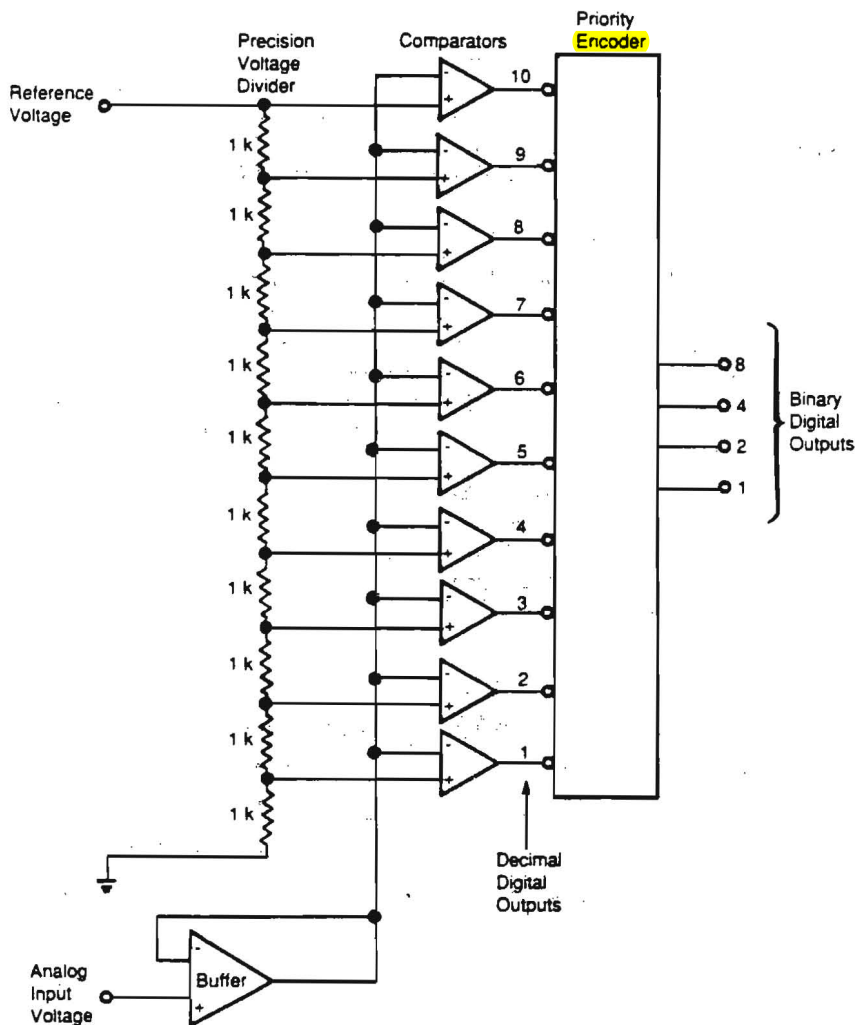

FIGURE 10-5. Flash A/D Converter.

10.2.4 Successive Approximation A/D

Successive approximation A/D converters are the most commonly encountered type of sequential A/D circuit. In the past, ramp type converters which would generate a digital ramp input into a comparator whose other input is the voltage to be converted were widely used. These devices have been replaced by successive approximation devices since successive approximation is a faster technique. In fact successive approximation converters are about 100 times faster than ramp type converters.

The conversion time required for a successive approximation converter to convert an input to digital is constant regardless of the level of the input voltage. A successive approximation converter requires the circuits shown in Figure 10-6.

FIGURE 10-6. Successive Approximation A/D Converter.
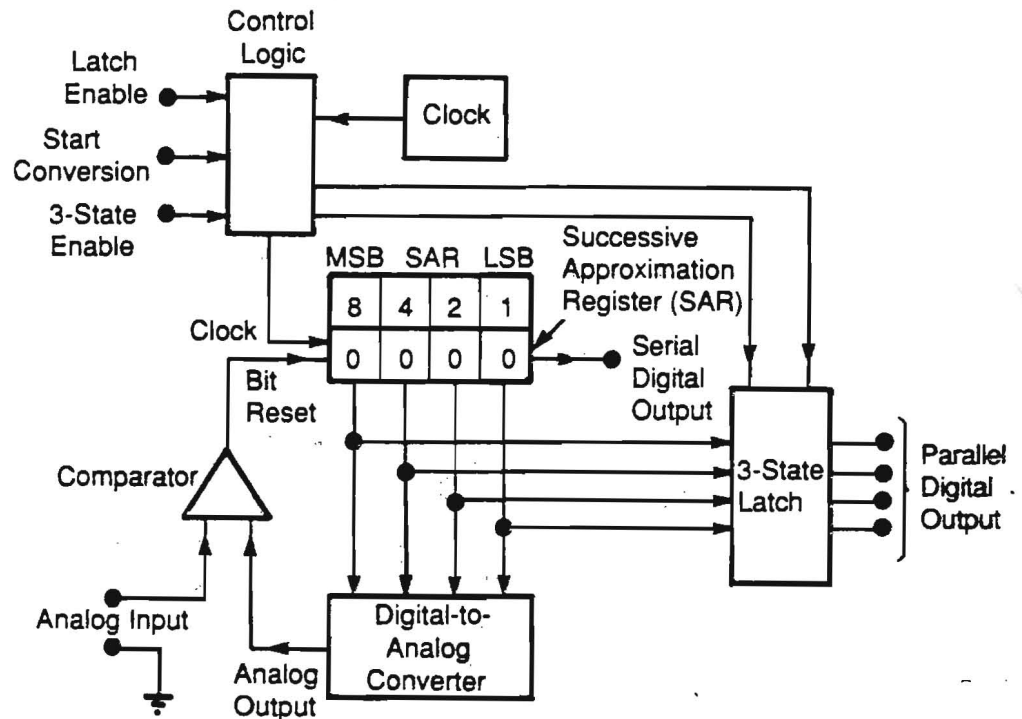
The basic components are the control logic, a successive approximation register or SAR, a comparator, a DAC, and a latch for the output. This device works in a straight forward fashion.

The MSB of the SAR is loaded with a one. this value is converted to analog by the DAC and compared to the analog input voltage to be converted. If the value in the SAR is the higher of the two values, the SAR is cleared. If the voltage to be converted is the greater of the two values, the one in the MSB is retained, and a one is loaded into the next MSB and the entire

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comparison process is repeated. This process continues until the LSB is processed. After processing the LSB, the SAR will contain the digital equivalent of the voltage to be converted. After conversion the contents of the SAR are transferred to the output latch which is often a 3-state latch for use in bussed systems.

10.2.5 Data Acquisition

A/D converters are the primary component used for acquiring data or data acquisition. Data is often acquired from analog sources. This data is processed either immediately by a digital computer or stored for processing later. For example, data from a temperature sensor could be converted to digital, and compared to some value. If the temperature were out of range the computer could activate a fan to lower the temperature or turn on a heater to increase the temperature. This sort of techniques is employed in digital thermostats.

Not all data acquired is processed immediately. Data from sensors in an oil field can be converted to digital, stored on a tape then transported to a large computing facility for processing later. While the A/D converter is the primary data acquisition circuit, other circuits are employed for data acquisition such as sample and hold circuits and analog multiplexers.

10.2.6 Sample and Hold Circuits

A sample and hold circuit performs the functions which it's name implies. These devices sample an analog input and hold the value. This type of device is frequently used in data acquisition to hold the analog data until the A/D converter is able to convert the data to digital form. Figure 10-7 shows the circuitry needed for a sample and hold circuit.
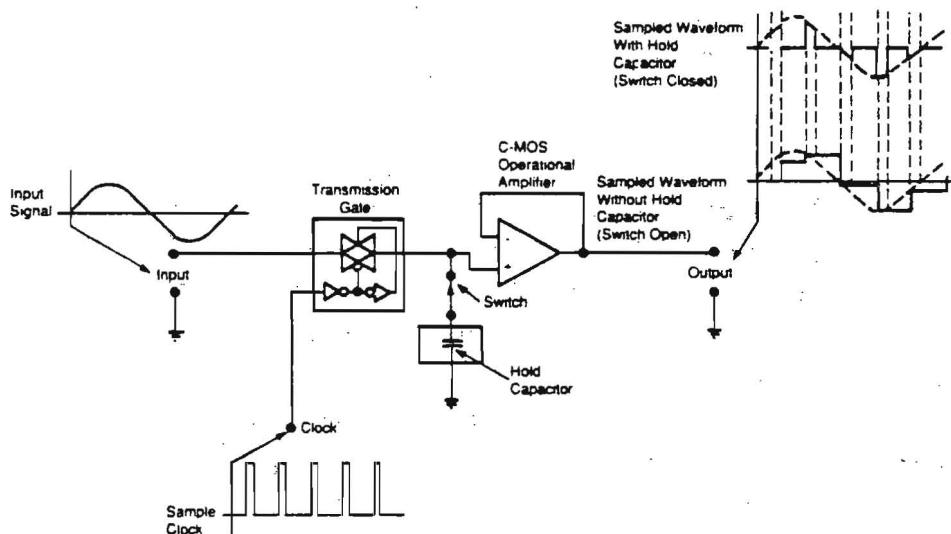

FIGURE 10-7. Sample and Hold Circuit.

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This circuit consists of an input amplifier, a digital switch, a capacitor for storing the voltage to be held, and a high input impedance amplifier for the output. Both the input and output amplifiers are voltage followers.

The circuit function is straight forward. When the switch is closed the input amplifier quickly charges the capacitor to the level of the analog input. This is the sample mode. At the end of the sample period, the switch is opened and the device is in the hold mode.

The output amplifier will be capable of providing a voltage equal to that stored on the capacitor. This type of device can be constructed quite easily from CMOS switches and FET amplifiers. The device will show some voltage sag from the ideal input voltage since the capacitor will exhibit some leakage. This type of circuit is used to improve the stability of the A/D conversion process for rapidly changing signal inputs and to hold the data in systems where the A/D serve many multiplexed analog inputs.

10.2.7 Multiplexing

Digital multiplexing was discussed earlier. Analog multiplexing is the same basically except that the range of output voltage is greater for analog signals hence simple gates cannot perform the multiplexing function. An analog multiplexer is really a multi-position rotary switch. This type of device can route any of several inputs to a single output. An example of such a switch is shown in Figure 10-8.
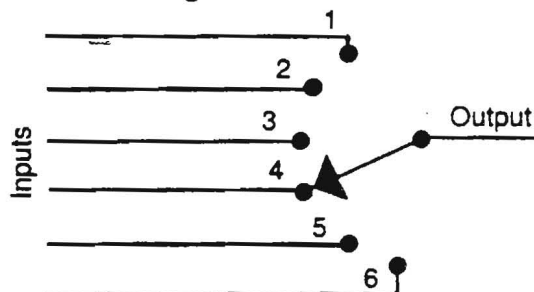

FIGURE 10-8. Rotary Switch.

This same type of switch can be easily implemented with CMOS devices. CMOS is chosen for this application since switches with a very low 'on' resistance can be constructed in CMOS. Multiplexing will allow one A/D converter to service several analog inputs.

The combination of the A/D with a multiplexer and sample and hold forms a modern data acquisition system. A block diagram for a typical data acquisition system is shown in Figure 10-9.

FIGURE 10-9. Typical Data Acquisition Systems.
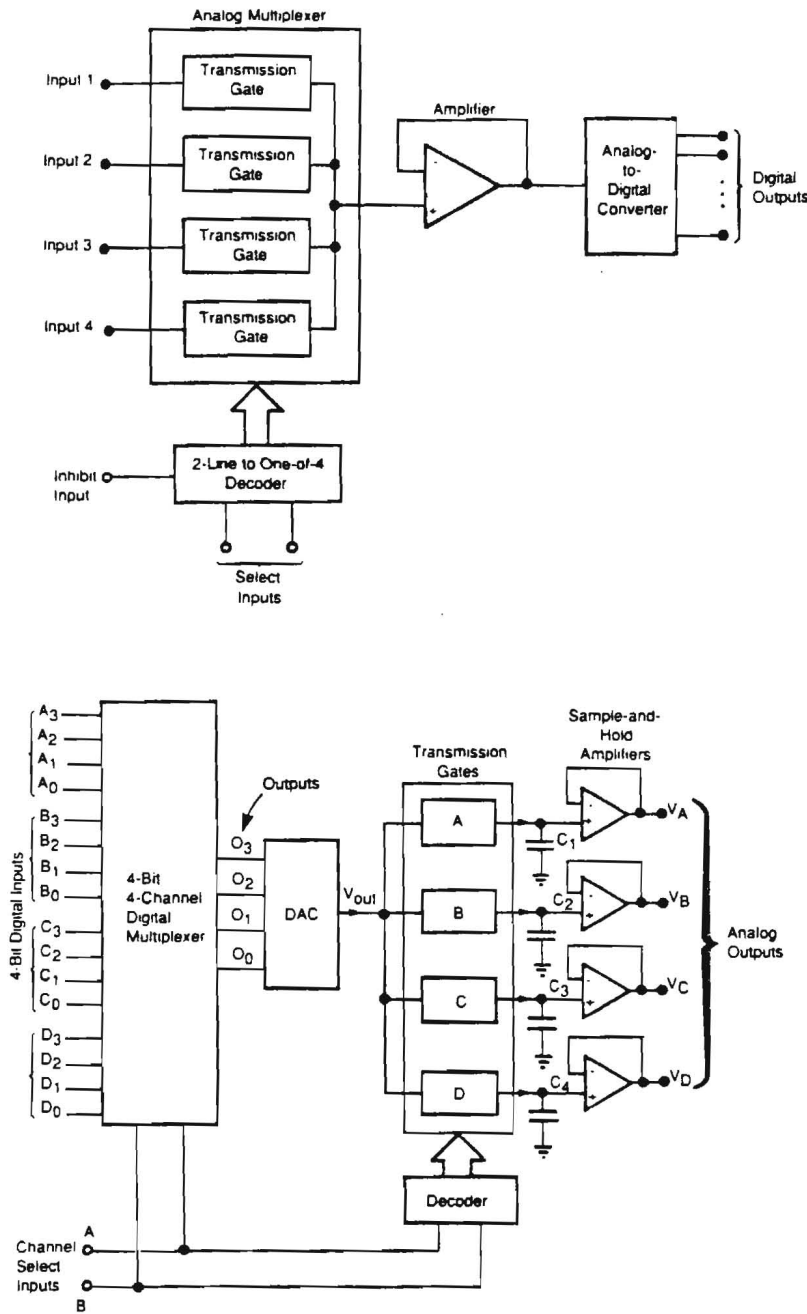
In this chapter you have learned about data conversion and data acquisition circuits. You studied DACs, their implementation and the specifications effecting their performance. You studied two types of A/D converters and highlighted their differences. You have learned about the sample and hold circuit and it's application in data acquisition. You studied analog multiplexers

10.3 SUMMARY

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and their application for allowing one A/D to serve several analog inputs.

10.4 REVIEW QUESTIONS

1. Name the three general areas of DAC specification that are the most important in determining device performance.

    _____

    _____

    _____

2. Name two types of ladder circuits used in DACs.

    _____

    _____

3. Give two applications for DACs.

    _____

    _____

4. Name two types of A/D converters.

    _____

    _____

5. What parts are required to form a successive approximation A/D?

    _____

    _____

    _____

6. What is data acquisition?

    _____

    _____

7. What part of a sample and hold circuit performs the hold function?

_____

_____

8. Give two reasons for using sample and hold circuits in data acquisition.

_____

_____

9. Explain the difference between analog and digital multiplexers.

_____

_____

_____

In this lab exercise you will learn about D/A converters. You will study the DAC 0808 digital to analog converter IC. You will use this IC to form a simple D/A converter.

LAB EXERCISE 10.1
D/A Converters
Objectives

Materials

LD-2 Logic Designer

DAC 0808 Digital to Analog Converter IC

LF 353 Dual Bifet Op-Amp

4700 Ohm Resistors (3)

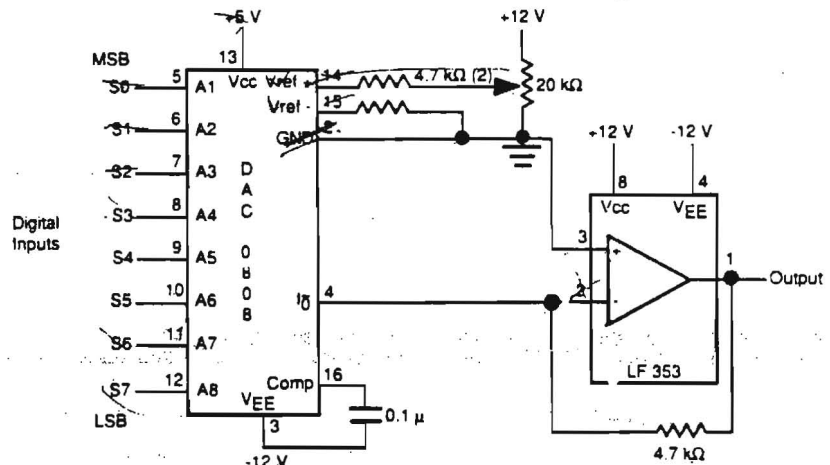20 Kohm Potentiometer

Capacitor 0.1 Microfarrad

Digital Multimeter

Jumper Wires

Procedure 1. Place the DAC 0808 and the LF 353 onto the LD-2 breadboard.

2. Wire power and ground to the ICs. +12 VDC should go to pin 8 of the LF 353. -12 VDC should go to pin 4 of the LF353 and to pin 3 of the DAC 0808. +5 VDC should go to pin 13 of the DAC 0808. Ensure that you have wired the power correctly to both of these circuits.

3. Wire the circuit shown in Figure 10-10. This is a simple D/A converter with a 10 V maximum output.

FIGURE 10-10. Simple D/A Converter.

4. Place S0-S7 to LO. Turn power on. D1 should light. Use the DMM to adjust the wiper of the potentiometer to a level of 10 VDC. Connect the DMM to the output of the op-amp. Place S0 to HI. The DMM should read about 5 VDC. If it doesn't check the wiring of your circuit.

5. Use the switches S7-S0 as the digital inputs. Observe the circuit output on the DMM. Observe the operation of this circuit and record your observations. Pay particular attention to determining the resolution of the D/A converter.

6. Leave this circuit assembled while you answer the following questions.