Preface

This book is meant to serve as the text/lab book for a first course in digital electronics. The object of the course is to help you become familiar with the use of digital electronic circuits. After completing the course, the student should be able to design, construct, and effectively troubleshoot digital electronic circuits.

Each chapter of the book contains clearly stated objectives that the student will be able to perform when the chapter is completed. The objectives are followed by text which discusses the subject of the chapter. The text is followed by questions to test the student's understanding of the material. After the questions, most chapters will have several experiments which will demonstrate and reinforce the subjects covered in the chapter.

The course is structured so that most of the material is actually learned in the laboratory. Figures are used generously throughout the text to provide clarity. The course is designed so that most contemporary topics in digital electronics are addressed.

The author would like to hear from you regarding the effectiveness of the material included in the text and the organization of the material. Please email your comments to enoch@hwangs.net.

Getting Started

If you have never built any digital circuits with a breadboard then you will want to familiarize yourself with the material presented in the rest of this section. And even if you have, you may still want to quickly glance through it. The standard tools and components that are used for building any digital circuits will be discussed.

0.1 Breadboard

The breadboard allows you to connect components and wire your circuit very easily and quickly. The breadboard consists of many holes for you to connect hook-up wires and integrated circuit (IC) chips. All of the holes are already connected together in groups. This way, you can connect two wires together (or connect a wire to an IC pin) simply by plugging the two wires into two holes that are already connected together. Figure 0.1 shows a picture of a breadboard and Figure 0.2 shows a layout of the breadboard.

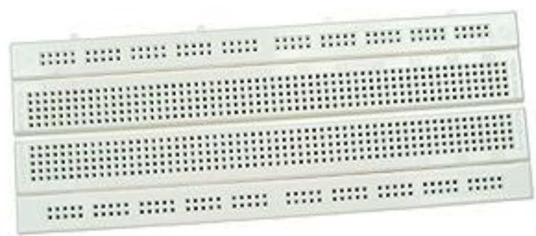

Figure 0.1: Picture of a breadboard.

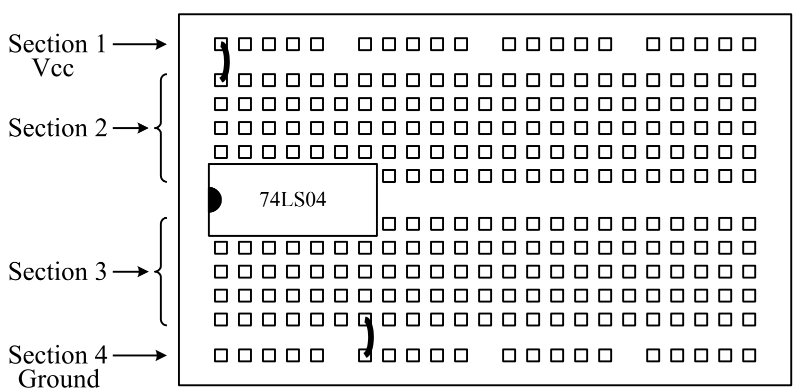

Figure 0.2: Breadboard layout. The holes in section 1 are connected horizontally. The holes in section 2 are connected vertically. The holes in section 3 are connected vertically. The holes in section 4 are connected horizontally. Holes in any two different sections are not connected.

There are four general sections on the breadboard. All of the holes in section 1 are connected in common horizontally. The holes in this section are usually connected to VCC to provide power or the logic 1 signal to your circuit on the breadboard. Like section 1, all of the holes in section 4 are also connected in common horizontally. The holes in this section are usually connected to GND to provide a common ground or the logic 0 signal to your circuit. The holes in section 2 are connected vertically, so the five holes in each column are connected in common, but the vertical columns are not connected together. The holes in section 3 are also connected vertically like those in section 2, so the five holes in each column are connected in common, but the vertical columns between section 2 and section 3 are not connected together. Finally, holes in any two different sections are not connected together.

Be especially careful when inserting integrated circuits into the breadboard socket. Unless the IC pins are straight, it is very easy to crush the pin into a zigzag shape or fold the pins underneath the body of the IC. Either way the result is a bad connection or no connection at all.

Use only 20 or 22 gauge solid copper wires for making your connections on the breadboard, and only plug one wire into one hole. When stripping the wire ends, be careful not to strip more than about three eighths of an inch of insulation from the wire. Too much bare wire may result in unintentional connections near the wire end.

After you have built up a few circuits, you will have a good collection of pre-stripped jumper wires. Save them. By re-using these wires, you can save even more time and effort in assembling future circuits.

0.2 Power Supply

Most digital circuits require a 5V DC power supply to operate. For simple circuits such as the ones that you will be doing in this courseware, the voltage does not have to be too precise, so a standard 5V DC power adapter rated for about 300 mA will suffice. However, for more complex circuits, a regulated 5V DC power supply is a must. A regulated 5V power supply will produce a precise 5V power source under any load condition.

In addition to a 5V DC power supply, a +12V DC and a –12V DC power source are needed for one lab exercise in Chapter 10.

0.3 LEDs

Light-emitting diodes (LEDs) emit light (in various colors) when an electric current passes through them. Thus, they allow us to easily see the outputs of digital circuits. Normally, we want the LED to turn on when the digital circuit output is a logic 1 or HI signal, and turn off when the output is a logic 0 or LO signal.

Figure 0.3 shows a red and green LED, and the symbol used in circuit diagrams. Notice that one lead is shorter than the other. The shorter lead is the cathode and must be connected to ground. The longer lead is the anode and must be connected to power. LEDs must be connected the correct way. Never connect a LED directly to a batter or power supply. It will be destroyed almost instantly because of too much current. In order to protect a LED from too much current, a resistor must be connected in series with the LED as shown in Figure 0.4.

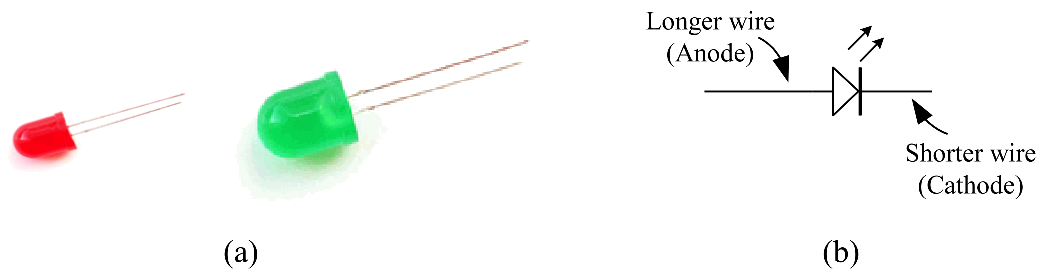

Figure 0.3: LED: (a) Picture of a red and green LED; (b) Circuit symbol.

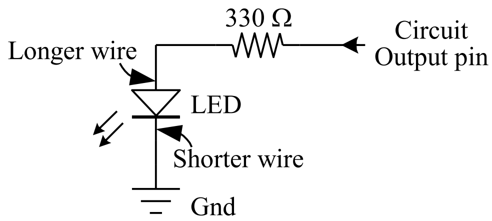

Figure 0.4: LED circuit connection in series with a 330 Ω resistor.

0.4 Toggle Switches

A toggle (SPST) switch is a mechanical on-off switch with contacts that can either be connected or disconnected. Usually, you want the switch to output a logic 1 or HI signal when the switch is in the on position, and output a logic 0 or LO signal when the switch is in the off position. A picture of a DIP switch with eight separate switches and the symbol used in circuit diagrams are shown in Figure 0.5.

Figure 0.5: (a) Picture of an 8-input DIP switch; (b) Circuit symbol for a switch.

A typical circuit for connecting a toggle switch is shown in Figure 0.6. When the switch is opened (off), the circuit input pin will get a logic 0 or LO signal from ground through the 10K Ω resistor. When the switch is closed (on), the circuit input pin will get a logic 1 or HI signal directly from the +5 V. The 10K Ω resistor prevents a short circuit between power and ground.

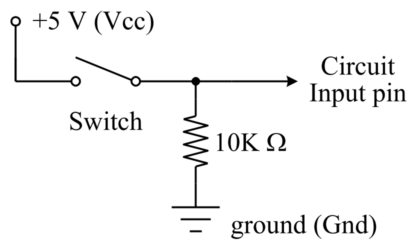

Figure 0.6: A toggle switch circuit connection.

0.5 Push Buttons

A push button switch is a mechanical switch that normally is in the off position and outputs a logic 0 or LO signal. It will output a logic 1 or HI signal only when pressed. A picture of a push button and the symbol used in circuit diagrams are shown in Figure 0.7. A typical circuit for connecting a push button is shown in Figure 0.8.

(a) (b)

Figure 0.7: (a) Picture of a push button; (b) Circuit symbol for a push button.

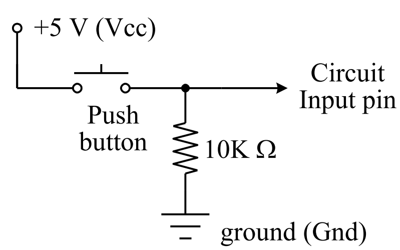

Figure 0.8: A push button circuit connection.

0.6 Debounced Push Buttons

When closing a mechanical switch, the contacts actually bounce back and forth between making a contact and no contact very briefly several times before it settles. Even though this period of time is brief, digital circuitry is fast enough to falsely interpret this as several closures rather than just one. In order for a circuit to work correctly, we need to eliminate the multiple switch closures and produce just one closure signal by electronically debouncing these switches. A debounced push button switch consists of the physical mechanical switch with additional electronic circuitry to eliminate the multiple switch closure signals. A typical debounced push button circuit is shown in Figure 0.9.

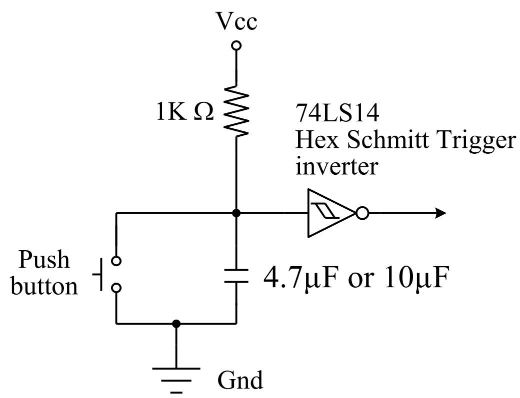

Figure 0.9: Circuit for debouncing a push button.

0.7 Clock

All digital circuits that include memory elements such as counters and controllers need to have a clock to synchronize its operations. The clock is simply a square wave with regular repeating cycles. The speed of the clock determines how fast your circuit will perform its operations. You will learn more about the clock signal in Chapter 5. The astable circuit using the 555 IC in Lab Exercise 11.1 is a typical clock generation circuit.

0.8 Integrated Circuits

An integrated circuit (IC) is a miniaturized electronic circuit manufactured on a thin piece of semiconductor (usually silicon) material. Thousands of tiny transistors (the fundamental building block of all digital circuits) forming large digital circuits are integrated into a single small package known as a chip. Figure 0.10 (a) shows an integrated circuit chip with two rows of ten connection pins. This double row packaging is known as dual-in-line (DIP). Notice the notch at the left end of the picture. This marking is used to show the pin orientation. With the marked end of the IC on the left side, the pins are numbered counterclockwise from the bottom left corner starting with 1 as shown in Figure 0.10 (b).

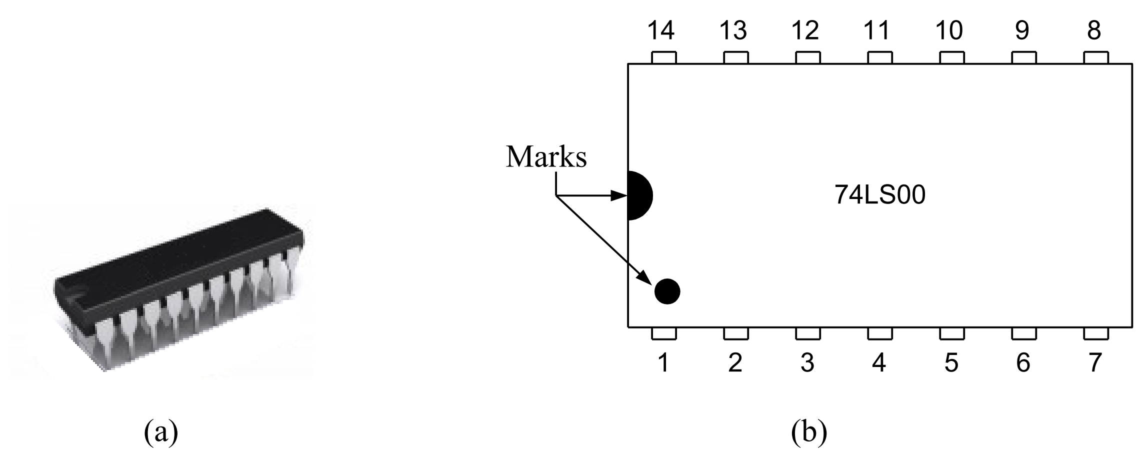

Figure 0.10: Dual-in-line (DIP) integrated circuit (IC) chip: (a) picture; (b) orientation and pin numbering.

Appendix A shows the basing or pin-out diagrams of all of the ICs used in this courseware. If you need more detail on the operation of an IC, you will need to refer to a TTL data book. Appendix B is a parts list of the ICs used.

0.9 Circuit Construction

Some general rules of circuit construction are provided here to help the student efficiently complete laboratory assignments.

1. Construct circuits neatly. Neat construction makes troubleshooting possible should the circuit not perform as expected.

2. Get into the habit of always touching some metal objects to discharge yourself of static electricity before handing ICs.

3. Devote special attention to the routing and connection of the power and ground connections to the ICs used in a circuit. Reversing these connections is normally sufficient to destroy the misconnected IC. Shorting power and ground may damage the power supply by overheating it.

4. Always turn off the power when making connections, and turn it on only after you have finished making all of the connections.

5. Under normal operating conditions, ICs might feel slightly warm. However, if it is hot to the touch, turn off the power immediately and double check the power and ground connections. Most likely this is caused by reversing of these connections.

6. If a circuit fails to function, make sure that power is properly applied to the circuit. This prevents embarrassment.

7. Pay special attention to safety. Work in an uncluttered area. Be careful with metallic objects and loose wires because they can accidentally short across power leads resulting in high currents, hot conductors and the potential for burns and fires. Don’t work on electronic circuits when tired or impaired by medications. Do not engage in horseplay in the laboratory.

One final advice to students wanting to improve laboratory success is to keep an accurate laboratory notebook. Such notebooks are often required by companies involved in circuit design, evaluation, and quality assurance particularly when involved in research that may end up as part of a patented product. Describe all experiments performed and record all data in this book. Develop the habits involved in keeping a laboratory notebook because it will be an invaluable aid to the experimenter as digital circuitry is mastered.

0.10 Materials and Parts

Refer to Appendix B for the list of ICs and other miscellaneous parts needed to perform the experiments in this lab manual. You might want to have access to a TTL data book if you need more detail on a particular IC. All of the lab experiments will require a 5V DC power supply, and preferably a regulated one. A +12 V DC and a –12 V DC power supplies will be needed for doing Lab Exercise 10.1. Finally, no lab bench is complete without a digital multimeter. Although not required, a logic probe might also come in handy for troubleshooting your digital circuits.

Chapter 1: Introductory Concepts

1.1 Introduction

In this opening chapter, you will review some basic concepts required to understand the characteristics of digital circuits. These concepts are important since they will form the basis of all further study of digital circuits.

Digital circuit and system characteristics will be compared to analog circuit and system characteristics. This comparison will emphasize the difference between the continuous nature of analog circuits and systems and the discontinuous nature of digital presentation of information.

Some knowledge of how transistors work is helpful in understanding the material presented in this chapter.

1.2 Objectives

After completing this chapter you should be able to:

- Distinguish between digital and analog signals
- Discuss how 1's and 0's are used either to represent quantity or to represent condition.
- Represent binary quantities.
- Explain the operation of a basic digital circuit.

1.3 Discussion

The recent boom in integrated circuit (IC) electronics has largely come about because integrated circuits are inexpensive, compact, consume very little power, and are highly reliable. Integrated circuit technology is applied to both analog and digital circuits. The most popular analog circuits are amplifiers, especially operational amplifiers.

The great utility of digital integrated circuits has added to the popularity of ICs. Digital integrated circuits are the building blocks in all electronic devices such as computers, calculators, cell phones, and personal digital assistance.

1.3.1 Digital and Analog Circuits

We live in two very different electronic worlds. The analog world or the real world where all changes are continuous, and the digital world or man-made world that is discontinuous.

In the analog world you have smoothly changing electrical voltages and currents that represent changes in physical things such as temperature, water level, and pressure such as those shown in Figure 1.1.

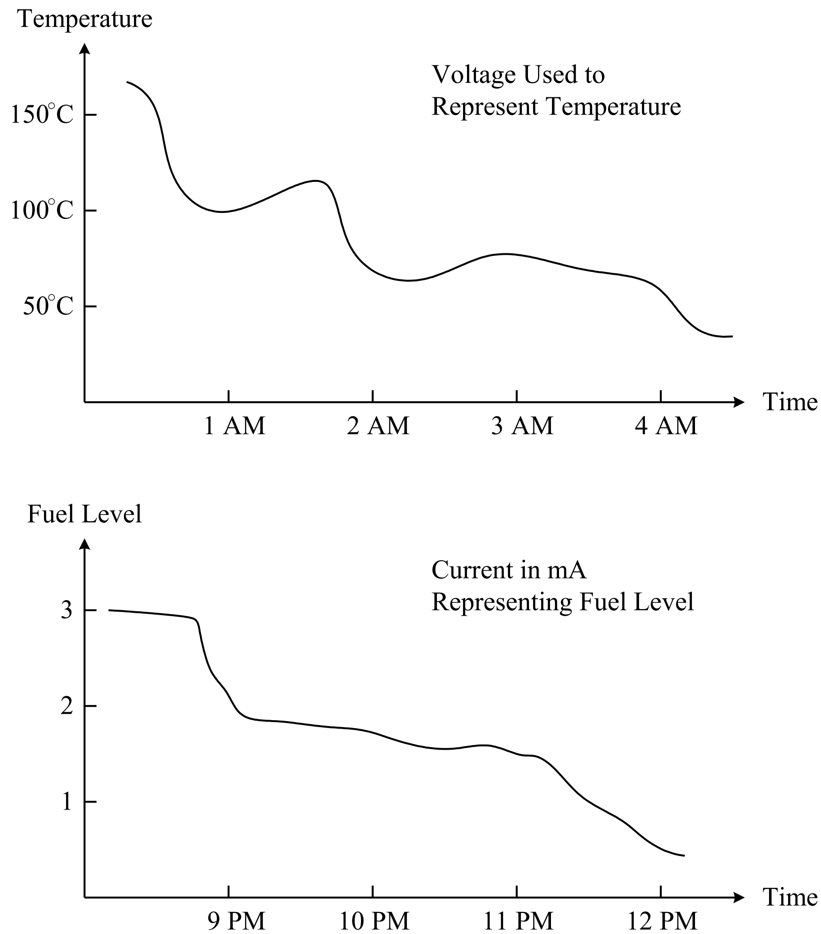

Figure 1.1. Typical analog signals.

Other, more familiar, continuous signals that are considered analog are television signals, radio waves, and police radar signals. The trait common to all analog signals is that they are continuously variable.

Circuits used to reproduce these continuously changing signals are termed analog circuits. They feature active devices, such as transistors, operating as amplifiers in their linear region. Transistors operating as amplifiers in their linear region amplify small input signals with a minimum of distortion. As long as an input signal is applied an amplified reproduction of that signal is presented at its output. This amplified output signal may be used to drive chart recorders or x-y plotters.

In using analog circuits, it is important to keep input signals small enough to keep the amplifier out of the cut-off and saturation regions of operation. Analog output signals become distorted or clipped when the amplifier is forced to its cut-off and/or saturation limit(s).

Digital signals are not continuous. They are quantized, that is, at any given time they are at one of two allowed voltage levels only. A collection of these states or digital words may be used to represent a quantity. Digital words that might represent temperature at particular times are illustrated in Figure 1.2. These signals are not smoothly continuous.

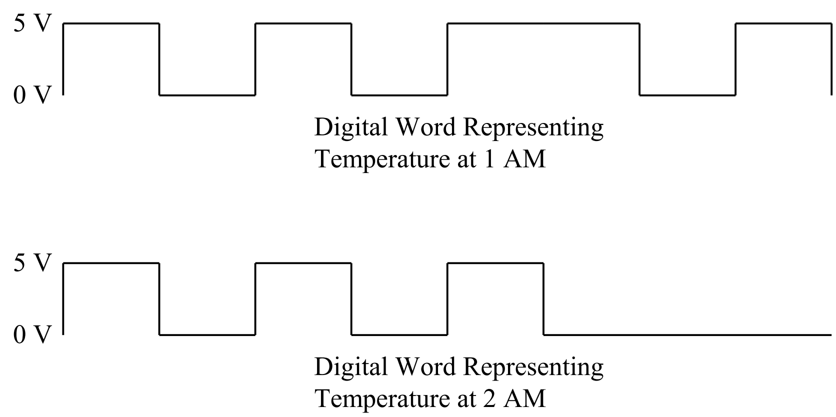

Figure 1.2. Typical digital signals or words.

A common example of a digital signal is a light which can be either on or off. Another example is the traffic light which may be green, yellow or red. Digital signals could have any number of discrete steps possible with a particular sort of signal. Using this convention, the simple light represents binary digital signals (having only two allowed conditions) and the traffic light represents tertiary digital signals (having three allowed conditions). Practical digital circuits are binary. Binary circuits are simple to construct because they require only two states for operation.

In the 1800s a researcher, George Boole, studied the mathematics of how humans think. He discovered that humans use "either/or" logic. That is, we think of things as being either one thing or another. For example: statements can be true or false; it is either light or dark; etc. Thus a system of binary (two state logic) is quite natural to us. George Boole's work led us to use binary digital devices.

Unlike the analog circuit, the binary digital circuit operates in only the cut-off or saturation condition of the active element, usually a transistor. The digital circuit is in its linear operating region only during transition from its cut-off state to its saturation state or vice versa. When the transistor is operated in this way, the circuit is said to be operating in a switching mode. In a switching mode, the output can only be very close to either Vcc or ground. Vcc and ground are like the plus and minus terminals on your battery. While this mode of operation would be abnormal and undesirable for an analog circuit, it is the normal operating mode for digital circuits.

Older ICs typically use the voltages +5 volts and 0 volts for Vcc and ground respectively. Newer ICs usually use lower voltages such as +3.3 volts for Vcc. The +5 volt output is used to represent a logic 1, true, or HI level, while the 0 volt output is used to represent a logic 0, false, or LO level.

1.3.2 Use of Binary Digital Ones and Zeros

The signals generated by the digital circuits discussed in the preceding section have no inherent meaning. The signals are symbols used to represent abstract concepts. One use of such signals is to indicate the state of a device. For example, the door on a microwave oven must be closed before the oven is operated. A switch on the door can be used to provide a digital signal which is symbolic of the state of the door (open or closed). The decision to enable the oven's cooking circuit is based on the door being in the closed state. The choice of whether a logic 0 represents the open or closed state of the door is arbitrary.

In this microwave example, the binary output of a digital circuit is being used to sense and report the condition of the door (open or closed). Sensing and reporting conditions is one of the main uses of binary digital circuits.

Binary digital signals are also used to represent a quantity or an amount. A single binary digit (referred to as a bit) can have the numerical value of one or zero. Again, the choice of whether +5 volts represents a one or a zero is arbitrary though convention frequently results in the selection of +5 volts as the signal level representing a value of one. Several bits can be combined together to represent any desired binary number or quantity.

It is important to note that the output of a digital circuit can represent a condition (HI or LO, logic 1 or 0, true or false) or a number (1 or 0). This is an extremely important concept to grasp as it allows the representation of state and quantity by the same type of circuits. It is up to the user or the designer of the circuit to interpret the data accordingly.

As stated in the previous paragraph, bits can be combined to represent numbers of any size. The method of representing these numbers is similar to that used for decimal (base 10) numbers. In the decimal system each digit left of the decimal point represents an integer power of ten. For binary quantities (base 2) each digit left of the "binary point" represents an integer power of two. Each of these systems starts numbering the power of the base with zero (base 0). Thus the number 10 in the decimal system represents one TEN and zero ONES. Likewise, the number 0.1 in the decimal system is one TENTH. The number 0.1 in the binary system is one HALF. For further clarification of these points see Figure 1.3.

Decimal:

$$10.01 = (1\times10^{1}) + (0\times10^{0}) + (0\times10^{-1}) + (1\times10^{-2})$$

$$= 10 + \frac{1}{100}$$

Binary:

$$10.01 = (1\times2^{1}) + (0\times2^{0}) + (0\times2^{-1}) + (1\times2^{-2})$$

$$= 2 + \frac{1}{4}$$

Figure 1.3. Comparison of binary and decimal numbers.

1.3.3 Digital Circuits

Circuits used for analog and digital applications differ greatly. Since analog circuits must represent a large number of values between extremes, they are designed to have a region of operation with linear gain (Vout = A Vin). Digital circuits are designed to switch between the two digital states as quickly as possible. The simplest digital circuits are switches as shown in Figure 1.4.

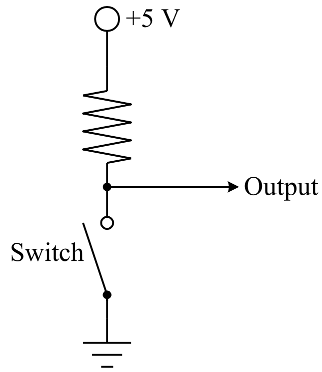

Figure 1.4. Schematic diagram for a digital switch.

This circuit produces a +5 volt output when the switch is open and a zero volt output when the switch is closed. Switches such as this have limited application since the switch contacts tend to bounce (i.e., changing back and forth between open and close several times before settling) resulting in slow switching from one state to the other. Digital circuits have been constructed using discrete diodes and transistors. An example of a basic digital circuit implemented with a bipolar junction transistor (BJT) is shown in Figure 1.5.

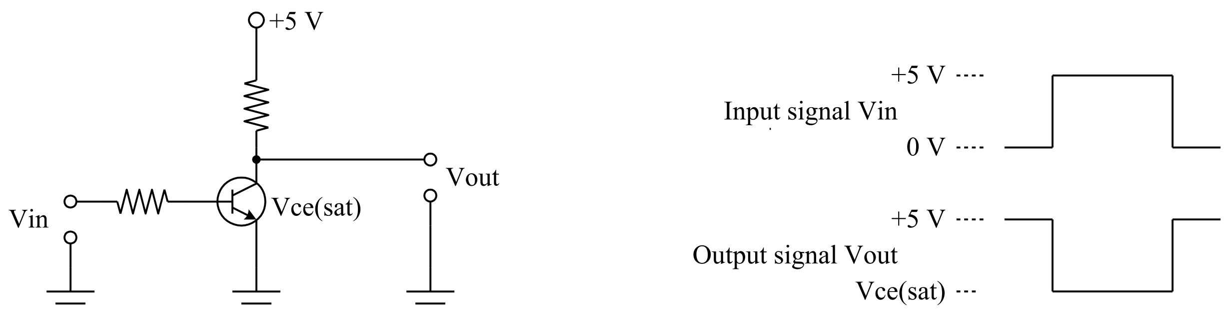

Figure 1.5. Bipolar junction transistor (BJT) acting as an inverter.

This digital circuit operates only in the saturated mode or the cut-off mode of transistor operation. This means that the emitter-base and collector-base junctions are either both forward biased or both reverse biased. This mode of operation is chosen so that when the transistor conducts, the resistance from the collector to the base will be minimal. So, when the transistor conducts in response to a +5 volt input (logic 1) to the digital circuit at Vin, the output of the switch at Vout will be very near ground (logic 0). Actually this voltage, Vce (sat), is about 0.2 to 0.6 volts for silicon bipolar junction transistors. When the transistor is cut-off in response to a 0 volt level at the circuit input at Vin, the output at Vout will be +5 volts.

Such a circuit is termed a digital inverter since the output logic level is the inverse of the input. It is the simplest digital circuit. When used as a logic circuit it is called a "NOT" gate.

This technique of circuit construction while workable was rightly perceived as being cumbersome and wasteful of space and designer's time. Out of the need for compact easily usable circuits, the monolithic integrated circuit was developed by Texas Instruments in 1959. The digital integrated circuit combines several circuits similar to those just described onto a single piece or "chip" of silicon. Such ICs are available to perform a wide variety of logic functions. These digital circuits will be studied throughout the remainder of this book.

1.4 Summary

The difference between analog and digital signals was discussed in this chapter. Analog signals are continuous and digital signals are discontinuous. Digital signals can be used to symbolize either quantity or state. Binary quantities are represented by strings of bits similar to the digits used to represent decimal numbers. The circuits used to represent digital signals are the same whether the signal will symbolize a quantity or state. Digital circuits are easily constructed from discrete components such as transistors and diodes, but are most often encountered in the form of ICs.

1.5 Review Questions

1. Explain the difference between digital and analog signals.
2. What states can a bit be in?
3. What numbers can a bit represent?
4. Draw the schematic of a simple digital switch. Why do these switches seldom appear as shown?
5. Who constructed the first integrated circuit?
6. Name some qualities of an analog circuit.
7. Name some qualities of a digital circuit.
8. Draw the schematic for a simple BJT digital inverter. Explain its operation.
9. Explain what an integrated circuit is.