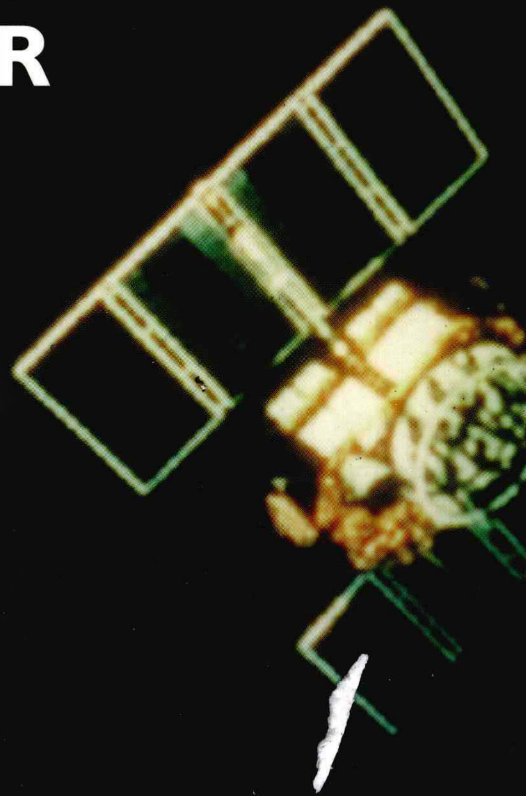
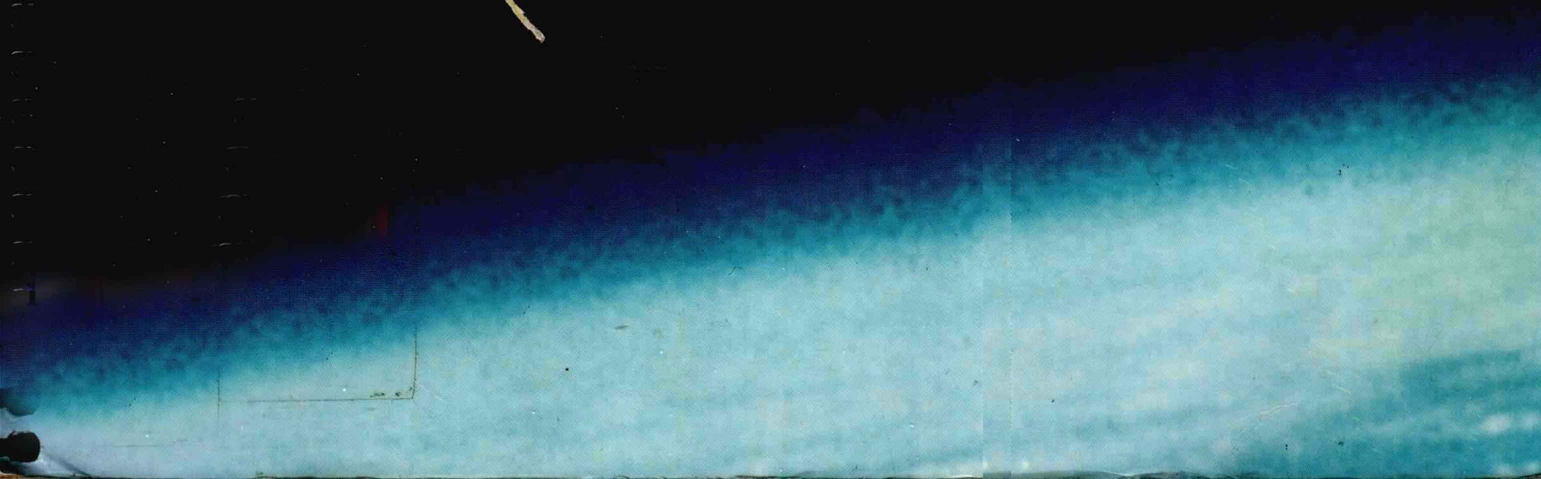
EXPERIMENTAL CONTEXT FOR

INTRODUCTION TO ELECTRICAL AND COMPUTER ENGINEERING



Richard L. Carley and Pradeep Khosla
GPS Adaptation and Additional Material by Robert M. Unetich



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GPS RECEIVER EDITION REVISED

Richard L. Carley and Pradeep Khosla
GPS Adaptation and Additional Material by Robert M. Unetich
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Preface and Acknowledgements

This text was developed to support the new GPS version of the laboratory course taken by students who are also taking Introduction to Electrical and Computer Engineering, a freshman or sophomore course at Carnegie Mellon. It can be used to replace the Robot version of this lab and it closely follows the sequence of the introduction of concepts in the corresponding course textbook.

Please forward information concerning errors or omissions to my attention. There is an Instructor's Guide that corresponds with this text and it is recommended reading for TA's or others interested in the background of this lab course development.

The cover design illustrates orbiting GPS satellites. I would like to thank NASA for the artwork and I owe special thanks Margaret Hanley of CMU for not only designing the cover but for laying out and styling all of the pages of the text. Much of the original material, including a large portion of the original robot lab text, has been retained. I wish to thank the authors of the original document for their support in the development of this new version and Professor Charles Neuman, who assisted in the development of Appendix B. I would also like to acknowledge students Lindsay Smith and James Casazza for their efforts in modifying and updating the text. I would also like to thank the alpha and beta test groups of Course 18-100, Fall 1998, Section B and Spring 1999, Section F for putting up with early drafts of this work – your enthusiasm and probing questions made this an exciting project.

Robert M. Unetich
Adjunct Professor
Carnegie Mellon University
May, 1999

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CHAPTER 1

Introduction

Welcome to the world of Electrical and Computer Engineering. In the series of laboratory exercises presented in this text, we hope to give you a "hands-on" tour of much of what this field is about. In working through this set of laboratory exercises, you will gain practical insights and experience with a series of basic concepts in Electrical and Computer Engineering. This series of laboratory exercises is organized around the construction of a Global Positioning System (GPS) receiver. Although one goal of this series of laboratory exercises is the construction of the receiver kit, they are designed to take the reader much further than simply assembling a kit and getting it to work. In each chapter one or more important concepts are first illustrated by assembling the circuit being studied on a prototyping board (protoboard) and then by performing a series of experiments and observations. After the basic concepts have been fully explored, each subsystem of the interface is soldered onto the kit's printed circuit board.

The hardware constructed in this course will use radio signals from the constellation of satellites launched to support the Global Positioning System (GPS). You will be using the hardware that you build to determine the position of a variety of campus landmarks and this requires that you can acquire a basic understanding of certain navigation concepts and conventions. It is also the intention of this course to allow you to explore some of the characteristics of radio waves including their ability to carry useful information and how they propagate between points. Two appendices have been created to provide you with some background in GPS and Radio Waves and these will be referred to as required in the chapters that follow.

Assuming that you pursue further study in Electrical and Computer Engineering, you will have many opportunities to delve deeper into the theory behind how the circuit elements presented in this text work and interact. One of our goals in this text is to give you a broad set of experiences with some of the elements of Electrical and Computer Engineering. As your practical knowledge is developed through experience, you will have a greater pool of observations and experiences to which your later theoretical understanding can be connected.

Background

The following is an overview of the various electronic components that will be used in the laboratory exercises presented in this text. It is included here for reference only and it is not intended to stand alone as a presentation of this material.

Electrons

All matter is composed of atoms. These atoms have a heavy middle part called a nucleus made up of protons and neutrons. The proton carries a "positive charge" and the neutron carries no charge. Around every nucleus there is a cloud of little particles called electrons, which carry a "negative charge." The reason that the electrons are there is that they are attracted to the protons – opposite charges attract. If the protons weren't there, the electrons would push away from each other – like charges repel. So everything we see and touch is actually composed of millions of nuclei floating in a sea of electrons.

This all becomes relevant to electrical engineering (named for the electron) because we can access the energy inherent in electrons moving around. About 150 years ago, a scientist named Michael Faraday discovered that when electrons were moving, part of their kinetic energy could be transferred to a nearby magnet, thus making the magnet move. Conversely, if you physically moved a magnet near an electron sea, you could get an electric current to flow. This was a very important discovery, for it was the link between our mechanical world and the world of electrons (also known as electronics). Mechanical energy could be transferred to electrical energy, where it could be stored and transported efficiently, and then brought back to mechanical energy. For example, water going over Niagara Falls can spin large magnets through metal coils. This causes electricity to flow in the coils, which can be wired into nearby homes. The energy is then available through wall outlets, where you can plug in your vacuum cleaner, and the electric currents can spin the magnets in the vacuum cleaner's motor.

Current and Voltage

Electric current flow is the means of communication between different parts of any circuit. Effectively, a circuit is just a network of different components that allow the electric current to flow in specific ways. Together, the materials can act as switches, amplifiers, oscillators etc. The network is arranged so the desired input/output relationship holds for the circuit. As you build your GPS receiver throughout the sequence of laboratory exercises described in this text, you will be able to see some of these examples of electrical communications. Fundamentally, one of the causes of current flow is a difference in the potential energy of a free electron at two different points. This is analogous to the gravitational potential energy difference that causes water to flow down a hill. When electric currents were first being studied it was known that things were flowing, but it was not known exactly what was moving, nor in which direction. Benjamin Franklin chose a convention for current flow, objects flowing from a positive electrical potential (called voltage) toward a negative electrical potential, which turned out to be wrong. This is the reason that the charge on an electron is by definition negative. If point A is at a higher voltage than point B, then electrons want to move from B to A (see Fig. 1.1). However, the direction of current flow is defined to be from A to B, opposite to the direction of electron flow. We take care of the difference in direction by assigning a negative charge to the electron. For example, in a battery, the current flows from the positive terminal to the negative terminal, but the electrons go from the negative terminal to the positive terminal. In electronics, the standard is to talk of the current flow, not the electron flow.

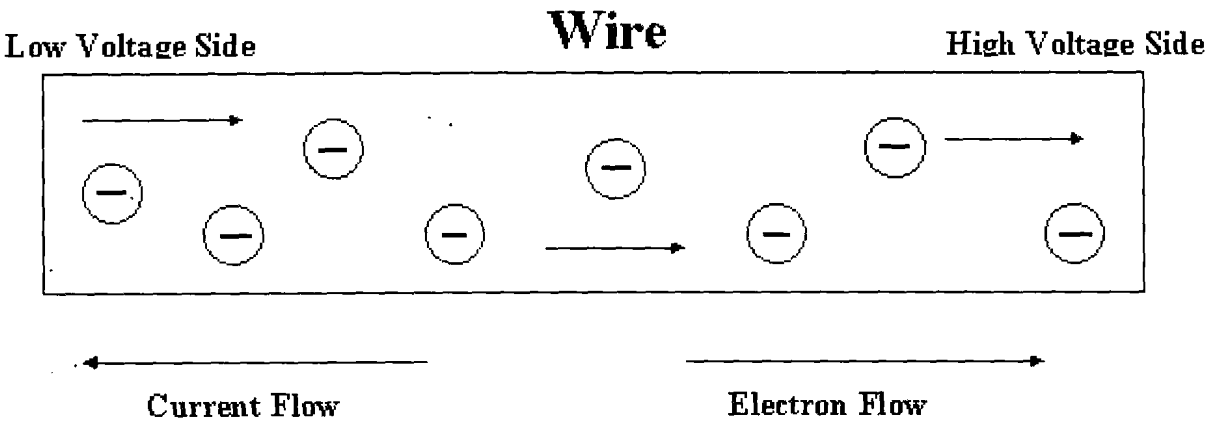

Figure 1.1 Current flowing in a wire

Current is measured in units called Coulombs. A Coulomb is defined as the negative of the charge of 6.25×10^{18} electrons. When 1 Coulomb per second passes by a given point, we say that 1 Ampere of current is flowing. It is written as 1A. The letter I is the standard variable for current in equations. We also need to measure the driving force making the current flow. When there is a high voltage (electrical potential) at a location, it is like a compressed spring whose energy will be released when charge can move "down hill" to a lower voltage. The higher the voltage, the more energy electrons lose as they move to a lower voltage. If one Joule of energy is released when one Coulomb of charge moves from A to

B, we say that the point A is 1 Volt higher than the point B. One volt is written as 1V. Voltage is always measured between two points. When you say that a particular point in a circuit has a voltage level, you are really giving the voltage relative to the defined reference voltage for the circuit. This reference voltage is typically called ground or common.

In order for charge to flow from one place to another, there must be some path for it to take. Referring back to our water analogy, even if a field is lower than the river, water will not flow into the field if there is a dike that is higher than the river in between. If there is an air gap between two objects, electrons cannot flow between them even if there is a voltage difference. However, a high enough voltage difference will cause the electrons to jump through the air. This is what happens when lightning strikes. In a laboratory, this is both dangerous and impractical for manipulating current flow. It has been discovered that some materials require very little voltage across them to allow a sizable current flow, due to their higher free electron concentration. These are called conductors. Most metals are good conductors, and thus metal wires are useful in connecting parts of the circuit together. Generally, it is assumed that there is no voltage difference between any two points of an unbroken metal wire because electrons move easily throughout the metal.

On the opposite end of the scale, there are other materials that are very resistant to current flow. These are called insulators. Plastics are commonly used as insulators. In between conductors and insulators, there exists a third class of materials called semiconductors. These are materials that can conduct current, but not nearly as well as conductors. Semiconductors have useful current-regulating properties when two different kinds of semiconductors are placed in contact. You will learn about that later.

Resistors

In many cases it is necessary to produce a specific current given a specified voltage. To accomplish this, elements known as resistors are constructed. They look like color banded cylinders with wires coming out either end. They limit the current that goes through them. The value of a resistor is determined by the ratio of the voltage across it to the current through it. The unit used for resistors is the Ohm, abbreviated as Ω, and it is defined as 1 Volt per Ampere. For example, if 2A are flowing through a 5Ω resistor, then there must be 10V across the resistor.

The key formula here is that voltage = current x resistance, which is known as Ohm's Law. Symbolically,

$$V = I * R$$

Where V, I and R are the standard variables used in representing voltage, current, and resistance, respectively. In electronic circuits, 2A is a fairly large amount of current. Often, it is convenient to write current in terms of thousandths of an Ampere, or milliamperes (ma). Resistors, on the other hand, often have values of thousands of ohms, or kilohms (KΩ). In a typical lab, you might have 6V across a 2K resistor, resulting in 3 ma of current.

Normally, a circuit will contain more than one resistor. When there is a voltage difference between two points, we know that a resistor connecting the points will allow a current to flow through it. If there are two or more resistors each connecting the same two points together, those resistors are said to be in parallel with each other. Ohm's Law gives the current through each resistor. The equivalent resistance would be one which caused the same total current to flow (see Fig. 1.2); i.e.,

$$Req = 1 / (1 / R1 + 1 / R2)$$

If a current that flows between two points must go through at least two resistors, those resistors are said to be in series with one another. When resistors are used in a line like this, they act as one big resistor whose value is the sum of the component resistors. The current that flows through all of the resistors is the voltage between the endpoints divided by the sum of all of the resistances. The voltage across each component resistor is the current times the individual resistance (see Fig. 1.2); e.g., for 2 resistors in series,

$$Req = R1 + R2$$

Remember that the voltage across a resistor is the amount of energy released when one coulomb passes through the resistor. The current is the number of coulombs passing through the resistor per second. When you multiply the voltage and the current, you get the energy released per second, which is the power dissipated.

$$P = V I = V^2 / R = I^2 R$$

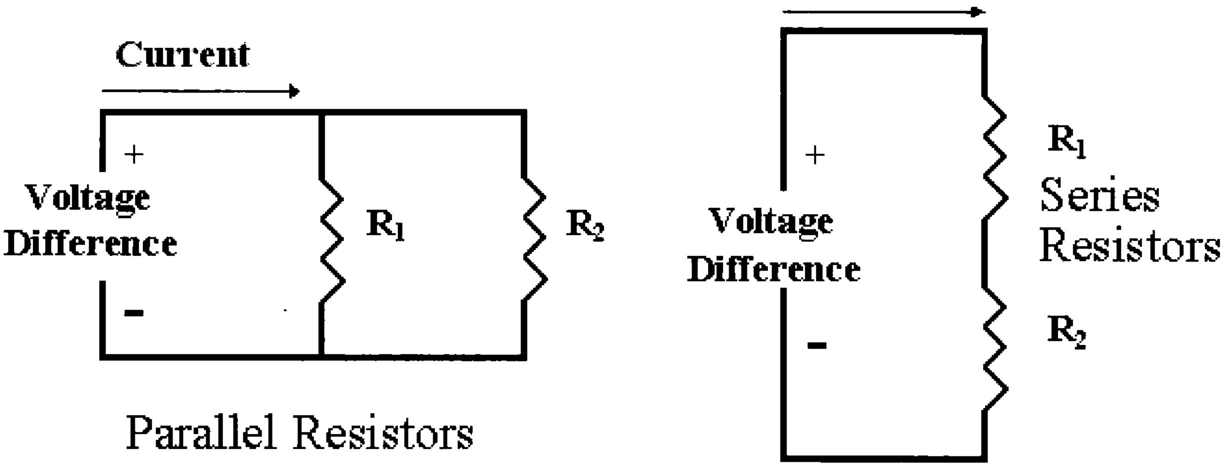

Figure 1.2 Examples of resistors in series and in parallel

This electrical energy is converted into heat energy by the resistor, and it warms up. Resistors can usually cool off into the surrounding air, but only so fast. There is a maximum power, or rate of heat energy, that you can put into a resistor before it becomes damaged. Most of the resistors you will use have a power rating of ¼ Watt. 1 Watt is 1 Joule / second and equals 1 V times 1 A.

A standard color coding convention is used for specifying the value of a resistor. Table 1 shows the numerical value associated with each color. The first two color bands indicate the first two digits in the resistor's value. The third color band indicates the power of ten that the first two digits are multiplied by. The fourth color band specifies the tolerance of the resistor. For example, a resistor with a band set of yellow-violet-orange-gold will have a value of 47×10^3 ohms (47 KΩ) with a tolerance of ± 5%.

Table 1: Resistor Color Code

Black	0	Gold	±5%
Brown	1	Silver	±10%
Red	2	No Band	±20%
Orange	3		
Yellow	4		
Green	5		
Blue	6		
Violet	7		
Gray	8		
White	9		

Capacitors

Next, we introduce an element called a capacitor. In its simplest form, it consists of two parallel metal plates separated by an insulator. Capacitors are energy storage devices. When a current flows into a capacitor, the electrons leave the positive plate, leaving a positive charge. The extra positive charge pulls electrons onto the negative plate and the electrons are held there. Consequently, a charged capacitor holds a voltage across its terminals. The voltage between the plates is proportional to the amount of charge. Symbolically,

$$Q = C \times V$$

Where Q is the charge stored, and V is the voltage across the terminals. C is called the capacitance of the element. When you divide the charge stored in a capacitor by the voltage across it, you get the value of the capacitor in units of Farads. A 1F capacitor is quite large for most circuits, so capacitors are usually specified in microfarads (μF) - 10^{-6} F - or picofarads (pF) - 10^{-12} F.

The capacitor discharges when current is allowed to flow between the plates. This causes the electron concentration to equalize on the two plates, and current flows through the connection. When the connection is a circuit, the capacitor acts as a power supply for the circuit as it discharges. For this reason, a capacitor is called an energy storage device. This is illustrated in Fig. 1.3.

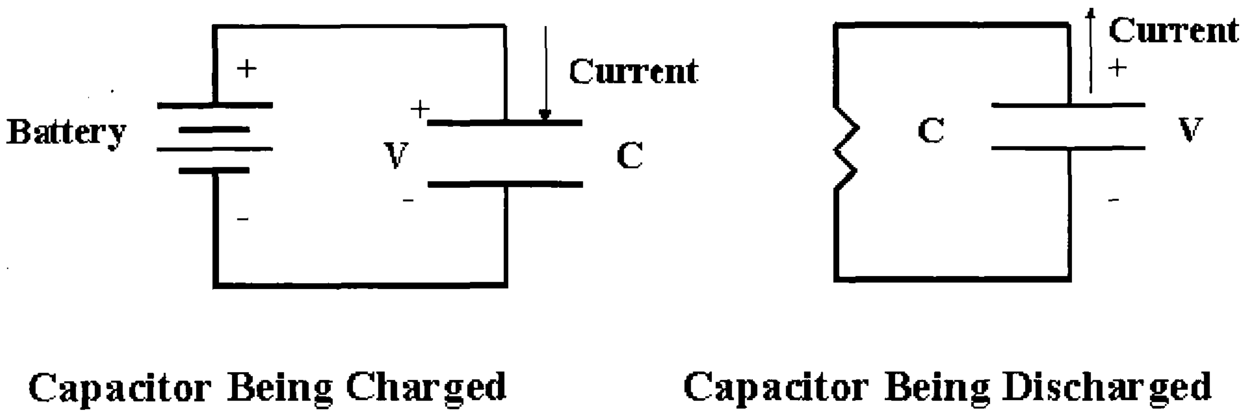

Figure 1.3 Example of capacitors being charged and discharged.

There are two kinds of capacitors on your GPS interface board, polarized and non-polarized. The two polarized capacitors are electrolytic, and cylindrical in shape. In these electrolytic capacitors the dielectric only acts as a good insulator for voltages of one polarity. When voltages of the opposite polarity are applied the dielectric may fail and allow significant currents to flow directly from one plate of the capacitor to the other – usually resulting in its destruction. For these polarized capacitors you must always make sure that the terminal labeled with a "+" will be connected to the point in your circuit that is at a higher voltage and the terminal with a "–" will be connected to a point in your circuit at a lower voltage. There is a black stripe down the side of each of the capacitors in your kit, which indicates the negative lead of the capacitor. All the electrolytic capacitors have their value written on them. The rest of the capacitors have a three-digit number on them followed by a K (or JT). The three-digit number reads just like the three colored bands on resistors and the K stands for pF. For example, a capacitor reading 682K would be a 68×10^2 pF capacitor.

Diodes

The simplest "semiconductor" device is the diode. A diode is like a one way street for current flow. It is made from two different kinds of semiconductors (called N and P - but don't worry about why now) next to each other. The current can flow from semiconductor P to semiconductor N, but not the other way around. You can also think of a diode as a water pipe with a valve inside that can only swing one way. Water can never flow in the direction that would push the valve the wrong way. Water can flow in the other direction, though, as long as there is a little pressure to push the valve open. In diodes, this "little pressure" is usually about 0.7V. When current is flowing through diodes, there is almost no resistance, but the end of the diode where the current enters is always about 0.7V higher than the end that the currents exits. Fig. 1.4 illustrates the schematic representation of a diode.

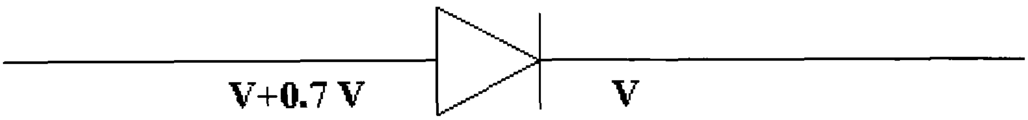

Figure 1.4 Example of how a diode operates

Of course, nothing is perfect. If you do put a large voltage across a diode in the wrong direction, a current will push through the wrong way (breaking the "one way valve" in the pipe). The voltage at which this occurs is called the reverse breakdown voltage and it varies between diodes. This characteristic of diodes is utilized in Zener diodes. Zener diodes are designed to have well-controlled reverse currents at predetermined breakdown voltages. They are characterized by the voltage at which they allow reverse current. In this lab we will be using a 5.6V

Zener diode. This means that 5.6V across the diode in the reverse direction will cause reverse current to flow, just as 0.7V in the forward direction will cause a forward current. The Zener diode representation is shown below; and, it is identical to the regular diode but for the crooked bar. An example of what current would flow if you applied various voltages to the 5.6V Zener diode in your Kit is shown in Fig. 1.5.

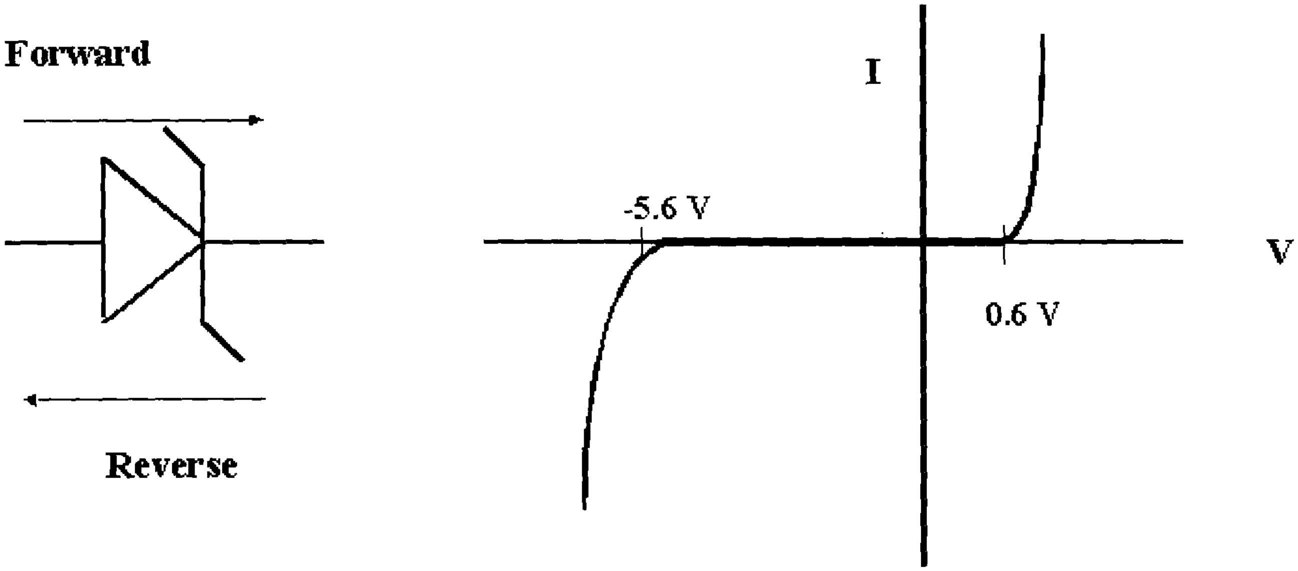

Figure 1.5 Zener diode symbol (left) and I-V curve (right).

There are four kinds of diodes you will be using in your receiver. First, there are standard "signal" diodes. These are the elements with a black stripe and labeled with the number "1N4148". You will note that the stripe is closer to one of the diode leads. The end with the stripe is the N type semiconductor (see Fig. 1.6). Hence, current will only flow from the other end toward the end with the stripe. The "power" diodes in your kit are similar to the signal diodes but they are designed to handle higher current. The 1N4006 diode is a very common power diode. It normally has a black plastic case and a white band at one end; a printed part number on the case should identify it.

There is another element similar to the power diodes, only it is labeled as "5.6" or "1N5232." This is the Zener diode used in the power circuit. Just as in regular diodes, the stripe is on the N side of the diode (see Fig. 1.6). However, a Zener diode is normally used in reverse breakdown, hence the current will flow from the end with the stripe to the other end.

The last kind of diode you will be using is the light emitting diode (LED). This is a domed red element with two leads coming out of the bottom (see Fig. 1.6). When sufficient current flows through it in the forward direction, it will light up red. You will notice when you look down on the LED that it has a circular base except for a flattened edge on one side. This flattened edge is directly above the N semiconductor side of the diode.

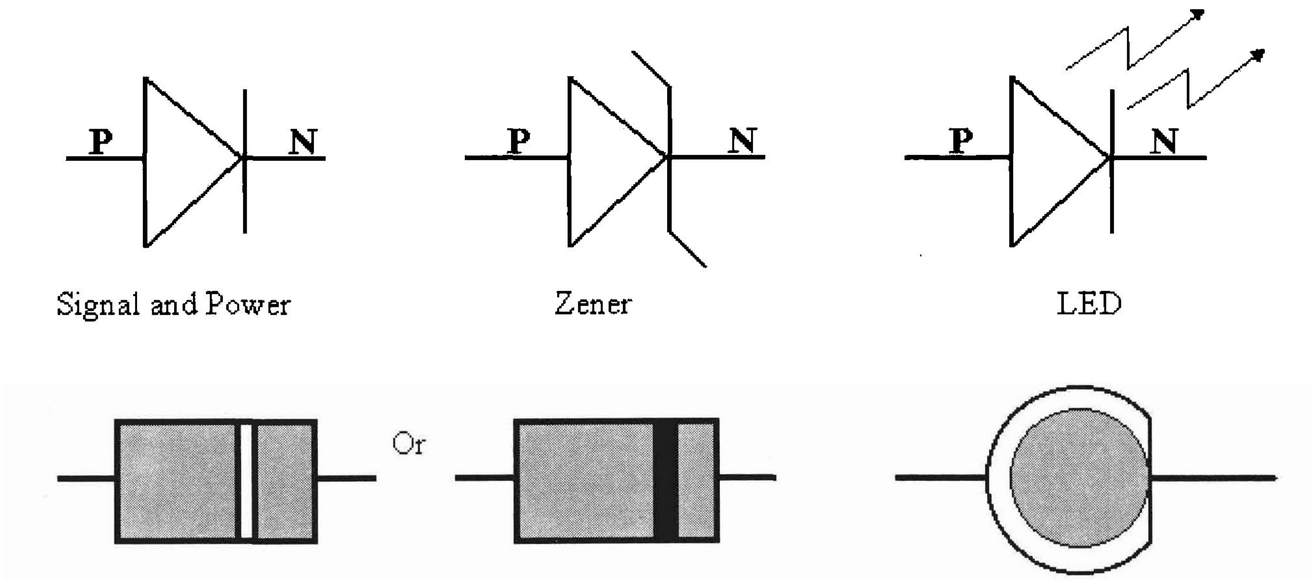

Figure 1.6 **Schematic symbols for diodes. From left to right: normal signal or power diode, Zener diode, and light emitting diode**

Transistors

Another important device is the transistor. Like diodes, they are made of semiconductors. In our kit, we will use them as current amplifiers and as switches. There are three leads into a transistor, and they are called the emitter (E), base (B), and collector (C). If you leave the C lead floating (i.e. not connected), and just look at the B and E terminals, you would find that between these leads there is just a diode. There are two basic types of transistors depending on whether the base region is P or N type semiconductor. The Emitter and Collector are always of the opposite type from the base; therefore, the transistors are called NPN or PNP indicating the semiconductor type of the Emitter-Base-Collector. In an NPN transistor, current can only go from B to E, and when it does, lead B is typically about 0.7V higher than lead E. When lead C is hooked up to a voltage greater than the voltage at lead B, a current will flow from C to E which is a multiple of the current going from B to E.

This current multiplier is called the ß (the second letter of the Greek alphabet, "beta") of the transistor, and usually varies from about 20 to 400. However, it is nearly constant for a given transistor, and doesn't vary much with the current it multiplies. The current coming out of the E terminal (called the emitter current) equals the current going into the B terminal (the base current), plus ß times the current going into the B terminal (which is the current going into the C terminal). Symbolically,

$$I_E = I_B + I_C = I_B + \beta I_B = (\beta+1)\ I_B.$$

There is only one kind of transistor you will need to build your interface, the 2N3904, a regular NPN transistor. They look like black semicircular cylinders with three leads coming out of one end. To determine which lead is which, do the following: facing the flat side of the transistor, with the leads pointing down, and reading from left to right, the leads are Emitter, Base, and Collector, in that order. This is the same for all of the transistors (see Fig. 1.7).

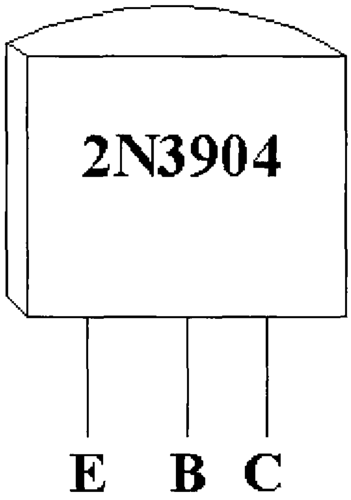

Figure 1.7 The physical appearance of the bipolar transistor

Integrated Circuits

Combining many semiconductor devices inside of one package provides many advantages. Modern Integrated circuits (ICs) can have millions of individual devices in one package, especially for digital applications. In this lab we will be using several ICs that will combine all of the devices described individually above. Each device will be briefly described on the parts list and on the schematic and the student is encouraged to learn more about these devices from reference data books and other sources.