by Henry D'Angelo

MICROCOMPUTER STRUCTURES

An Introduction to Digital Electronics, Logic Design, and Computer Architecture

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by

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PREFACE

The remarkable advances in the manufacture of microelectronics have made the small, low-cost digital computer system a reality. Digital computers are now affordable to many small enterprises that cannot afford the technical consulting and maintenance services typically purchased along with the expensive large machines. As a result, there is an increasing demand for computer users who are not only well versed in software, but who can also maintain, modify, and design their own computer systems. This book is intended for those computer users (programmers, system analysts, managers, engineers, scientists, etc) who plan to maintain, modify, or design a microcomputer system. It is particularly directed to those who have little or no background in digital computer hardware and, as a result, would find it difficult to obtain a working knowledge of microcomputers. The object of this book is to introduce computer users to the basic computer structures used in microcomputer design and in microcomputer interfacing.

The book is based on a one-semester computer science course which I designed for students with some programming experience. In several instances, however, students have taken this course along with their first programming course. Importantly, the course has had a strong laboratory component associated with it, and the book reflects this both in its point of view and in the laboratory problems included at the end of each chapter. The book, like the course, assumes no electronics background and is designed to guide the reader through a series of laboratory exercises beginning with exercises on elementary electric circuits and electric measurements, proceeding to exercises on digital electronics and logic design, and ending with exercises on microcomputer design and interfacing.

Although a one-semester course spanning such broad areas of computer science and electronics is not a substitute for major concentrations in computer science and electrical engineering, the material presented here does provide a foundation for microcomputer design and microcomputer interfacing. Importantly, the combination of subjects presented and the relationships between them provide a framework within which several important technologies come together. Without such a framework, a quantitative study of microcomputers could be formidable, especially if the study is undertaken in a traditional manner. Specifically, consider the problem of having to take courses in electric circuits, electronics, logic design, computer architecture, and computer programming in preparation for a study of microcomputer design and microcomputer interfacing. At most universities such a program of study would take two to three years, with the objectives being broader than just to provide background for a study of microcomputers. This book is based on the premise that only a small subset of the material normally covered in a traditional electrical engineering program is fundamental to the limited objective of obtaining a background for microcomputer design and microcomputer interfacing.

Although the laboratory exercises are considered to be an essential part of this study of microcomputer structures, those without access to an electronics laboratory should not be discouraged. The cost of the electronic components and instruments necessary to set up a laboratory suitable for carrying out most of the suggested exercises is minimal. In fact, the course on which this book is based was initially taught to nine students in a department of mathematical sciences which at that time had no electronic laboratory facilities. Those students conducted most of the laboratory exercises using my eleven-year-old son's collection of electronic laboratory equipment. The main items in this collection included a $19 Radio Shack multimeter, a $15 solderless breadboard, an $11 Edmond's variable DC power supply, and a random assortment of resistors, capacitors, integrated circuits (ICs), and wire. Before the semester was over an additional $600 was spent. These funds were used primarily for additional solderless breadboards, components to build 5-volt power supplies, ICs, and some general-purpose tools. In addition, four microcomputers were available for the later interfacing exercises. The point is that a laboratory necessary to carry out the major laboratory exercises described in this book is neither complex nor expensive. In fact, the cost of many short courses on microprocessors and microcomputers is greater than the cost of setting up a modest digital-electronics laboratory.

I confess that, given a choice, I would have selected better laboratory equipment than that used initially; the laboratory I eventually developed was rather well equipped. It is especially helpful to have access to a good high-frequency oscilloscope at the time that the microcomputer exercises are being conducted; almost any inexpensive oscilloscope is adequate for the study of electric circuits, electronics and digital logic. However, it is interesting that the students who took that first course developed rather ingenious latching schemes which did not require the use of an oscilloscope to test their sequential-logic and interface designs. It is perhaps significant that most of these students had never used an oscilloscope and, at this introductory level, did not feel handicapped without one. Nevertheless, the oscilloscope is the most versatile of all electronic instruments, and if it is at all possible to arrange to have access to one during this study, do so. Appendix B provides a list of electronic components, instruments, and supplies suitable for conducting the suggested laboratory exercises.

The material on which this book is based has been taught for three years as a one-semester (42-session) course. The following schedule has proved effective:

Chapter	0	1	2	3	4	5	6
Number of Sessions	7	7	6	4	6	4	5

The students were assigned to do all the exercises at the end of each chapter. In addition, one session was used to introduce the course, and two sessions were used for exams. The Instructor's Manual for this book details the material covered in each session and the homework problems assigned.

This book contains seven chapters, numbered 0 through 6. In starting the numbering of the chapters with 0 rather than 1, as is customary, the thought was that readers with backgrounds in electric circuits (eg: engineers who have taken an electrical engineering course in circuits, scientists who have taken a physics course in circuits, technicians, etc) would wish to skip the introduction to electric circuits and begin with Chapter 1 on digital electronics. Since most students I have taught have been computer science majors and have not had a strong background in electric circuits, I have always started teaching the course with Chapter 0. However, a number of graduate electrical engineers (none with significant experience in digital computer hardware) have taken the course; all felt that Chapter 0 was a worthwhile review and would not have chosen to skip it. Nevertheless, I would not recommend Chapter 0 to those who have just recently completed a study of electric circuits.

In teaching this course I have been using the KIM-1 microcomputer for the laboratory exercises requiring a microcomputer. The KIM-1 has proved to be excellent for this purpose. Any other microcomputer which provides easy access to the data bus, the address bus, and all the important control signals would be equally effective.

In carrying out this project I have had many rewarding interactions with students, colleagues and friends. I am indebted to many and with pleasure acknowledge my gratitude to them. I am indebted to Stanley P. Franklin, Chairman of the Department of Mathematical Sciences at Memphis State University, for the opportunity to introduce the course on which this book is based. At the time that the course was introduced, the department had no hardware laboratories. Dr. Franklin made space, equipment, and time available to me for carrying out the project. Can an administrator do more? I am indebted to Thomas G. Windeknecht who, as a close colleague and friend, played a major role in determining the type of hardware course needed by computer science majors. It is difficult to imagine that the project would have begun without Dr. Windeknecht's enthusiastic encouragement and support. I am indebted to Leonard R. Marino, whose two magnificent lectures introduced me to the marvelous world of microprocessors. Then, over the next several years, Dr. Marino allowed me access to his formidable collection of early microprocessor literature, including his own excellent notes. I am indebted to Gregg Williams, a student in the first course and now an editor of BYTE magazine. Mr. Williams' enthusiasm for the course was a major factor in my decision to write the book, and his bringing the manuscript to the attention of the editors of BYTE Books aided in publication. I am indebted to Michael J. Connolly, an excellent student who endured the first complete draft. Mr. Connolly generously gave me his well-written problem solutions to use in preparing the Instructor's Manual. I am indebted to Mary Thorpe, Secretary of the Department of Mathematical Sciences at Memphis State University, for her infinite patience in handling the many logistical problems involved in copying and distributing notes to the students and in purchasing and maintaining laboratory equipment and supplies. I am indebted to David Saxton, a close friend and philosopher, who contributed several days of a precious short vacation to the cause: he constructed power supplies. I am indebted to my students whose enthusiasm for the course in general and whose skepticism toward particulars stimulated and directed the project. I am especially indebted to Gail Cepnik, Charles Crowe, Linda Edminster, Andrew Halford, Gordon Helyer, Pik Chi Hui, Dan Lasley, Yaw Lin, Marjorie Martin, Timothy McCain, Sid Moody, Austin Smith, Donald Swearingen, Sammy Turner, and David Tzai.

I am indebted to my four children, Gus, Jim, Peter, and Paul, for the many hours they spent helping to get the laboratory started and then helping to keep it going. They wired, sorted parts, swept floors, assembled kits, put up shelves, and made repairs. I am especially indebted to Jim, whose sustained contribution to the laboratory over a three-year period, often requiring an afterschool bus ride to the University, was an important factor in the success of the laboratory operation.

It is a gross understatement to say that the project could not have been completed without the collaboration and cooperation of my wife, Gail. The fact is that the project would not have ever been started. Gail argued strongly that we undertake the project. This was at a time when, in view of other conflicting demands, it seemed prudent not to do so. Her offer to support the effort by taking total responsibility for all the editing, typing, and layouts, was monumental. Considering the magnitude of her contribution (note that even the cover illustration is hers), Gail should rightfully be a coauthor. Since her modesty doesn't allow that, I lovingly dedicate the book to her.

CONTENTS

Chapter 0

Introduction to Electricity

Digital electronics is a special area of electronics which deals with the design of logic devices used in digital computers and other digital equipment. Even though the general field of electronics is a complex subject embedded in an intricate mosaic of mathematics, physics, and engineering, it is possible to obtain a fundamental working knowledge of *digital* electronics in a relatively short time. For example, compared with the mathematical models used in the design of electronic amplifiers for high-fidelity sound equipment, rather simple models can be used to analyze and design digital electronic networks. In fact, the models used for digital networks seldom need to be precise and rarely take into account second-order effects.

Because the functional accuracy of a digital device rarely depends, within large ranges of variation, upon the accuracy of the components used in its construction, it is possible to use coarse models to analyze and design digital networks. For example, a typical electronic logic component is considered to be functional if its only two possible output states, *HIGH* and *LOW*, can be distinguished from each other. Thus, in a 5 V logic system, one might define any voltage between 2.5 and 6.0 volts as the HIGH state and any voltage between 0 and 1.0 volts as the LOW state; a voltage in the *forbidden region* lying between 1.0 V and 2.5 V would be indicative of a malfunction. With such wide ranges of voltage possible in defining a HIGH and a LOW, low-precision components can be used to construct logic devices. From the standpoint of analysis and design, the need for high-precision models is diminished. Nevertheless, many rather sophisticated digital electronic problems frequently arise that cannot easily be solved without a fundamental understanding of electricity. As background for the study of digital electronics, this chapter presents the fundamentals of electricity, electric networks, and electrical measurements.

0.1 Physical Quantities and Units

In the study of electricity, only four fundamental physical quantities need to be defined: *length, mass, time,* and *electric charge.* A unit of a physical quantity is a standard of measurement defined for that physical quantity. In this text the MKS (meter-kilogram-second) system of units is used. The following table gives the MKS units for the four fundamental physical quantities.*

Physical Quantity	MKS Unit
Length	Meter (m)
Mass	Kilogram (kg)
Time	Second (s)
Electric Charge	Coulomb (q)

Table 0.1: *The MKS system of units.*

All other physical quantities can be expressed through definitions or physical laws in terms of these four fundamental physical quantities.

For example, *velocity* is defined as the rate at which distance is traversed. Thus, if the variable x represents the distance in meters from a point on a line (ie: a point representing the position of an object on that line) to a fixed point of reference on that line, and the variable t represents time in seconds, then the velocity v of that object as it moves along the line is given by

$$v = \frac{dx}{dt}$$

Therefore, a unit of velocity is expressed in meters per second (m/s). Similarly, *acceleration* a is defined as the rate of change of velocity:

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

Therefore, a unit of acceleration is expressed in meters per second per second (m/s^2). Thus, velocity and acceleration are *defined* in terms of the fundamental quantities *length* and *time.*

The physical quantities of velocity and acceleration are *mathematically*

Temperature, a fifth fundamental quantity, which, in the MKS system, is measured in degrees Kelvin (°K), is not essential to most electric network modeling. It is generally assumed that all networks are at room temperature (ie: at approximately 300°K).

defined physical quantities, but the physical quantity *force* is more subtly defined. It seems somewhat natural for masses to be at rest and to be inclined to remain at rest. More interesting and mysterious, however, is a moving mass. The concept of a force was invented to describe the phenomenon that causes a mass to be set in motion from its apparently natural state of rest. Through the ages many ingenious mechanisms for developing useful forces have been devised (eg: levers, pulleys, screws, magnets, air foils). It was not until the seventeenth century that Sir Isaac Newton proposed that a simple relationship exists between force, mass, and acceleration. Newton hypothesized that force is proportional to the product of mass and acceleration. This is now called *Newton's second law of motion*. In the MKS system, Newton's second law of motion provides a convenient definition for force:

$$f = ma$$

Therefore, a unit of force is expressed in kilogram-meters per second per second (mk/s^2). This unit of force is appropriately called a *newton*.

For many applications, the MKS units of measure are awkward in that the quantities used are either several orders of magnitude larger or smaller than the standard unit. For example, the time required for a typical electronic logic device in a digital computer to respond to a command signal is on the order of 20×10^{-9} seconds. Thus, 20 *nanoseconds* (or simply 20 ns), where *nano* (or n) is defined to be a factor of 10^{-9}, is 20×10^{-9} seconds. Table 0.2 summarizes some of the more common symbols for such factors.

Terminology	Symbol	Factor
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}

Table 0.2: *Scale factor symbols.*

0.2 Electric Charge

The observation of certain forces other than those well known in mechanics (eg: inertial forces, gravitational forces, spring forces, frictional forces, etc) led to the hypothesis of the existence of the physical quantity called *electric charge*. Specifically, very lightweight object such as pith balls repel each other after being touched by a glass rod that has been rubbed with silk. Similarly, very lightweight objects repel each other after being touched by a hard rubber rod that has been rubbed with fur. Such objects are said to be *electrically charged*. Furthermore, an object charged by the glass rod *attracts* an object charged by the rubber rod. The existence of both forces of attraction and repulsion led to the conclusion that there are two distinct types of electric charge. Arbitrarily, the glass rod is said to be *positively* charged and the rubber rod is said to be *negatively* charged. A qualitative model is now clear: a force of repulsion exists between two similarly charged bodies (ie: either two positively charged bodies or two negatively charged bodies), and a force of attraction exists between two dissimilarly charged bodies.

In 1913, Niels Bohr modeled the atom as a planetary structure in which negatively charged particles, called *electrons*, whirl around a nucleus which consists of positively charged particles, called *protons*, and uncharged particles, called *neutrons*. Although the proton is considerably heavier than the electron (1.674×10^{-27} kilograms versus 9.11×10^{-31} kilograms), both have the same magnitude of charge. The charge on an electron is a small fraction of a coulomb; it takes the charge of 6.25×10^{18} electrons (or protons) to make a coulomb.

0.2.1 Coulomb's Law

In the eighteenth century, Charles A. Coulomb hypothesized a mathematical model from which a quantitative measure of charge could be obtained. Now known as *Coulomb's law*, this model is based upon the observation that the force f between two point charges, q_1 and q_2, is proportional to the product of the charges and inversely proportional to the square of the distance r between them, as follows:

$$f = \frac{q_1 q_2}{4\pi\epsilon r^2}$$

The constant of proportionality, $4\pi\epsilon$, depends upon the medium in which the charges are placed. The constant ϵ is called the *permittivity* of the medium. The permittivity of free space (ie: a vacuum) has been experimentally determined to be $\epsilon_v = 8.854 \times 10^{-12}$ (approximately $10^{-9}/36\pi$). For all practical purposes the permittivity of air can be assumed to be equal to that of free space.

Clearly, the forces that charges exert on each other are inversely proportional to the permittivity of the medium. It is convenient to compare the permittivity of a material to that of free space. The ratio of the permittivity of a material to that of free space is called the *dielectric* constant. Table 0.3 gives the dielectric constants for some common materials.

Material	Dielectric Constant
Glass	5 - 10
Hard Rubber	2.9 - 3.1
Mica	5.7 - 8.7
Paper	2 - 2.5
Paraffin	2 - 2.3
Water (pure)	81

Table 0.3: *The dielectric constants for some common materials.*

Example 0.1

Two point masses, each with a positive charge of 1 coulomb, are separated by a distance of 1 meter, as shown in figure 0.1. The force of repulsion on each charged body is determined by the application of Coulomb's law:

$$f = \frac{q_1 q_2}{4\pi\epsilon r^2} = \frac{(1)\,(1)}{4(3.142)(8.854 \times 10^{-12})(1)^2} = 9 \times 10^9$$

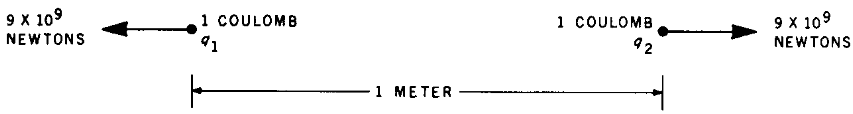

Figure 0.1: *Force between two charged bodies.*

Thus, the force on q_1 is 9×10^9 newtons at an angle of 180° (a vector directed horizontally and to the right is said to be at 0°; all other angles are measured in a counterclockwise direction from this 0° reference) and the force on q_2 is also 9×10^9 newtons, but at an angle of 0°. The angle of force is always in the direction of a straight line drawn between two charges, away from the charges if both charges are positive or both are negative, and toward the charges if one is negative and the other is positive.

A force of 1 newton is equivalent to the force produced by the earth's gravitational field on a weight of 0.2248 pounds at sea level. Thus, a force of 9×10^9 newtons is an extraordinarily huge force (over 1 million tons) and, consequently, a charge of 1 coulomb is an extraordinarily huge charge.

Example 0.2

Three point masses, two with positive charges of 1 coulomb each and one with a negative charge of 1 coulomb, are separated from each other by distances of 1 meter, as shown in figure 0.2. The force f_2 on charge q_2 is determined as the vector sum of the force f_{12} (exerted on q_2 by q_1) and the force f_{32} (exerted on q_2 by q_3). Therefore, $f_{12} = 9 \times 10^9$ newtons at 300° (q_1 and q_2 repel each other), $f_{32} = 9 \times 10^9$ newtons at 180° (q_3 and q_2 attract each other), and the resultant force $f_2 = 9 \times 10^9$ newtons at 240°.

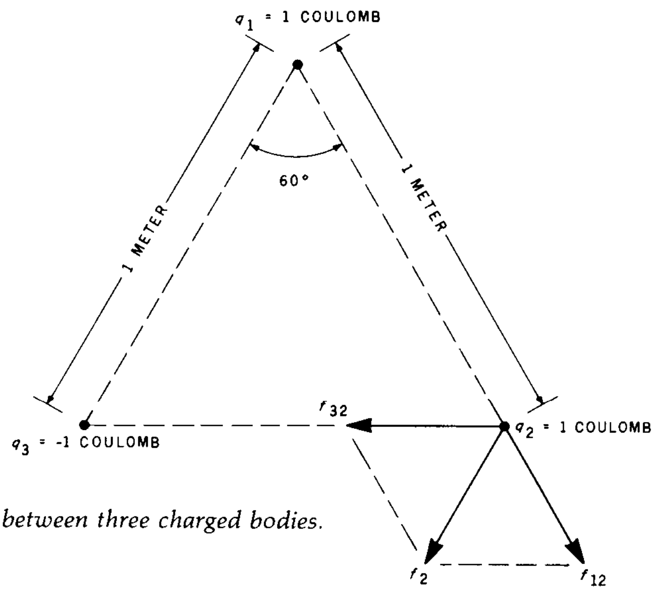

Figure 0.2: *Forces between three charged bodies.*

0.2.2 Electric Field

Although the application of Coulomb's law is sufficient to determine the forces on stationary point charges,* the concept of an *electric field* is convenient in situations where a large number of charges are distributed in complex geometric patterns. An electric field is defined as an infinite set of vectors such that, corresponding to each point in space, there is a vector equal to the force that would be experienced by a positive unit charge placed at that point in space. Such forces produced by interactions with other charges can be determined by using Coulomb's law. Knowledge of the electric field produced by a stationary distribution of charges in space is thus equivalent to a description of the charge distribution. However, knowing what the

*Moving charges can experience additional forces due to the presence of *magnetic fields* (see section 0.9.1.1).