

Fundamentals of Applied Microcontrollers Manual

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Chapter 1

Introduction

This book is the accompanying text to a class introducing microcontrollers to upper division, non-electrical engineering undergraduate students who have taken some C programming.

Chapter 2

Number Systems

This chapter introduces the concepts of different numbering systems that are relevant to microcontrollers.

2.1 Decimal Numbers

The standard number system used by humans is based on 10. This logically flows the usual numbers of fingers or toes humans have. When counting in the base 10 (decimal) we start at 0, count up to 9, then run out of numbers to use. When runs out of numbers, we put a number to the left of the column we were counting in, and then start over at zero again which gives us the number 10. A more clear way to count would be to count from 00 to 09, then increment the left digit and start the right digit back at 0. This can be continued until 99 is reached. But now we have a model to follow. If a column gets to 9, we increment a column to the left and start the current column over at 0. This leads to the number 100. This concept can be continued forever.

When given a particular number, 3254, in decimal the value is calculated as

$$3254 = 3 \cdot 1000 + 2 \cdot 100 + 5 \cdot 10 + 4 \quad (2.1)$$

It could also be represented as

$$3254 = 3 \cdot 10^3 + 2 \cdot 10^2 + 5 \cdot 10^1 + 4 \cdot 10^0 \quad (2.2)$$

This is the basis for a positional number system.

2.2 Binary Numbers

Computers run a base 2 system, also known as binary. This means that we only have two options at each position, 1 or 0, instead of the 10 available in the decimal system. However, counting is done in the same way, when you run out of symbols, increment the position to the left and then start over at zero in the current position.

Binary numbers are also positional so a number like 1011 is

$$1011 = 1 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 = 11_{10} \quad (2.3)$$

where 11_{10} indicates that the number 11 is base 10.

The maximum value a binary number can have is determined by the number of bits it has. The formula is:

$$V_{max} = 2^n - 1 \quad (2.4)$$

where n is the number of bits. For example, an 8 bit number has a maximum value of $2^8 - 1 = 255$.

2.3 Hexadecimal Numbers

The problem for humans is that we have a very difficult time reading binary numbers. Especially once the numbers get long such as 11101101010010110101_2 . The first thing we can do to improve intelligibility is to put a space in every 4 digits so that we aren't completely bowled over by all the digits. This gives us $1110\ 1101\ 0100\ 1011\ 0101_2$. This is better but still leaves some challenges. Someone pointed out that since 4 bits can have 16 different values, what if each 4 bits (also called a nibble) was represented by a single base 16 number. Base 16 is called hexadecimal. It has the problem that it runs out of digits once we get to 10, so it was decided to simply start on the alphabet so 10_{10} is A_{16} , 11_{10} is B_{16} , and so forth. Now the cumbersome binary number we've been playing with can be represented as $ED4B5_{16}$.

A comparison of the different numbering system representations of 0 through 15_{10} are shown in Table [2.1](#).

Decimal	Binary	Hexadecimal
00	0000	0
01	0001	1
02	0010	2
03	0011	3
04	0100	4
05	0101	5
06	0110	6
07	0111	7
08	1000	8
09	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

Table 2.1: Decimal, binary, and hexadecimal numbers align as shown in this table.

2.4 Binary Background

The reasons for this stem from early computers using switches (relays) as their basic computing elements and the fact that telling the difference between a “high” voltage and a “low” voltage is easier to do than to differentiate 10 different voltages. It also allows for a gap between high and low that creates some immunity to noise. (TODO: insert figure or reference figure from logic chapter)

2.5 Converting Between Bases

2.5.1 Binary to Decimal

Converting to decimal is straightforward since we can simply sum each digit multiplied by the power of 2 it represents.

$$V_{10} = \sum_{i=0}^p d_i \cdot 2^i \quad (2.5)$$

In Equation 2.5 the p digits, d_i , of the binary number are summed from right to left while being multiplied by the power of 2 they represent. As an example, convert 1011 0111 to decimal.

$$\begin{aligned} V_{10} &= 1 \cdot 2^0 + 1 \cdot 2^1 + 1 \cdot 2^2 + 0 \cdot 2^3 + 1 \cdot 2^4 + 1 \cdot 2^5 + 0 \cdot 2^6 + 1 \cdot 2^7 \\ &= 1 + 2 + 4 + 0 + 16 + 32 + 0 + 128 \\ &= 183 \end{aligned} \quad (2.6)$$

I usually find it easiest to just remember the powers of two for each place and add them up.

$$\begin{array}{cccccccc} 128 & 64 & 32 & 16 & 8 & 4 & 2 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \end{array} = 1 + 2 + 4 + 16 + 32 + 128 \quad (2.7)$$

2.5.2 Decimal to Binary

Converting decimal numbers to binary involves dividing by 2 until the remainder is 0 or 1. The process goes as follows:

1. Divide the number by 2. If the remainder is 1 then the least significant bit is 1 otherwise if the remainder is 0 (it was an even number) then the least significant bit is 0.
2. Take the quotient from the previous step and divide by 2. The remainder is the next more significant bit in the binary representation.
3. Repeat Step 2 until the quotient is 0.

As an example, let's convert 11_{10} to binary.

$$\begin{aligned} 11 \div 2 &= 5R1 \rightarrow 1 \text{ (LSB)} \\ 5 \div 2 &= 2R1 \rightarrow 1 \\ 2 \div 2 &= 1R0 \rightarrow 0 \\ 1 \div 2 &= 0R1 \rightarrow 1 \text{ (MSB)} \end{aligned} \quad (2.8)$$

That means that 11_{10} is 1011_2 . As another example let us convert 20_{10} to binary.

$$\begin{aligned}
 20 \div 2 &= 10R0 \rightarrow 0 \text{ (LSB)} \\
 10 \div 2 &= 5R0 \rightarrow 0 \\
 5 \div 2 &= 2R1 \rightarrow 1 \\
 2 \div 2 &= 1R0 \rightarrow 0 \\
 1 \div 2 &= 0R1 \rightarrow 1 \text{ (MSB)}
 \end{aligned}
 \tag{2.9}$$

This shows that 20_{10} is 10100_2 .

2.5.3 Binary and Hexadecimal

For conversions between binary and hexadecimal I tend to use the table lookup method. After using it enough times you begin to memorize the conversions. In my head I'm usually converting from binary to decimal on each nibble and then converting decimal into hexadecimal. So if I see 0101 I remember it is 5 in decimal which is the same in hex. If I see 1010 I remember that it is $8 + 2 = 10$ which is one more than 9 so it is A in hex.

2.6 Colors

Colors for display on computers are represented as binary numbers. Colors are 24 bit which is broken down into 3 8 bit numbers representing red, green, and blue (RGB). Eight bits give values over the range of 0 to 255 so colors are represented by 3 numbers such as (255, 0, 255) which gives a **color like this**. It is good to note that (255, 255, 255) is white, (0, 0, 0) is black, and (X, X, X) where all three numbers are the same is gray.

Sometimes colors are represented as a 6 digit binary number in hexadecimal form prefixed by 0x such as 0xFF00FF for the color we looked at previously.

2.7 ASCII

Since computers operate using binary numbers, how do we get them to represent human languages? The method caught it is called **American Standard Code for Information Interchange (ASCII)**. Basically, 7 bit numbers were

mapped to letters, numbers, punctuation, symbols, and control characters. Some examples are A is 65, Z is 90, a is 97, z is 122, 0 is 48, 9 is 57. The most used control characters are carriage return (13 or `\r`) and line feed (10 or `\n`). Unix based operating systems (Linux, OS X) use line feed to indicate a new line. Windows uses both (`\r\n`).

Look up an ASCII table online when you need to know the values.

2.8 Assignment

There is a numbers quiz on Canvas as the assignment for this lab.

Chapter 3

Boolean Logic

3.1 Introduction

This chapter introduces some basic Boolean logic including gates and Boolean algebra.

How do you start a car? In the cars I have driven I have to press on the break at the same time as I turn the key. To say it another way, the car starts when I press the break AND turn the key.

$$pressBreak \text{ AND } turnKey = startedCar \quad (3.1)$$

Again on a car, a blinker will turn on if you turn on the turn signal or if you turn on the 4-way blinker.

$$turnSignal \text{ OR } 4wayBlinker = blinking \quad (3.2)$$

The AND and OR in the equation are Boolean operators.

3.2 Methods of Representing Logic

It is important to differentiate between different forms of representation because \overline{EN} means **active low** enable. It does not mean NOT(E AND N). The understanding of which method is being used is usually derived from context. Using the dot (\cdot) everywhere can become burdensome, so when context makes it obvious (usually examples involving A, B, and C or X and Y) we may drop the dots and just use adjacency to represent the AND function.

3.3 Boolean Algebra

3.3.1 Theorems of Boolean Algebra

Ways to show NOT:

$$\text{NOT}(X) = \overline{X} = X' \quad (3.3a)$$

$$\overline{\overline{X}} = (X')' = X \quad (3.3b)$$

Rules of AND and OR:

AND	OR	
$0 \cdot 0 = 0$	$1 + 1 = 1$	(3.4a)

$1 \cdot 1 = 1$	$0 + 0 = 0$	(3.4b)
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$0 \cdot 1 = 1 \cdot 0 = 0$	$1 + 0 = 0 + 1 = 1$	(3.4c)
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AND	OR	
$X \cdot 1 = X$	$X + 0 = X$	(3.5a)

$X \cdot 0 = 0$	$X + 1 = 1$	(3.5b)
-----------------	-------------	--------

$X \cdot X = X$	$X + X = X$	(3.5c)
-----------------	-------------	--------

$X \cdot \overline{X} = 0$	$X + \overline{X} = 1$	(3.5d)
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(3.5e)

3.4 Logic Gates

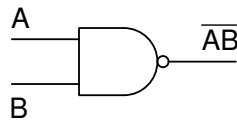


Figure 3.1: The NAND gate outputs NOT(A AND B).