

DESIGN YOUR OWN VIDEO GAME CONSOLE

**A BEGINNER'S GUIDE TO VIDEO GAME CONSOLE AND EMBEDDED
SYSTEM DESIGN, DEVELOPMENT, AND PROGRAMMING.**

André LaMothe

Nurve Networks LLC

Design Your Own Video Game Console

A Beginner's Guide to Video Game Console and Embedded System Design, Development, and Programming.

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Version & Support/Web Site

This document is valid with the following hardware, software and firmware versions:

- XGS Micro Edition 1.5 or greater.
- XGS Micro Studio IDE version 1.0.
- XGS ME Programmer Unit Firmware version 1.0.

The information herein will usually apply to newer versions but may not apply to older versions. Please contact Nurve Networks LLC for any questions you may have.

Visit www.xgamestation.com for downloads, support, the access to the XGS ME user community, and more!

For technical support, sales, or to ask questions, share feedback, please contact Nurve Networks LLC at:

support@nurve.net

Introduction

Thank you for purchasing the XGameStation™ Micro Edition! We have worked hard to provide a unique, high-quality, and educational product that will both engage and entertain. The XGameStation™ Micro Edition is the world's first do-it-yourself video game system and an empowering tool that will bring you an unprecedented level of knowledge and understanding, whether you're a hobbyist, student, or both.

This document is Chapter 1 from the work “***Design Your Own Video Game Console***”. We have broken the book up into separate documents, so that you might load and view it more easily with lower performance systems.

Installing the CD

The CD contains all the sources, schematics, tools, and content discussed in this document. There is no installer, simply work from the CD or drag the entire contents from the CD to your hard drive. Also, you may want to install one or more of the tools, especially **Labcenter's Proteus PCB Design Tools**, so you can look at the XGS ME designs in their native format.

Please read the README.TXT file at the root of the CD for any last minute instructions and changes. Also, each directory also has a README.TXT explaining the contents. The CD root for this content is laid out as follows:

```
XGSME_HW_CD <DIR> - The main directory/CD root for this content (may be within another
                    directory).
    |
    \Datasheets      <DIR> - Contains datasheets for all chips.
    \General_Papers  <DIR> - Contains articles, papers, on SX and XGS programming.
    \Schematics_Circuits <DIR> - Contains XGS schematics and circuits.
    \SX_Docs_Books   <DIR> - Contains SX related docs and eBooks.
    \SX_Key_IDE      <DIR> - Contains Parallax Inc.'s SX-Key Software.
    \Tools           <DIR> - Contains various tools for engineering.
    \TricksI         <DIR> - Contains a eBook version of "Tricks of the windows game
                          Programming Gurus" and all sources.
    \XGSME_Sources   <DIR> - Contains source code, demos, games.
    \XGSME_Studio    <DIR> - Contains complete XGS ME Studio Software and manual.
    \XGSME_Tutorials <DIR> - Contains tutorials on XGS ME programming.
```

WARNING! READ ONLY FLAG

This is a very important detail, so read on. When creating a CD ROM disk all the files will be written with the READ-ONLY flag enabled. This is fine in most cases unless you copy the files to your hard drive (which you will) and then edit and try to write the files back to disk. You will get a READ-ONLY protection error.

Fixing this is a snap. You simply need to clear the READ-ONLY flag on any files that you want to modify. There are 3 ways to do it. First, you can do it with Windows and simply navigate into the directory with the file you want to clear the READ-ONLY flag and then select the file, press the RIGHT mouse button to get the file properties and then clear the READ-ONLY flag and APPLY your changes. You can do this with more than one file at once by selecting a group of files.

The second way is to use the File Manager and perform a similar set of operations as in the example above. The third and best way is to the Shell command:

ATTRIB command with a DOS/Command Shell prompt. Here's how:

Assume you have copied the entire SOURCE directory on your hard drive to the location C:\SOURCE. To reset all the READ-ONLY attributes in one fell swoop you can use the ATTRIB command. Here is the syntax:

C:\DIRECTORY> ATTRIB -r *.* /s

This instructs the command shell to clear the READ-ONLY flag "r" from all files "*.*" and all lower sub-directories "/s".

Getting Started

Before reading this document and experimenting with the hardware and low level programming I highly recommend you read cover to cover the **XGameStation™ Micro Edition User Guide** which will help you become familiar with the tools, IDE, programming, debugging (if you have an SX-KEY), as well as other aspects of the XGS ME such as adjustments, troubleshooting, and so forth.

Viewing the Schematics

The XGameStation Micro Edition was designed using Labcenter's Proteus schematic entry and PCB layout tools. I consider these to be the best tools for the price and performance. If you wish to view any of the schematics for the XGS ME then you will need to install Proteus on your computer, you can find a copy of the installer in the **Tools** sub-directory. However, the latest version can always be downloaded from their site directly at:

<http://www.labcenter.co.uk/>

Dedication

I dedicate this book to the “big bang” without which none of this would be possible.

Acknowledgements

In no particular order the following people or companies helped with the development of the XGS and or this book in one way or another (even if they didn't realize it).

Special thanks to Future Electronic's Suzanne Lobue for all those samples, Tamim Hofioni and Ray Duran for the free classes on Altera FPGAs, Todd Mason for hand assembly contacts. Thanks to Absolute Turnkey's Michael Underbrink for the most professional execution of manufacturing one could ever want. Thanks to Digikey's Scott Fogarty for getting me good pricing on prototyping parts. Thanks to AllAmerican's Brian Batza for samples. Thanks to Nuhorizon's Mike Goode for samples and manufacturing contacts. Thanks to PCB Fab Express's Niles Parate for being flexible and providing excellent customer service and pricing. Thanks to David at PRWEB Special thanks to Parallax Inc.'s Ken and Chip Gracey for helping with XGS project in a direct way and parterning on large and small aspects of the project. you guys rock! Thanks to Iain of Labcenter Electronics for providing copies of Ares and Isis PCB development software, you saved me from having to crack Protel! Special thanks to Mac Ma and Patrick Ho of JJ Electronics and Assembly in Hong Kong for excellent manufacturing and business relations. Thanks to Todd at Excess Solutions for excellent pricing on bulk parts. Thanks to Mr. Andre' at Halted Specialties for excellent pricing on bulk parts. Thanks to Rusty at Dreamstation.cc for following the XGS project and releasing PR on a timely basis. Thanks to our new advertising partner Robin Lemieux at Nuts N Volts magazine. Thanks to our new advertising partner Sean Donnelly at Circuit Cellar Magazine. Thanks to Lisa Mason at Game Informer for the feature on the XGS. Thanks to Craig Pearson at PC Gamer UK for the feature on the XGS. Special thanks to Sellam Ismail of Vintage Tech for general help with the XGS in relation to obtaining "hard to get" retro items, loan of technology and equipment, and for finally realizing Windows is better than Linux :) Special thanks to David Perry of Shiny Entertainment for speaking at my game conference and for that wonderful letter of recommendation for the XGS. Special thanks to Mark Bell of BelmDesignGroup for the loan of photographic equipment, software, and duplication, and design work. Thanks Mike Perone of Barracuda Networks. Thanks to Lance Ringquist of Video 61 for selling us his precious stock to make sure that all customers have real Atari compatible joysticks. Special thanks to the "demo coder" team of Kieren Johnstone, Remi Veilleux, and Michael Ollanketo for creating the early demos for the XGS and making me realize I NEVER want to FedEx anything to Europe, I am still in debt :) Thanks to Josh Hintz for creating the XGS Digital Logic Kit. Thanks to Texas Instruments for product samples.



"DavidPerry - Recommended" is my personal stamp of approval awarded only to extremely key projects / games / books related to video game development. You can be CERTAIN that you will not see it often, and when you do, you should know that I highly recommend this product. I'm in no way affiliated with this hardware, and I've bought my own XGameStation unit.

I started developing games over 20 years ago, in high school. Back then we did all the programming, art, design, audio, testing etc. We did everything! It was fun and it's an incredible rush when you realize that you've taken complete control over the system you're developing for. The problem for me was that I had little-to-no help to learn, and I had to struggle constantly with very dodgy development systems. I just can't believe how lucky developers are today, with so many free tools on the Internet, so many books, so many classes in colleges popping up around the world, and now (thanks to Andre) you can even have your own personal development console at home! (Heck, he's even making a community for people to share their progress and what they learn!)

All I can say, is seize the opportunity, learn, try, network & enjoy! You will learn a lot about yourself and your abilities as you attempt to get a game going. You can bet that this machine alone will trigger some hiring, when game companies see just how passionate and dedicated and talented you are. This console will give you that chance to show your ability.

I predict Andre getting thank you letters in the future from people who not only realized they now love making games (via their XGameStation), but that ended up with a professional game making career!

My first professional job was for \$5,000 a year, in 2002 my company Shiny Entertainment sold for close to \$50 Million. Thank goodness I got started (even when the going was tough!) I would have KILLED to be where you are now!

If you've ever thought of making games professionally, and you want to stick a toe in the water, if you want to see how games get made, I can't think of a better way than this.

Some of you will thrive, some will fail.... For the ones that have the passion, I sincerely look forward to playing your games!

David Perry, 2004
President, Shiny Entertainment Inc.

Creators of "Earthworm Jim", "MDK" and "Enter the Matrix".

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Chapter 1

Introduction to Electronics, Electrons and Light Speed

In this chapter you are going to get a general overview of electronics and the fundamental laws and units that are used in the field. Many of the topics may seem quite alien to you, but don't worry about that -- alien is good. This chapter is just to get you started and give you a breadth of ideas and will probably be the largest and most technical chapter. The remainder of the book will of course clear each concept up in practice as we develop the XGS ME and related digital systems. At least that's the plan! The topics we cover in this chapter are:

- Introduction to Digital and Analog Electronics
- Electrons and Holes
- Units of Measure
- Current & Voltage
- Understanding Power
- Power Sources in Circuits
- Using Basic Test Equipment

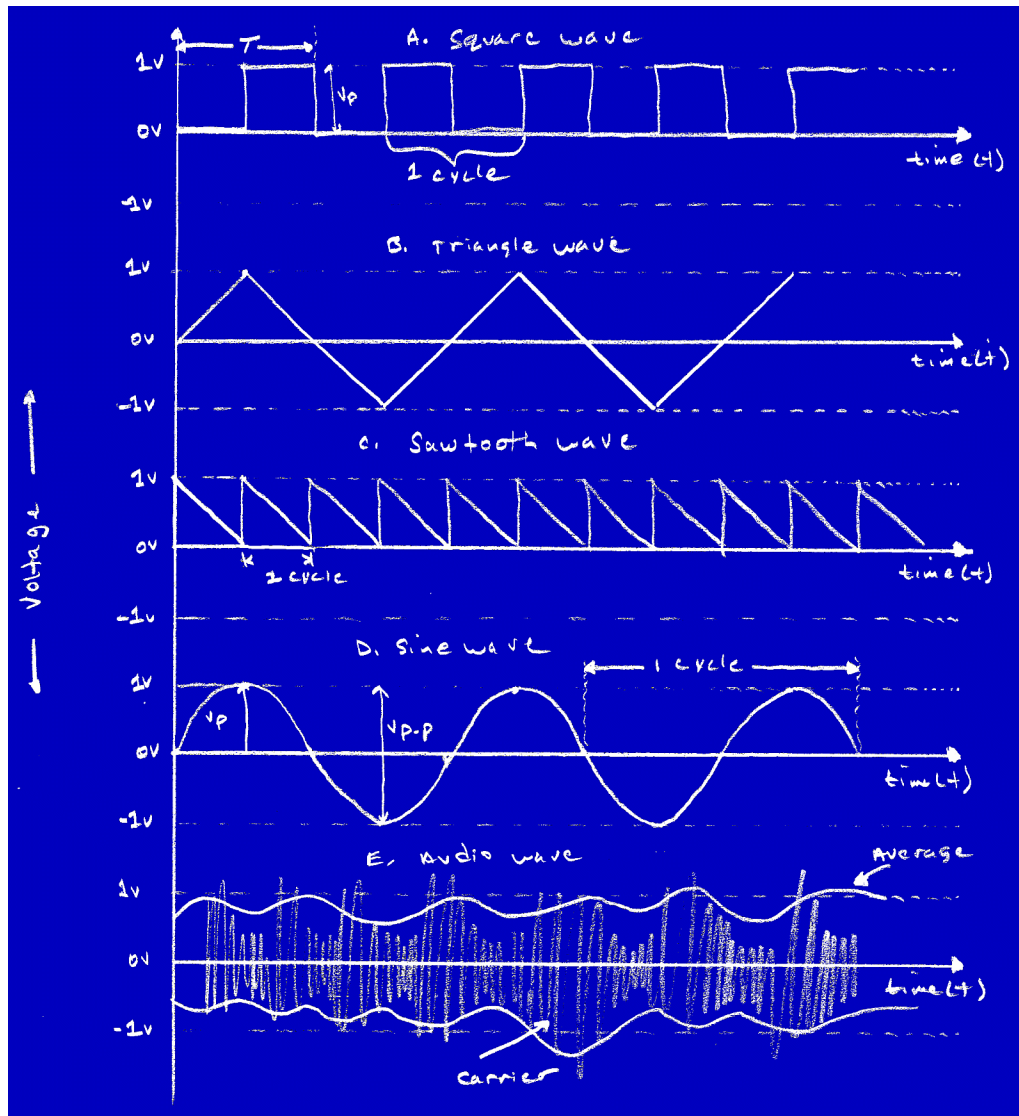
1.1 Introduction to Digital and Analog Electronics

The word **electronics** is derived from the word **electron** which is the sub-atomic particle that has negative charge. Thus electronics is the study of electrons in action, more specifically their properties in electrical circuits. More fundamentally though, electronics is based on electromagnetic wave theory which is the study of electromagnetic fields and their respective properties. However, electronics has simplified the field theory into manageable models that can be used to create circuits that perform various functions. Now, you have probably heard the terms; digital and analog electronics before, these are two different methods of modeling electrical circuits, but they are both based on the exact same laws.

1.1.1 Analog Electronics

Analog electronics is the study of electrical systems that process smoothly varying electrical signals. Some examples of analog devices are stereo amplifiers, older televisions, radios, power supplies, filters, and so forth. Figure 1.1 illustrates a number of analog signals as a function of time.

Figure 1.1 – Analog Signals as a Function of Time.



Analog electronics is really nothing more than understanding very complex laws about the properties of electrical current and its interaction with various electrical devices that perform various functions. The key to remember though is that the building blocks of analog electronics are very few. The major building blocks are:

Resistors	Resist current flow, drop voltages.
Capacitors	Store electrical charge.
Inductors/Coils	Store/transfer electromagnetic energy.
Diodes	Allow current to flow in one direction only.
Transistors	Used as amplifiers and switches.
Batteries	Sources of electrical current / voltage generators.

Wires

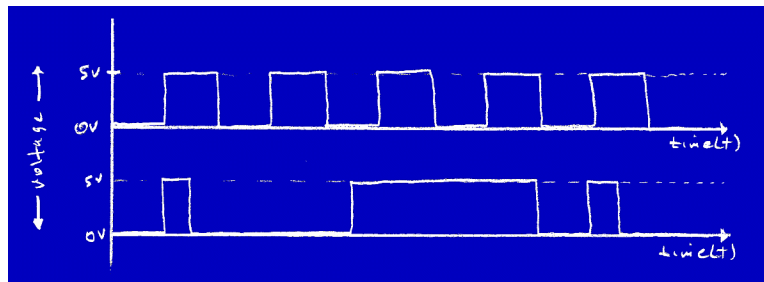
Used as conductors so that electrical current and signals can flow one electrical element to another.

Diodes and transistors are both based on semiconductors, but we will cover more about that and the other devices later in the chapter. Only in the 1960's and 1970's did digital electronics start gaining momentum, before then nearly everything was analog even computers!

1.1.2 Digital Electronics

Digital electronics are ultimately based on analog building blocks, but these building blocks have been encapsulated in chips (in most cases) and operate with only two states: **HIGH** (ON) and **LOW** (OFF). Figure 1.2 shows some digital signals. The beauty of digital electronics is no longer do you have to be a math guru to design circuits. Children can literally create digital systems very easily. Moreover, due to the building block nature of digital electronics in most cases you can completely forget about the electrical properties of the circuits and think of them as ideal virtual circuits.

Figure 1.2 – Digital Only Signals.



In reality, digital circuits are composed of many analog building blocks, but these parts are internal to each digital building block, hence, each digital component is a black box as far as we are concerned. Only when designing interfaces, or very high speed systems do you really have to worry about the electrical characteristics of the chips (which we are going to learn anyway). Some examples of digital systems are:

- Computers
- Calculators
- LCD watches
- Video game consoles (the most important!)

Additionally, more and more analog systems are being completely replaced with digital systems, including televisions. And systems that are inherently analog like audio amplification may be totally digital up to the final point where the digital data signal is converted into an analog signal that drives the speakers. The bottom line is the whole world is digital.

ADVANCED

TIP

There is another field of electronics which is referred to as ***mixed signal electronics***. This is the field that models the mixing of both types of electronics in complex systems. It is estimated that in the United States there are thousands if not tens of thousands of qualified digital engineers, but only a couple hundred analog experts, and I can probably count on my fingers the number of mixed signal experts – really hard stuff!

1.2 Units of Measure and Their Origins

Before we get started talking about real quantities, it's probably a good time to find a common ground for measurement of units. The system that is most widely used in the world of electronics is the **International System of Units** or the **SI** system. It's a mystery to me why the United States holds onto the incredibly aged and illogical English system, but thankfully we will use the "metric" system. I don't think I could handle it if I had to talk about mass units in the English system with slugs! In any case, let's start with the basics. The basic units of measure in the SI system are shown in Table 1.1.

Table 1.1 – Basic SI Units of Measure

Quantity	Name	Symbol	Fundamental Units
Time	Second	s	NA
Length	Meter	m	NA
Mass	Kilogram	kg	NA
Force	Newton	N	1 kg*m/s ²
Charge	Coulomb	C	6.24x10 ¹⁸ electrons
Energy	Joule	J	1 N*m
Current	Ampere	A	1 C/s
Voltage	Volt	V	1 J/C
Power	Watt	W	1 J/s

Most of these units should be familiar to you such as seconds, meters, kilograms, but the remaining units are a little less intuitive. Hence, let's take a look at them one by one. Force is measured in **newtons** named after **Sir Isaac Newton**. 1 newton (N) is equal to the amount of force needed to accelerate a mass of 1 kg to one meter per second per second or 1 m/s². The **coulomb** (C) is the standard measure of charge named after **Charles Augustin de Coulomb**. One coulomb is equal to 6.24x10¹⁸ electrons or put in another way, the charge of one electron is 1/6.24x10¹⁸ = 1.6021 x 10⁻¹⁹ C.

The **joule** (J) is a measure of work or energy, named after **James P. Joule**. One joule is the amount energy or work of a 1 N force applied for a 1 m distance. As you can see many of these concepts seem circular in nature. In reality, that's not the case, but when you are trying to define a concept as fundamental as energy, you end up using energy in the textual description, but if you stick to the units they tell the true story. Let's continue now to the units that interest us in the context of electrical circuits.

Electrical current is measured in **amperes** (A), named after the **Andre' Marie Ampere**. 1 A is equal to 1 C/s or the flow of 6.24x10¹⁸ electrons per second past a point of reference. The fundamental unit of electromotive force (the force that moves electrons) is named the **volt**, named after **Alessandro Volta**. Now, there are a couple ways to define a volt; voltage is the potential difference between two points in space. However, as you see, I have used the word to define itself, so we must defer to a more fundamental unit. A more fundamental way to describe a

volt is; if you were to move 1 coulomb of charge while expending 1 joule of energy between any two points in space then the potential difference is 1 volt.

ADVANCED

TIP

The definition of voltage is a bit counterintuitive though? How could the voltage between any two points in space be the same as long as the aforementioned premises are met? The reason is that the amount of work to move charge from one electro-potential to another is the same irrelevant of path. This is the basis of the definition of voltage.

The last unit of measure is the **watt**, which is a measure of power, named after **James Watt**. A watt is a measure of energy expended per second, amazingly enough the units are just that joules/second or 1 watt equals 1 J/s.

Many of these units still don't mean much to you since you have no experience with them. For example, if I ask you, "what's your mass in kilograms?". You probably couldn't answer. Similarly, you have no frame of reference for volts, amps, watts, and coulombs thus you have no "feel" for them, but you will get a better understanding of them as we go.

1.2.1 SI System Prefixes

The SI system also has a number of prefixes that can help you write large or small quantities in **scientific notation**.

MATH

Scientific notation is a standard way of writing numbers in mathematics. In scientific notation all numbers are written as powers of 10 in the form (mantissa x 10^{exp}). Where the *mantissa* is a number greater than or equal to 1.0 and *exp* is any positive or negative integer. For example, 35.0 would be written 3.5x10¹ and -0.002323 would be written as -2.323x10⁻³.

Table 1.2 lists some of the most common prefixes used in the SI system.

Table 1.2 – Common Prefixes in the SI System

Symbol	Prefix	Scaling Factor
a	atto	10 ⁻¹⁸
f	femto	10 ⁻¹⁵
p	pico	10 ⁻¹²
n	nano	10 ⁻⁹
μ	micro	10 ⁻⁶
m	milli	10 ⁻³
k	kilo	10 ³
M	mega	10 ⁶
G	giga	10 ⁹
T	tera	10 ¹²
P	peta	10 ¹⁵
E	exa	10 ¹⁸

Note: *there are other prefixes that are based on multiples of 100, but most commonly in electronics the multiples of 1000 or 10^3 are used.*

These prefixes are for convenience only, meaning you don't have to get carried away. For example, 50 volts would be written as 50V. Although, .05 kV (kilo volts) is equivalent, there's no point in using the prefix. Here are some examples of using the prefixes to write large and small numbers more compactly:

Example: 30000 watts

In pure scientific notation = 3.0×10^4 watts

Using the kilo (10^3) prefix = 30k watts or 30kW

Using the mega (10^6) prefix = .03M watts or .03MW

Example: .005 amps

In pure scientific notation = 5.0×10^{-3} amps

Using the milli (10^{-3}) prefix = 5.0m amps or 5ma

Using the micro (10^{-6}) prefix = 5000 μ amps or 5000 μ a

TIP

In most of the circuits discussed in this book current will be in the range of milliamps, voltage from 0-12 volts, and resistance in the k range.

1.3 Atomic Theory: Electrons and Holes

I can't think of any better place to start learning electronics than talking about what makes the whole thing tick – electrons and **holes** (the absence of electrons). To do this we need to talk about atoms.

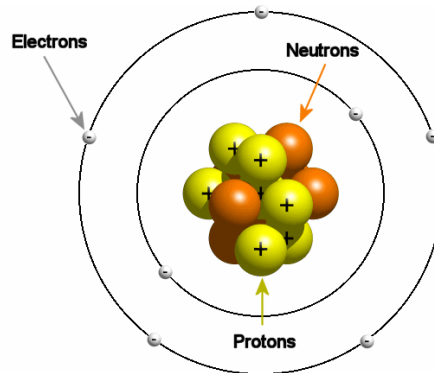
Now, we have come a long way since the original model of an atom, in fact, every time I turn around a new sub-atomic particle has been discovered, or a new theory about the nature of matter, energy, and space disturbs the world of physics. For example, **Super String Theory, M-Theory, Quantum Foam, Information Theory etc.** However, for our purposes the standard **Bohr Model** (based on the work of physicist **Niels Bohr**) will suffice.

1.3.1 The Bohr Model & The Periodic Table

The Bohr model of the atom states that an atom is composed of a number of **neutrons** (without charge) and **protons** (positively charged) that create the nucleus which is surrounded by a cloud of orbiting **electrons** (negatively charged). This model is shown in Figure 1.3. Basically neutrons and protons give atoms their mass, while electrons account for the electronic and chemical properties of atoms. The most accepted theory about electrons is that they exist in energy bands

or shells that “orbit” the nucleus. In reality, they don't really orbit, but the analogy suffices for our purpose.

Figure 1.3 – A Basic Model of the Atom.



In general there are about 106 (give or take some of the man-made elements that we don't find naturally occurring in the universe, but can be synthesized) elements that count for all the matter in the universe. The properties of each element are given in the standard periodic table (remember that?). Figure 1.4 depicts a standard periodic table with a number of elements highlighted that are of interest to electrical engineers.

Figure 1.4 – The Periodic Table.

GROUP
IA

1

H

Hydrogen
1.00794

IIA

2

He

Helium
4.00260

Solids

Liquids

Gases

Artificially Prepared

Atomic Number

Symbol

Name

Atomic Weight

26

Fe

Hydrogen

1.0079

1

2

3

4

5

6

7

PERIOD

11

12

13

14

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111

112

IIIA

IVA

VIA

VIIA

VIIIA

IB

IIB

IIIB

IVB

VB

VIB

VIIB

Li

Be

B

C

N

O

F

Ne

Na

Mg

Al

Si

P

S

Cl

Ar

K

Ca

Sc

Ti

V

Cr

Mn

Fe

Co

Ni

Cu

Zn

Ga

Ge

As

Se

Br

Kr

Rb

Sr

Y

Zr

Nb

Mo

Tc

Ru

Rh

Pd

Ag

Cd

In

Sn

Sb

Te

I

Xe

Cs

Ba

La

Ce

Pr

Nd

Pm

Sm

Eu

Gd

Tb

Dy

Ho

Er

Tm

Yb

Lu

Fr

Ra

Ac

Th

Pa

U

Np

Pu

Am

Cm

Bk

Cf

Es

Fm

Md

No

Lr

6.941

9.01218

10.811

12.0107

14.00674

15.9994

18.9984

20.1797

22.98977

24.3050

26.98154

28.0855

30.97376

32.06

35.4527

39.948

39.0983

40.078

44.95591

47.867

50.9415

51.9961

54.93805

55.845

58.9332

58.9334

63.546

65.39

69.723

72.61

74.9216

78.96

79.9047

83.80

85.4678

87.62

88.90585

91.224

92.90638

95.94

98.9062

101.07

102.9055

106.42

107.8662

112.411

114.818

118.710

121.760

127.60

126.90447

131.29

132.90545

137.327

138.90547

140.90765

140.90765

143.91019

144.24

150.36

151.964

157.25

158.92534

162.50

167.26

168.93421

173.04

175.10

176.48

178.49

180.9479

183.84

186.207

190.23

192.227

195.078

196.96655

200.59

204.3833

207.2

208.98038

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The green highlighted elements are commonly used to construct conductors, resistors, and semiconductors. Table 1.3 lists them for your reference. Note that this is a partial list, and the most commonly used, but there are many variations.

Table 1.3 – Some Important Electrical Engineering Elements

<i>Element Name</i>	<i>Symbol</i>	<i>Use</i>
Copper	Cu	Conductor
Silver	Ag	Conductor
Gold	Au	Conductor
Aluminum	Al	Conductor
Silicon	Si	Semiconductor
Cobalt	Co	Semiconductor N-type dopant
Phosphorous	P	Semiconductor P-type dopant
Carbon	C	Poor Conductor

Note: Copper, gold, and silver are all good conductors, and from the IB group/column of the periodic table.

The periodic table lists the elements in order of atomic number, and then grouped vertically based on the electron configuration of each element. Any given element (atom) has a number of **protons** which is also referred to as the **atomic number**. The number of protons is always equal to the number of electrons in a neutrally charged atom. The number of neutrons in an atom can be computed using the atomic weight (rounded to the nearest whole number) with the following formula:

Atomic weight = number of neutrons + number of protons.

Eg. Silicon has an atomic weight of 28.0855 with an atomic number of 14, therefore, we can write:

$$28 = \text{number of neutrons} + 14$$

Therefore the number of neutrons is 14 in Silicon.

The defining properties of each particle is listed below in Table 1.4 and highlighted in the Figure 1.3.

Table 1.4 – Properties of common sub-atomic particles

<i>Particle</i>	<i>Rest Mass</i>	<i>Charge</i>
Neutron	$m_n = 1.674 \times 10^{-27} \text{ kg}$	0
Proton	$m_p = 1.672 \times 10^{-27} \text{ kg}$	$e^+ = +1.602 \times 10^{-19} \text{ C}$
Electron	$m_e = 9.109 \times 10^{-31} \text{ kg}$	$e^- = -1.602 \times 10^{-19} \text{ C}$

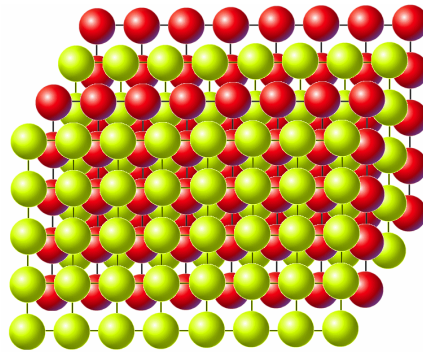
Some interesting things to note about neutrons, protons, and electrons: neutrons and protons have relatively the same mass, but an electron has roughly 1/1837th the mass of a proton, but has the same charge – weird huh?

1.3.2 Ions and Isotopes

If the number of protons or electrons in a neutral atom changes then the atom becomes charged and is referred to as **ion**. In most cases, atoms lose or gain electrons, not protons to become ions. If an atom loses a neutron then the atom is said to be an **isotope** of the original. For example, if you take carbon which has 6 neutrons and remove one of the neutrons then you have the isotope “carbon-11” or written with the proper notation: $^{11}_{6}\text{C}$, where 11 is the atomic mass written as a super-script and the atomic number 6 is written as a subscript. Interestingly, most isotopes have roughly the same properties as the original atoms. It's the ions that have wildly different properties than the neutral versions of the atoms since the charge is different. This is based on the fact that most of the chemical (and obviously the electrical) properties of matter are based on charge rather than mass.

The reason why all this atomic structure is important is that all electricity or current is nothing more than a flow of electrons from point **a** to point **b** via a conductor of some type. And understanding why and how electron current flows helps clarify other facets of electronics, so hang in there.

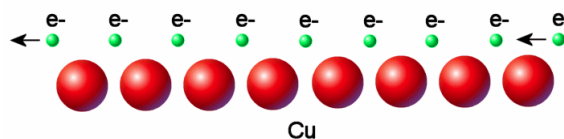
Figure 1.5 – A Matrix of Copper Atoms.



1.3.3 Conductors, Insulators, and Valence

The whole point of an electric circuit is to send signals from one point to another in an electrical network. These signals are electrical currents. But how and why do these currents work? Electrical current is the flow of electrons from one point to another. In a standard conductive material like a copper wire the matter that makes up copper wire is really a crystal lattice or matrix of copper (Cu) atoms as shown in Figure 1.5. The interesting thing about copper (Cu) and most metals is that they have unpaired (loose) electrons in their outermost shell, or what's called the valence shell. These loose electrons can very easily shift from one atom to another in the lattice and thus create an electron flow or current as shown in Figure 1.6. Hence copper (Cu) is a good conductor, as are many metals.

Figure 1.6 – Current Flow in Copper.



Insulators are just the opposite of conductors, the valence electrons are tightly bound and thus electrical current doesn't flow well at all. In most cases, good conductors are single elements, but insulators are usually composed of molecular compounds of two or more atoms like polymers, or even alloys.

Let's take a look more closely at conductance. Back in the previous section, you learned that electrons populate various "shells" or energy level orbitals around the nucleus of the atom. This is key to understanding conductance. Let's go into some detail about shells which should help with the puzzle.

Each electron orbital shell can only hold so many electrons based on the theories of quantum mechanics which we will trust. Moreover, electrons like to be paired with other electrons (it's like a buddy system), again this is based on quantum mechanics, but it's due to the fact that electrons have a spin and a clockwise spinning electron always wants to be paired with a counterclockwise spinning partner. In any case, the electron orbital shells have names. They are:

1s, 2s, 2p, 3s, 3p, 3d, 4s, 4p, 4d, 4f, 5s, 5p, 5d, 5f, 6s, 6p, 6d, 7s, 7p

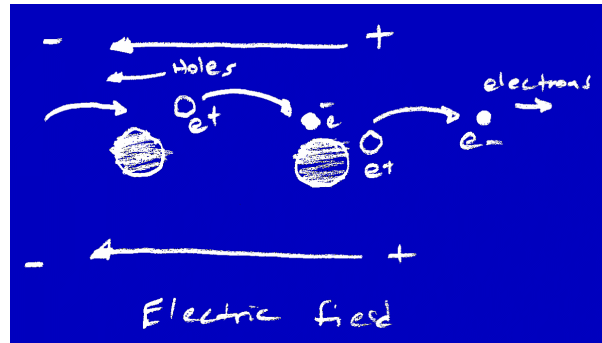
And each can hold a various number of electrons. For example, here are some electronic configurations for some common elements:

Table 1.5 – Electronic Configurations for Various Elements

<i>Element</i>	<i>Name</i>	<i># Electrons</i>	<i>Shell Configuration</i>
H	Hydrogen	1	1s ¹
He	Helium	2	1s ²
Li	Lithium	3	1s ² 2s ¹
.			
.			
C	Carbon	6	1s ² 2s ² 2p ²
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.			
Si	Silicon	14	1s ² 2s ² 2p ⁶ 3s ² 3p ²
Cu	Copper	29	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ¹

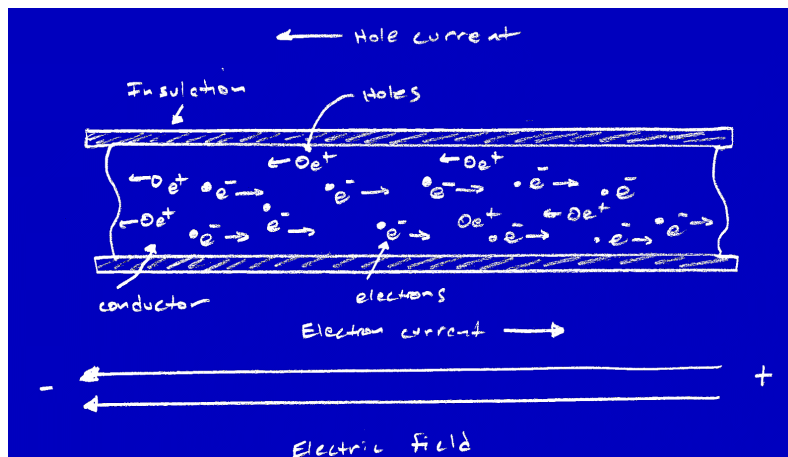
The exact mechanics of the shells filling are beyond the scope of this text, but that doesn't really concern us. All we really care about is the end results and the configuration of the electrons in the outermost or valence shell. This is what gives a conductor the property of a conductor and an insulator the property of an insulator.

Figure 1.7 – General Current Flow in a Conductor with an Electric Field Applied.



If you take any metal and apply a voltage to it, what you are really doing is applying an electric field to the metal. This electric field causes the loose valence electrons in the outer shells of the crystal lattice that makes up the piece of metal to move or shift from one position to another. This shifting is electron current. This is shown in Figure 1.7. However, there's an interesting side effect caused by the flow of electrons from atom to atom. As an electron moves from one atom to another, it leaves a "hole" momentarily. Hence, if we apply an electric field, that is a voltage, this voltage causes electrons (negative charges) to move in one direction and holes (positive charges) to move in the other.

Figure 1.8 – An X-ray View of a Simple Circuit Showing Electron and Hole Currents.



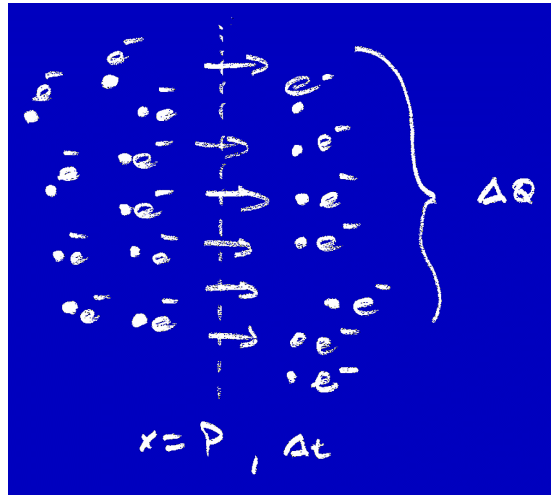
Of course, holes don't really exist, but perceptually they do, they are the lack of electrons. I'm going to get ahead of myself here a second to show you something. If you look at Figure 1.8, we see a piece of wire that a voltage is being applied to creating a circuit. The voltage is positive on the left and negative on the right. As drawn, electrons will move from negative to positive, and holes will move from positive to negative. The electron flow is called **electron current** and the hole flow is called **conventional current**. We will use conventional current in this book since it is easier to work with due to less sign problems. But, remember it's just a convention, in reality electrons are always moving from negative to positive.

1.4 Current & Voltage

Up to this point we have been looking at current as a very fundamental atomic concept, now that you have the underlying theory about what current is, it's time to abstract current somewhat, so

we can start to get some real work out of it. With that in mind, now we are going to forget about the atomic underpinnings of current and think of it simply as the motion of charges.

Figure 1.9 – Measuring Current.



1.4.1 Current Defined

Referring to Figure 1.9, the amount of charge q (electrons) that pass point p as a function of time defines the current. Or mathematically, current is equal to the amount of charge per unit time:

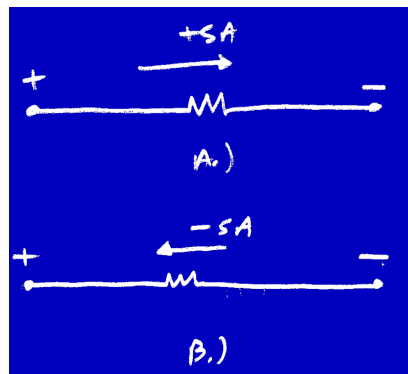
Equation 1.1: Definition of current.

$$i = dq/dt$$

MATH The notation dq and dt are read “**delta q**” and “**delta t**”, simply meaning the change in q and the change in t , this dq/dt is the change in q with respect to t .

That probably doesn't mean much without some point of reference or metric to scale it by, so here's an example: 1 C (coulomb) of charge per second or 1 C/s is equivalent to 1 ampere.

Figure 1.10 – Labeling Current Flow.



Now, in general, we like to talk about **conventional current** or **positive hole** flow. So the convention is that when you see a current indicated in a circuit there is both an arrow showing its direction along with a value for the current with a sign. For example, Figure 1.10 depicts two currents that are exactly identical. In Figure 1.10a the current flows from left to right and has a value of 5 A, on the other hand, the current in Figure 1.10b is flowing in the opposite direction, but has a value of -5 A. Hence, the two currents are the same.

NOTE	You can always switch the sign of a current as long as you switch the direction of a current. The resulting current will algebraically be the same in all circuit analysis. The bottom line is that we will think of current as a mathematical concept now rather than a flow of electrons. In the next section we'll get into detail on how currents are generated, but right now, let's take a look at some examples of various currents to give you an idea of scale. This is very important in electronics since if you have no idea how much is a little or a lot, when you do calculations, you won't see blatant errors of scale. Table 1.6 lists some electronic/electromechanical devices and their average current needs.
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Table 1.6 – Devices and their rough current needs.

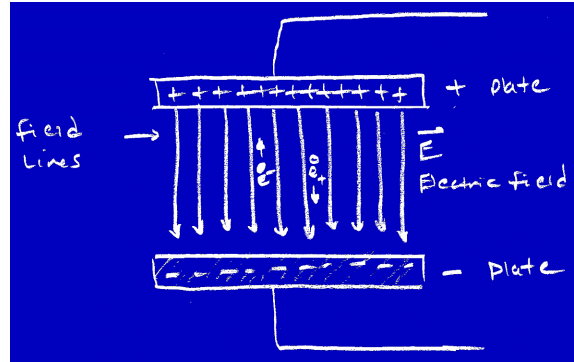
<i>Device/System</i>	<i>Average Current Drain</i>
Single Gate in a uProcessor	10nA
Light Emitting Diode	20mA
Digital TTL Chip	30mA
Single Gate in TTL Chip	5mA
LCD Calculator	50mA
27" Television	2A
Personal Computer	5A
Hairdryer	10A

From Table 1.6 you can see that as the transition from basic electronic component to larger system the current goes up quite a bit. But this table is also a sanity check for you. If you are doing calculations on the design of a digital circuit and you are getting currents of 10 - 20A then you are definitely doing something wrong! But, if you answers are in micro ampere to milli ampere range then that's about right. Conversely, if you want to design a TV then expect a couple amps of current to be needed.

1.4.2 Voltage Uncovered

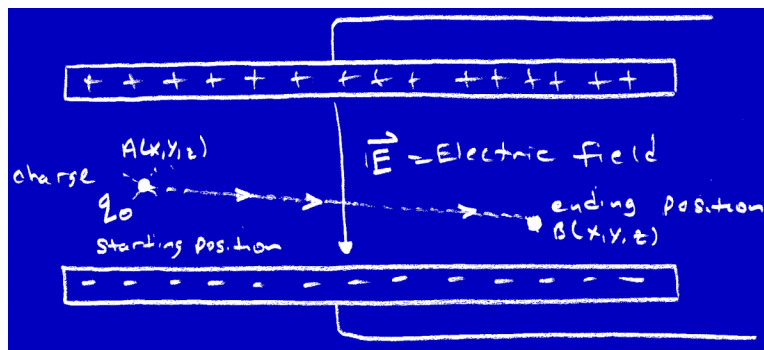
I have mentioned voltage a few times now, and you probably have some idea of what it does, but you still don't know exactly what it is or how it's generated. Voltage is really a manifestation of the **electric field**. But what's an electric field?

Figure 1.11 – An Electric Field Between two Conductive Plates.



Every single charge in the universe creates an electric field, when you place a number of charges together they create an electric field that is the sum of the individual electric fields. Figure 1.11 depicts an electric field set up by two charged plates separated by a distance d . If you take a single electron and move it around in the electric field, you will have to do work to accomplish this task. Moreover, if you were to just drop the electron into the field, the electron would feel a force and be accelerated. This force would be proportional to the electric field. The bottom line is that an electric field can do work on a charge or moving a charge in an electric field takes work or uses energy.

Figure 1.12 – Moving a Charge in an Electric Field.



Given that a charge q_0 is positioned in an electric field E and we want to move it from point a to b as shown in Figure 1.12 we are going to change the charge's "**potential energy**" by this motion. Potential energy is referred to as U . This is the basis of voltage.

Voltage is the potential energy per unit charge or mathematically:

Equation 1.2: Definition of voltage.

$$V = U/q_0$$

Therefore, the difference in voltage from one point to another is:

Equation 1.3: Change in potential.

$$\text{Change in } V = dV = dU/q_0$$

Since potential energy is a form of energy it is measured in joules, and the charge q is of course represented by **coulombs**, therefore, 1 volt is defined as:

Equation 1.4: Units of voltage.

$$1 \text{ V} = 1 \text{ J} / 1 \text{ C}$$

What this says is that 1 J of energy must be used to move 1 C of charge through a potential difference or voltage of 1 V. And that's voltage!

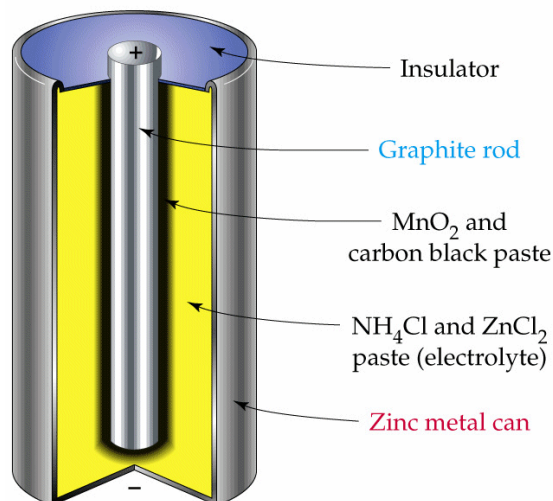
1.4.3 Generating Voltage

There are a number of ways to generate voltages, but most are based on three general principles: **chemicals**, **magnetic fields**, and the **photo-electric effect**. Let's begin with chemical batteries.

1.4.3.1 Chemical Batteries

Batteries are devices that use chemicals (dry or wet) to create an accumulation of charge and hence a voltage. Figure 1.13 depicts a standard dry cell.

Figure 1.13 – A Standard Dry Cell Battery.

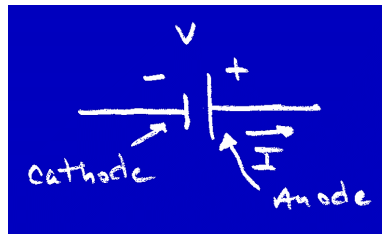


The dry cell battery is the most common battery that you are probably familiar with. It generates a voltage of about 1.5 volts (actually a little less). Referring to Figure 1.13, you see that the dry cell is made of a positive center rod or electrode that is composed of graphite (which is nothing more than carbon). The contents of the cell are composed of a paste mixture of ammonium chloride (NH_4Cl), manganese dioxide (MnO_2), and zinc chloride (ZnCl_2). The casing of the cell is also made of zinc (Zn) and acts as the negative anode.

The battery works on the principle of **oxidation-reduction**, which is beyond the scope of this text. But, in brief there is a chemical reaction whereby the zinc casing oxidizes giving off electrons which are “**reduced**” or absorbed by the cell and the +electrode (cathode) creating a voltage difference of around 1.5 volts.

Of course, many different types of dry and wet (eg. car battery) chemical cells can be created with various elements for the desired properties – high voltage, high current, long life, re-chargeability, temperature invariance, and so forth. However, most batteries are of the zinc chloride, Lithium, or Nickel-Cadmium (rechargeable) design. There are even exotic “fuel cells” based on hydrogen-oxygen reactions that are used in space craft and new experimental hydrogen powered cars.

Figure 1.14 – The Symbol for a Battery.

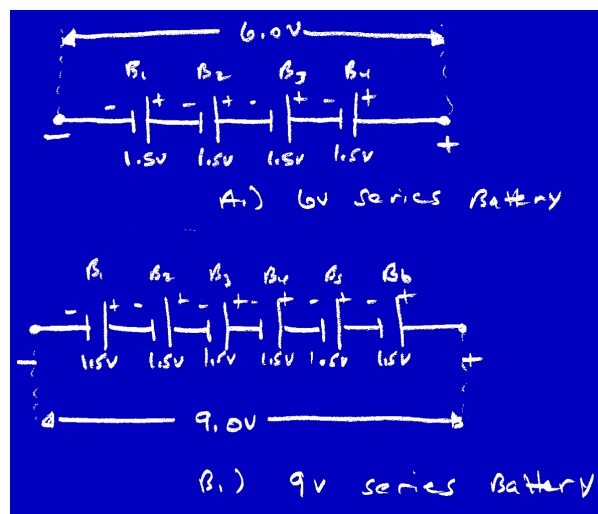


The basic battery or voltaic cell is represented by two parallel lines as shown in Figure 1.14. The short line is always the cathode or negative terminal and the long line is the anode or positive terminal. Additionally, you can place cells in series or parallel. Let's take a look at that now.

1.4.3.1.1 Increasing the Voltage - Series Cells

If you place a number of batteries or cells in series with one another in anode-cathode order then the voltage of the resulting power source is the sum of the individual cells (remember conventional current flows from the positive terminal to the negative terminal). For example if you take a look at Figure 1.15 you see a 6V and 9V power source built up by putting (4) 1.5V cell batteries in series and (6) 1.5V batteries in series to arrive at 6V and 9V respectively.

Figure 1.15 – Connecting Batteries in Series.



WARNING!

Never place chemical batteries in series in such a way that the current flow from one battery will flow in the opposite direction of another this can cause the batteries to be damaged, overheat, or in the very extreme case – explode!

1.4.3.1.2 Increasing the Current - Parallel Cells

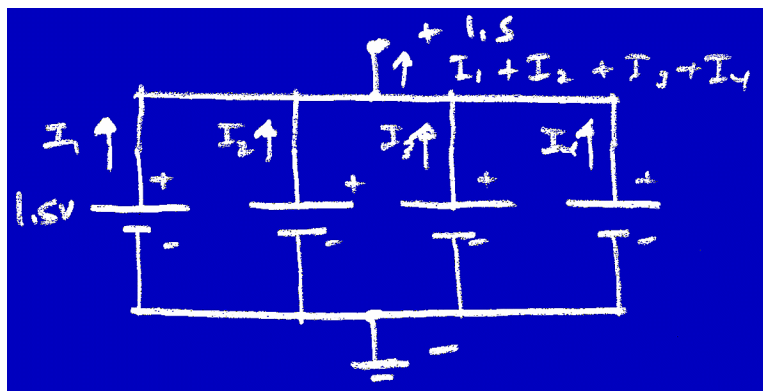
A battery is a source of voltage or a potential if you will. However, all batteries have a finite amount of current that they can provide before the battery voltage starts fluctuating and/or falling to zero (this is based on the rate of the oxidation-reduction reaction and the internal resistance of the battery). In general, your standard household AAA, AA, C, D, 9V, and watch cells as shown in Figure 1.16 can provide tens of milliamps (AAA cell) to hundreds of milliamps (D cell) without a problem. However, within some given amount of time, the chemicals in the battery will deplete and the cell(s) will die. This lifetime is usually measured in milliamp hours or **MAH**.

Figure 1.16 – Standard Household Batteries.



For example, if a 1.5 V battery is rated for 100 MAH then the battery can supply 100 mA for 1 hour at the given voltage of 1.5V before the battery starts to die or deplete and the voltage drops. The question you might have is; how to increase the current capability of a battery based power supply? The answer is to put the cells into parallel by connecting each cathode to cathode (+ to +) and anode to anode (- to -) as shown in Figure 1.17.

Figure 1.17 – Parallel Battery Connections to Increase Current Drive.



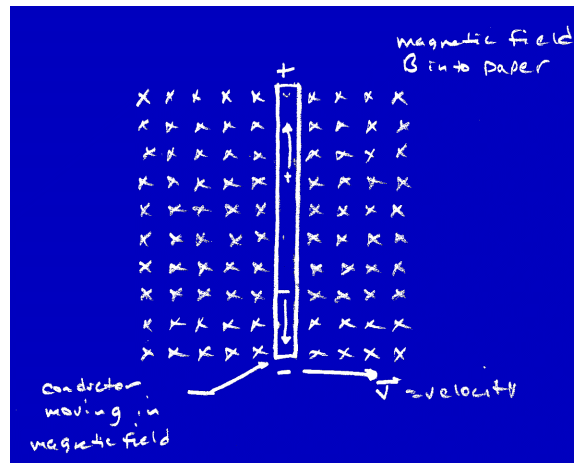
Referring to Figure 1.17, you see a power source with a voltage of 1.5V but with a current capability of 4 times the current supply of a single cell or a 4 times longer mAH rating of single cell. Now, the first thing you might exclaim is that I just warned you about putting cells anode-anode or cathode to cathode? And I did! But, that's only if the direction of current isn't the same for all cells. As long as the voltage of each cell is the same polarity then the cells connected in parallel will still act like a single cell where current from each cell will still flow from the positive terminal of each. Except with the property that each cell will supply a fraction of the total current. Hence, in Figure 1.17, if you were to drain 100mA from the then each cell would supply approximately 25ma, but the voltage stays the same.

NOTE Although we have been talking about using batteries as power sources for increasing the current and voltage in a circuit the principle is the same for all power sources in general. That is if you put voltaic power sources in series then the voltage increases, if you put them in parallel then the current driving ability increases.

1.4.4 Generating Voltage with Magnetic Fields

The other primary method of generating an electrical current or voltage is by means of a magnetic field based on Michael Faraday's **law of induction**. It states that when a conductor is passed through a magnetic field a current is generated in the conductor or if a stationary conductor is placed in a changing magnetic field the same will occur.

Figure 1.18 – Electromagnetic Induction.

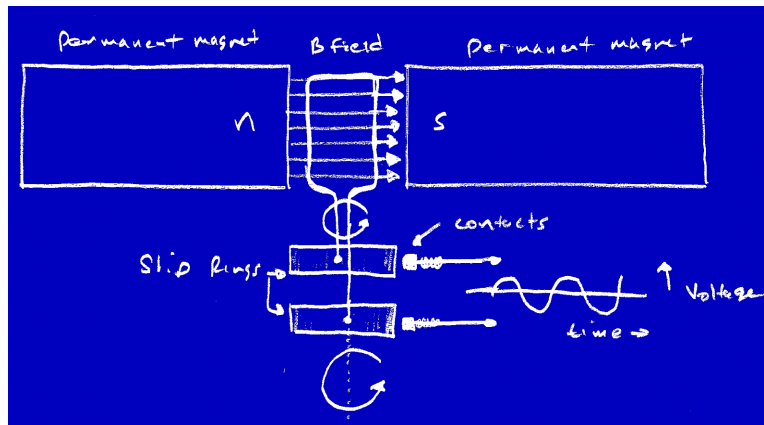


Take a look at Figure 1.18 to see this graphically. A magnetic field B (created with a permanent or electro-magnet) is directed into the paper, as the conductor moves in the constant magnetic field, the free electrons in the conductor will feel a force. This force will cause them to migrate toward the bottom end of the conductor and the net charge at the top of the conductor will become positive due to this migration. This effect is called **electromagnetic induction** and the result is a potential difference in the conductor, and hence a voltage.

This effect is the basis of the majority of all power stations in the world. No matter what kind of power station; wind, hydroelectric, nuclear. The mechanical, and or thermal energy is converted into electrical energy by means of a generator based on electromagnetic induction.

For example, most nuclear power plants today use nuclear **fission** (tomorrow they might use fusion), the results of the fission process are a neutron flux, a by product isotope of uranium, and lots of **heat**. The heat is the key. The heat is used to create steam, which turns turbines that are mechanically connected to the generators with fixed magnetic fields. As the turbines turn the generators, the coils in the generator cut through magnetic fields in the generator creating a voltage as shown in Figure 1.19.

Figure 1.19 – Basic Generator Design Used to Create Power.



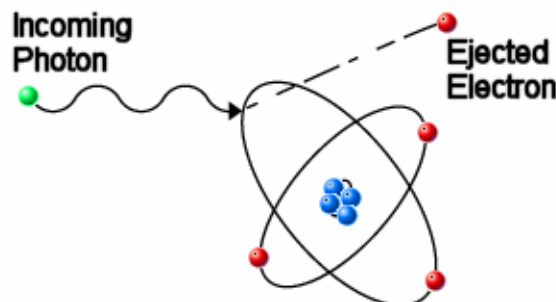
As another example, wind is used to turn giant propellers that are directly connected to generators. And in hydroelectric plants water rushing through gates from high pressure or altitude zones turns turbines that are once again connected to generators.

Even your car uses a generator to turn the chemical and mechanical energy of the internal combustion engine into electrical current. The gasoline is a chemical fuel that is converted into mechanical energy and heat during combustion (at a horrific 60% efficiency if that). Some of the mechanical energy is converted into electrical by means of a generator (or alternator) connected to the main crankshaft of the engine and the mechanical-rotational work is converted into an electrical current for the car to use.

1.4.5 The Photoelectric Effect

The last common method of creating an electrical current that you should be aware of is based on the **photoelectric effect**. This is the premise of how solar cells work. Referring to Figure 1.20, the photoelectric effect occurs when photons of light hit a surface (composed of certain kinds of materials) and cause the electrons in the surface matter to become excited to the point that they are ejected out of orbit and fall onto a **collector** causing a current flow.

Figure 1.20 – The Photoelectric Effect.



The explanation of the process is due to **Albert Einstein** and is simply this: photons can be thought of as particles just as electrons. If a photon of enough energy strikes an electron then the electron's kinetic energy increases enough to cause it to jump out of orbit and onto the other plate

causing a current flow. This minimal energy is referred to as the **work function** or **work energy** of the electron and usually is a few electron volts. Of course, different metals/materials have different work functions. Hence, you can design a photoelectric or solar cell based on this effect.

However, the interesting thing about the photoelectric effect is that it's not the intensity of light, but the **frequency** of light that matters. This is due to **Planks Law** for energy of a photon:

Equation 1.5: Plank's Law.

$$\text{Energy in electron volts eV} = h \cdot f = h \cdot (c/\lambda)$$

Where: h is Plank's constant = 6.626×10^{-34} J*s

c is the speed of light = 3.0×10^8 m/s

f is the frequency in hertz of the light

λ (lambda) is the wavelength of light

For a photoelectric cell to work, the photons of light must have the correct frequency and hence energy that at least matches the work function of the material. If the frequency of light (of each photon to be exact) isn't greater than or equal to the minimum energy to eject an electron, no current will be generated no matter what the photon intensity.

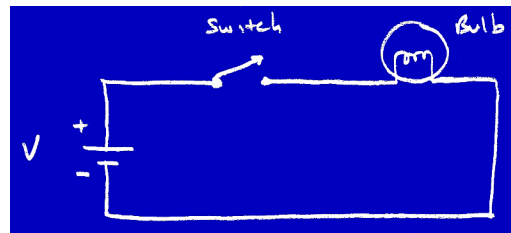
1.5 Alternating and Direct Current

Up to this point, we really haven't been too specific about the difference between **alternating current** (AC) and **direct current** (DC). My reasoning is that there is no difference between them as far as the physics and math goes. AC is simply a current or voltage that changes as a function of time, and DC doesn't. That's all there is to it. However, working with AC and DC circuits are two completely different things since when current or voltage changes as a function of time it's just one more variable or degree of freedom to deal with. Moreover, other physical effects start to manifest when current or voltage changes over time. But, we'll get to some of those effects later in the chapter. For now, let's just talk about AC/DC and understand what the terms mean.

1.5.1 Direct Current/Voltage

Direct current really has a misleading name. There's nothing direct or indirect, it simply means that the voltage and hence the current in a circuit is always flowing in the same direction. The current may fluctuate based on the power consumption of the circuit, but the main voltage supply stays constant at some value. For example, take a look at Figure 1.21, it depicts a very common DC circuit – a flashlight. Here you see the power source, a battery (which is inherently DC), a switch, and a light bulb. When the switch is closed, then current can flow, the light bulb lights and the circuit is DC.

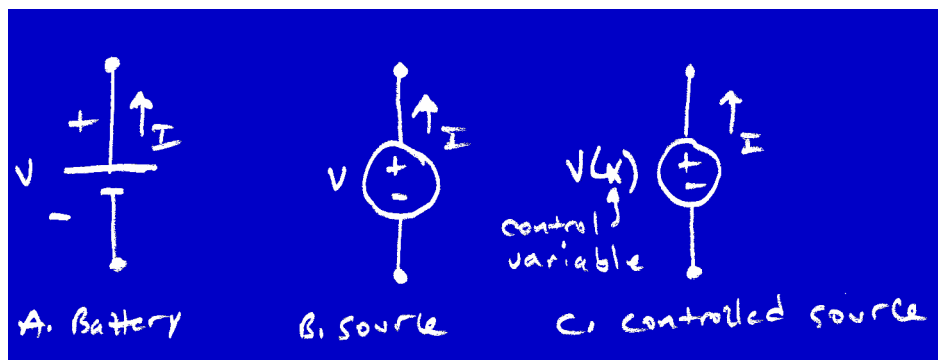
Figure 1.21 – A DC Flashlight Circuit.



NOTE

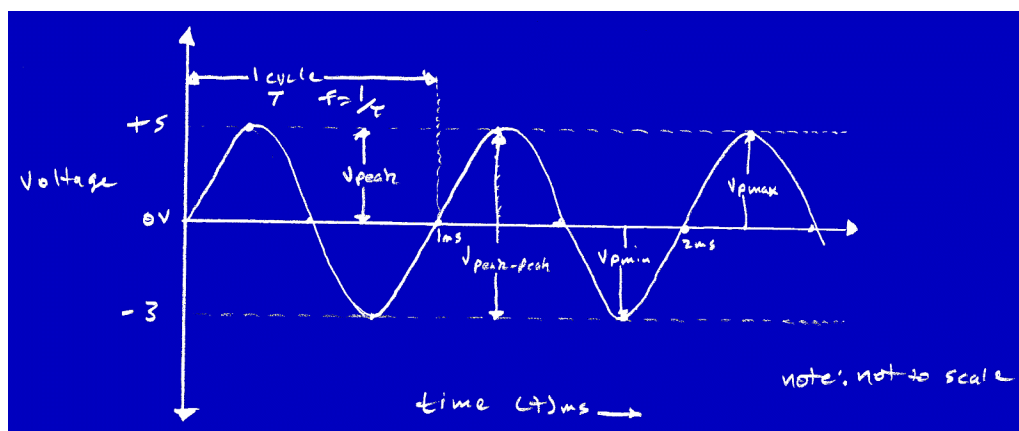
All digital circuits are powered by DC sources. However, the circuits themselves have fluctuating voltages and currents due to the switching nature of digital circuits. And hence you might think that digital circuits are AC, but they are not per se since current is always flowing in one direction, although it might drop to zero. Therefore, when we talk about AC/DC we are usually referring to the power supply and the basic mode of operation of the circuit.

Figure 1.22 – DC Voltage Symbols.



DC sources are usually represented by the symbols in Figure 1.22 along with a value and direction of current flow. Additionally, DC sources can be variable, in this case they are a function of another circuit element. In this case, instead of a specific voltage identifying them, the DC voltage source will have a variable next to it that is called the “**controller**”.

Figure 1.23 – A Voltage as a Function of Time.



1.5.2 Alternating Current / Voltage

Alternating current or voltage means that the supply source is changing as a function of time. Figure 1.23 shows a sinusoidal alternating voltage as a function of time. There are a number of values that we can discuss when referring to AC signals; **frequency**, **peak value**, **peak to peak value**, and **root-mean-square** (RMS) value.

The **frequency** of the signal is the number of complete cycles per second. In Figure 1.23 the signal is a pure sine wave, so computing the frequency is as simple as looking how much time it takes for one complete sine wave (the period T) and then taking the inverse. Referring to Figure 1.23, we see that it takes 1 ms for a cycle, therefore:

Equation 1.6: Frequency of a signal.

$$\text{frequency} = 1/T = 1/1 \text{ ms} = 1000 \text{ Hz.}$$

Additionally, we can talk about the **peak** values and **peak to peak** (V_{p-p}) values of the signal. The peak values are the values of each peak of the voltage, both positive (V_{pmax}) and negative (V_{pmin}) going. In this case, the voltage has a positive peak of 5 volts and a negative peak of -3 volts. Additionally, the peak to peak voltage is the total stride or change in voltage, or mathematically:

Equation 1.7: Peak to peak voltage.

$$V_{p-p} = V_{pmax} - V_{pmin}.$$

In the example above, the peak to peak voltage would be $5V - (-3V) = 8V$.

Finally, when talking about power systems and AC, the peak and peak to peak values of the voltage aren't enough information since the shape of the wave form has a lot to do with the "average" voltage at any time. Hence, a value called the **root-mean-square** or **RMS** is used to refer to AC voltage in many cases. The RMS value is computed by squaring the value of the voltage, so that all negatives become positive, then taking the average, and finally taking the square root of the result. The RMS voltage of a sinusoidal power source can be computed as follows:

Equation 1.8: Root-mean-square voltage.

$$V_{rms} = 0.5 * V_{p-p} / \text{sqrt}(2) = 0.5 * V_{p-p} * .707$$

For example, the voltage supplied by your standard 120V 60Hz wall socket is really 120 V RMS. What is the V_{p-p} value? To compute the V_{p-p} value, we can use the equation in reverse:

$$\text{Given: } V_{rms} = 0.5 * V_{p-p} / \text{sqrt}(2)$$

$$\text{Then: } V_{p-p} = 2 * V_{rms} * \text{sqrt}(2) = 2 * 120 * 1.414 = 339.4V$$

Additionally, if the sine wave is symmetrical, or in other words the magnitude of the positive peak is the same as the magnitude of the negative peak then both the positive and negative values V_{pmax} and V_{pmin} are the same (except for sign) and can be computed with the formula:

Equation 1.9: Voltage peak value.

$$V_{pmax|pmin} = |0.5 * V_{p-p}|$$

Which in this case equals $0.5 \times 339.4V = 169.7V$. Hence the positive peak V_{pmax} is 169.7V and the negative peak V_{pmin} is

−169.7V.

Luckily for us, we won't be doing much with AC signals and analysis since digital circuitry works with DC power supplies. However, knowing something about AC is important even when working with digital electronics since the digital electronics have to be powered by AC lines that must be converted to DC.

1.6 OHM'S Law and Power

Although, we haven't talked about how to compute current, voltage, and resistance in circuit elements, I'm going to skip ahead for a bit to show you one equation referred to as **Ohms Law** derived by **Georg Simon Ohm** in the 1800's. Ohms Law is a relationship between current, voltage, and resistance in a circuit element. If you know two of them, you can compute the third from Ohms law. Here's the formula:

Equation 1.10: Ohms Law

$$\text{voltage} = \text{current} * \text{resistance}$$

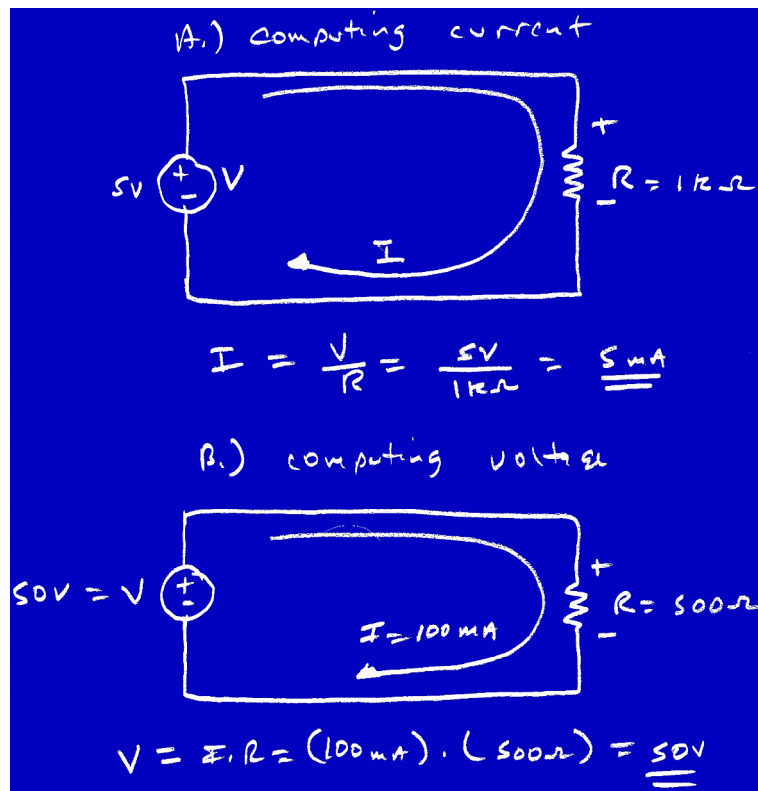
or using the symbols for voltage, current, and resistance, we have:

$$V = I * R$$

And we can re-arrange to get relationships for I and R directly.

$$I = V/R \text{ and } R = V/I$$

Figure 1.24 – Using Ohms Law on Simple Circuits.



TIP

This is one of the most important formulas in electronics to remember and we will use it continuously.

Example 1.1 – Computing Current in a Circuit.

As an example, take a look at the circuit in Figure 1.24, here we see a power source that is supplying 5V to a resistor of 1K Ω . Hence the entire voltage of 5V drops over the resistor. The question is what's the current in the circuit?

We know voltage and resistance, so we just plug them into the formula:

$$V=5V, R=1K \Omega, I=?$$

$$I=V/R, I=5V/1K \Omega = 5.0 \times 10^{-3}A \text{ or } 5mA$$

Example 1.2 – Computing Voltage in a Circuit.

As another example, take a look at the circuit in Figure 1.24(b), here we see a power source that is supplying 100mA to a resistor of 500 Ω . Since all the current is flowing through the resistor we know that $I=100ma$ and we know that $R=500\Omega$. Again, we can use Ohms Law to compute the voltage drop:

$$V=?, R=500 \Omega, I=100mA$$

$$V=I \cdot R, V=100ma \cdot 500 \Omega = 50V$$

Of course, you may be a little bewildered about the rules of how current and voltage interacts in a circuit. In these examples, it looks like current stays the same in a circuit, but voltage can change? This is in the ballpark, but we will nail it down in following chapters. I just wanted you to be able to do the calculation on a single device level, so I can show you a couple more examples later in the chapter.

1.6.1 Understanding Power

The next topic of discussion is **power**. Power is another fairly abstract concept in electronics and in real life, for example who's more powerful **Pikachu** or **Squirtle**? We may never know. Loosely defined power is the ability to "**do work**". Power in the context of electronics means the amount of energy (w) absorbed or produced by an element as a function of time t .

To construct a formula for power we can use the following derivation: the amount of work or energy that a circuit element absorbs or produces as a function of time is related to the amount of charge q that passes through the element due to the voltage V across the element:

Equation 1.11: Definition of power.

$$dw = V \cdot dq/dt$$

This states that the change in energy (work) per unit time is equal to the voltage multiplied by the rate change of charge with respect to time. But, if you recall, dq/dt is equal to current i . Hence, dw can be written:

Equation 1.12: Power in terms of voltage and current.

$$dw = V \cdot dq/dt = V \cdot I = P$$

And that's power, which we usually call P .

This is a very important equation. It tells us what the instantaneous power is given that a circuit element is absorbing or producing a current i with a voltage v . This leads us to the concept of a power **source** or **sink**.

Figure 1.25 – Elements and their Power.

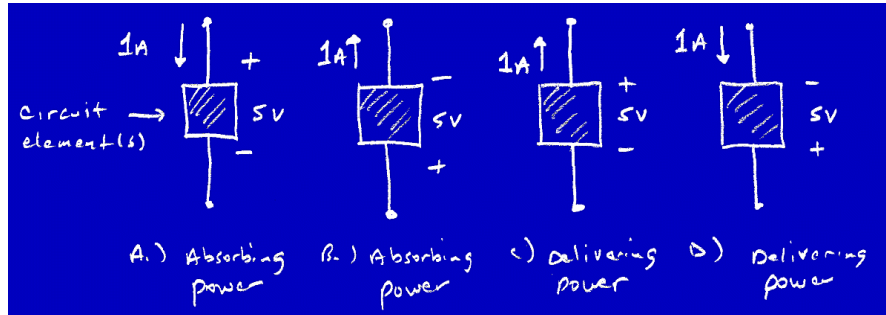
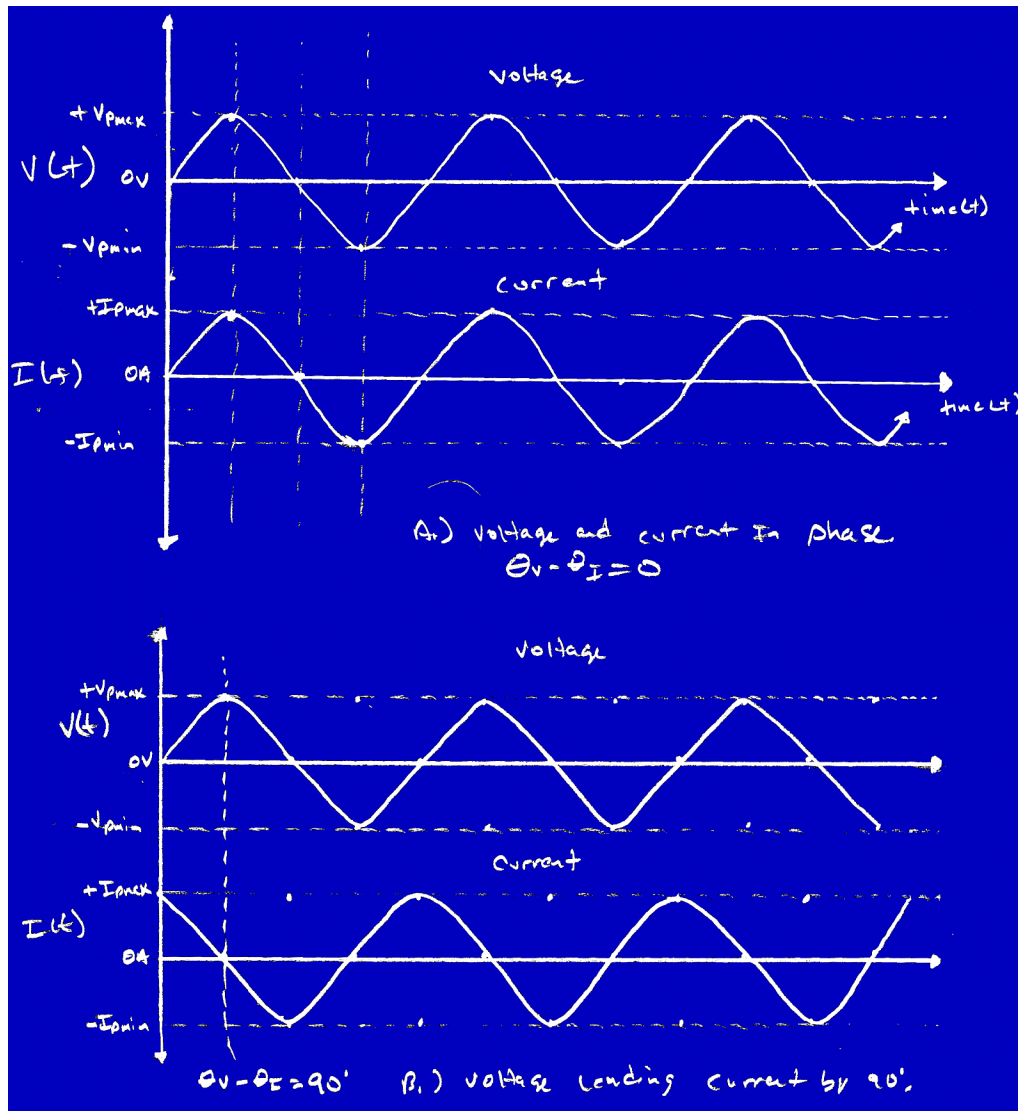


Figure 1.25 depicts a number of circuit elements with various currents and voltages. Notice that the elements in Figure 1.25c, and 1.25d, are both sourcing power while the elements in Figure 1.25a, and 1.25b are all sinking or absorbing power. The rule to remember is that when the current is positive and in the direction of decreasing voltage then the circuit is absorbing power. Why? Because the voltage is dropping in the same direction as the current is flowing, thus the element is resistive and thus absorbing power. On the other hand, when a circuit element is sourcing power then the positive current flow will be in the direction of increasing voltage.

Now, the thing about power in electronics is it has a lot of different meanings. If you ask an analog engineer, digital engineer, and physicists what power is they will all give you the same general answer, but their specific answers may vary wildly. The reason is power in an AC circuit is calculated differently than power in a DC circuit. The definition of power is always the same, but Equation 1.12 assumes that the voltage and current are constant and only gives the **instantaneous power**. If someone asked you what the power rating of a wall socket was that's a much more complex question. The reason why, is when AC signals come into play, the voltage and current are usually changing and a function of time and can be out of phase to boot. Take a look at Figure 1.26 to see this.

Figure 1.26 – AC Voltage Current Relationships.



Referring to Figure 1.26a, you see that both the voltage and current are sinusoidal, in phase, and at a frequency of 60 Hz, but in Figure 1.26b, everything is the same, but the current is “lagging” the voltage by 90 degrees. Hence, the power both circuits provide are different. The maximum power that Figure 1.26a can provide is the peak voltage (V_{pmax}) multiplied by the peak current (I_{pmax}) or:

Equation 1.13: Instantaneous power in a steady state AC circuit.

$$P_{max} = V_{pmax} * I_{pmax}$$

This looks very much like the instantaneous power Equation 1.12 in the previous section, and it is. However, equation 1.13 isn't very useful since it doesn't tell us much about the “average” power that we can expect. Additionally, we can't really use Equation 1.13 to calculate the power of Figure 1.26b since the voltage and current are out of phase and the maximum current and voltage spike don't occur at the same time!

The solution to the out of phase problem is to add a term called **power factor** (p_f) into the equation to take into consideration the phase difference. Power factor is defined as the cosine of the phase angle difference of the voltage (ϕ_v) relative to the current (ϕ_i) or mathematically power factor is:

Equation 1.14: Power factor.

$$\begin{aligned} p_f &= \cos(\phi_v - \phi_i) \\ &= \cos(\theta), \text{ where } \theta = (\phi_v - \phi_i) \end{aligned}$$

If the phase difference θ is 0 degrees, that is, the voltage and current are in phase then the power factor is 1.0, as it should be.

With this new information about the power factor now we can re-write the instantaneous maximum power of an AC signal as:

Equation 1.15: Maximum instantaneous power in a steady state AC circuit element.

$$P_{\max} = V_p * I_p * \cos(\theta)$$

That's great, but it still doesn't tell us about the average power that the power source is producing or absorbing in an AC circuit and this is what we really need. Who cares if the circuit element is producing or absorbing some amount of power for a split second? We need to know the average power it can supply. This is easily computed with the RMS value of both the voltage (V_{rms}) and the current (I_{rms}):

Equation 1.16: Average Power for an AC steady state circuit.

$$P_{\text{rms}} = V_{\text{rms}} * I_{\text{rms}} * \cos(\theta)$$

$$\text{Where } V_{\text{rms}} = V_{\text{pmax}} * .707,$$

and,

$$I_{\text{rms}} = I_{\text{pmax}} * .707$$

So if you need to compute power now you know how to! For example, if you know that the average current drain of a computer chip is 5ma and the supply voltage is 5V then you would use the DC power formula:

$$P = V * I = 5V * 5\text{ma} = 25\text{mW}, \text{ or } 25 \text{ milliwatts.}$$

NOTE But, remember RMS only works for pure sinusoidal signals.

1.7 Introduction to Discrete Components

In Chapters 2 and 3 we're going to cover more discrete components, their use, and current/voltage relationships. But at this point, I just want to familiarize you with some of them, their symbols, their general operation, and purpose. In most cases you won't need to use discrete

components when building digital circuitry. However, there are some areas that we are stuck using them such as power supplies, and interfacing, so basic knowledge is a good thing. So let's take a look at **resistors**, **capacitors**, **inductors**, **transformers**, **diodes**, and **transistors**.

Figure 1.27 – Symbols for Resistors.

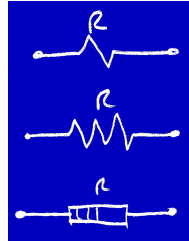
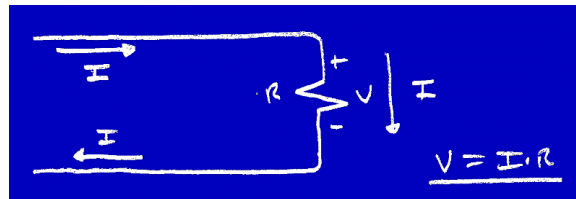


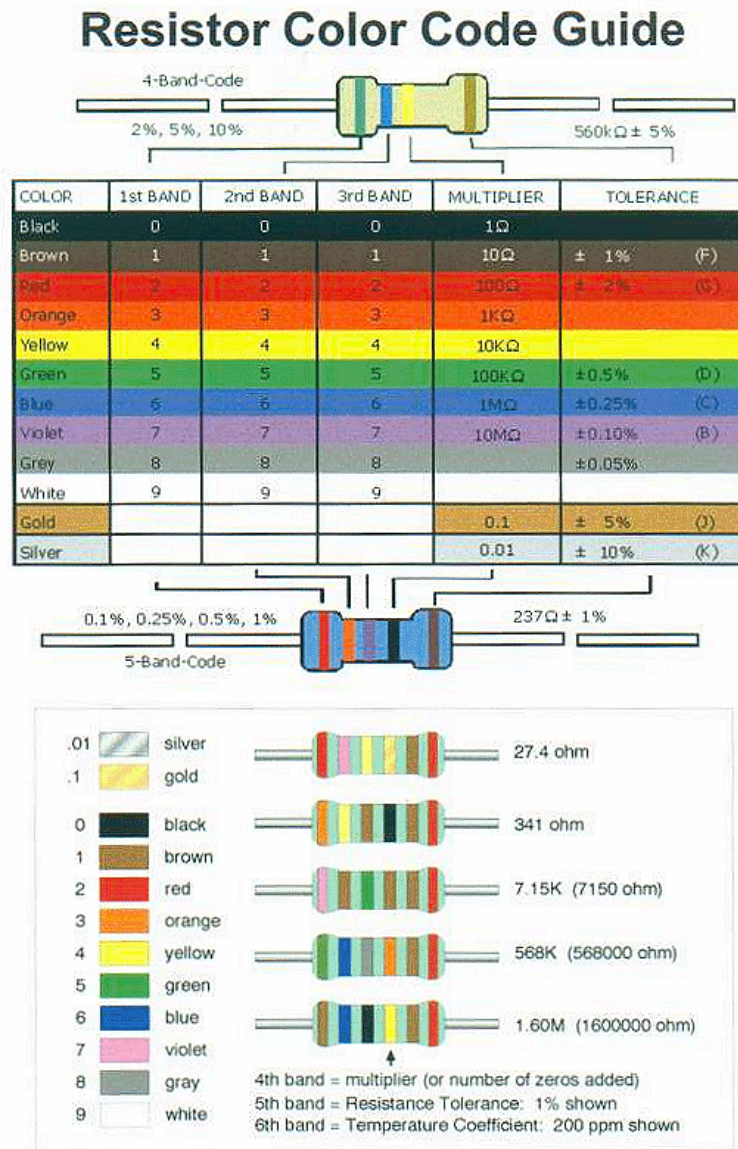
Figure 1.28 – The Voltage Current Relationship for a Resistor in a Circuit.



1.7.1 Resistors

Resistors are the simplest of all discrete devices. Figure 1.27 shows the symbols typical used for resistors. Resistors are usually made of carbon and act as current limiters in circuits, that is, when a I current flows thru a resistor with value R , a voltage drop develops as shown in Figure 1.28. Resistors come in many different values and power ratings and are measured in **ohms** (Ω), named after **Georg Simon Ohm**. The value of a resistor can be read off the resistor using a color code as shown in Figure 1.29.

Figure 1.29 – The Resistor Color Code.



1.7.1.1 Reading Resistor Color Codes

The typical carbon resistor has 4 colored bands on it labeled b_1 (tens place), b_2 (ones place), b_3 (multiplier), b_4 (tolerance) respectively. b_1 to b_3 compose the numeric value while b_4 is the tolerance value in percent. The tolerance value simply defines how accurately the resistor manufacturing processing is. Hence, a 5% tolerance says that you can trust that the resistor is within 5% plus or minus its value.

TIP

There are also “**chip**” resistor networks that exist where many resistors are enclosed in a chip for a smaller footprint and better thermal tracking properties.

The value of any resistor is computed based on the first 3 bands using Table 1.7 as a reference.

Table 1.7 – Color Code for Carbon Resistors

Color Numeric Value

Black	0	
Brown	1	
Red	2	
Orange	3	
Yellow	4	
Green	5	
Blue	6	
Violet	7	
Gray	8	
White	9	
Gold	-1	(only valid for the 3rd band b_3)
Silver	-2	(only valid for the 3rd band b_3)

The fourth band (b_4) is the tolerance band and has the following possible values: Gold $\pm 5\%$, Silver $\pm 10\%$.

To read a resistor all you do is look at the bands and plug the values into Equation 1.17 below:

Equation 1.17: Carbon Resistor Color Code Formula

$$R = (10*b_1 + b_2) * 10^{b_3} \pm b_4$$

It may look complicated, but it's really not, once you memorize the color codes then it's a snap. Most people make up a rhyme to recall the color code.

Let's try a couple examples to get the hang of it, we'll use very common resistance values that will be very important to pick out quickly, since you will find yourself using them over and over.

Example 1.3: Brown(b_1), Black(b_2), Red(b_3), Gold(b_4)

Based on the values in Table 1.7, let's plug the data into Equation 1.17:

$$\begin{aligned} R &= (10*b_1 + b_2) * 10^{b_3} \pm b_4 \\ &= (10*1 + 0) * 10^2 \pm 5\% \\ &= (10) * 100 \pm 5\% \\ &= 1000 \text{ Ohms} \pm 5\% \text{ or } 1\text{k Ohm} \pm 5\% \end{aligned}$$

And based on the $\pm 5\%$ tolerance, we can further say that the resistor may be anywhere from:

$$\text{Lower Limit: } 1000 - (5\% * 1000) = 950 \text{ Ohms}$$

$$\text{Upper Limit: } 1000 + (5\% * 1000) = 1050 \text{ Ohms}$$

Example 1.4: Orange(b_1), Orange(b_2), Brown(b_3), Silver(b_4)

Based on the values in Table 1.x, let's plug the data into Equation 1.17:

$$\begin{aligned} R &= (10 \cdot b_1 + b_2) \cdot 10^{b_3} \pm b_4 \\ &= (10 \cdot 3 + 3) \cdot 10^1 \pm 10\% \\ &= (33) \cdot 10 \pm 10\% \\ &= 330 \, \Omega \pm 10\% \end{aligned}$$

And based on the $\pm 10\%$ tolerance, we can further say that the resistor may be anywhere from:

$$\text{Lower Limit: } 330 - (10\% \cdot 330) = 297 \, \Omega$$

$$\text{Upper Limit: } 330 + (10\% \cdot 330) = 363 \, \Omega$$

Note: Ω means Ohms.

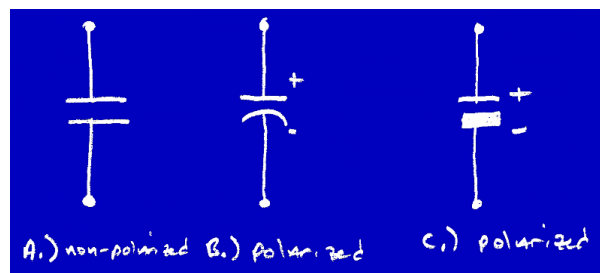
TIP

100 Ω , 1k Ω , 10k Ω and 330 Ω are very common values, so be sure to have a good supply of them. 1k Ω and 10k Ω are typically used as a pull-up resistors (which you'll learn about later) and 330 Ω is used as a current limiter in LED (light emitting diode) output circuits.

1.7.1.1.1 Resistive Power Rating

Finally, all resistors have a power rating, that is the maximum amount of power the resistor can dissipate. Typical values are 1/10th watt, 1/8th watt, 1/4th watt, 1/2 watt. For values larger than that, the resistors are usually packaged differently and have the value, tolerance, and wattage rating written right on the package.

Figure 1.30 – The Capacitor.



1.7.2 Capacitors

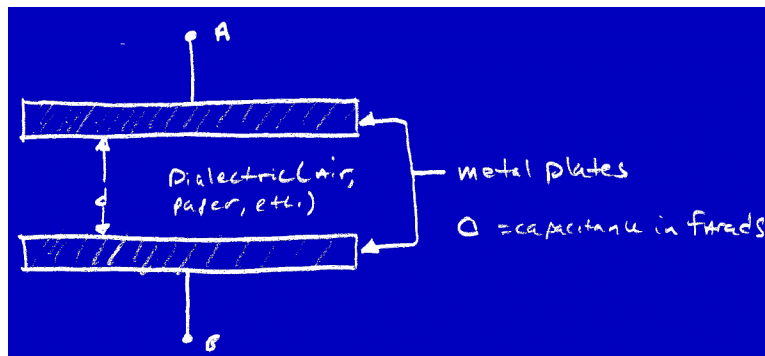
Capacitors are energy storage devices that are typically used in analog circuits to store energy, and filter signals. Figure 1.30 shows the symbols for capacitors which is usually nothing more than two parallel plates of equal length (straight lines for non-polarized, one curved for polarized or sometimes grayed). Capacitors have capacitance C , which is measured in **farads** (F) named after **Michael Faraday**. However, a single Farad is a huge amount of capacitance and most capacitors that we will work with will be in the microfarad (μf) to picofarad (pf) range. Additionally, capacitors have a voltage rating which is the maximum voltage that can be applied to capacitor

before it breaks down and is damaged or worst yet explodes. Also, some capacitors are polarized meaning that a voltage applied to them must have a specific polarity, typically electrolytics and tantalums are polarized.

TIP

The value and voltage rating of a capacitor is usually written right on it. However, sometimes, it's not, and you actually have to test the capacitor to deduce the capacitance or look up the numbering conventions from the manufacturer, that is, if you can tell that either. Bottom line, when you buy them put them into containers with labels.

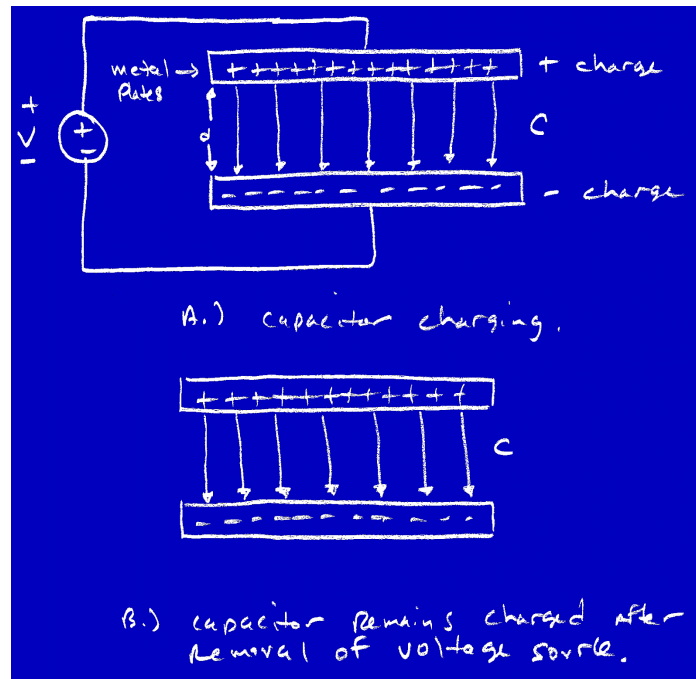
Figure 1.31 – The Basic Parallel Plate Physics Model of a Capacitor.



1.7.2.1 The Physics of a Capacitor

I don't want to get too involved with the physics of how capacitors work, or the math involved until we know a little more about circuit analysis, but let's take a quick look nonetheless to tide you over. Referring to Figure 1.31, you see the basic physical capacitor model. It's nothing more than two parallel metal plates, separated by air (or another dielectric material, insulator) a distance d . When a voltage is applied between the plates, an electric field is setup. The field causes positive and negative charges to accumulate on each of the opposing plates as shown in Figure 1.32. When the voltage is removed, the charge is still there, and hence, the device stores the charge for later use.

Figure 1.32 – A Capacitor in Action.



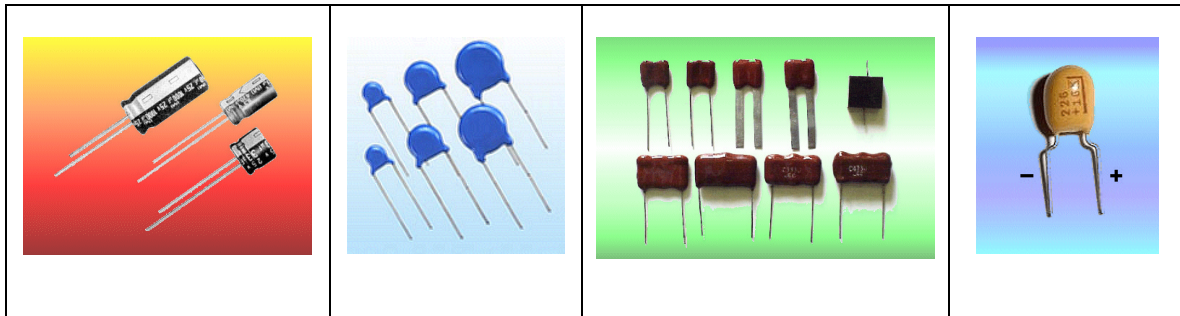
The actual values of capacitance and the time it takes to charge for any given physical configuration isn't important at this point. You just need to know that a capacitor can be constructed by two parallel plates separated by an air gap (or other suitable dielectric) a distance d . When a voltage is applied, the capacitor charges, and will hold the charge even when the voltage is removed.

1.7.2.2 Types of Capacitors

Capacitors are energy storage devices that are used for many different purposes. The capacitors used to build a power supply may have very different properties than the capacitors used in a radio, amplifier, or microwave transceiver. Hence, various types of capacitors exist that are better suited for a particular job. Some of the key parameters that are of interest when selecting a capacitor are voltage, capacitance, leakage (the amount of current that leaks as a function of time), frequency range, stability relation to temperature, average failure time, and so forth.

Based on these parameters many types of capacitors have been designed. Some are good at high frequencies, but can only withstand low voltages. Some have high capacitance, but have high leakage currents, and so forth. Figure 1.33 depicts the 4 main types of capacitors that are common in circuit design:

Figure 1.33 – Illustrations of Common Capacitors (left to right; electrolytic, ceramic, mica, tantalum).



1. **Aluminum Canister Electrolytic/Polarized** – Capacitance range approximately $0.001 \mu\text{F}$ – 1 F . Very high capacitance up to one or more Farads, high voltage, relatively high frequency stability and tolerance.
2. **Ceramic** – Capacitance range approximately 1 pF - $1 \mu\text{F}$, medium voltage, fairly stable. Good for bypass circuits, and medium frequency timing circuits.
3. **Mica** – Capacitance range approximately 1 pf – $20,000 \text{ pF}$. Very high performance for high frequency applications. High voltage, high stability.
4. **Tantalum** – Capacitance range approximately $0.1 \mu\text{F}$ to $1000 \mu\text{F}$. Very low leakage, low inductance, best for power supply filters and bypass capacitors for chips.

TIP

Most of the time, we will use either aluminum electrolytic in power circuits, ceramic capacitors for general capacitors and filters, and tantalums for bypass and low loss situations.

Figure 1.34 – The Inductor.

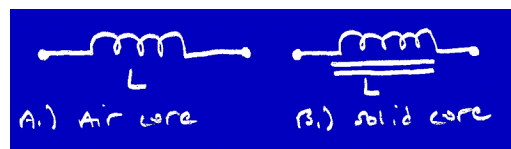
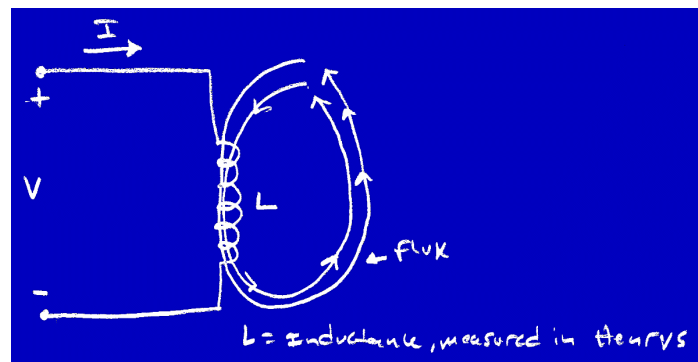


Figure 1.35 – The Inductor in Action.



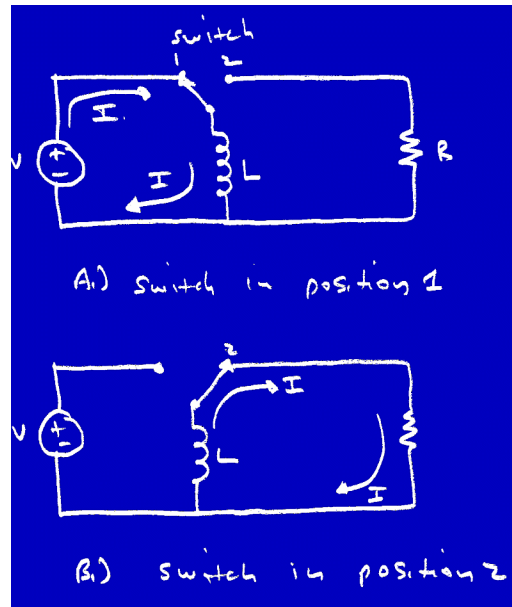
1.7.3 Inductors

Inductors are coils of wire, as are their symbols as shown in Figure 1.34. Inductors are energy storage devices that operate based on the generation and collapse of magnetic fields as shown in Figure 1.35. Inductors are used in electronics similarly as capacitors are in filtering circuits, but to a lesser extent as energy storage devices due to their nature. Inductors have inductance L which is measured in (ready for this) **henrys** (H) after **Joseph Henry**. Similarly to capacitance, 1 H is huge and most inductors are in the range of mH to μ H.

1.7.3.1 Inductor Operation

The basic inductor is nothing more than a coil of wire (usually insulated) with a number of coils and a coil radius. The operation is as follows; as a current is applied to the inductor coil a magnetic field sets up. This magnetic field stores energy and when the current is removed from the inductor the field will collapse and generate a voltage and hence current in the opposite direction that the initial current set the magnetic field up with. This is shown in Figure 1.36.

Figure 1.36 – Current Flow in an Inductor.

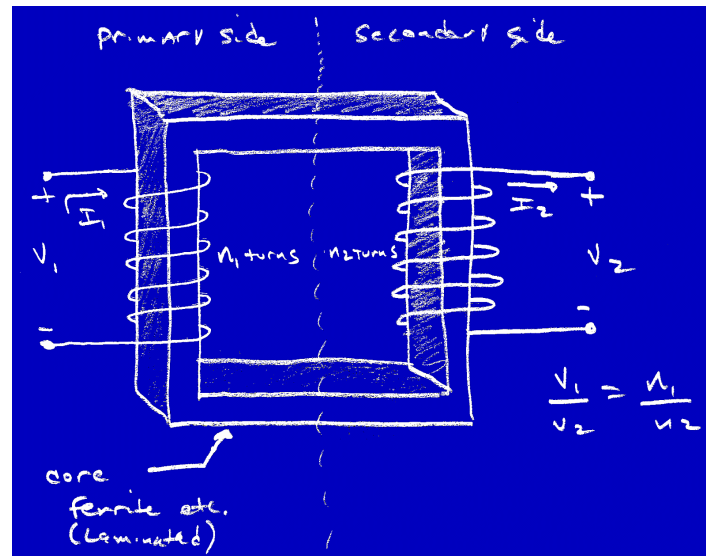


Inductors have a less obvious use than do resistors or capacitors, but are just what's needed in many analog circuit designs. However, digital circuits seldom use or need inductors as discrete components unless part of an interface circuit.

1.7.3.1 Types of Inductors

Inductors aren't as varied as capacitors are. In general, inductors are all basically coils of wire. However, some are freestanding in air, some wrapped around paper, some around plastic, some are even adjustable.

Figure 1.37 – A Detailed View of the Transformer.



1.7.4 Transformers

The transformer is one of the most useful electronic devices in existence. They're almost magical to tell you the truth. When you first learn about transformers, you might think that you have stumbled onto perpetual motion, but I assure you, we still don't get anything for free. In any event, Figure 1.37 depicts the symbol for a transformer along with a more detailed labeled drawing. Transformers aren't measured in anything per se, but are more of "transformation" devices that can be used to change one voltage or current to another. So they "rating" usually refers to the "step up or step down" action.

Transformers are used all over your house to step up and down voltages. For example, to convert the 120 V AC signal from the wall outlet into 12 V DC (with a DC filter) signals for your favorite video games system, or to step up the 120 V AC signal to 30,000 V AC to power the electron gun inside your T.V.! Hence, most of the time when speaking of transformers we talk of the power rating and the step up or step down ratio.

1.7.4.1 Transformer Operation

Referring to Figure 1.37 transformers are nothing more than coupled inductors. The key to their operation is a property called **mutual inductance**. Meaning, that as long as the two coils of the primary and secondary are wound together in close proximity (or around a ferromagnetic core like iron) then the magnetic field created in the primary coil will create a magnetic field in the secondary coil, and hence a voltage/current will be induced. This voltage is proportional the ratio of the number of turns in the secondary N_2 to the primary N_1 along with the input voltage.

Transformers are bit tricky since there are a lot more going on to their operation than I have eluded to. Including, self inductance, coil impedance (AC resistance), heat loss, frequency relationships, and so forth, but for our purposes we will assume that all these effects don't matter and we are talking about an ideal transformer (the kind found on Fantasy Island). With that in mind, the following equations relate the output voltage to the input voltage:

Equation 1.18: Ideal Transformer Formulas for Voltage and Current

Given the primary has N_1 turns and the secondary has N_2 turns and the input voltage is V_1 then:

$$V_2 = V_1 \cdot (N_2/N_1)$$

$$I_2 = I_1 \cdot (N_1/N_2)$$

Or calling n the turns ratio $n=(N_2/N_1)$ then we have:

$$V_2 = V_1 \cdot n$$

$$I_2 = I_1 \cdot 1/n$$

NOTE	To use the model of an ideal transformer, we assume a lot, but most importantly the input signal is AC and a fairly high frequency and that the output connected to the secondary has very high resistance or impedance, so there isn't a lot of current flow in the secondary.
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1.7.4.2 Putting Transformers to Use

One of the most common uses for transformers are in power supply designs. In fact, we are going to use a transformer when we design the AC powered version of the 5V DC power supply you'll need to build the projects in this book. We'll use a transformer that takes as its input 120 V AC from the wall outlet and transforms it down to 12 V AC roughly. Then the 12 V AC signal will be filtered and regulated with a voltage regulator down to 5 V DC which we will use to power our digital logic which is based on 5V TTL/CMOS (transistor transistor logic and complementary metal oxide semiconductor) technologies. But, we'll get to that a little later.

1.7.5 Semiconductor Devices and the P-N Junction

The next two devices we are going to cover are diodes and transistors. These devices are the basis of all switching logic from a single chip to the Pentium processor. But, before that, we need to briefly cover the basis of all semiconductor devices, the semiconductor and the P-N junction.

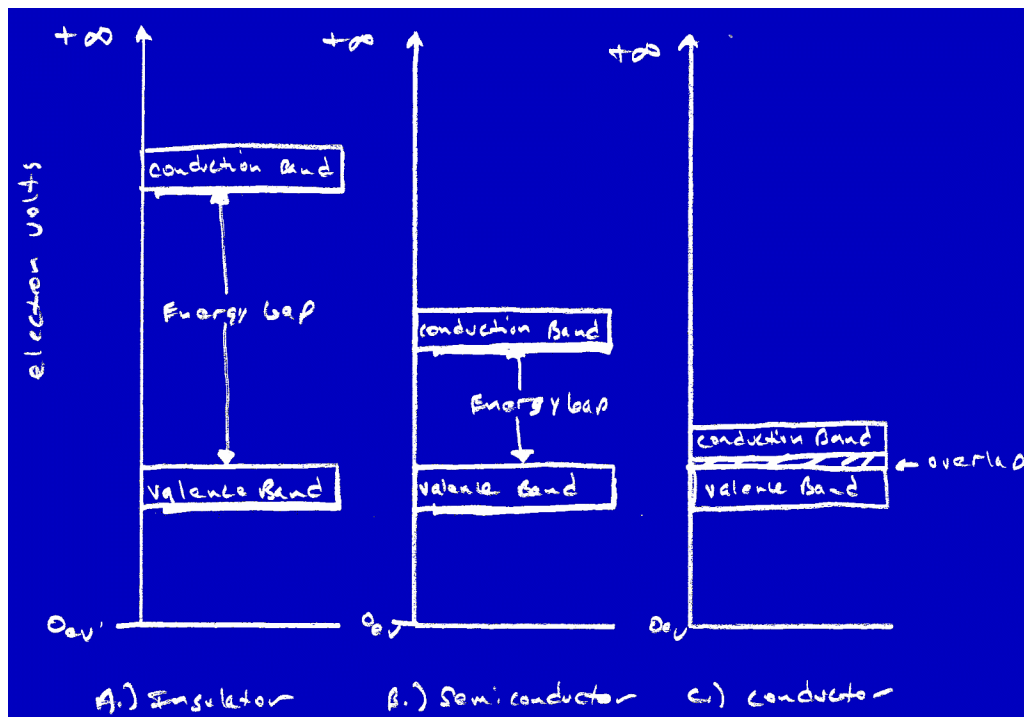
WARNING!	Semiconductor theory is very complex and not necessary for digital design, hence, a detailed explanation is beyond the scope of this book. If you want a more detailed understanding then try " <i>Electric Circuit Analysis by Johnson and Johnson</i> ", or " <i>Electronic Devices by Floyd</i> ". They both have excellent sections on semiconductor theory.
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You have already learned about conductors and insulators. Conductors conduct electric current very well and insulators don't. Conductors conduct because the outer valence electrons are nearly free and take very little energy to loosen up and move to an adjacent atom. Insulators are good insulators since the valence electrons are tightly bound up and higher energies are needed to free them.

There is however, a material that has properties somewhere between a conductor and an insulator, called a **semiconductor**. Most semiconductors are single elements like silicon (Si), germanium (Ge), and carbon (C). However, there are compound semiconductor materials like gallium-arsenide (Ga-As), and many others. However, silicon is the most common in use today and the cheapest.

The key to the semiconductor property is the energy gap needed for electrons to jump from the valence band to what's called the **conduction band**, that is the band or state where current will flow and the electrons will free up. Figure 1.38 depicts typical energy diagrams for a conductor, insulator, and semiconductor.

Figure 1.38 – Energy Band Diagrams for Conductors, Insulators, and Semiconductors.



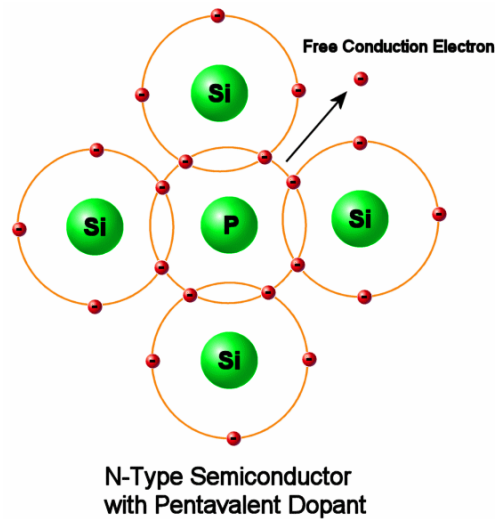
As you can see, the semiconductor's energy diagram is somewhere between the insulator and the conductor. As it stands the semiconductor (silicon in this case) is rather useless to us. However, silicon has an interesting property in relation to its valence shell. There are 4 valence electrons in its valence shell, normally if we create pure crystal of silicon then the 4 valence electrons form bonds with 4 other silicon atoms creating the crystal lattice structure.

However, if we mix the pure silicon with another element then we can change the electrical properties of the silicon as a compound and increase the number of free current carriers. This process is called **doping**.

1.7.5.1 N-Type Semiconductors

We know that silicon has 4 electrons in the valence shell, but they are tightly bound, not as tight as an insulator, but tight nonetheless. If silicon is therefore compounded with a **pentavalent** material (5 electrons in the valence shell) then 4 of the valence electrons will create bonds with the 4 valence electrons of the silicon and 1 electron will be left free for conduction.

Figure 1.39 – An N-Type Semiconductor.

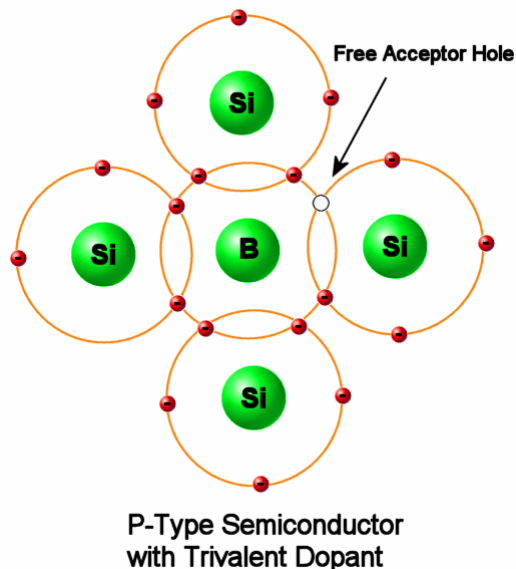


Some examples of pentavalent elements are arsenic (As), bismuth (Bi), phosphorous (P), and antimony (Sb). Figure 1.39 illustrates what happens when silicon is doped with phosphorous. As you can see, there is 1 free electron for every 4 silicon atoms that bond to a phosphorous atom. Hence, silicon doped with a pentavalent material such as phosphorous results in a compound with a surplus of negative charges, hence, we call this a N-type semiconductor. By itself, it's not that exciting, but we're getting there, bear with me...

1.7.5.2 P-Type Semiconductors

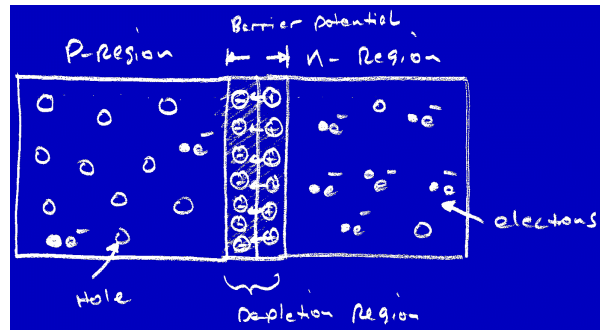
P-type semiconductors are the exact opposite of N-type. If we compound silicon with a trivalent material (3 electrons in the valence shell) then 3 of the valence electrons from the impurity material will create bonds with 3 of the 4 valence electrons of the silicon and 1 electron will be unpaired in the silicon atom. Creating a hole or acceptor atom for an electron.

Figure 1.40 – A P-Type Semiconductor.



Some examples of trivalent elements are aluminum (Al), boron (B), and gallium (Ga). Figure 1.40 illustrates what happens when silicon is doped with a trivalent material such as boron (B). As you can see, there is a hole created for every 4 silicon atoms that bond to a boron atom. Hence, silicon doped with a trivalent material such as boron results in a compound with a surplus of positive charges or holes, hence, we call this a P-type semiconductor.

Figure 1.41 A P-N Junction at Equilibrium.



1.7.5.3 The P-N Junction

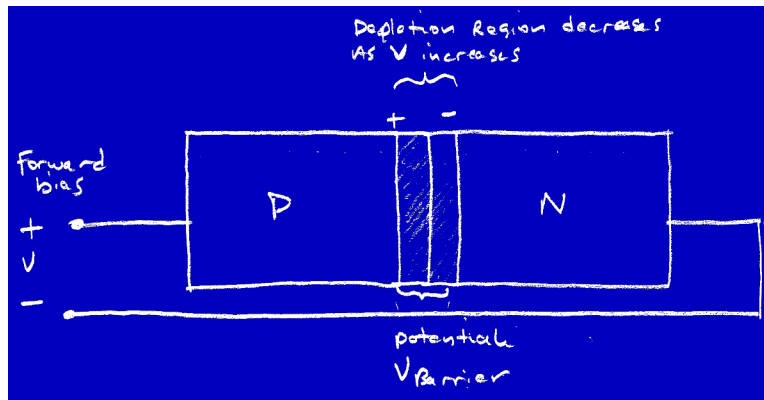
By themselves a P-type material or a N-type material don't do much, but when you sandwich them together physically that's when you see some action! Take a look at Figure 1.41. Here you see a P-N junction (of course the electrons are not drawn to scale) after some initial time t_0 which for our purposes will be nearly zero seconds. What's happened is that the free electrons in the N-type material have migrated or diffused over to the P-type material filling in holes, this causes a net increase of positive charge in the N-type region and a net increase in negative charge in the P-type region. This diffusion process happens very quickly and can be thought of as instantaneous.

The results of the electron diffusion from the N region to the P region creates what's called the depletion region, that is a region void of charge. Moreover, as electrons diffuse from the N region into the P region a potential difference or barrier potential is generated at the interface of the P-N junction. This becomes the steady state of the P-N junction and must be overcome for any current to flow from the P region to the N region.

Now, here's the clincher – as it stands the P-N junction is still pretty useless, it doesn't do much, but if we apply a voltage to it, two things can happen: a current will flow if the voltage **forward biases** the P-N junction and no current will flow if the voltage **reverse biases** the P-N junction.

NOTE	Bias simply means a voltage applied to a device, usually a semiconductor device.
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Figure 1.42 – A Forward Biased P-N Junction.



1.7.5.3.1 Forward Biasing the P-N Junction

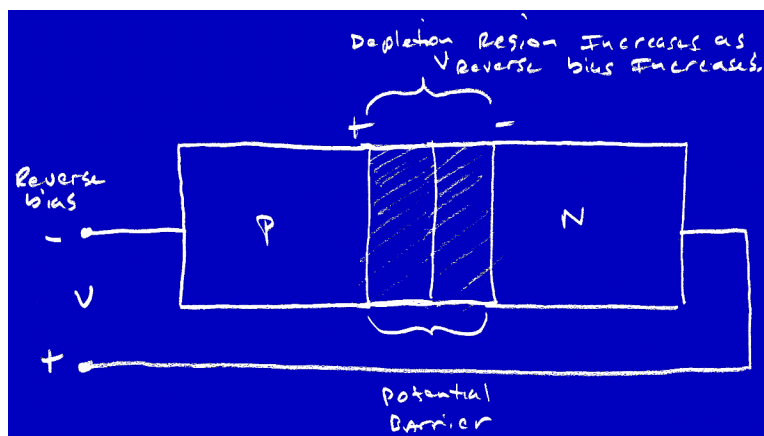
The P-N junction creates a depletion region where a **barrier potential** exists. This barrier potential can be thought of as an energy barrier that can be overcome by the application of an electric field. An electric field or voltage if applied as shown in Figure 1.42 will increase the energy levels of the electrons in the N region giving them enough energy to cross the depletion region into the P region where they find a hole to occupy, once there the positive voltage applied to the P region strongly attracts the electrons now occupying holes in the P region and the results are a constant flow of current.

Additionally, there will be a voltage drop over the depletion region to overcome the potential barrier setup by the P-N junction. This voltage drop depends on the materials used to make the P-N junction, but is approximately 0.7V for silicon based P-N junctions and 0.3V for germanium based P-N junctions.

ADVANCED

There will actually be a small voltage drop in both the P and N type regions since they aren't perfect conductors, but it's usually negligible compared to the 0.7V or 0.3V drop across the depletion barrier.

Figure 1.43 – A Reverse Biased P-N Junction.

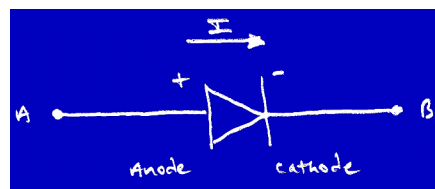


1.7.5.3.2 Reverse Biasing the P-N Junction

If the voltage is applied in the opposite direction used to forward bias the P-N junction, that is, positive voltage to the N region and negative voltage to the P region as shown in Figure 1.43, then the depletion region gets larger as shown in Figure 1.43. Hence, the P-N junction's resistance is virtually infinite (in the millions of ohms range).

Therefore, current only flows in a P-N junction if the junction is sufficiently forward biased, that is a voltage is applied in the correct direction. If a P-N junction is reverse biased, that is, a voltage is applied in the opposite direction then the P-N junction acts like an insulator. This property is the key to all switching circuitry, the ability of a circuit element to pass current in one direction and not the other.

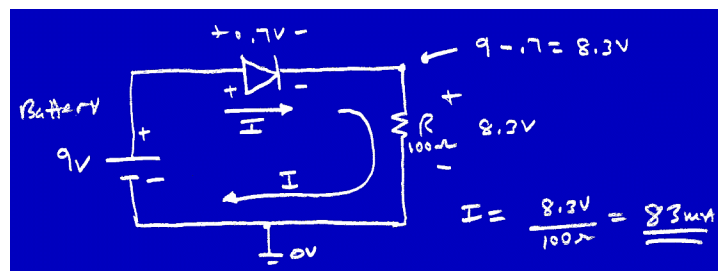
Figure 1.44 – The Diode.



1.7.5.4 The Diode

The diode is the simplest device that uses a P-N junction. In fact, a diode is nothing more than a P-N junction. Figure 1.44 illustrates the basic symbol used to represent a diode. As you can see a diode has two contacts; the **anode** (A) and **cathode** (K) – weird huh? Conventional current flows into the anode and out of the cathode. However, since the diode is really nothing more than a P-N junction, current will ONLY flow from anode-cathode. This is the desired property of the diode. Moreover, for current to flow in the diode, the diode has to be forward biased enough to overcome the barrier potential. This forward bias is usually in the range of 0.3V for germanium based diodes and 0.7V for silicon based diodes to initiate conduction.

Figure 1.45 – A Diode Circuit with Forward Bias.



Referring to Figure 1.45 we see a diode forward biased by a battery with voltage 9V, in the circuit there is a limiting resistor R to keep the current from getting too high. The circuit works as follows: when the voltage is first applied, the diode junction is biased on the forward direction, very quickly the depletion zone is overcome and the potential barrier is equalized and current flows. Assuming that the voltage drop over the diode is 0.7V (it's a silicon based diode) then that means that $9 - 0.7 = 8.3V$ must drop over the resistor R . Additionally, since R is 100Ω then the current in the circuit must be $I = V/R$, $I = 8.3V/100\Omega = 83mA$. And what's the power?

1.7.5.4.1 Diode Characteristics

The diode current is important to compute since there are limits to the current a diode can handle. Diodes have various current ratings. One of them is the maximum allowable **forward bias current**. Another important property is the maximum **reverse bias breakdown voltage**. Remember, current only flows if you forward bias the diode with a proper voltage. But, what happens if you reverse bias the diode? Well the depletion region gets larger in the P-N junction and current doesn't flow – which is what we want. But, what happens if you continue this reverse biasing? The answer is you will cause the diode to “breakdown” and conduct in the wrong direction. Additionally, you may damage the diode! Hence, be aware of this breakdown voltage.

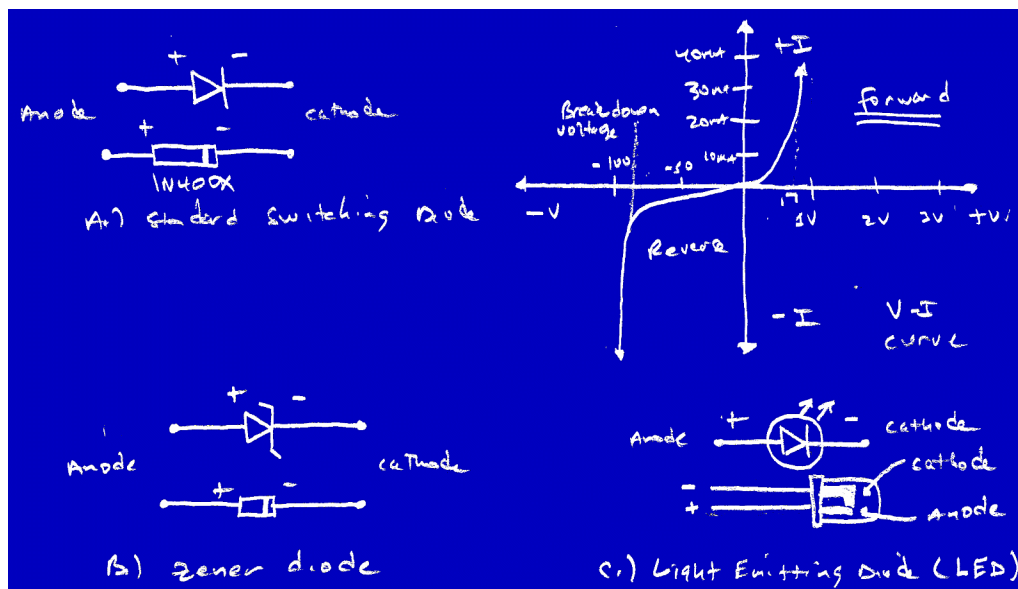
For example, if you are building a circuit with a diode and the maximum voltage you expect in the reverse bias direction is 10V then a diode that handles 50V is more than adequate, but if you expect a reverse bias voltage of 500V then you are going to see a burnt up diode!

The final value of interest when working with diodes is the **reverse bias leakage current**. This current exists when the diode is reverse biased, but not in the breakdown stage. So even under normal working conditions and normal reverse bias, a little bit of current will flow due to thermal excitation. This current is usually in the micro to nano ampere region, but might still be a concern to you especially if you are using them in low power digital circuits and a small current can possibly cause a problem.

1.7.5.4.2 Types of Diodes

You may be wondering if there are different types of diodes? The answer is yes! There are many types of diodes all designed for various applications and ratings. However, most of the time, we are going to use standard “diodes”, but there are a number of special kinds listed below and shown in Figure 1.46:

Figure 1.46 – Various Diode Packages and Types.



Rectifier Diode – The standard rectifier diode is what you will use most of the time you use a diode. You will design the diode to operate as a “**switch**” in the forward bias direction. There isn't a color code or anything for diodes, you basically just need to know the number of the part and

what its characteristics are. The common garden variety diode is the 1N400X series. Various versions that can handle more current, higher breakdown voltages and current ratings, have incrementing numbers like 1N4001, 1N4002, etc. Also, the packaging changes based on the power absorption; hence, a power diode might be in a larger package.

Zener Diodes – Zener diodes are very interesting devices. The symbol is shown in Figure 1.46. They are designed to operate in the reverse bias direction or in breakdown mode portion of the operational curve, that is you purposely reverse bias a zener diode into the breakdown region and then it becomes a constant voltage drop with variable current. Hence, they are very useful as voltage regulators (devices that supply varying current at a constant voltage level). Of course, zeners wouldn't be very useful if you had to apply a breakdown of 100-200V, so they have much smaller reverse voltages on the order of a fraction of a volt to many volts.

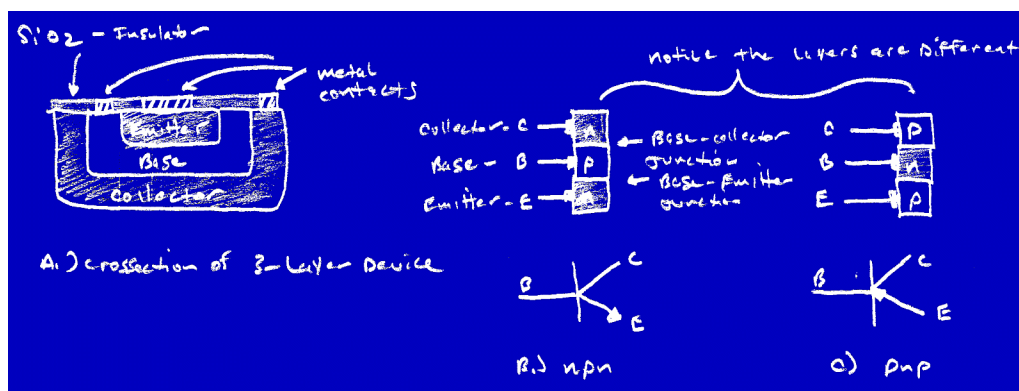
Switching Diodes – Switching diodes are just like normal diodes except that they are designed around the premise that they must switch from conduction to non-conduction very quickly for use in switching circuits such as digital electronics.

Light Emitting Diodes – These are very cool. LEDs are diodes that are enclosed in a transparent plastic package, so that the P-N junction is open for view. Figure 1.46 shows a light emitting diode. LEDs are diode, but have been doped and designed so that some of the electrons as they pass through the depletion region cause photons of light to be emitted. LEDs come in various sizes, power ratings, and colors such as red, green, yellow, orange, blue, and even white! LEDs are the indicators of choice in digital electronics and computer front panels. The more the better!

1.7.5.5 The Transistor (Bipolar Junction Transistor)

The BJT transistor is the last semiconductor device that we are going to cover in this introduction. Transistors are used for switching and amplification applications. However, due to their complexity, we will forego any detail until Chapter 3 since modeling transistors takes a bit of circuit analysis which we haven't covered yet. But, you'll get enough information to get started until then.

Figure 1.47 – The Bipolar Junction Transistor.

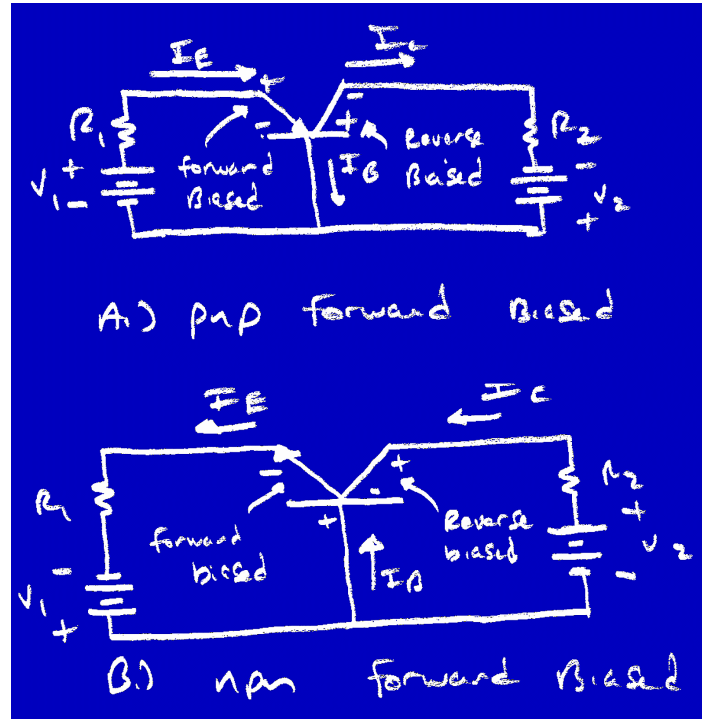


Transistors are 3 layer devices composed of doped P-N-P or N-P-N junctions in a sandwich configuration as shown in Figure 1.47. Basically, they are similar to 2 diodes back to back. There are 3 contacts made to a transistor; the **base** (B), **emitter** (E), and **collector** (C).

There are hundreds if not thousands of types of transistors and packaging available with various properties. However, for our purposes we will use the standard general purpose NPN and PNP

that are easy to find such as the 2N2222 (NPN), 2N3904 (NPN), and 2N3906 (PNP). These are good all around transistors, and cheap which is important since you will probably burn a lot of them out in your circuits!

Figure 1.48 – Forward Biasing PNP and NPN Transistors.



1.7.5.5.1 Transistor Operation

The difference in the PNP and NPN is how they are biased. In general, transistors are biased in such a way that the base-emitter junction is forward biased while the collector-emitter junction is reversed biased. This configuration is shown for both a PNP and NPN in Figure 1.48. Let's talk about the NPN's operation since the PNP works in the same way with opposite bias voltages.

In the case of the NPN, when the base-emitter junction is forward biased this shrinks the base-emitter depletion region and allows electrons to flow from the emitter through the depletion region as shown in Figure 1.48. However, once these electrons get into the base region, there are hardly any that make it out of the base region and flow out of the base contact. The majority of electrons pass right through the base-collector depletion zone that is reverse biased, into the collector and out of the contact. Hence, a very small base current creates a very large collector current. This is the key to operation of the transistor and its amplification property.

Now, you don't get something for free here! You still have to have the power available on the collector circuit, but the point is that you can send a small signal to the base and then have it largely amplified out of the collector. Typical amplification ratios are on the order of tens to hundreds.

1.7.5.5.2 Simplified Model of a Transistor

Although we are going to cover this once again in Chapter 3, I want to give you another way to think of a transistor using a model. Basically, the way that I like to think of a transistor is a variable resistor. When sending a current into the base, this current causes the resistance of the collector-emitter junction to decrease and hence, the current increases. The ratio of base current to collector current is the amplification ratio of the transistor named h_{fe} . Hence, if there is an amplification factor of 100 and you send 1 mA into the base then $100 \times 1\text{mA} = 100\text{mA}$ will flow into the collector (and $100\text{mA} + 1\text{mA}$ will flow out of the emitter) -- roughly. Later, when you know more about circuit analysis we will actually take a look at this model.

1.8 Using Basic Electronics Equipment

Talking about electronics is one thing, building them is quite another. I can't tell you how many senior level EE students I met that could do a fourier analysis in their heads, but still didn't know how to wire wrap a circuit or test current! Therefore, part of the goal of this book is to actually tell you what test equipment does what, and what tools you'll need to build the circuits in this book along with many others.

1.8.1 Test Equipment

The first thing we need to do is take a look at some tools of the trade. What they look like, what they do, and how much they cost?

1.8.1.1 The Power Supply

The first thing that you are going to need when building an electronic device or circuit is a power supply. Now, there are a number of options that you have. You can use batteries if you like. For example, if you need a 6V supply then you could string 4-1.5V D cells together and make a crude power supply. This works, but isn't very stable, and the voltage isn't very regulated (meaning that as various currents are drawn from the batteries the voltage fluctuates). However, I will show you later in the book how to build a power supply based on batteries and on an AC line input.

Your second choice for a DC power supply (and my suggestion for real work) is a pre-made variable power supply that allows you to change the voltage and regulates the voltage. There are a number of manufacturers that build power supplies such as Protek and BK-Precision among others. A decent power supply with a single output and from 0-30V variable output will run you \$100-\$300, so if you're on a budget then the battery method may be for you. Of course there is always eBay!

Figure 1.49 – A Bench Power Supply.



Figure 1.49 shows a picture of a typical power supply (the BK Precision 1621A). In most cases, you will dial in the voltage with a dial or digital adjustment and then simply connect the power leads to the input of your project. The nicer power supplies have actual digital displays that show the voltage and the current being supplied.

Figure 1.50 – A Digital Multimeter.

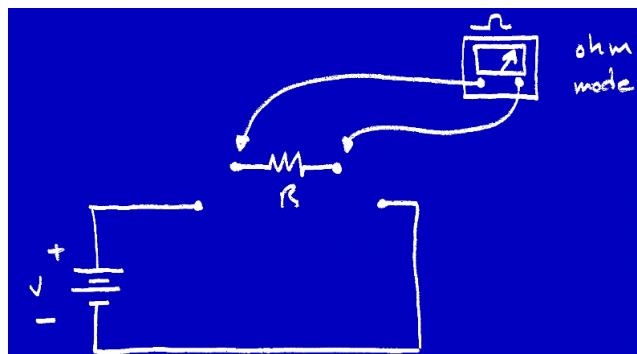


1.8.1.2 The Multimeter

The next piece of equipment that is an absolute must for any electronics development is a multimeter as shown in Figure 1.50. A multimeter is a device that can measure various electrical values such as resistance, voltage, or current. However, new meters can also test capacitance, diodes, transistors, temperature, and even download data to your computer – crazy huh? Some good manufacturers of digital multimeters are Fluke (the meter gods), and BK-Precision. You can get a cheap meter for about \$20.00 and really nice digital meter for about \$100.00, but if you want the farm, the sky is the limit and Fluke makes meters that range into the hundreds and even thousands of dollars with on-board computers and screens. However, if you are going to buy one, it might be worth getting a few bells and whistles like capacitance, diode, and transistor testing built in. I have a \$90.00, BK 388A and it rocks! But, I also like my little BK 2704B.

Figure 1.50 shows a picture of your garden variety digital multimeter. It can measure voltage (AC/DC), resistance, and current (AC/DC). Notice, the various ranges. Using a meter is sometimes confusing, so let's take a minute to see how to measure these basic values.

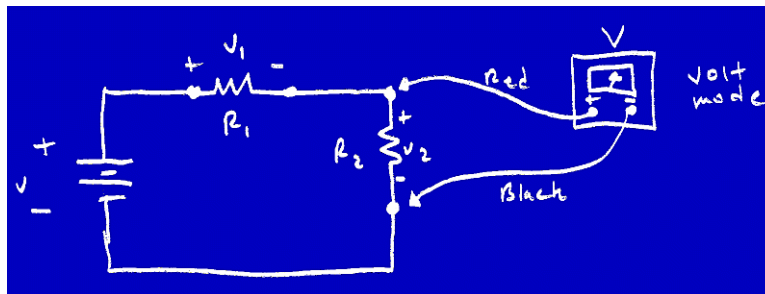
Figure 1.51 – Measuring Resistance.



1.8.1.2.1 Measuring Resistance

Referring to Figure 1.51, we see to measure resistance of a circuit element, the element **MUST** be disconnected from any circuitry and have **NO** power going through it. If these premises are not met you can damage your multimeter or at very least get an erroneous reading! Anyway, to measure resistance, the first thing you do is select an appropriate range on the meter, for example, if you think that the value of your resistor is in k Ohm range then you might start with a range setting of 100k or 400k. Then simply touch the leads of the meter to each lead of the resistor (it doesn't matter which lead, black or red touches which lead of the resistor) and then let the meter compute the value. If the meter goes out of range, then turn up the range setting until you get a good resistance reading.

Figure 1.52 – Measuring Voltage.

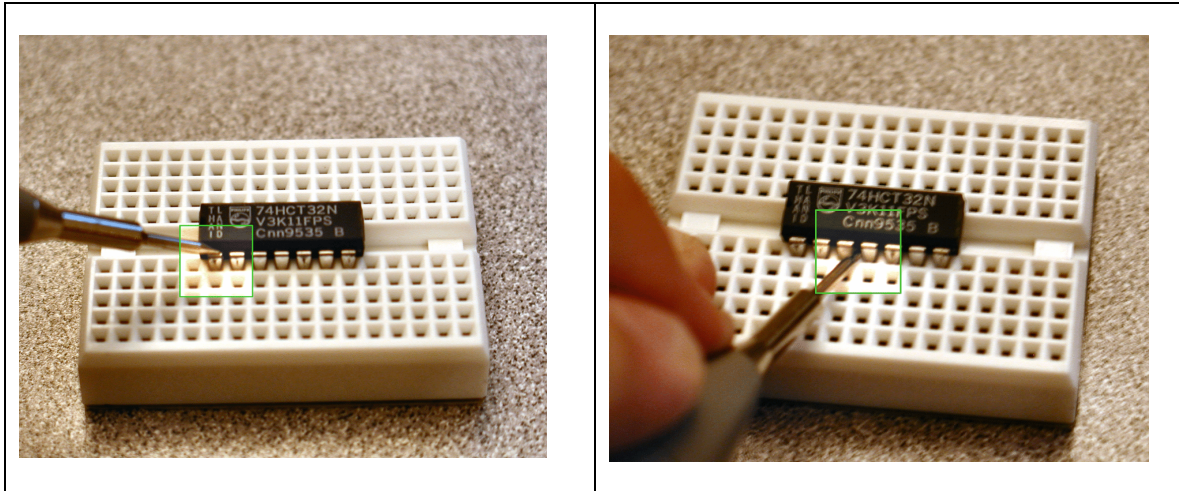


1.8.1.2.2 Measuring Voltage

Referring to Figure 1.52, voltage is easy to measure. However, you have to remember to put the meter on voltage in the range you expect the voltage that you're measuring to be in. Additionally, make sure you have the RED lead in the lead marked (V) and the black in the common lead. Finally, if you are measuring AC or DC make sure you set that (if the meter supports it).

To measure the actual voltage on the device the circuit must be powered (that's the whole point of measuring a voltage). Then simply touch the RED and BLACK leads to the two points that you want to see the potential difference. Note, that I said "points". Many times, you don't want to know the voltage over a single device, but between any two points, this is a perfectly normal thing to want to test. In fact, it's kind of fun to place the BLACK common lead of the meter on the ground of a circuit and then poke around with the RED lead and see all the various voltages in the electrical network.

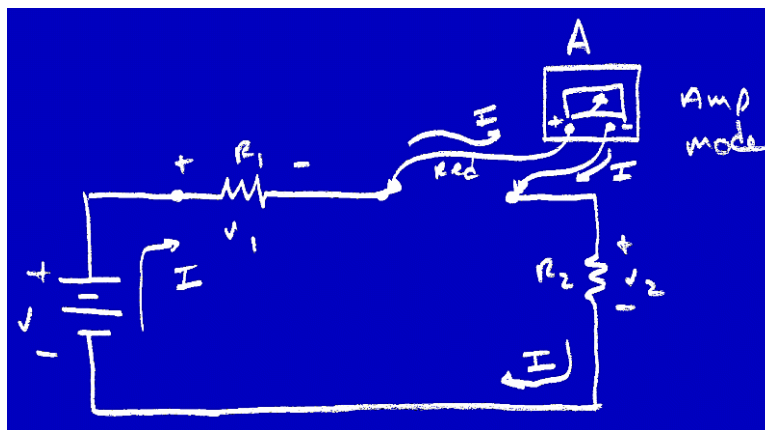
Figure 1.53 – Probing a Lead (left correct, right incorrect).



WARNING!

Although you can't hurt a powered circuit by testing the voltage, you can short one out if you're not careful with the leads. For example, Figure 1.53 shows a test lead that is correctly and incorrectly placed on a pin of a chip. Notice in the case of the incorrect placement, two leads of the chip are shorted together – this could destroy the chip or device being tested. Hence, be careful and have a steady hand when placing the probe leads.

Figure 1.54 – Measuring Current.



1.8.1.2.3 Measuring Current

Current is always a problem for people to test correctly. I'm not sure why, but I guess, it's because they really don't know what it is? However, at this point you are an expert at current right? And you know that it is the flow of charge in a circuit, thus to test current, you must be able to “count” the charge (electrons more specifically) flowing in any particular part of an electrical network. Figure 1.54 shows how this is done.

As usual, you must set the meter to current or “**amp**” mode by selecting a current range. Additionally, you might have to pull the **RED** test lead out and plug it into the **current** jack (A).

WARNING! Be careful that you don't measure current or voltage with the RED lead plugged into the wrong jack.

In most cases, the current you will be measuring in digital circuits will be in the microamp to milliamp range, so a current range setting of 100-500mA will usually suffice. Now, once you have the meter set and are ready to go then you actually have to “open” the circuit up while it is powered. This is tricky, and usually only possible when prototyping, but the point is that if you have a current flowing into point A then you must disconnect the circuitry at point A and then send the current into the meter and then back into point A. Hence, the multimeter actually becomes part of the circuit (and a very small voltage will drop over the meter as well which could potentially disturb the circuit).

WARNING! In most cases, you always want to put a current limiting resistor in series with a LED, but in this case, 3V isn't going to blow it up, so it's fine for an example.

Figure 1.55 – The Logic Probe.



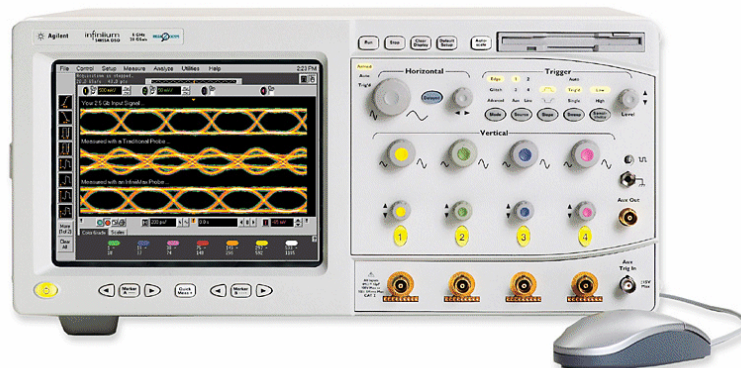
1.8.1.3 The Logic Probe

The logic probe is a device that is used to test the state of digital signals in a digital circuit. A typical logic probe is shown in Figure 1.55. Typically, the logic probe is connected directly to the power supply of the system being tested or at least a common ground is made. Then the tip of the probe is touched to various digital outputs. The logic probe then lights up and indicates if a “1” or “0” is present. This is usually done so by means of a green/red light. **Green** for “1”, **Red** for “0”.

Additionally, more advanced logic probes can also detect changing signals and pulse trains. A logic probe is an absolute must when working with digital circuits, and costs about \$20-\$50.00 for a really good one. I have always had luck with **Wavetek** products LP10A and LP25A.

TIP Some logic probes can also “**source**” a signal and send a pulse train or logic high/low to an input. This is useful when trying to trace a problem in a digital circuit. Logic probes that have these abilities are sometimes called **pulsers**.

Figure 1.56 – The Oscilloscope.



1.8.1.4 The Oscilloscope

The oscilloscope (o-scope) is probably one of the most complex pieces of test equipment there is. You can actually do so much with an oscilloscope that it would take a whole book to explain one in detail. For our purposes, all I want you to know is that o-scopes are used to view signals that change as a function of time. Basically, an o-scope takes as an input a signal and then has sweeping circuitry that scans an electron beam from left to right a number of times a second. As the signal changes, you can “see” it on the screen. The X-axis is time and the Y-axis is voltage. Figure 1.56, shows a typical 2-channel input o-scope. Notice there are controls for how fast the sweep happens, the range of the inputs, and much, much more.

Say you wanted to display a signal that was in the range of 1kHz with a peak-peak value of 5V. To view this on the o-scope you would first tie the ground of your circuit to the ground of the o-scope (so they have a common return path). Then you would set the o-scope channel 1 to say 1V/division then the signal would have a height of 5 division max. And then you might set the sweep rate to 0.1ms/division, so that on a screen of 10 divisions you would see 1 cycle.

In general, we won't need an o-scope, but knowing how to use one and owning one definitely comes in handy. If you're interested then they cost from \$300.00 to \$10,000.00. Tektronics, HP, and LG Electronics are some of my favorite manufactures.

Figure 1.57 – The Logic Analyzer.



1.8.1.5 The Logic Analyzer

The logic analyzer is a very useful device which is similar to an o-scope, but it's more of a multi-channel o-scope just for digital signals. Figure 1.57 depicts a typical logic analyzer. Logic analyzers typically have 1 or more banks of digital inputs that have from 8-32 inputs. You can connect the inputs of a logic analyzer to various points of interest in your digital circuit (computer circuitry most of the time) and watch what happens as a function of time.

Logic analyzers have to operate at very high sample rates in the MHz and GHz range since computers and digital circuits have become so fast. The only problem with logic analyzers is that they are incredible expensive. They range from \$1,000.00 on up. Now, you can find some budget analyzers that are computer cards that plug into a PC and give you 16-32 channels for \$500.00, but obviously a \$500.00 card isn't going to be able to sample a 1GHz digital circuit. A top of the line logic analyzer or "LA" is about \$50,000.00!

1.8.2 Building Materials

The last topic of discussion is building materials. Again, you would be surprised at how many people have EE degrees and have never built anything! They have simulated everything using computers. Since this book takes a more hands on tact, let's take a look at some common tools and materials needed to build the circuits of this book and more.

1.8.2.1 Basic Tools and Wire

To build simple prototypes on a breadboard or anything for that matter, you are going to need two things at very least; some basic tools and some wire. For tools, it's good to have a pair of small wire cutters, and a combination wire crimper / stripper. Although, a skilled hand can use the wire cutter to strip, it does take some skill.

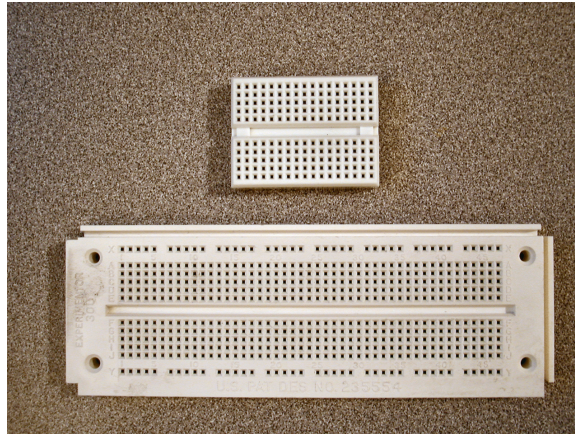
For wire that you will use to connect up your circuits, I suggest a good supply of various colors of both 22 and 24 gauge solid wire (gauge is a measure of diameter, the higher the number the smaller the diameter of the wire).

Also, it's nice to have little stranded wire of the same gauges, 22, and 24, especially to run signals over long distances off the board maybe to an output or from an input. Stranded wire is more flexible and won't tend to break like solid will for these types of applications.

TIP

Colored wire is a great way to keep track of things when you are prototyping a complex circuit. Red and black are usually used for power, and then various colors are used depending what system they compose. For example, sometimes I use yellow for logic, blue for buses, green for I/O. Whatever convention you select, it is better than a rat's nest of all the same color!

Figure 1.58 – Experimenter Boards.



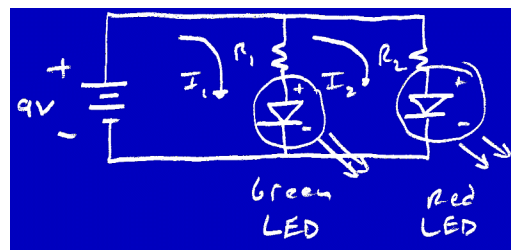
1.8.2.2 Prototype Boards

When a final production ready circuit is built, it is usually built on a printed circuit board or PCB in mass. However, printed circuit boards are manufactured using a photographic etching process and there are chemicals involved. This is surely not the way to go for quick prototyping. Hence, we are going to use “experimenter” boards. These are boards made of a hard plastic that have rows of connector blocks. Each block usually has 5 connectors each that are all electrically connected. Additionally, there are usually two power rows. Figure 1.58 shows pictures of small and large experimenter boards.

Experimenter boards come in various sizes, and you can usually pick them up at any reputable electronics store. Even Radio Shack has them (in fact, the good old **Experimenter 300** manufactured by Global Specialties can be found at Radio Shack).

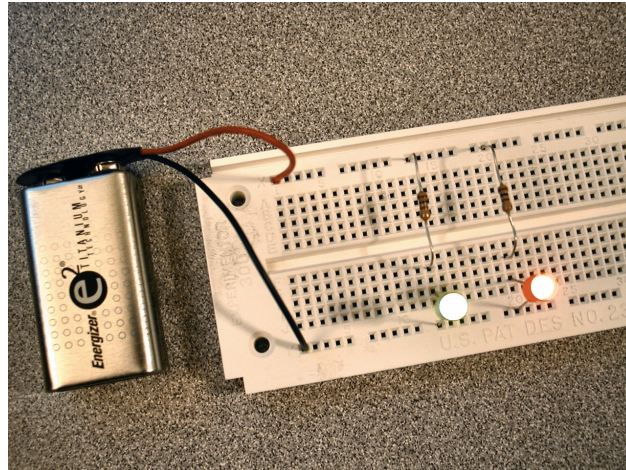
Some experimenter boards even come with power supplies that supply +5, -5, +12, and -12. But, of course they are much more expensive. In most cases, you can pick up a standard board for \$5-10 and if you get them from the same manufacturer then they usually can be snapped together to make larger boards to work with.

Figure 1.59 – A Basic LED Circuit.



Building a circuit with the experimenter board is simple, you just plug a wire or device into a connector clamp and then you have 4-5 other holes in the connector that are electrically tied together, hence you can plug other wires and components and build a circuit. Figure 1.59 shows the electrical diagram of a circuit that has a red and green LED both powered by a 9V battery. I have built the circuit and a picture of it is shown in Figure 1.60. Take a good look at it, so you understand how the connector blocks are attached.

Figure 1.60 – The LED Circuit Implemented with an Experimenter Board.



Finally, you can use various gauge wire when connecting up circuits with experimenter boards, but I find that 22 or 24 gauge works best. If you use wire that's too thick, 20 gauge for example, you will tend to “stretch” out the connector contacts over time, since they are only metal and will fatigue after a while.

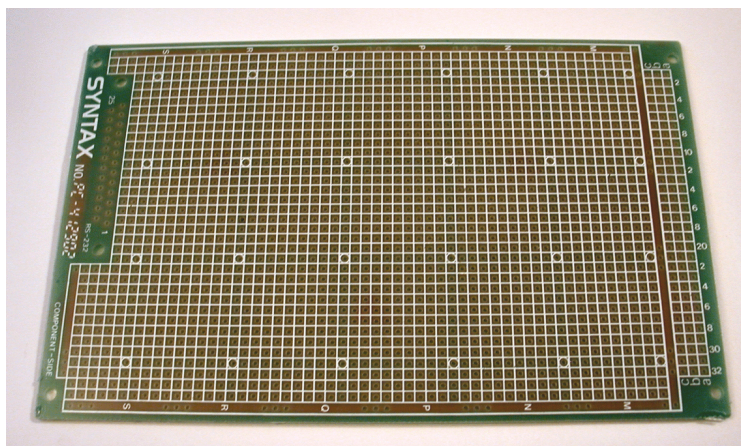
TIP

Try cutting a supply of 1”, 2”, 4”, and 8” wires, and pre-stripping them. I usually cut 50 of each and then re-use them, this way, you don't have a bunch of different length wires (one for each connection) and you can always select the shortest possible length. Remember, shorter leads are better always, the less distance signals have to travel the better.

1.8.2.3 Wire Wrapping

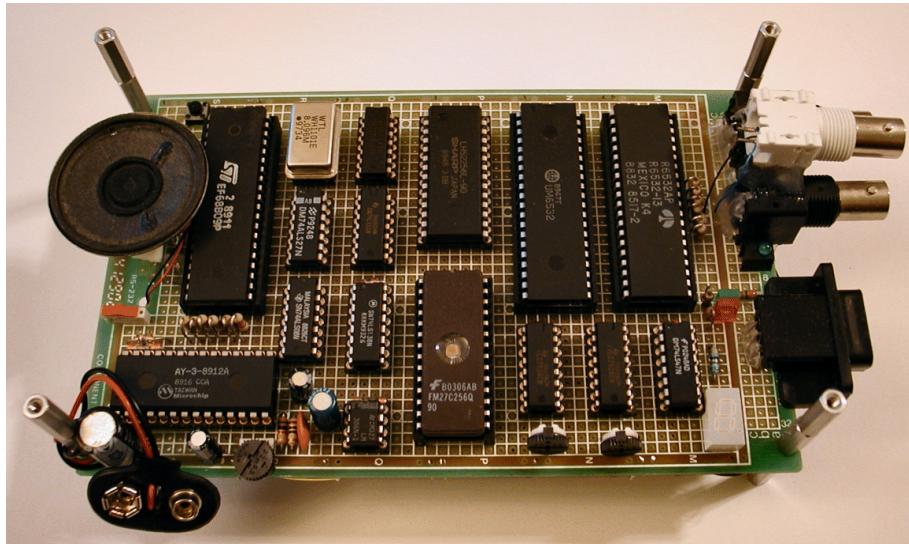
Once you have a circuit all working on experimenter boards and you are ready to clean it up and make a more permanent version of it, you could actually create a printed circuit board; however, a much easier solution is to use a wire wrap board. Later in the book we will discuss PCB design and manufacturing.

Figure 1.61 – A Wire Wrap Board.



Wire wrapping is a construction technique based on using a perforated board that has holes in a regular matrix as shown in Figure 1.61. Basically, you plug the electrical components into the board and then on the opposite side where the leads push out, you make connections with a special wire and tool. For devices that have short leads, you can first plug them into special wire wrapping sockets and then into the wire wrapping board. Figure 1.62 shows the front and back of a little computer that I built with wire wrapping – cool huh?

Figure 1.62(a) – A Wire Wrapped 6809 XGS Prototype (top view).



Now, wire wrapping is a little like sewing, so again it takes a bit of finesse, but after a bit of trying, it goes very quickly.

Figure 1.62(b) – A Wire Wrapped 6809 XGS Prototype (bottom view).

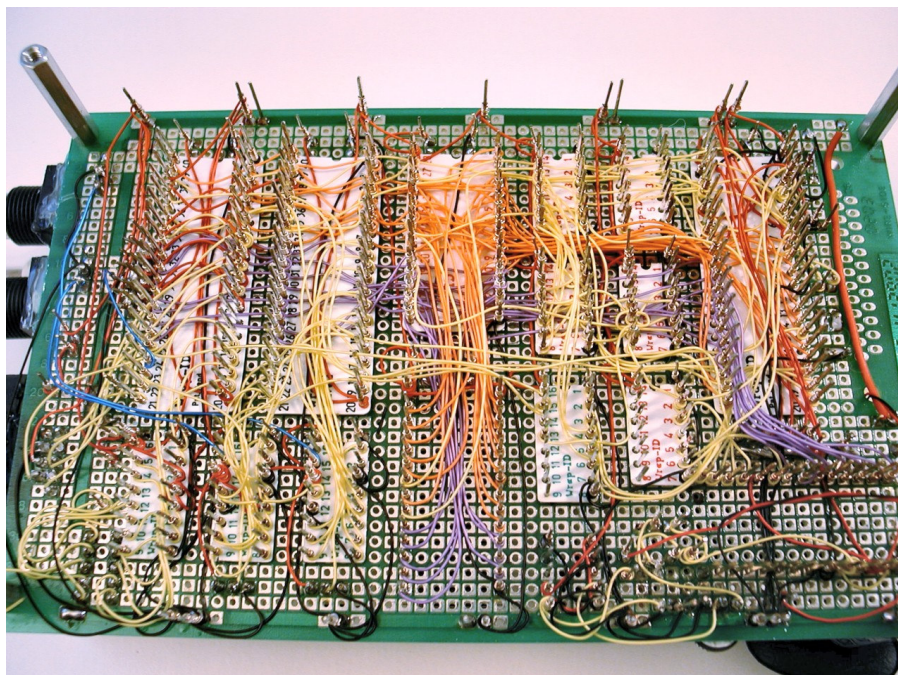
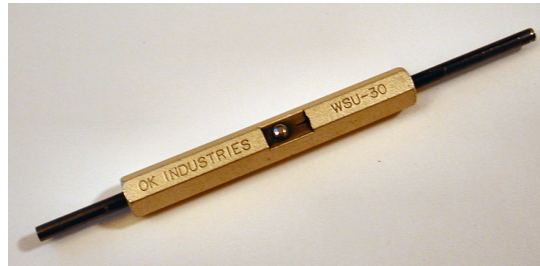


Figure 1.63 shows the tool that is used to make the connections. Basically, you first cut off a piece of wire wrap wire which is usually 28-32 gauge (very thin), and then use one end of the tool to strip off about 1/2" and then you put the striped end of the wire into a special hole in the other end of the tool and then you place the lead into the tool that you want to wire wrap on and slowly turn the wire wrap tool. It will then "wrap" the wire perfectly around the lead of the device. Then connect the other end of the wire to the other point of the circuit and you're done. You then continue this until the circuit is complete.

Figure 1.63 – A Standard Wire Wrapping Tool.

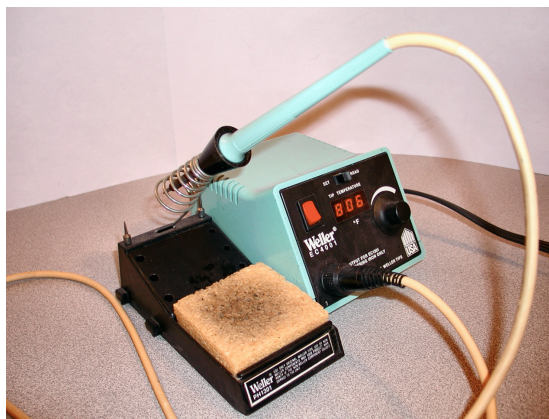


TIP

As you are wire wrapping the shorter the leads the better. And try to run wires perpendicular to each other if they cross, stray noise from signals in one wire can cause signals in another wire if they are running parallel. However, common signal buses should be kept parallel. Power lines should be thicker and more plentiful, try and distribute power in a regular matrix with lots of connection points.

Finally, wire wrap boards can handle signals up to 10MHz if wrapped by a professional engineer, so most anything you want to make will run under this speed.

Figure 1.64 – A Basic Soldering Iron.



1.8.2.4 Soldering Irons

The last tool of the trade is the soldering iron. I left this as last since it's about the only tool that can really hurt you if you don't pay continuous attention to it. Figure 1.64 shows a typical soldering iron. Basically, a soldering iron is a device that you plug into the wall, has a heating

filament that heats a metal tip which you use to liquefy “solder”. Electronics solder is usually, 20-26 gauge and is composed of tin and rosin (flux) in a 60/40 ratio.

Soldering is used when you want to make a permanent connection between two circuit elements. We may need to do a little soldering in this book, but I will try to avoid it. However, if you are going to build electronics then you NEED a soldering gun. I suggest paying about \$15.00-\$30.00 and getting something with about 25-35 watts. Weller and Hakko are good manufacturers. However, if you have the money then a digitally controlled iron is the best, so you can carefully control the tip temperature. This is especially important when soldering surface mount devices.

Soldering is another one of those things that takes skill, the trick is to “wet” the tip of the soldering iron with a little solder, then touch the tip of the soldering iron to the junction you want to solder, then in about 1 second start applying the solder to the tip and let it “flow” onto the junction. This whole process should take no longer than 2-3 seconds. If you take longer, then you may overheat the junction, melt the component, lift a PCB trace etc. However, if you don't take long enough and get a good hot solder joint, then the joint will be “cold” and conduct poorly. A good solder joint is very shiny, whereas, a poor cold joint is dull.

Practice makes perfect. Just remember to keep the soldering iron in the holder when you aren't using it and don't bump into it -- ouch!

Summary

In this chapter, we covered a lot of ground! At this point, you should have a general understanding of the physics behind current, and voltage and how to generate them. Also, you should understand basic electronic devices such as resistors, capacitors, diodes, inductors, transformers, and transistors. Finally, basic electronics equipment used to test and build circuits should be familiar to you.

Important Terms

Transformer – An AC device that transforms current or voltage from one level to another by means of electromagnetic mutual inductance.

Joule – A unit of energy equal to 1 N*m, or the amount of energy exerted when applying a 1 N force for 1 m.

Watt – A unit of power equal to 1 J/s. Also, used to measure power in electrical circuits using the formula $\text{power} = \text{voltage} \times \text{current}$.

Coloumb – A measure of charge. 1 C is equal to 6.24×10^{18} electrons.

Electron – A sub-atomic particle with negative charge found in orbit around the nucleus of an atom.

Proton – A sub-atomic particle with positive charge found inside the nucleus of an atom. Protons account for approximately half the mass of an atom's total mass.

Neutron – A sub-atomic particle with neutral charge found inside the nucleus of an atom. Neutrons account for approximately half the mass of an atom's total mass.

AC – Alternating current or voltage. Usually, means that the voltage or current is changing as a function of time sinusoidally.

DC – Direct current or voltage.

Analog – Electronics that are based on signals that are changing as a function of time or continuous signals.

Digital – Electronics that are based on discrete digital values of on/off or true/false.

Current – The flow of electrons (or holes) in a circuit. Measured in amperes (A) and referred to as I.

Resistor – An electrical device that resists the flow of current. Resistance is measured in ohms (Ω). Usually made of carbon and referred to as R.

Capacitor – An electrical device that stores charge. Capacitance is measured in farads (F) and referred to as C.

Inductor – An electrical device that stores magnetic flux. Usually constructed as a coil of wire. Measured in henrys (H) and referred to as L.

Voltage – The electrical potential between any two points. Measured in volts (V). Voltage is the “force” that pushes current in a circuit.

SI System – The international system of units based on the metric system for the most part.

RMS (Root Mean Square) – The common method of computing “average” in AC analysis. An RMS value is computed by taking the square root of the average of the squared values in question.

Power – The product of voltage and current. Measured in watts. Used to measure the overall “energy” a source can supply or is absorbing.

Semiconductor – A material that partially conducts. Silicon for example.

Voltaic Cell – An electrical energy cell that produces a voltage based on chemical reactions.

Magnetic Field – An invisible field generated by charge in motion. Travels at the speed of light and can produce force on charged particles.

Electric Field – An invisible field generated by charge itself. Travels at the speed of light. Usually measured in volts per meter.

Self-Test

(Test yourself with the following quiz. All the answers are within the text you have just read.)

1. Name the (3) sub-atomic particles and what their purpose is?
2. Define current and voltage in your own words? And give their units of measure?
3. What is the unit of measure for resistance, capacitance, and inductance?
4. Name 3 ways to generate a voltage?

5. Convert 12434.23 into scientific notation.
6. A circuit element has a voltage of 3V and 25A flowing through it, what is the power it is absorbing?
7. What does L.E.D. stand for?
8. Explain what a hole is?
9. What is conventional current?
10. How many electrons in the valence shell of Silicon?