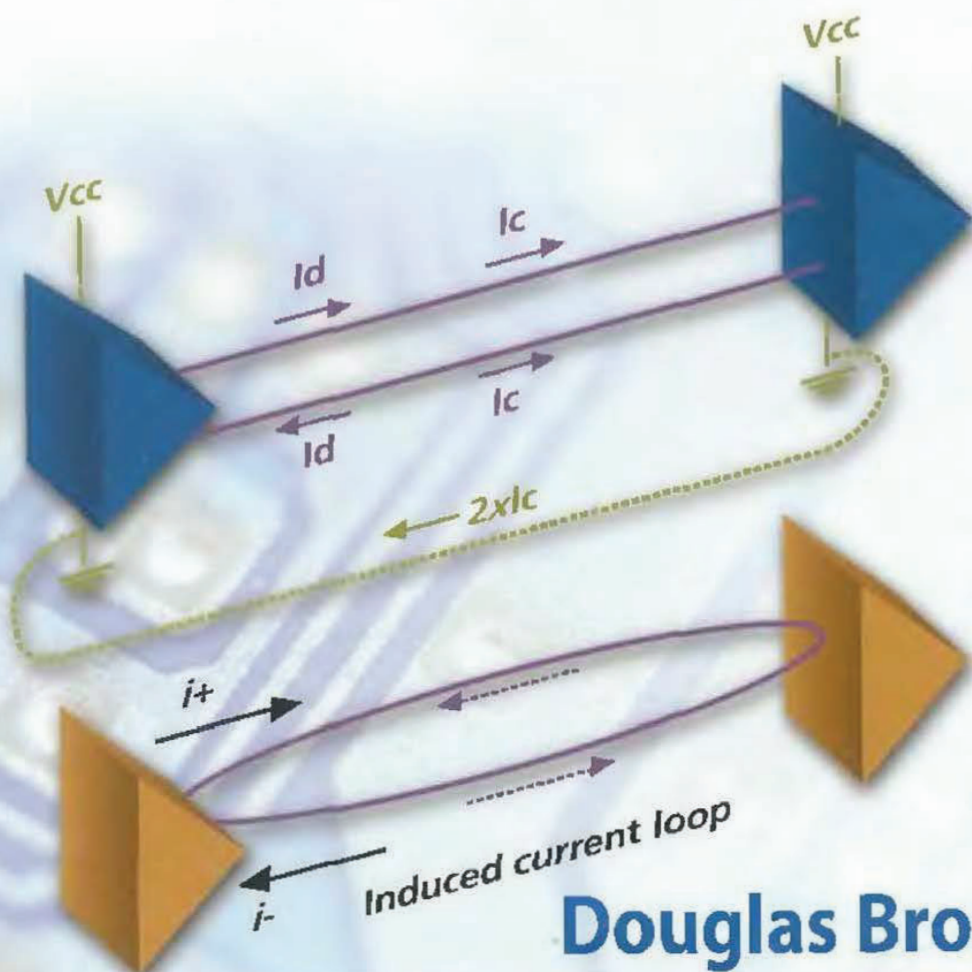


SIGNAL

Integrity Issues and Printed Circuit Board Design



Douglas Brooks

Prentice Hall Modern Semiconductor Design Series

***Signal Integrity Issues
and
Printed Circuit
Board Design***

Signal Integrity Issues and Printed Circuit Board Design

Douglas Brooks



Prentice Hall PTR
Upper Saddle River, NJ 07458
www.phptr.com

**INTEL-1010
U.S. Patent 7,151,430**

Library of Congress Cataloging-in-Publication Data

A CIP catalog record of this book can be obtained from the Library of Congress

Production Supervisor: Wil Mara
Publisher: Bernard M. Goodwin
Cover Design: Nina Scuderi
Cover Design Director: Jerry Votta
Editorial Assistant: Michelle Vincenti
Marketing Manager: Dan DePasquale
Buyer: Maura Zaldivar
Composition: Douglas Brooks



© 2003 Pearson Education, Inc.
Publishing as Prentice Hall Professional Technical Reference
Upper Saddle River, New Jersey 07458

Prentice Hall PTR offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales. For more information, please contact: U.S. Corporate and Government Sales, 1-800-382-3419, corpsales@pearsontechgroup.com. For sales outside of the U.S., please contact: International Sales, 1-317-581-3793, international@pearsontechgroup.com.

Company and product names mentioned herein are the trademarks or registered trademarks of their respective owners.

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Printed in the United States of America

Fourth Printing

ISBN 0-13-141884-X

Pearson Education Ltd.
Pearson Education Australia Pty., Limited
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd.
Pearson Education Canada, Ltd.
Pearson Educación de México, S.A. de C.V.
Pearson Education—Japan
Pearson Education Malaysia, Pte. Ltd.

DEDICATION

*T*here are a great many PCB designers in the world who do not have a technical degree. They struggle each day to keep up in an industry that is advancing very rapidly. This book is dedicated to them with the sincere hope that it will help them in their journey.

About the Web Site

The author is president of UltraCAD Design, Inc. UltraCAD maintains a Web site at <http://www.ultracad.com> where you can find a wealth of information about board design.

The site includes —

- Reprints of the articles the author has written during the past seven years
- Technical and design notes related to the board-design process
- Five freeware calculators to help board designers handle difficult tasks
- Information regarding seminars Brooks offers from time to time

As support/errata information becomes available for the book it will be posted on this site.

Prentice Hall Modern Semiconductor Design Series

- James R. Armstrong and F. Gail Gray
VHDL Design Representation and Synthesis
- Mark Gordon Arnold
Verilog Digital Computer Design: Algorithms into Hardware
- Jayaram Bhasker
A VHDL Primer, Third Edition
- Eric Bogatin
Signal Integrity: Simplified
- Douglas Brooks
Signal Integrity Issues and Printed Circuit Board Design
- Kanad Chakraborty and Pinaki Mazumder
Fault-Tolerance and Reliability Techniques for High-Density Random-Access Memories
- Ken Coffman
Real World FPGA Design with Verilog
- Alfred Crouch
Design-for-Test for Digital IC's and Embedded Core Systems
- Daniel P. Foty
MOSFET Modeling with SPICE: Principles and Practice
- Nigel Horspool and Peter Gorman
The ASIC Handbook
- Howard Johnson and Martin Graham
High-Speed Digital Design: A Handbook of Black Magic
- Howard Johnson and Martin Graham
High-Speed Signal Propagation: Advanced Black Magic

Pinaki Mazumder and Elizabeth Rudnick
Genetic Algorithms for VLSI Design, Layout, and Test Automation

Farzad Nekoogar and Faranak Nekoogar
From ASICs to SOCs: A Practical Approach

Farzad Nekoogar
Timing Verification of Application-Specific Integrated Circuits (ASICs)

David Pellerin and Douglas Taylor
VHDL Made Easy!

Samir S. Rofail and Kiat-Seng Yeo
Low-Voltage Low-Power Digital BiCMOS Circuits: Circuit Design, Comparative Study, and Sensitivity Analysis

Frank Scarpino
VHDL and AHDL Digital System Implementation

Wayne Wolf
Modern VLSI Design: System-on-Chip Design, Third Edition

Kiat-Seng Yeo, Samir S. Rofail, and Wang-Ling Goh
CMOS/BiCMOS ULSI: Low Voltage, Low Power

Brian Young
Digital Signal Integrity: Modeling and Simulation with Interconnects and Packages

Bob Zeidman
Verilog Designer's Library

TABLE OF CONTENTS

PREFACE	xvii
Part 1 BASIC CONCEPTS.....	1
1 Electronic Concepts.....	3
Current	3
Charge	5
Voltage.....	6
Direct and Alternating Voltage and Current	8
Harmonics	11
Measurement of AC Voltage or Current	12
Frequency, Rise/Fall Times, and Period	13
Frequency Measurement	16
Complex Waveforms (Fourier Analyses).....	18
Chapter Endnotes	23
Direction of Current Flow.....	23
Some Standard Symbols Used in Electronics	24
Some Fundamental Definitions.....	25
Important Names in Electronics.....	26
2 Propagation Times.....	27
Propagation Speed.....	27
Propagation Times	28
Trace Configurations and Signal Propagation.....	29
Circuit Timing Issues	32
Wavelength	35

3 Electrical Components	37
The Three Basics	37
Resistance	38
Ohm's Law	39
Capacitance	43
Charge Storage	47
Formula for Capacitance	48
Capacitance Functions and Effects	49
Inductance	50
Formulas for Inductance	55
Charge and Discharge Currents	56
Resonance	60
4 Voltage and Current Changes and Time Constants	63
Voltage and Current Changes Through Resistors	63
Voltage and Current Changes Through Capacitors	64
Voltage and Current Changes Through Inductors	66
Some Interesting Inductive Circuit Dynamics	69
Time Constants	71
A Note on Charge and Discharge Equations	76
5 Resistance	77
Kirchhoff's Laws	77
Series Resistors	79
Parallel Resistors	81
Voltage Dividers	83
Amplifier Feedback and Gain	85
Power	86
Equivalent Circuits	88
Power Curve	91
Power Sources	93
Conductance	94
6 Reactance	97
Capacitive Reactance	98
Inductive Reactance	99
Ohm's Law for Reactance	101
Series LC Combinations	104
Parallel LC Circuits	107
Resonance	111
Poles and Zeros	115

Susceptance	119
7 Impedance and Phase Shift.....	121
Impedance	121
Effect of Frequency	128
Another RC Example	129
Classic RC Filter	131
Combining Impedances.....	133
Resonance and Q.....	134
Series RLC Circuits.....	137
Series RLC at Resonance	140
Admittance	142
Chapter Endnotes	144
Detailed Calculations for Figure 7-8.....	144
RLC Simulation	145
Imaginary Numbers.....	146
Part 2 SIGNAL INTEGRITY ISSUES.....	147
8 Signal Integrity Overview.....	149
9 Electromagnetic Interference (EMI)	155
Background	155
Fields and Cancellations	156
Some Basic Truths	158
Signal Coupling.....	159
Loop Area	161
Slots in Planes 1	162
Return Pathways	163
Power Plane Returns	164
Changing Trace Layers	165
Unrelated Planes	166
Stripline.....	167
Stubs.....	168
Common Mode	169
The 20-H Rule.....	173
Picket Fences (Faraday Shields).....	174

10 Reflections and Transmission Lines	175
Communications Model	175
Transmission Lines	178
Critical Length	181
Reflection Coefficients	183
Visualizing Reflections	184
Determining Trace Impedance	185
Termination Techniques	190
Parallel	192
Thevenin	192
AC Termination	194
Series	194
Diode	195
Some Design Issues	196
Changing Trace Layers 1	196
Power Planes	197
Changing Trace Layers 2	197
Slots in Planes 2	199
Stubs	200
Absolute vs. Relative Value of Z_0	201
Chapter Endnote	203
On Formulas	203
11 Some Transmission Line Simulations	207
Basic Simulation	207
Series Termination	215
Placement Issues	217
Branches, or Ys	219
12 Crosstalk	221
Forward versus Backward Crosstalk	221
Backward Crosstalk	223
Forward Crosstalk	225
In Summary	226
Estimating Crosstalk	226
Calculations	226
Coupling	227
Distance	227
Terminations	229
UltraCAD Calculator	230
HyperLynx Simulation Tool	231
Design Considerations	232

Slots in Planes 3	232
Guard Bands.....	233
13 Crosstalk Simulations	235
Basic Model	235
Add an Uncoupled Region	239
Effect of Length	240
Stripline	242
Stripline With Terminations	242
More Realistic Example	244
Summary	247
14 Differential Traces and Impedance.....	249
Background	249
Advantages.....	249
Key Assumptions	251
Design Rules	255
Design Rule 1 (Equal Length).....	255
Common Mode Implications	255
Differential Signals and Loop Areas.....	256
Design Rule 2 (Close Together).....	257
Rule 2 Consequence.....	258
Design Rule 3 (Differential Impedance)	260
Differential Mode Impedance	260
Common Mode Impedance	261
Design Rule 4 (Constant Separation).....	262
Differential Simulations	262
Calculating Differential Impedance	265
Edge Coupled.....	266
Broadside Coupled.....	268
15 Bypass Caps and Decoupling Systems	269
Traditional Approach	269
Size and Quantity	273
Placement.....	275
Connection	276
Power System Impedance Approach.....	277
Ideal Response	277
Capacitor Response.....	278
Inductance Effects.....	278
Multiple Capacitors.....	280
Additional Capacitor Value.....	281

Planar Capacitance	282
Equivalent Series Resistance (ESR).....	285
Self Resonant Frequencies	287
Effects of Multiple Capacitors	288
Parallel Capacitors	288
Resonance	290
Impedance at Self-Resonant Frequency	291
Impedance at Anti-Resonance.....	292
General Case Analysis	293
Consequences.....	294
Summary	296
16 Power Systems	297
Power Supply Voltages	297
Need For Power Planes	300
Strategies For Designing With Plane	300
Some Design Rules	303
Connecting Reference Planes Together	303
Overlapping Planes	304
Decoupling to Wrong Plane.....	305
Signals Crossing Separations	305
Stack-Ups	307
Conclusion	308
17 Lossy Lines and Eye Diagrams	311
Lossy Lines	311
Skin Effect	312
Dielectric Absorption.....	314
Lossy Line Model	314
Eye Diagrams	316
Equalization	318
Passive Equalization	319
Active Equalization.....	319
Summary	320
Part 3 Appendices, Glossary, and Index.....	323
Appendices	325
A UltraCAD's Square Wave Simulator.....	325
B Why Inductors Induct.....	329
C Logarithms.....	345

Table of Contents**xv**

D Phase Shift Simulation	351
E Complex Algebra	357
F Transmission Line Simulation.....	367
G Echo Illustration	369
H UltraCAD Freeware Calculators	371
I TDRs and VNAs	375
J Right Angle Corners.....	383
 Glossary.....	 387
 Index	 397
 About the Author.....	 403

PREFACE

HOW IT ALL STARTED

Writing has been an avocation of mine for most of my career. And I have spent a few of my years teaching at the college level. After I became involved in the printed circuit board (PCB) design business in 1991 I submitted a couple of articles, which were subsequently published, to *Printed Circuit Design* magazine. Later, Pete Waddell asked me, as one of his contributors, to come to a press function at PCB West in 1997. Afterwards, I half-facetiously asked him if he would send me to PCB East the following fall. His answer was, "Sure, if you'll put on a seminar."

And that was how it all started.

I presented a seminar that fall entitled "Circuit Noise and EMI Control." My motivation was twofold: First I wanted to make a contribution back to an industry that had been good to me through the years. And, I wanted to go to Boston, a city I have always enjoyed visiting. Soon, I had several different seminars I was offering.

There are several of us who are sometimes considered "regulars" on the seminar circuit. Most of us like each other, respect each other, sit in on each other's seminars, and learn from each other. After a couple of years I realized that all of our collective signal integrity seminars talked about things like capacitive and inductive coupling and bypass capacitor lead-inductance-caused antiresonant impedance peaks, and so on, but most of the seminar attendees had no technical background. They didn't know what a capacitor was, much less what an antiresonant peak was!

That led to the development of a one-day "course" in electrical engineering. We titled it "Electrical Engineering for the Non-Degreed Engineer," a title that

varies from time to time. I wanted to add the words “and for the engineer who didn’t get it the first time” to the title, but Pete wouldn’t let me (probably for good reason). I don’t know how to politely say this, but I know there are a large number of engineers who just didn’t get the EMI and magnetic coupling stuff when it was presented in school, and almost no college program addresses the practical engineering problems associated with board design in their college-level curriculums. There are more people who need to read this book than we can politely invite!

Occasionally I am asked if we need to keep putting on these seminars and writing these books. After all, with more and more electronics being packaged in the chip, won’t the board problems disappear? Won’t higher and higher levels of circuit integration make PCBs obsolete?

I love that question. I heard it the first time when the integrated circuit was developed. I heard it again when the microprocessor was developed. And we hear it every time there is another increase in system-level integration. My answer is simple. Printed circuit boards are not going to diminish in importance in the future for the same reason that they haven’t diminished in importance in the past. There will *always* be a need to interconnect devices on some sort of physical surface.

ACKNOWLEDGMENTS

There are a great many people who have contributed to this book in some way or another. Pete Waddell and his team have been great to work with through the years on both the article and the seminar levels. I have been very grateful to have met and come to know many of the leaders in our field—wonderful colleagues who learn from each other and who have a lot of fun together. People like Glenn Wells and Gary Ferrari have been inspirations as I have watched how much they have given back to the development and growth of new designers starting out in our field. Glenn, in particular, seems to be everywhere in our industry—classroom, seminar room, college administrator’s office pounding the desk for more funds for program development, Top Gun contestant, and Top Gun program coordination. I am honored to count him as a friend and I appreciate the help he has given me with this book during the various phases of its development.

My partner, Dave Graves (himself a Top Gun award winner) has been invaluable in his review of my seminar materials and article drafts as they have been prepared through the years. He has often been the first to see something as it was

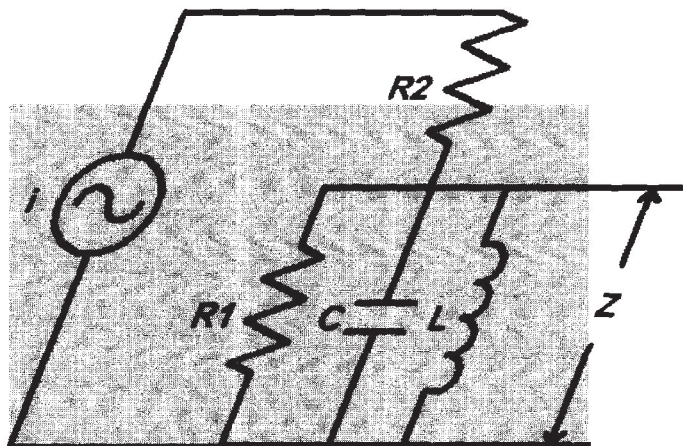
being created, and I can't tell you how many times I've gone back to the drawing board when his response was "I don't get this! What are you trying to say?" Everything is better because of his reviews and support (and numerous contributions).

I would also like to acknowledge three vendors who have been especially generous with their support for my article and seminar activities through the years. Mentor Graphics, HyperLynx (now a part of Mentor), and Polar Instruments have offered licensing and technical support whenever asked. And I appreciate the fact that they have offered that support without ever trying to exert any type of control over any of the ways that support was being used.

I've enjoyed preparing this book and have mixed emotions now that it is finished. But there are a couple of people who are *really* happy this project is finally finished, particularly my (nontechnical) wife. She has been wondering what all this fuss has been about, but is glad that I finally can think and talk about other things.

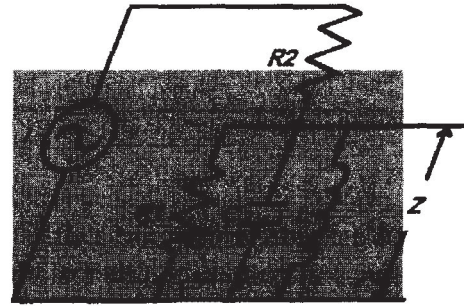
Finally, I am grateful that Bernard Goodwin at Prentice Hall decided to publish this. Going through the process of preparing a manuscript for formal publication with Bernard and with Wil Mara has been a real learning experience for me. I hope you, the reader, determine that it has all been worthwhile.

PART 1



BASIC CONCEPTS

Charles Augustin de Coulomb is credited with Coulomb's Law (1785) regarding positive and negative charges. In the century between that and the publication of James Clerk Maxwell's Equations in 1873, the knowledge of electronics expanded rapidly. This Part 1 covers the basic concepts of electronics. It starts with perhaps our most fundamental definition: Current is the flow of electrons. It ends with impedance as a complex function with both magnitude and phase shift. Along the way we discuss many fundamentals: the nature of resistance, capacitance, and inductance; combinations of these components; fundamentals of waveforms; simple circuits; and time constants. The objective is not to turn you into an engineer. This part is not that complete. But the objective is to give you the fundamental background you will need to understand the concepts discussed in Part 2.



1 ELECTRONIC CONCEPTS

CURRENT

Current is the flow of electrons.

That is a great sentence. But its simplicity belies its importance and significance. Almost every fundamental definition in electronics is based on this one, and almost every problem in signal integrity has its basis in the flow of electrons, especially if that flow changes rapidly. If I were to identify the two most important concepts in this book, this would be one of them. (The other would be Ohm's Law.)

So, let's look at this thing called an *electron*. In the early 1900s a model of the atom was developed that consisted of a nucleus, containing protons and neutrons, and one or more outer shells containing electrons (Figure 1-1). It is called a *planetary* model because it resembles a central star with planets circling around it. The protons are positively charged and the electrons are negatively charged. Since the net charge must (in a stable state) be zero, there must be an equal number of protons and electrons in any atom. The atomic number of an atom represents the number of protons in the nucleus (which also represents the number of electrons), and the atomic weight of an atom is the sum of the protons and neutrons in the nucleus.

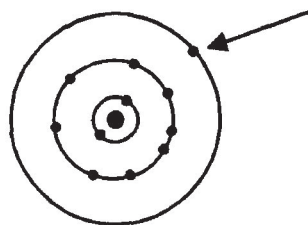


Figure 1-1 Planetary model of an atom.

We picture electrons as circling in shells, or orbits, around the nucleus. Shells have a maximum number of electrons they can hold. The innermost shell, for example, can only contain a maximum of two electrons. As one shell, or orbit, fills, electrons start occupying the next shell. (In fact, these shells are more like energy states than physical positions, but we don't know how to draw pictures of energy states.) Thus, hydrogen, the most basic element, has one proton and one electron. It has an atomic number of one. Its electron exists in the innermost shell. Helium has two protons, two electrons, and an atomic number of two. Its electrons completely fill the innermost shell. Lithium, with an atomic number of three, has three protons and three electrons. Two of those electrons occupy the innermost shell, and the third one occupies the next higher shell.

If you are familiar with the Periodic Table of the Elements, you are aware that one way elements are grouped is by the number of electrons in an element's outer shell. We also know intuitively that gold, silver, and copper are among the very best conductors of electricity. We might ask what makes these three elements so special. Well it happens that among the things these three elements have in common is that they (a) are metals, (b) they are solids at normal temperatures, and (c) they each have only a single electron in their outermost shell.

We can think of a single electron in the outermost shell as being loosely held by the nucleus and being easily dislodged by external forces. Remember the rule that like charges repel and unlike charges attract. If an external electron were to somehow approach an atom with a single electron in the outermost shell, it might easily dislodge and repel the atom's outer electron and replace it.

Now, let's say we had a whole bunch of copper atoms, stretched out in a wire. We "put" an electron into one end of the wire (perhaps by using a battery). That electron might dislodge the outer electron belonging to the first atom and replace it. That atom's electron, now free, might move along and replace the next atom's outer electron, and so on. When we finally get to the last copper atom in the wire, that atom's electron must have a place to go if it is to be replaced. If we have connected a battery at both ends of the wire, this last electron will flow back into the battery. If we have not connected the battery to both ends of the wire, there is no place for the last electron to go. Since there is no "room" for it, the process will immediately stop and no (current) flow occurs.

This very simple illustration already highlights three points:

1. This movement of electrons constitutes current.
2. Current must have a place to go; that is, it must flow in a loop. If there is no connection at the far end of the wire, there is no place for the last electron to go. Electrons will instantly build up and block the flow of any additional electrons into the wire. Electrons can only *flow* along the wire if there is a connection at both ends of the wire.
3. Batteries consist of a chemical process that provides a source of electrons at one terminal, and a corresponding shortage of electrons at the other terminal. Thus, a battery can *push* an electron in one end of a wire, as long as it receives an electron at its other terminal.

A common misconception is that the electron that goes in one end of a wire is the very same one that comes out the other end. As the illustration above suggests, this is not true. It may take a very long time (even hours) for an individual electron to travel through a wire. As an analogy, picture a *very* long train tunnel filled with identical cars moving through it. As one car enters the tunnel, another (identical) car leaves. There is a flow rate we can measure in terms of cars-per-unit-time; each time one car goes in, one car goes out. But it may take a very long time for the individual car that just went in to finally emerge at the other end.

In truth, neither illustration is exactly correct. The electrons do not move from atom to atom. They may skip over several atoms before they dislodge and replace another electron (see Figure 1-2). In crystalline copper, the overall average length of travel of an individual electron is approximately four atoms.

CHARGE

The fundamental unit of measure of charge is the coulomb (named for Charles Augustin de Coulomb. (See the note at the end of this chapter for a list of names and lifetimes of significant people in the development of electronics.) One coulomb is defined as the combined charge of 6.25×10^{18} electrons. One amp of current (named for Andre Marie Ampere) is defined as the flow of one coulomb of charge in one second of time. Thus, a current of one amp is the flow of 6.25×10^{18} electrons passing one point in one second. This is the core definition in electronics. Everything else is derived from it. (See the summary of definitions at the end of this chapter.)

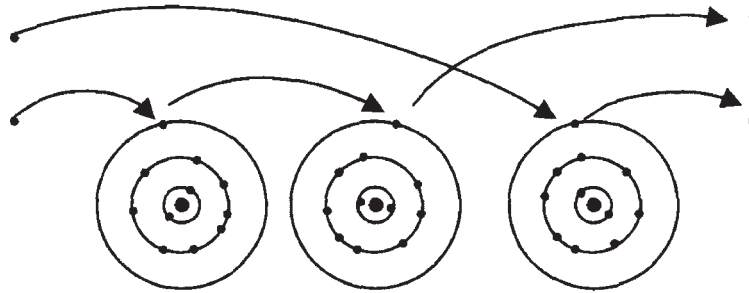


Figure 1-2 Electrons can dislodge and replace those in adjacent atoms.

Charge has polarity. Electrons have negative charge. Protons have positive charge. But charge is also a relative concept. Another way to have positive charge is to have a shortage of, or fewer, electrons. (We will later learn that as electrons flow onto one plate of a capacitor, electrons flow away from the other plate. Thus one plate has a positive charge *relative* to the other one. But both plates could be negatively charged with respect to a third plate with still fewer electrons.) Coulomb's Law states that like charges repel each other and unlike charges attract each other, with a force that is inversely related to the square of the distance between them. Two electrons, for example, will repel each other.

VOLTAGE

Voltage is a force. It is the force of voltage that causes electrons to flow (current). It is easiest to think of voltage as being a buildup of charge. For example, if we had a bunched-up "ball" of electrons, each with a negative charge, they would generate a force that would try to move themselves away from each other (since like charges repel each other). The magnitude of this force (the voltage) would be directly related to the number of electrons bunched together.

We often use hydraulic analogs to help us visualize voltage and current. Picture water flowing through an ordinary garden hose. It will flow out just a little way from the end of the hose. That is analogous to current flowing through a wire. There is only a little pressure built up in the hose, mostly caused by friction. The bigger the hose, the smaller the friction, and the closer the water will fall to the end of the hose.

Now put your thumb across half the end of the hose. You are impeding (as in impedance) the flow of the water. Pressure builds up against your thumb. This is analogous to voltage building up. The impedance causes a smaller flow of water (smaller current), but the pressure increases and causes the water to squirt further away from the end of the hose.

Using your thumb, now cover three-fourths of the end of the hose. A smaller amount of water (current) flows, but it squirts out further because of the increased pressure (voltage). If you tried to cover the end of the hose completely with your thumb, you probably couldn't. Few of us have enough strength in our hands and thumbs to completely counteract the pressure of the water.

This example intuitively points out that there is a relationship between impedance (your thumb), current (water flow), and voltage (pressure). Increasing the impedance results in less current and/or higher voltage.

Voltage is the “push” behind current. There are only a few ways we can create voltage sources. One way is to build a supply of electrons on a cathode and a “shortage” of electrons on an anode of a battery through chemical action. The difference in charge creates the force we call voltage. If we connect a circuit between the anode and cathode of a battery, current will try to flow through the circuit. Another way to create voltage is to use changing magnetic energy to “generate” the force to move electrons (the principle behind a generator or a transformer). We can temporarily store energy (voltage) in something like a capacitor. Fuel cells, photocells, and thermocouples can convert other forms of energy to voltage or current. And we can accidentally generate voltage simply by walking across a carpet (static electricity.)

We generally think of “high” voltage as being dangerous and “low” voltage as being safe. But this is not always true. Sometimes at fairs or magic shows there is equipment that will give us a one-million-volt shock without harm! And you can seriously burn yourself around a 12-volt car battery if you accidentally short the two terminals. It is power, the combined effect of voltage and current, that is dangerous, not necessarily just voltage by itself.

DIRECT AND ALTERNATING VOLTAGE AND CURRENT

We generally think of current and voltage as either direct current (DC) or alternating current (AC). DC voltage holds a steady value and DC current flows at a constant rate in a single, constant direction, at least during the relevant time of consideration. AC voltage and current change with time. We usually think of these changes as going in one direction, + (positive) voltage or current, to the opposite direction, - (negative) voltage or current, and then going back in the first direction again. But that does not always have to be the case. AC voltage could, for example, simply change from one positive level to another positive level. We also tend to consider these changes as being periodic, or repetitive. But the changes could also be random. (See the note at the end of this chapter about which direction the electrons flow.)

Figure 1-3 illustrates two typical classic AC waveforms. These are sine waves and they are fundamental to the analysis of what happens in electronic circuits. The signal grows to a positive peak and then starts to decline in magnitude until it crosses over the horizontal axis. At that time, the signal reverses itself and becomes negative. It grows to a negative peak and then declines in (negative) amplitude until it crosses the horizontal axis and reverses itself again. It continues in this fashion indefinitely.

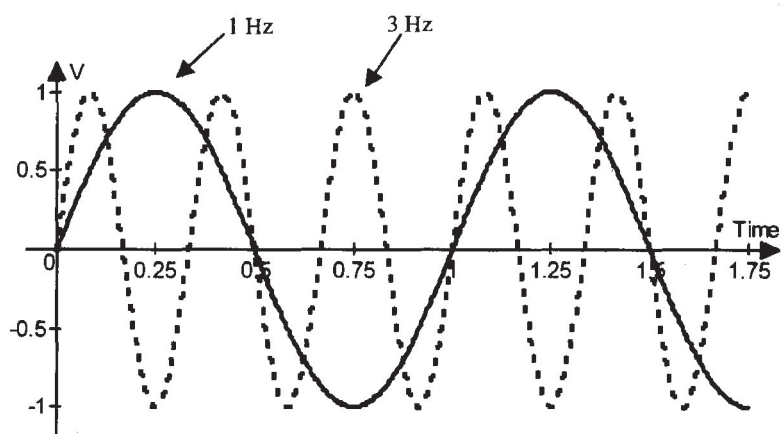


Figure 1-3 Two typical voltage sine waves.

The formula for a sinusoidal voltage waveform in its simplest form is

$$V = A \times \sin(360 \times f \times t)$$

where A is the amplitude of the waveform, 360 is the number of degrees in a cycle, f is the frequency of the waveform in Hertz (cycles per second), and t is time in seconds.

An AC waveform is characterized by three measures, its frequency (f), its amplitude (A), and its phase (Θ). Thus, a more general description of a simple voltage waveform might look like this:

$$V = A \times \sin(360 \times f \times t + \Theta)$$

Perhaps you recall from high school geometry that a sine wave and a cosine wave are shifted from each other by 90 degrees. That is, $\sin(x) = \cos(x - 90)$, or $\sin(x + 90) = \cos(x)$. We say a cosine waveform is shifted 90 degrees *ahead* of a sine waveform (the sine wave doesn't reach the same value as the cosine wave until 90 degrees later). In this instance we say that the cosine waveform *leads* the sine waveform by 90 degrees or that the sine wave *lags* the cosine wave by 90 degrees (see Figure 1-4). In this illustration, the phase shift, Θ , between a sine and a cosine waveform is 90 degrees. Phase shift is an important concept in impedance, as we will see in Chapter 7.

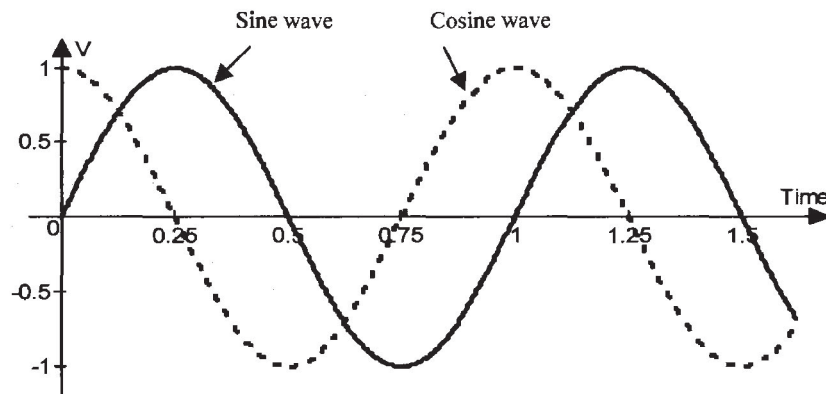


Figure 1-4 A 1-Hz cosine wave leads a 1-Hz sine wave by 90 degrees.

Phase shift, Θ , is relative. So we always need to know what the arbitrary reference point is when we are using formulas like this. Often, but not always, the reference phase (where $\Theta = 0$) is that of the driving voltage or driving current signal in our circuits. Then we speak about other voltages and currents being shifted in phase from this reference.

A sine wave is symmetrical around the horizontal axis. So, although it has a peak value (equal to $A = 1.0$ in Figure 1-4) and a peak-to-peak value (equal to 2.0, from -1.0 to $+1.0$, in Figure 1-4), its average value through time is zero.

A sinusoidal (really trigonometric) waveform is a naturally occurring waveform in nature. A bouncing ball can be described by such a waveform. Oceanic tidal action is described by a combination of such waveforms. The motion of planets around stars is described by such waveforms. The flow of AC currents is described by such waveforms. And the mathematics of calculus deals nicely with such waveforms. The problem is, the shapes of the signals in our circuits are usually not described by such waveforms (at least not directly). For example, a clock square wave doesn't look very "trigonometric" and a simple audio waveform, Figure 1-5, is decidedly not periodic!

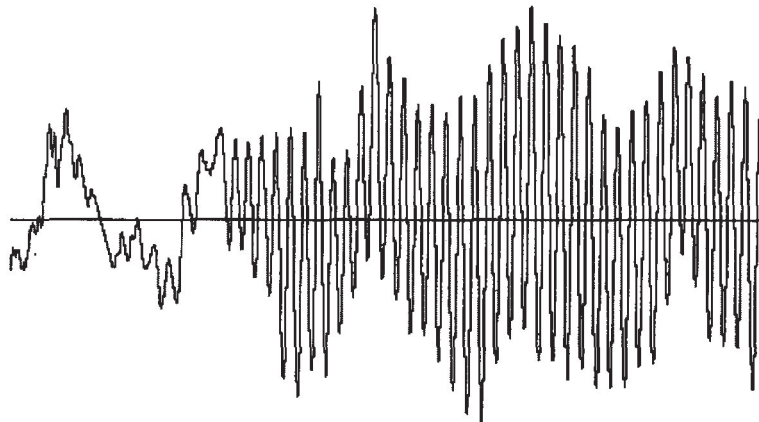


Figure 1-5 Picture of a nonperiodic audio waveform.

HARMONICS

Let's say we have a signal with a certain frequency and that we can describe that waveform by the relationship

$$V = \sin(x)$$

where x is a measure of frequency.

Then a waveform whose shape is given by the formula $V = \sin(2x)$ has twice the frequency of the first waveform, and another waveform $V = \sin(3x)$ would have three times the frequency. Figure 1-6 illustrates a signal and its third harmonic (reduced in amplitude).

We can generalize this by saying that a waveform with shape $V = \sin(nx)$ has a frequency n times higher than a waveform whose shape is $V = \sin(x)$. If the waveforms are related to each other [perhaps the $\sin(nx)$ waveform was somehow generated by the $\sin(x)$ waveform, or perhaps they were both generated by the same source] then such shapes (waveforms) are called harmonics. Harmonics are simply multiples of the base, or fundamental, frequency. In this case the $\sin(nx)$ signal is called the n th harmonic of the fundamental $\sin(x)$ signal. Harmonics will become very important later.

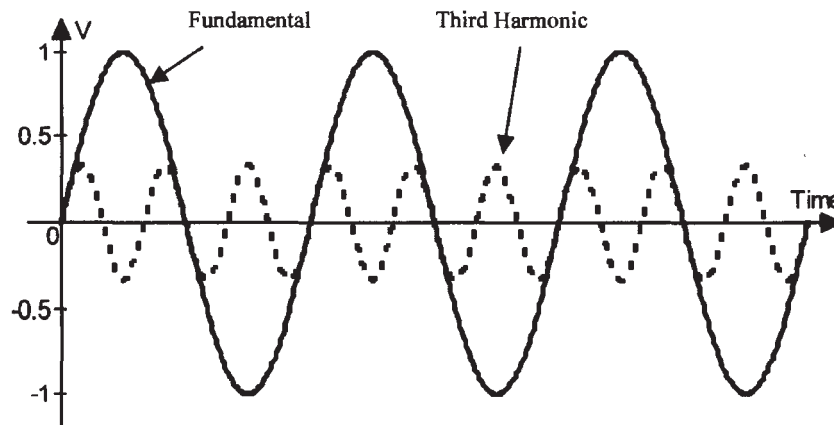


Figure 1-6 A fundamental waveform and its third harmonic.

MEASUREMENT OF AC VOLTAGE OR CURRENT

The measurement of DC voltage or current is straightforward. It is simply the observed value. But the measurement of AC waveforms is a different matter. Assume the waveform cycles around zero (the horizontal axis, see Figure 1-7). We can't use the average value, since that is always zero no matter what the peak value is. The peak value (1.0 V in Figure 1-7) and the peak-to-peak value (2.0 V in the figure) also are misleading, since that doesn't take into consideration the "shape" of the waveform.

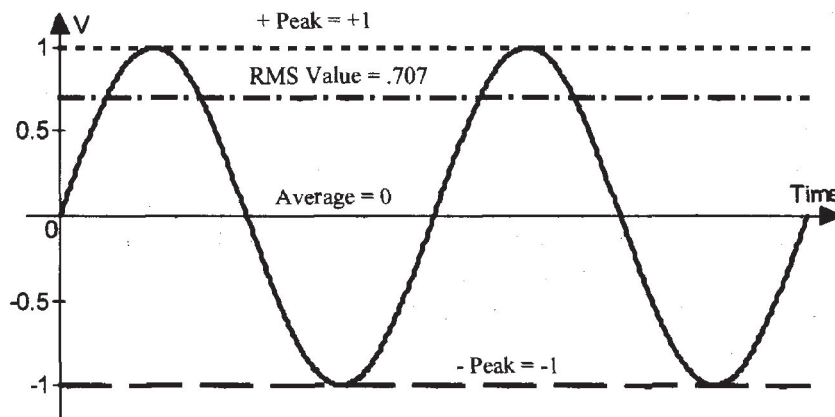


Figure 1-7 RMS value in relationship to other measures of amplitude.

Instead, we use a measurement value for AC waveforms called the RMS value. RMS stands for Root-Mean-Square. Conceptually, we find the RMS value by breaking up the waveform into a large number of small sections, and then (a) squaring the amplitude of the waveform for each section, (b) calculating the mean value of all of these squared values, and (c) then taking the square root of this mean value. Mathematically we represent the RMS value of a waveform with this formula:

$$\text{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^n \sin^2(n)} \quad [1-1]$$

The RMS value of a 1.0-V sine wave as shown in Figure 1-7 works out to be .707 volts. In general, the RMS value of a sine or cosine waveform is .707 times the peak value. That means that the 117-volt AC waveform in our homes has a peak value of $117/.707 = 165.5$ volts and a peak-to-peak value of 231 volts.

The true RMS value of any waveform actually relates to power. Suppose we applied the sine wave voltage waveform in Figure 1-7 across a resistor. The RMS value is the equivalent DC voltage that would generate the same power (i.e., heat) in the resistor. Thus, a DC voltage of .707 V across a resistor will heat the resistor exactly the same amount that a ± 1.0 V sine wave would.

But this value, .707, is only the true RMS value for a sine wave. What if the waveform were a different shape? What if the waveform were random? The audio waveform shown in Figure 1-5 seems pretty random when you look closely at it. How could we then measure its RMS value?

A simple AC meter measures AC waveforms accurately only if they are sine waves. The meters typically rectify the AC waveform and are then calibrated to apply a fraction to the peak value or to the average value of the rectified waveform. But this technique only works when the shape of the waveform is known to be sinusoidal. There are really only two primary ways to measure the “true” RMS value of a nonsinusoidal waveform. In the past, so-called “true” RMS meters often applied the test voltage across a resistor and measured the heat generated, inferring the RMS value that way. More recently, with improved calculational power, we can use microprocessor-based instruments to actually do the calculations in Equation 1-1.

Even today, meters that do not *expressly* indicate that they are true RMS meters probably only measure AC voltages accurately if the waveforms are sinusoidal.

FREQUENCY, RISE/FALL TIMES, AND PERIOD

Frequency is the measure of how many times the current cycles through a change in direction in one unit of time (usually one second). Thus, the dotted curve in Figure 1-3 illustrates a higher frequency wavelength than does the solid line waveform in that figure. If the horizontal axis in the figure represents seconds, then the solid waveform in the figure has a frequency of one cycle per second (or 1 Hertz) and the dotted waveform has a frequency of 3 Hertz. We now commonly see waveforms on our circuit boards with frequencies in the range of hundreds of mil-

lions of cycles each second (hundreds of MHz) and sometimes much higher. That means the AC waveform, or the current, is cycling back and forth, or changing direction, hundreds of millions of times each second!

It is a common misconception that *frequency* is the issue in high-speed designs. As we will learn in this book, it is *rise time* that is the real culprit. Figure 1-8 illustrates two waveforms, one a sine wave and the other a square wave. (The square wave is representative of what we would like (even wish) our clock signals to resemble) Each of these waveforms has the same frequency. But these two waveforms have significantly different rise times.

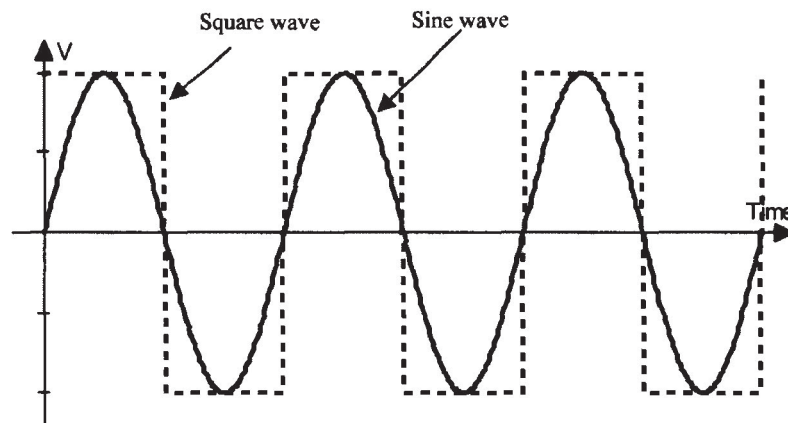


Figure 1-8 Frequency versus rise time.

Rise time is normally defined as the length of time required for the waveform to rise from the 10% point on the waveform to the 90% point (Figure 1-9). Occasionally you will see rise time defined between the 20% and 80% points. Fall time is defined exactly the same way, the time for the waveform to fall from the 90% point to the 10% point. If you superimposed a sine wave alongside the rising edge of a signal, as shown in Figure 1-9, it can be shown that the 10% to 90% portion of a sinusoidal waveform is just about one-third the time for a complete cycle, or period, τ , of the waveform.

The time required for a single cycle is $1/f$ where f is the frequency. The time for a single cycle is called the period (τ). So a sine wave with a frequency of 1 MHz (one million cycles in a second) has a period of one-millionth of a second,

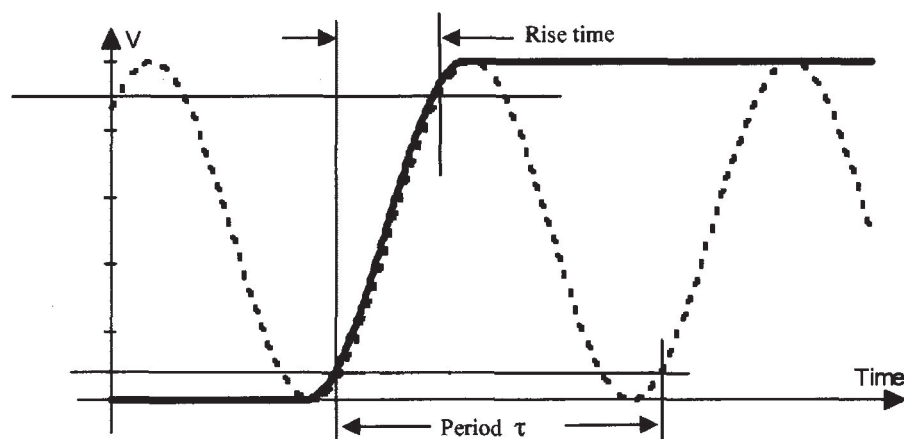


Figure 1-9 The rise time of a pulse is approximately 30% of the period of the underlying sine wave.

or 1 μs , or 1,000 ns. Therefore, the rise time of a 1-MHz sine wave is about one-third of that, or about 333 ns.

You might ask why we refer to the 10% to 90% range of amplitude for rise time and not the 0% to 100%. Or why some use the 20% to 80% measure for rise time. The answer may be somewhat less than satisfying, but it goes like this: Almost all switching devices follow a switching pattern similar to that shown by the rising line in Figure 1-9, but they may differ significantly in the very first or last portions of their switching pattern. For example, one type of device may reach 100% very quickly, but another device may roll off as it approaches the 100% level, and actually may not reach 100% for several moments (we sometimes say it may approach 100% *asymptotically*). Switching devices might have quite different switching patterns in the very beginning or ending stages of their switching range, but usually all have quite similar patterns during their main transition. Therefore, we use the 10% to 90% points of the switching range for the rise time measure in order to compare “apples to apples.” Sometimes others may use the 20% to 80% range because the beginning and ending parts of the switching range are a little “broader” than other devices, or because they are engaging in “specsmanship” (the 20% to 80% range is shorter and therefore faster).

Suppose we have a voltage or current requirement in a circuit that changes rapidly. For example, suppose we have a current requirement that goes from 0 mA

to 10 mA within 1 ns. We can express this requirement as a “change in current divided by a change in time,” or $\Delta i/\Delta t$ (where Δ means change). If we consider the relationship, $\Delta i/\Delta t$, and think of Δt being an extremely short period of time, then we would mathematically express the relationship as di/dt (pronounced dee-eye-dee-tee). The term di/dt is a calculus expression that means “the change in current divided by the change in time as the change in time becomes vanishingly small,”—that is, as Δt becomes really small! In really fast circuits, the term dt equates to the rise (or fall) time of the signal. We will see later that it is this di/dt term that causes the signal integrity problems.

We in the industry often simply use the term *rise time* generically to describe a circuit requirement. The reader should understand that fall time is equally important. What is really important is the faster of the two. So when you read “rise time” think “rise or fall time, whichever is faster.”

FREQUENCY MEASUREMENT

We actually can measure, or refer to, frequency in three ways. The most common one is in cycles per second, or Hertz, often designated by the symbol “f.” Thus, the waveform shown in Figure 1-10 has a frequency of 3 Hertz, or $f = 3$. This is a very common measure of frequency. We can also refer to the number of degrees the waveform goes through in one second. A sine wave completes 360 degrees in one cycle, so in three cycles it completes 360×3 or 1080 degrees. Thus, the waveform in Figure 1-10 could be said to have a frequency of $360 \times f$ or 1080 degrees/second. In general we could describe any frequency as $360 \times f$ degrees/second. We almost never use this measure of frequency!

But there is a related measure of angular frequency we *do* use. We start by dividing the circumference of a circle into radians. A radian is the angle formed by a length along the circumference of a circle equal to the radius of the circle (Figure 1-11). Take a length equal to one radius and lay it along the circumference. Look at the angle formed by the beginning and the end of this length (arc). That angle is defined as a radian.

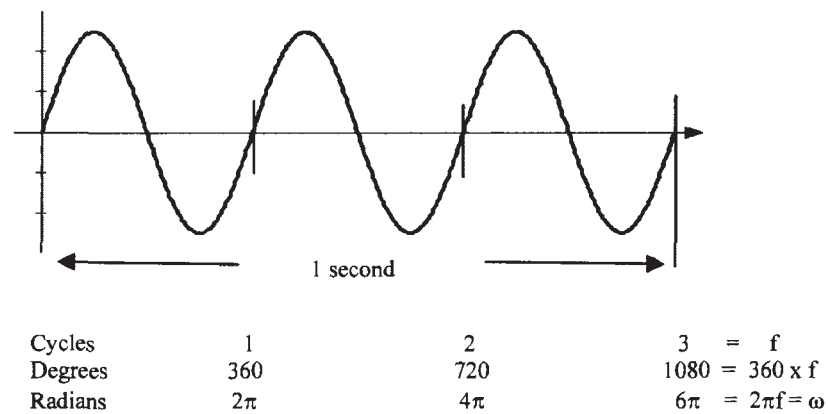


Figure 1-10 Alternative ways of measuring the frequency of a waveform.

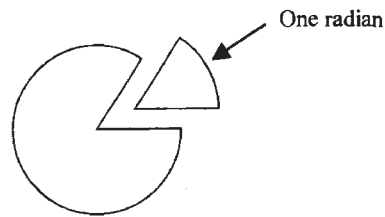


Figure 1-11 Definition of a radian.

The circumference of a circle is $2\pi r$, where r is the radius. So if we ask how many radians there are in a circle (360 degrees) the answer is:

$$\text{Circumference/radian} = 2\pi r / r = 2\pi.$$

So, 2π radians make up a complete circle (360 degrees).

Since there are 2π radians in 360 degrees, there are therefore $2\pi f$ radians completed by a sine wave in one second. This measure of frequency we *do* use in electronics and it is given a special symbol, ω , as shown in Equation 1-2.

$$\omega = 2\pi f \quad [1-2]$$

This measure of frequency is called the *angular frequency* and shows up in a great many formulas used in electronics. It measures the number of radians a sine wave goes through (completes) in one second.

COMPLEX WAVEFORMS (FOURIER ANALYSES)

We will find later in this book that there are only three types of passive components we have to worry about on our boards and in our designs, resistors, capacitors, and inductors. Each type of component offers an *impedance* to the flow of current. For a resistor, this impedance is simply a matter of the value of the resistor's size. But for capacitors and inductors, the impedance is a function of both the component's size and the frequency of the waveform that interacts with the component. So an inductor, for example, offers higher impedance as (a) its size increases and as (b) frequency goes up. (We will discuss the specifics of this in Chapters 5 and 6.)

What is not often stated, but is just generally understood, is that *frequency* in this context refers to a specific sinusoidal waveform of a single frequency, not something more complex. So when we say the impedance of a circuit is such-and-such a value at 1 MHz, we mean at a 1-MHz sine wave, not, for example, a 1-MHz square wave. That, then, means that when we analyze the performance of a circuit (using the basic formulas) we can do so only at a specific frequency and for a specific waveform (sinusoidal). This raises an interesting question: How do engineers analyze circuits when there are more complex waveforms?

The real answer, of course, is beyond the scope of this book. But in this part of the book I outline the basic approach that is used. Then, when you understand that, you will begin to understand some of the other subtleties we will talk about when discussing high-speed design issues.

There is a very important theorem in electronics called Fourier's Theorem. It forms the basis for many higher order analyses. It goes like this:

Fourier's Theorem: Every signal or curve, no matter what its nature may be, or in what way it was originally obtained, can be *exactly reproduced* by superposing a sufficient number of individual sine (and or cosine) waveforms of different frequencies (harmonics) and different phase shifts.

This means that any waveform (in theory it must be a repetitive waveform, but in practice we often wink at that requirement) can be reproduced by superimposing a sufficient number of sinusoidal waveforms at higher frequency harmonics. So, we take a look at our input waveform of interest (perhaps a video signal, perhaps a complex digital signal formed by a series of square waves and pulses) and reproduce it with a series of sinusoidal waveforms (which Fourier's Theorem says we can do). Then we analyze the performance characteristics of our circuit for *each one* of the individual sinusoidal waveforms. Finally, we add up (superimpose) all of these results to get the combined result of the circuit to our input waveform.

Conceptually, this is simple and straightforward. From a practical standpoint, this is unmanageable, particularly since some waveforms (such as a square wave) require an infinitely long series of harmonically related terms. The way it is actually done involves very complex calculus and higher order transforms. But we don't have to deal with the complexities of how it is done. We simply need to understand that it can be done. Then we can appreciate the implications.

Let's look at some examples. A square wave is not a natural waveform that exists in nature. We can use a Fourier transform, however, to represent it as an infinite series of cosine or sine waves. One form of a square-wave series is as follows:

$$\text{Square}(\theta) = \text{Cos}(\theta) - \frac{\text{Cos}(3\theta)}{3} + \frac{\text{Cos}(5\theta)}{5} - \frac{\text{Cos}(7\theta)}{7} + \text{etc} \quad [1-3]$$

Each component (term) in the series shown in Equation 1-3 represents a harmonic of the fundamental frequency, Θ . As it happens, a square wave, when represented by this cosine series, only contains odd harmonics. Figure 1-12 illustrates what happens as we use progressively more terms (harmonics) to represent the function. Each additional harmonic makes the resulting waveform look a little more like a square wave.

Figure 1-13 shows an example of this same series carried out to 101 harmonics ($2 \times 50 + 1$). The example was created using Mathcad, a readily available software package available from Mathsoft, Inc. If you have Mathcad software, you can replicate this example on your own.

There is a demonstration program available on the UltraCAD Web site called Square.exe. Instructions for using it are included in Appendix A. It allows

you to explore this cosine series in some detail and see how various assumptions affect the nature of the waveform.

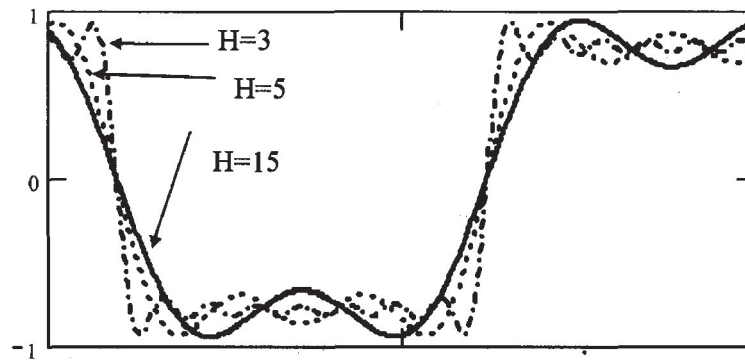


Figure 1-12 As we add more harmonics to the series, a better approximation to a square wave results.

Square Wave:
$$y(wt) := \sum_{n=0}^{50} (-1)^n \cdot \frac{\cos[(2 \cdot n + 1) \cdot wt]}{(2 \cdot n + 1)}$$

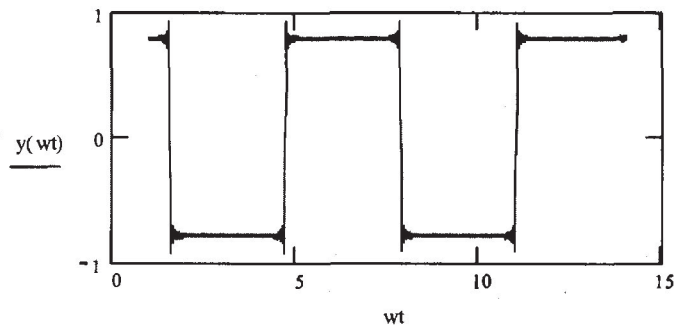


Figure 1-13 Fourier series for a square wave carried out in Mathcad.

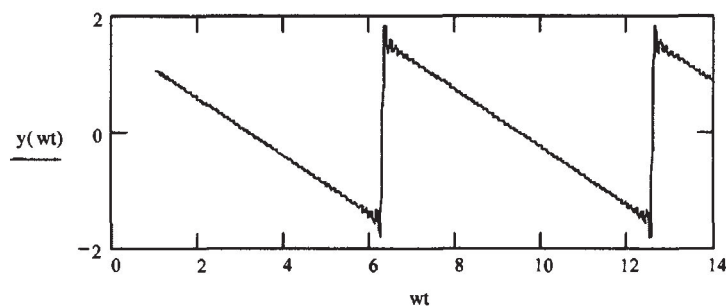
Figure 1-14 illustrates various series for forming some other standard waveforms. What is instructive here is that any waveform can be “decomposed” into a series of sinusoidal harmonic terms that can then (at least conceptually) be individually analyzed, then summed, to determine the response of a circuit. Again, conceptually this is straightforward. In practice it can be quite difficult and involves very complex math and calculus.

If you understand this so far, then you can appreciate that there is a very significant implication of this for board design. Digital logic circuits deal with signals that look a lot like square waves. If we put a square wave onto a trace at one end, we want to get a square wave at the other end. That means our boards must be designed to handle not only the fundamental frequency of our digital signals, but also all of the higher order harmonics that are contained within it. Figure 1-12 suggests we want to be able to handle at least the tenth or fifteenth harmonics. So if we are dealing with a 10-MHz clock square wave, we need to be able to handle frequency harmonics up to at least 100 or 150 MHz. This is why we say it is not the (clock) frequency that matters, it is the rise time of the waveform and the harmonics needed to reproduce it that are important.

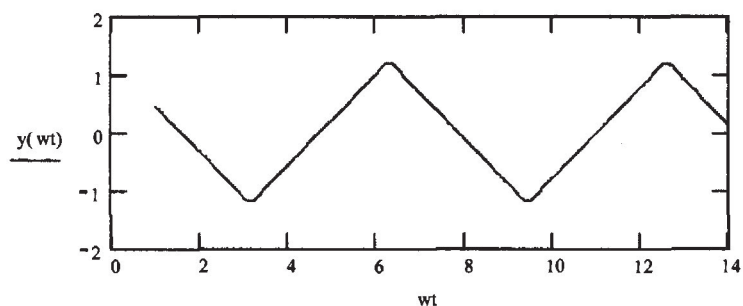
The term *bandwidth* is used to describe this requirement. The bandwidth is the range of frequencies we need to be able to deal with to faithfully maintain the integrity of our signals. One way to look at bandwidth requirements is suggested in the previous paragraph. Another way is suggested by Figure 1-9. Determine the fastest rise time you will encounter on the board and then determine the bandwidth requirement from the formula in Equation 1-4:

$$\text{bandwidth (Hertz)} \cong .3/\text{rise time} \quad [1-4]$$

Sawtooth Wave $y(wt) := \sum_{n=1}^{50} \frac{\sin(n \cdot wt)}{n}$



Triangular Wave: $y(wt) := \sum_{n=0}^5 \frac{\cos[(2 \cdot n + 1)(wt)]}{(2 \cdot n + 1)^2}$



Impulse Signal:

$$y(wt) := 1 + \sum_{n=1}^{10} \cos(n \cdot wt) \quad y1(wt) := 1 + \sum_{n=1}^{30} \cos(n \cdot wt)$$

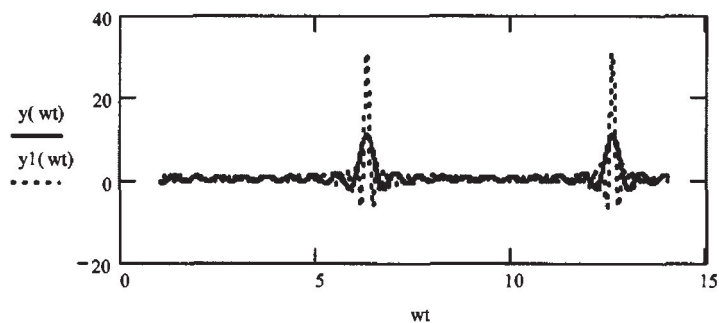


Figure 1-14 Fourier series for three common complex waveforms.

Chapter Endnotes

DIRECTION OF CURRENT FLOW

There is a point that I will mention once, here, and then we won't mention it again. I believe it was Benjamin Franklin who stated that current flows from positive to negative. And we have followed that convention ever since. But current is the flow of electrons, and electrons are negatively charged little critters that flow toward positive charges (or, perhaps more accurately, toward the absence of negatively charged particles). So electrons (current) flow from negative to positive, not from positive to negative! This anomaly has been with us since the beginning of electronic study and is usually ignored. We always use the convention that current flows from positive to negative, and the only time in my career when this has truly been an issue is when I have studied semiconductor theory, where the behavior of electrons is really at the heart of what is happening. So, if it ever does confuse you that there seems to be a contradiction here, well, Benjamin Franklin made at least one mistake in his life, and that has stuck with us for all time since!