

**The
Essential
Guide to
Digital Signal
Processing**

This page intentionally left blank

**The
Essential
Guide to
Digital Signal
Processing**

**Richard G. Lyons
D. Lee Fugal**

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed with initial capital letters or in all capitals.

The authors and publisher have taken care in the preparation of this book, but make no expressed or implied warranty of any kind and assume no responsibility for errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of the use of the information or programs contained herein.

For information about buying this title in bulk quantities, or for special sales opportunities (which may include electronic versions; custom cover designs; and content particular to your business, training goals, marketing focus, or branding interests), please contact our corporate sales department at corpsales@pearsoned.com or (800) 382-3419.

For government sales inquiries, please contact governmentsales@pearsoned.com.

For questions about sales outside the U.S., please contact international@pearsoned.com.

Visit us on the Web: informit.com/aw

Library of Congress Cataloging-in-Publication Data

Lyons, Richard G., 1948–

The essential guide to digital signal processing/Richard G. Lyons, D. Lee Fugal.

pages cm

Includes index.

ISBN-13: 978-0-13-380442-3 (alk. paper)

ISBN-10: 0-13-380442-9 (alk. paper)

1. Signal processing--Digital techniques. I. Fugal, D. Lee. II. Title.

TK5102.9.L958 2014

621.38522--dc23

2014006918

Copyright © 2014 Pearson Education, Inc.

All rights reserved. Printed in the United States of America. This publication is protected by copyright, and permission must be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, One Lake Street, Upper Saddle River, New Jersey 07458, or you may fax your request to (201) 236-3290.

ISBN-13: 978-0-13-380442-3

ISBN-10: 0-13-380442-9

Text printed in the United States on recycled paper at RR Donnelley in Crawfordsville, Indiana.

First printing, May 2014

Executive Editor

Bernard Goodwin

Managing Editor

John Fuller

Project Editor

Elizabeth Ryan

Copy Editor

Deborah Thompson

Proofreader

Christine Clark

Editorial Assistant

Michelle Housley

Cover Designer

Chuti Prasertsith

Composer

Shepherd, Inc.

Contents

Preface *xi*

| | | |
|----------|----------------------------------------------------|-----------|
| 1 | What Is Digital Signal Processing? | 1 |
| | The Phantom Technology | 1 |
| | What Is a Signal? | 2 |
| | Analog and Digital Signals | 3 |
| | Digital Signal Processing | 3 |
| | What You Should Remember | 5 |
| | | |
| 2 | Analog Signals | 7 |
| | What Is an Analog Signal? | 7 |
| | A Temperature Analog Signal | 7 |
| | An Audio Analog Signal | 8 |
| | An Electrical Analog Signal | 10 |
| | What Is an Electrical Voltage? | 10 |
| | Sinusoidal Wave Voltages | 13 |
| | Other Useful Periodic Analog Signals | 19 |
| | A Human Speech Analog Signal | 21 |
| | What You Should Remember | 22 |
| | | |
| 3 | Frequency and the Spectra of Analog Signals | 25 |
| | Frequency | 25 |
| | Cycles per Second | 26 |
| | Radians per Second | 28 |

The Concept of Spectrum 29**Analog Signal Spectra 30**

A Composite-Signal Spectral Example 32

Harmonics 34

Harmonic Distortion 37

Bandwidth 39

The Other Bandwidth 42

What You Should Remember 42**4 Digital Signals and How They Are Generated 43****What Is a Digital Signal? 43**

The Notion of Digital 43

Digital Signals: Definition #1 44

Digital Signals: Definition #2 45

How Digital Signals Are Generated 48

Digital Signal Generation by Observation 48

Digital Signal Generation by Software 48

Digital Signal Generation by Sampling an Analog Signal 49

The Sample Rate of a Digital Signal 52

A Speech Digital Signal 53**An Example of Digital Signal Processing 55****Another Example of Digital Signal Processing 57****Two Important Aspects of Sampling Analog Signals 61**

Sample Rate Restriction 62

Analog-to-Digital Converter Output Numbers 62

Sample Rate Conversion 63

Decimation 63

Interpolation 63

What You Should Remember 66**5 Sampling and the Spectra of Digital Signals 67****Analog Signal Spectra—A Quick Review 67****How Sampling Affects the Spectra of Digital Signals 71**

The Mischief in Sampling Oscillating Quantities 73

Sampling Analog Sine Wave Voltages 76

Why We Care about Aliasing 80

| | |
|---------------------------------------------------|-----------|
| The Spectrum of a Digital Sine Wave Signal | 82 |
| The Spectrum of a Digital Voice Signal | 85 |
| The Spectrum of a Digital Music Signal | 86 |
| Anti-Aliasing Filters | 89 |
| Analog-to-Digital Converter Output Numbers | 93 |
| What You Should Remember | 94 |

6 How We Compute Digital Signal Spectra 95

| | |
|---------------------------------------|------------|
| Computing Digital Spectra | 95 |
| The Discrete Fourier Transform | 96 |
| The Fast Fourier Transform | 96 |
| A Spectral Computation Example | 97 |
| The Computations | 97 |
| What the Computations Mean | 103 |
| A Spectral Analysis Example | 103 |
| What You Should Remember | 106 |

7 Wavelets 107

| | |
|------------------------------------------------------------------|------------|
| The Fast Fourier Transform (FFT)—A Quick Review | 107 |
| The Continuous Wavelet Transform (CWT) | 109 |
| Undecimated or Redundant Discrete Wavelet Transforms (UDWT/RDWT) | 114 |
| Conventional (Decimated) Discrete Wavelet Transforms (DWT) | 114 |
| What You Should Remember | 117 |

8 Digital Filters 119

| | |
|---------------------------------|------------|
| Analog Filtering | 119 |
| Generic Filter Types | 121 |
| Digital Filtering | 122 |
| What You Should Remember | 126 |

9 Binary Numbers 127**Number Systems 128**

Decimal Numbers, a Base-10 Number System 128

A Base-4 Number System 129

Binary Numbers, a Base-2 Number System 130

Using Binary Numbers at Home 132

Binary Data 133**Why Use Binary Numbers? 134**

Digital Hardware Is Easy to Build 134

Binary Data Is Resistant to Degradation 135

Binary Numbers and Analog-to-Digital Converters 136**What You Should Remember 139****A Scientific Notation 141****B Decibels 145**

Decibels Used to Describe Sound Power Values 146

Decibels Used to Measure Earthquakes 147

Decibels Used to Describe Signal Amplitudes 149

Decibels Used to Describe Filters 153

C AM and FM Radio Signals 155

AM Radio Signals 155

FM Radio Signals 157

Comparing AM and FM Radio 159

D Binary Number Formats 161

Unsigned Binary Number Format 161

Sign-Magnitude Binary Number Format 162

Two's Complement Binary Number Format 163

Offset Binary Number Format 165

Alternate Binary Number Notation 166

Octal Binary Number Notation 166

Hexadecimal Binary Number Notation 166

Glossary 169

Index 185

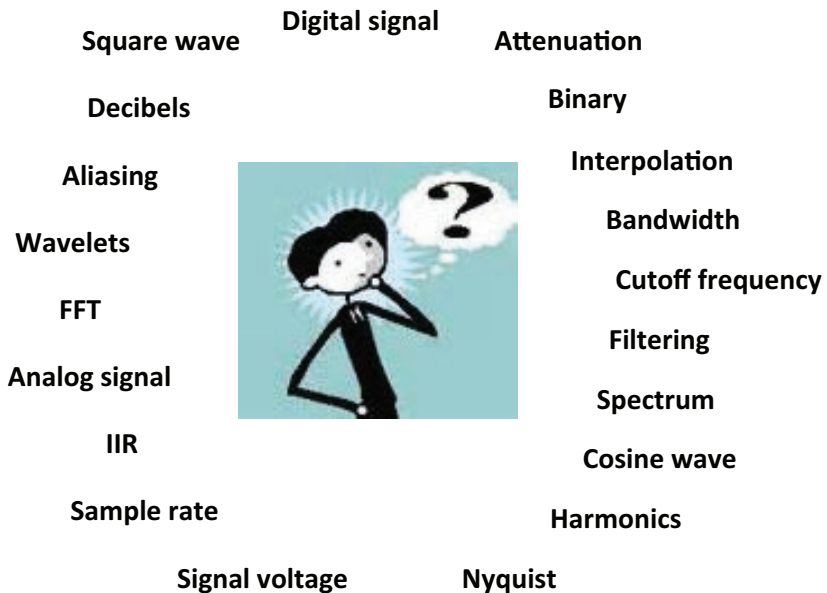
This page intentionally left blank

Preface

We're all familiar with the word *signal* as something that conveys information such as traffic signals, distress signals, or even smoke signals. In certain card games, we even try *not* to signal when we've been dealt a good hand. But what does it mean to *process* a signal? This book is written to answer that question for you as clearly and simply as possible, using real-world examples of signals and signal processing with which you are already familiar.

Although we don't often realize it, our daily lives are routinely influenced by signals and signal processing. This book not only shows why this is so, but goes further, to explain, for example, why the audio from an FM radio sounds so much better than the audio you hear from your cell phone.

This book is intended for nontechnical people rather than engineering students. As such, the book has two main objectives: to describe the fundamental concepts of signals and signal processing in an understandable way with a minimum of mathematics, and to introduce the reader to the language—the lingo—of signal processing. (To aid the reader, a comprehensive glossary of signal processing terminology and acronyms is included at the end of the book.)



In particular, for those nontechnical readers who are involved with companies that produce or use signal processing hardware or software, you have our utmost sympathy. You are exposed to a vast array of mysterious concepts and terminology. This book will remove that mystery so you can further understand signal processing and more effectively communicate with engineers and other technical people.

As it turns out, the topic of signals can be divided into two main categories: analog signals and digital signals. This book slowly and gently explains the nature of both types of signals and how they are used to improve the quality of our lives.

We've written this book in what we think is a sensible progression of chapters, but it's not necessary to read the chapters in order, or even to read all of them. Chapter 1 explains how and why signal processing has become so important in modern times. Chapters 2 through 5 describe the nature of analog and digital signals, while the other chapters cover the topics of the processing operations performed on analog and digital signals.

Having said all of that, please know your authors and publisher are on your side. We hope you enjoy this book and find it useful!

1 What Is Digital Signal Processing?

THE PHANTOM TECHNOLOGY

The technology of digital signal processing (DSP) has affected our modern lives in the most significant ways. If you watch television, connect to the Internet, use a digital camera, make a cell phone call, drive a car, type on the keyboard of a home computer, or use a charge or debit card, you are taking advantage of DSP. In fact, DSP is the technical *brains* in all those devices. Although we take advantage of DSP dozens of times a day, very few people have ever heard of digital signal processing and this strange situation is why DSP has been called a phantom technology. To show how much we depend on this *invisible* DSP technology, Table 1.1 provides a short list of what life would be like without DSP.

Table 1.1 Life without Digital Signal Processing

| Missing Technology: | Comments: |
|-----------------------------------|----------------------------------------------------------------|
| No cell or smartphones. | No texting or Web surfing. Anyone remember pay telephones? |
| No computers. | No Internet, no e-mail, no Facebook, no YouTube, no Skype. |
| No cable or satellite television. | Viewing restricted to a few local, low-definition TV channels. |
| No compact discs (CDs). | Go back to audio cassette tapes. |
| No digital video discs (DVDs). | Who remembers movies on low-definition VHS magnetic tapes? |
| No charge card purchases | Cash or check only. |

(Continues)

Table 1.1 (Continued)

| Missing Technology: | Comments: |
|----------------------------------------|------------------------------------------------------------------------------------------|
| No digital cameras. | Plan on taking exposed camera film to the drug store. |
| No ultrasound and no MRI or CAT scans. | Revert to exploratory surgery (opening you up) to investigate internal medical problems. |
| No Global Positioning System (GPS). | Go back to paper maps. |
| No Doppler radar. | No long-range weather predictions. |
| No advanced oil exploration. | Higher gasoline prices. (Yes, even higher.) |
| No video games. | Kids would have to go outside to play. |
| No airline flights during bad weather. | Bring your sleeping bag to the airport. |
| No musical greeting cards. | How boring. |

Given that we now realize how important DSP is in our daily lives, it's reasonable to ask just what is this thing called **DSP technology**. To understand the meaning of the phrase *digital signal processing*, we must first explain what we mean by the word *signal*.

WHAT IS A SIGNAL?

Any complete definition of the word *signal* must be, by necessity, somewhat vague. For example, some people define a signal as any representation of information conveyed to a receiver. Rather than discussing the meanings of those defining words, let's clarify what the word *signal* means to us by considering examples of signals that we've experienced in our daily lives. For example, when we listen to music produced by a loudspeaker, we're experiencing a signal in the form of sound waves traveling through the air that stimulates our eardrums. When we drive our cars to a traffic intersection, a light signal radiated by a red or green traffic light tells us whether we should stop or proceed. And if we ignore the red light, we find another red light following us down the road with a siren to *signal* us to pull over!

When you want to make a cell phone call, the symbol on your phone's screen, shown in Figure 1-1, is a visual indicator that your phone is receiving a sufficiently strong radio signal from a local cell phone tower. The height of a thermometer's mercury column is a visual signal indicating temperature. When we receive a kiss on the cheek, that's a tactile signal of affection. All of these examples are instances of receiving a *signal* that conveys information.

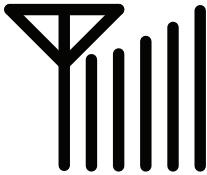


Figure 1-1 Cell phone signal-strength indicator.

ANALOG AND DIGITAL SIGNALS.....

As it turns out, all signals fall into one of two major categories, *analog signals* and *digital signals*. The signals that we experience in our daily lives, the examples of sound and light signals mentioned in the previous section, are **analog signals**. Chapters 2 and 3 discuss analog signals in more detail.

Strangely enough, **digital signals** are nothing more than sequences of numbers. It's true—sequences of numbers that can be stored in the electronic memories of computers, digital cameras, and video game machines, or recorded on CDs and DVDs. Signal processing engineers have developed a way to convert analog signals, such as a sound or light signal, into digital signals (sequences of numbers). The digital signals contain *all* the information of the original analog signals. In addition, signal processing engineers have also developed the means to convert a digital signal back into an analog signal (sound or light). Converting an analog signal to a digital signal and then converting the digital signal back into an analog signal doesn't seem too useful, but that's where digital signal processing comes in.

DIGITAL SIGNAL PROCESSING

Digital signal processing is the mathematical manipulation of the numerical values of a digital signal that changes the digital signal in some advantageous way. For example, let's say a vocalist is singing into a microphone and we convert that analog voice signal to a digital signal. Next, the values of the numbers in the digital signal can be modified such that when the modified digital signal is converted back to an analog signal and played through a loudspeaker, we hear a slight echo in the singing that gives us a more pleasant sound. Manipulating pop singers' voices is standard operating procedure in today's music business. We discuss that topic in more detail in Chapter 4.

For a more serious example of digital signal processing, consider undergoing an electrocardiogram (EKG or ECG) test to check for problems with the electrical activity of your heart. Small electrodes, taped to your chest, detect an analog electrical signal produced by your heart that often looks like that shown in Figure 1-2(a). For various practical reasons, the analog electrode signal is contaminated with abrupt,

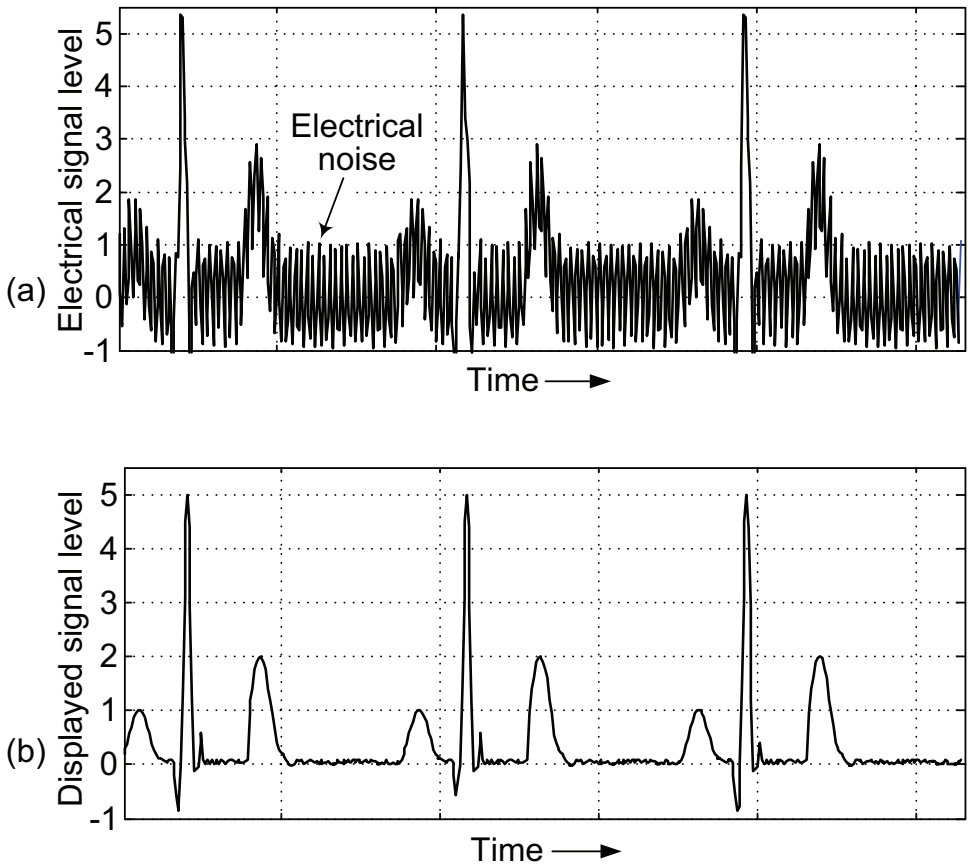


Figure 1-2 Electrocardiogram signals: (a) original measured noisy signal; (b) improved signal display after digital signal processing.

unwanted signal-level fluctuations, called **noise**, making it impossible for a doctor to evaluate your heart's electrical activity.

Today, digital signal processing comes to the rescue. As shown in Figure 1-3, the analog electrical sensor signal is converted to a digital signal. Next, the numerical values in the digital signal are modified in a way that eliminates the unwanted noise portion of the signal. The result is a clean EKG display, as shown in Figure 1-2(b), enabling a doctor to quickly evaluate the health of your heart

Other applications for DSP include military, industrial, space exploration, photography, communications, scientific, seismic, weather and many more. As we showed earlier in Table 1.1, life would go on without the benefits of DSP. However, we would have to do without so very many conveniences that we currently enjoy.

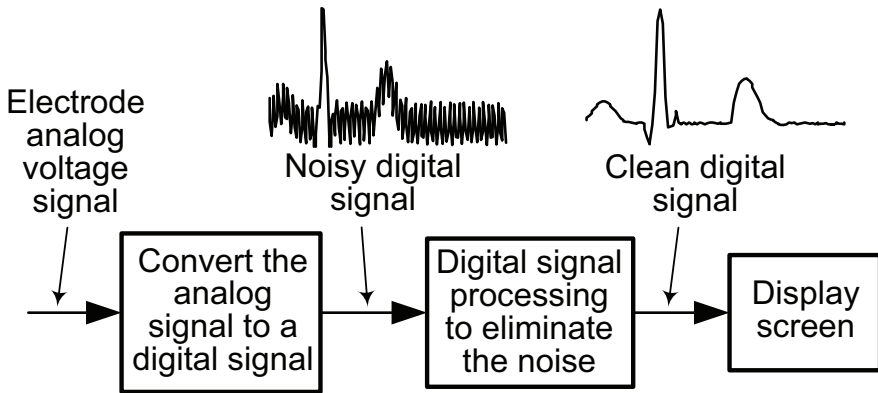


Figure 1-3 Using digital signal processing to improve an electrocardiogram signal display.

OK, this concludes our super-brief introduction to analog and digital signals, and digital signal processing. In later chapters, we'll learn more details about signals and signal processing.

WHAT YOU SHOULD REMEMBER

The concepts you should remember from this chapter are:

- We experience signals throughout our daily lives, usually in the form of analog sound and light signals.
- There is a way to convert analog signals, such as sound or light signals, into digital signals (sequences of numbers) that are stored in an electronic device. The digital signals contain *all* the information of the original analog signals.
- The numbers in a digital signal can be mathematically modified to improve some important characteristic of the signal, or reduce unwanted noise that contaminates it.
- The processed (modified and improved) digital signal can be converted back into an analog signal if necessary.
- The applications of DSP are many and varied. We may not always see where this phantom technology of DSP is used, but our lives would be very different without it.

This page intentionally left blank

Index

A

AC, 13, 169
ADC, 50, 169
Algorithm, 169
Aliasing, 78, 114, 169
Alternating current, 13, 14, 169
AM (amplitude modulation), 40, 69, 169, 170
Amplifier, 169
Amplitude, 10, 169
Amplitude modulation (AM), 40, 69, 169, 170
Analog filters, 119, 170
Analog signal, 7, 170
Analog-to-digital converter, 50, 59, 62, 71, 93, 136, 170
Anti-aliasing filter, 89, 121, 170
Attenuation, 170
Audio, 8, 170
Audio tone, 8
Auto-Tune, 55
Averager, 123, 170

B

Band reject filter, 170
Bandpass filter, 122, 153, 170

Bandstop filter, 122, 170
Bandwidth, 39, 170
Binary number formats
 defined, 161
 examples, 163
Binary numbers
 defined, 127, 131, 171
 hexadecimal, 176
 hexadecimal notation, 166
 octal, 179
 octal notation, 166
 offset binary, 165, 179
 sign-extend, 165
 sign-magnitude, 162, 181
 two's complement, 163, 184
 unsigned, 161, 184
 word length, 161, 184
Bit, 131, 171
Broadcast, 171
Byte, 134, 171

C

Carrier frequency, 69, 172
Cascaded filters, 172
Cell phone, 2, 172
Center frequency, 172

Chip, 134, 172
 Circuit, 10, 172
 Clock signal, 19, 172
 Compact disk (CD), 53, 86, 139, 172
 Composite wave, 34
 Continuous signals, 8, 19, 172
 Continuous wavelet transform, 109
 Correlation, 96, 103, 107, 109
 Cosine wave, 16, 173
 Cutoff frequency, 173
 Cycles per second, 26, 173

D

DAC, 173
 dB, 173
 DC, 12, 173, 174
 Decibels, 145, 173
 Decimal numbers, 128, 173
 Decimation, 63, 114, 174
 DFT, 96, 174
 Digital filter, 122, 174
 Digital number, 43, 45, 174
 Digital signal, 174
 definition #1, 44
 definition #2, 45
 example, 50
 Digital signal processing, 174
 Digital signal processor, 174
 Digital to analog converter, 174
 Digital video disk (DVD), 139, 174
 Direct current (DC), 173, 174
 Discrete Fourier transform, 174
 defined, 96
 example, 103
 Downsample, 174
 DSP, 1, 52, 174

E

Edison, Thomas, 13
 EKG, 3
 Electrocardiogram, 3
 Envelope of RF signal, 155

F

Fast Fourier transform, 96, 174
 FFT, 96
 Filters
 analog, 119, 170
 anti-aliasing, 170
 band reject, 170
 bandpass, 122, 153, 170
 bandstop, 122, 170
 cascaded, 172
 defined, 174
 digital, 122, 174
 finite impulse response, 175
 frequency response, 121, 175
 half-band, 175
 highpass, 122, 177
 impulse response, 177
 infinite impulse response, 177
 linear phase, 177
 lowpass, 121, 150, 180
 moving averager, 123, 178
 nonrecursive, 178
 passband, 121, 179
 phase response, 180
 recursive, 181
 stopband, 121, 182
 transition region, 183
 transversal, 183
 Finite impulse response filters, 175
 FIR, 175
 FM (frequency modulation),
 157, 175
 Fourier transform
 discrete, 96, 174
 fast, 96, 107, 174
 Frequency, 25, 175
 cycles per second, 26
 radians per second, 28
 Frequency modulation (FM), 41,
 157, 175
 Frequency response, 121, 153, 175
 Frequency-domain plots, 31

- G**
- Gain, 175
 - Ghz, 175
 - Gigabits (Gb), 175
 - Gigabytes (GB), 175
 - Ground, 175
- H**
- Half-band filter, 175
 - Harmonic distortion, 37, 175
 - Harmonics, 34, 175
 - HDTV, 176
 - hertz, 26, 176
 - Hertz, Heinrich, 27
 - Hexadecimal numbers, 166, 176
 - High fidelity, 41, 176
 - High-definition television, 176
 - Highpass filter, 122, 177
- I**
- IIR, 177
 - Image compression, 114
 - Impulse response (filter), 177
 - Infinite impulse response (IIR) filters, 177
 - Integers, 177
 - Integrated circuit, 134, 177
 - Interpolation, 63, 177
- J**
- JPEG, 114, 177
- K**
- kHz, 177
 - Kilobits (Kb), 177
 - Kilobytes (KB), 177
 - ksps, 177
- L**
- Least significant bit (lsb), 161, 177
 - Light refraction, 29
 - Linear phase filter, 177
 - Loudspeaker, 8, 177
 - Lowpass filter, 121, 150, 178
- M**
- Marconi, Guglielmo, 159
 - Marquette, Michigan, 8
 - Megabits (Mb), 178
 - Megabytes (MB), 178
 - Mhz, 178
 - Microchip, 178
 - Microphone, 10, 178
 - Mixing, 22, 178
 - Modulation
 - AM, 40, 69, 169, 170
 - FM, 157, 175
 - Most significant bit (msb), 161, 178
 - Moving averager, 123, 178
 - MPEG, 115, 178
 - Msp, 178
- N**
- Nibble, 178
 - Noise, 4, 178
 - Nonrecursive filter, 178
 - Numbers
 - base-10 (decimal), 128
 - base-2 (binary), 130
 - base-4, 129
 - Nyquist sampling criterion, 62, 82, 86, 178
- O**
- Octal numbers, 166, 179
 - Offset binary numbers, 165, 179
 - Oscilloscope, 10, 179
- P**
- Passband, 121, 179
 - PC board, 179
 - Period, 19, 179
 - Periodic sampling, 49
 - Periodic wave, 18, 180
 - Phase response (filter), 180

Pixel, 134, 176, 180

Pressure wave, 8

Printed circuit board, 180

Q

Quantization, 180

R

Radians per second, 28, 180

Radio frequency, 155, 181

Recursive filter, 181

Refraction, 29

RF, 155, 181

RF signal envelope, 155

Richards, Keith, 39

Richter scale, 147

S

Sample, 181

Sample frequency, 181

Sample rate, 52, 62, 71, 181

Sample rate conversion, 63, 181

Sampling, 49

Sampling frequency, 62

Scientific notation, 27, 141, 181

Signal

 analog, 7, 170

 continuous, 172

 digital, 45, 50

Signal-to-noise ratio, 181

Sign-magnitude binary numbers, 162, 181

Sine wave, 14, 181

Sinusoidal waves, 13, 181

SNR, 181

Sound, 8, 86, 146

Sound levels (dB), 146

Spectrum, 25, 29, 68, 181

Spectrum analysis

 defined, 182

 example, 103

Spectrum analyzer, 182

Square wave, 19, 182

Stopband, 121, 182

Stopband attenuation, 182

T

Tachometer, 183

Tesla, Nikola, 13, 159

Time domain, 183

Time-domain plots, 29

Touch-tone telephone, 58

Trace, 180, 183

Transceiver, 183

Transistor, 183

Transition region, 183

Transversal filter, 183

Triangular wave, 20, 183

Two's complement binary numbers,
163, 184

U

Unsigned binary numbers, 161, 184

Upsample, 184

V

Voltage, 10, 184

 AC, 13, 14, 170

 DC, 12, 173

W

Wave

 composite, 34

 cosine, 16, 173

 periodic, 18, 180

 pressure, 8

 sine, 14, 181

 sinusoidal, 13, 181

 square, 19, 182

 triangular, 20, 183

Waveform, 10, 184

Wavelets, 107

Westinghouse, George, 13

Word length, 161, 184