

Contents

Preface	v
Chapter 1 What Is Digital Signal Processing?	1
1.1 Some History and Philosophy	2
1.1.1 Digital Signal Processing under the Pyramids	2
1.1.2 The Hellenic Shift to Analog Processing	4
1.1.3 “Gentlemen: <i>calculemus!</i> ”	5
1.2 Discrete-Time	7
1.3 Discrete Amplitude	10
1.4 Communication Systems	12
1.5 How to Read this Book.....	17
Further Reading	18
Chapter 2 Discrete-Time Signals	19
2.1 Basic Definitions	19
2.1.1 The Discrete-Time Abstraction	21
2.1.2 Basic Signals	23
2.1.3 Digital Frequency	25
2.1.4 Elementary Operators	26
2.1.5 The Reproducing Formula	27
2.1.6 Energy and Power	27
2.2 Classes of Discrete-Time Signals	28
2.2.1 Finite-Length Signals.....	29
2.2.2 Infinite-Length Signals	30
Examples	33
Further Reading	36
Exercises	36
Chapter 3 Signals and Hilbert Spaces	37
3.1 Euclidean Geometry: A Review	38
3.2 From Vector Spaces to Hilbert Spaces	41
3.2.1 The Recipe for Hilbert Space	42
3.2.2 Examples of Hilbert Spaces	45
3.2.3 Inner Products and Distances	46

3.3	Subspaces, Bases, Projections	47
3.3.1	Definitions	48
3.3.2	Properties of Orthonormal Bases	49
3.3.3	Examples of Bases	51
3.4	Signal Spaces Revisited	53
3.4.1	Finite-Length Signals	53
3.4.2	Periodic Signals	53
3.4.3	Infinite Sequences	54
	Further Reading	55
	Exercises	55
Chapter 4	Fourier Analysis	59
4.1	Preliminaries	60
4.1.1	Complex Exponentials	61
4.1.2	Complex Oscillations? Negative Frequencies?	61
4.2	The DFT (Discrete Fourier Transform)	63
4.2.1	Matrix Form	64
4.2.2	Explicit Form	64
4.2.3	Physical Interpretation	67
4.3	The DFS (Discrete Fourier Series)	71
4.4	The DTFT (Discrete-Time Fourier Transform)	72
4.4.1	The DTFT as the Limit of a DFS	75
4.4.2	The DTFT as a Formal Change of Basis	77
4.5	Relationships Between Transforms	81
4.6	Fourier Transform Properties	83
4.6.1	DTFT Properties	83
4.6.2	DFS Properties	85
4.6.3	DFT Properties	86
4.7	Fourier Analysis in Practice	90
4.7.1	Plotting Spectral Data	91
4.7.2	Computing the Transform: the FFT	93
4.7.3	Cosmetics: Zero-Padding	94
4.7.4	Spectral Analysis	95
4.8	Time-Frequency Analysis	98
4.8.1	The Spectrogram	98
4.8.2	The Uncertainty Principle	100
4.9	Digital Frequency vs. Real Frequency	101
	Examples	102
	Further Reading	105
	Exercises	106
Chapter 5	Discrete-Time Filters	109
5.1	Linear Time-Invariant Systems	109
5.2	Filtering in the Time Domain	111
5.2.1	The Convolution Operator	111
5.2.2	Properties of the Impulse Response	113

5.3	Filtering by Example – Time Domain	115
5.3.1	FIR Filtering	115
5.3.2	IIR Filtering	117
5.4	Filtering in the Frequency Domain	121
5.4.1	LTI “Eigenfunctions”	121
5.4.2	The Convolution and Modulation Theorems	122
5.4.3	Properties of the Frequency Response	123
5.5	Filtering by Example – Frequency Domain	126
5.6	Ideal Filters	129
5.7	Realizable Filters	133
5.7.1	Constant-Coefficient Difference Equations	134
5.7.2	The Algorithmic Nature of CCDEs	135
5.7.3	Filter Analysis and Design	136
	Examples	136
	Further Reading	143
	Exercises	143
Chapter 6	The z -Transform	147
6.1	Filter Analysis	148
6.1.1	Solving CCDEs	148
6.1.2	Causality	149
6.1.3	Region of Convergence	150
6.1.4	ROC and System Stability	152
6.1.5	ROC of Rational Transfer Functions and Filter Stability	152
6.2	The Pole-Zero Plot	152
6.2.1	Pole-Zero Patterns	153
6.2.2	Pole-Zero Cancellation	154
6.2.3	Sketching the Transfer Function from the Pole-Zero Plot	155
6.3	Filtering by Example – z -Transform	156
	Examples	157
	Further Reading	159
	Exercises	159
Chapter 7	Filter Design	165
7.1	Design Fundamentals	165
7.1.1	FIR Versus IIR	166
7.1.2	Filter Specifications and Tradeoffs	168
7.2	FIR Filter Design	171
7.2.1	FIR Filter Design by Windowing	171
7.2.2	Minimax FIR Filter Design	179
7.3	IIR Filter Design	190
7.3.1	All-Time Classics	191
7.4	Filter Structures	195
7.4.1	FIR Filter Structures	196
7.4.2	IIR Filter Structures	197

7.4.3 Some Remarks on Numerical Stability	200
7.5 Filtering and Signal Classes	200
7.5.1 Filtering of Finite-Length Signals.....	200
7.5.2 Filtering of Periodic Sequences	201
Examples.....	204
Further Reading.....	208
Exercises	208
 Chapter 8 Stochastic Signal Processing	217
8.1 Random Variables	217
8.2 Random Vectors	219
8.3 Random Processes	221
8.4 Spectral Representation of Stationary Random Processes	223
8.4.1 Power Spectral Density.....	224
8.4.2 PSD of a Stationary Process	225
8.4.3 White Noise.....	227
8.5 Stochastic Signal Processing.....	227
Examples.....	229
Further Reading	232
Exercises	233
 Chapter 9 Interpolation and Sampling	235
9.1 Preliminaries and Notation	236
9.2 Continuous-Time Signals.....	237
9.3 Bandlimited Signals	239
9.4 Interpolation	240
9.4.1 Local Interpolation	241
9.4.2 Polynomial Interpolation	243
9.4.3 Sinc Interpolation.....	245
9.5 The Sampling Theorem	247
9.6 Aliasing.....	250
9.6.1 Non-Bandlimited Signals	250
9.6.2 Aliasing: Intuition	251
9.6.3 Aliasing: Proof	253
9.6.4 Aliasing: Examples	255
9.7 Discrete-Time Processing of Analog Signals.....	260
9.7.1 A Digital Differentiator	260
9.7.2 Fractional Delays	261
Examples.....	262
9.8 Appendix	266
Further Reading	268
Exercises	269
 Chapter 10 A/D and D/A Conversions	275
10.1 Quantization	275
10.1.1 Uniform Scalar Quantization.....	278
10.1.2 Advanced Quantizers	282

10.2 A/D Conversion	283
10.3 D/A Conversion	286
Examples.....	287
Further Reading.....	290
Exercises.....	290
Chapter 11 Multirate Signal Processing	293
11.1 Downsampling	294
11.1.1 Properties of the Downsampling Operator	294
11.1.2 Frequency-Domain Representation	295
11.1.3 Examples	297
11.1.4 Downsampling and Filtering	302
11.2 Upsampling	304
11.2.1 Upsampling and Interpolation	306
11.3 Rational Sampling Rate Changes	310
11.4 Oversampling	311
11.4.1 Oversampled A/D Conversion	311
11.4.2 Oversampled D/A Conversion	314
Examples.....	319
Further Reading.....	322
Exercises.....	322
Chapter 12 Design of a Digital Communication System	327
12.1 The Communication Channel	328
12.1.1 The AM Radio Channel	329
12.1.2 The Telephone Channel.....	330
12.2 Modem Design: The Transmitter	331
12.2.1 Digital Modulation and the Bandwidth Constraint	331
12.2.2 Signaling Alphabets and the Power Constraint	339
12.3 Modem Design: The Receiver	347
12.3.1 Hilbert Demodulation	348
12.3.2 The Effects of the Channel	350
12.4 Adaptive Synchronization	353
12.4.1 Carrier Recovery	353
12.4.2 Timing Recovery	356
Further Reading.....	365
Exercises.....	365
Index	367