Contents

Pı	Preface				
1	Intr	oduction	1		
	1.1	Computational approach	1		
	1.2	Statistical learning	2		
	1.3	Example	3		
	1.4	Prerequisites	5		
	1.5	How to read this book	6		
	1.6	Supplementary materials	7		
	1.7	Formalisms and terminology	7		
	1.8	Exercises	9		
2	Linear Models				
	2.1	Introduction	11		
	2.2	Ordinary least squares	13		
	2.3	The normal equations	15		
	2.4	Solving least squares with the singular value decomposition .	17		
	2.5	Directly solving the linear system	19		
	2.6	(\star) Solving linear models using the QR decomposition	22		
	2.7	(*) Sensitivity analysis	24		
	2.8	(*) Relationship between numerical and statistical error	28		
	2.9	Implementation and notes	31		
	2.10	Application: Cancer incidence rates	32		
	2.11	Exercises	40		
3	Rid	ge Regression and Principal Component Analysis	43		
	3.1	Variance in OLS	43		
	3.2	Ridge regression	46		
	3.3	(*) A Bayesian perspective	53		
	3.4	Principal component analysis	56		
	3.5	Implementation and notes	63		
	3.6	Application: NYC taxicab data	65		
	3.7	Exercises	72		

viii Contents

4	Line		5
	4.1	1.011-Editoditty	' 5
	4.2	Basis expansion	6
	4.3	itchici regressioni	31
	4.4	Local regression	35
	4.5	Regression splines	39
	4.6	(*) Smoothing splines	95
	4.7	(*) B-splines	0
	4.8	Implementation and notes)4
	4.9	Application: U.S. census tract data	15
	4.10	Exercises	:0
5	Gen	eralized Linear Models 12	3
_	5.1	Classification with linear models	23
	5.2	Exponential families	28
		Iteratively reweighted GLMs	31
	5.4	(*) Numerical issues	35
	5.5	(*) Multi-Class regression	18
	5.6	Implementation and notes	39
	5.7	Application: Chicago crime prediction	
	5.8	Exercises	18
6	Add	itive Models 15	1
	6.1	Multivariate linear smoothers	
	0.1		_
			55
	6.2 6.3	Curse of dimensionality	
	6.2	Curse of dimensionality	58
	6.2 6.3 6.4	Curse of dimensionality 15 Additive models 15 (*) Additive models as linear models 16	58 53
	6.2 6.3 6.4 6.5	Curse of dimensionality 15 Additive models 15 (*) Additive models as linear models 16 (*) Standard errors in additive models 16	58 53 56
	6.2 6.3 6.4 6.5 6.6	Curse of dimensionality	58 53 56 70
	6.2 6.3 6.4 6.5	Curse of dimensionality 15 Additive models 15 (*) Additive models as linear models 16 (*) Standard errors in additive models 16	58 56 70 72
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8	Curse of dimensionality 15 Additive models 15 (*) Additive models as linear models 16 (*) Standard errors in additive models 16 Implementation and notes 17 Application: NYC flights data 17 Exercises 17	58 56 70 72
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8	Curse of dimensionality 15 Additive models 15 (*) Additive models as linear models 16 (*) Standard errors in additive models 16 Implementation and notes 17 Application: NYC flights data 17 Exercises 17 adized Regression Models 17	58 53 66 70 72 78
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena	Curse of dimensionality 15 Additive models 15 (★) Additive models as linear models 16 (★) Standard errors in additive models 16 Implementation and notes 17 Application: NYC flights data 17 Exercises 17 alized Regression Models 17 Variable selection 17	58 53 56 70 72 78
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pens 7.1 7.2	Curse of dimensionality	58 53 56 70 72 78 79
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena 7.1 7.2 7.3	Curse of dimensionality	58 53 56 70 72 78 79 30
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena 7.1 7.2 7.3 7.4	Curse of dimensionality	58 53 56 70 72 78 79 30 32 36
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena 7.1 7.2 7.3 7.4 7.5	Curse of dimensionality 15 Additive models 15 (\star) Additive models as linear models 16 (\star) Standard errors in additive models 16 Implementation and notes 17 Application: NYC flights data 17 Exercises 17 Alized Regression Models 17 Variable selection 17 Penalized regression with the ℓ_0 - and ℓ_1 -norms 18 Orthogonal data matrix 18 Convex optimization and the elastic net 18 Coordinate descent 18	58 53 56 70 72 78 79 30 32 36 38
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena 7.1 7.2 7.3 7.4 7.5 7.6	Curse of dimensionality	58 53 56 70 72 78 79 79 80 83 86 88 93
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena 7.1 7.2 7.3 7.4 7.5 7.6 7.7	Curse of dimensionality	58 53 56 70 72 78 79 86 88 98
7	6.2 6.3 6.4 6.5 6.6 6.7 6.8 Pena 7.1 7.2 7.3 7.4 7.5 7.6	Curse of dimensionality	58 53 56 70 72 78 79 30 32 36 38 38 38 38 38 38 38 38 38 38 39 30 30 30 30 30 30 30 30 30 30 30 30 30

Contents ix

8	Neu	ral Networks	207		
	8.1	Dense neural network architecture	207		
	8.2	Stochastic gradient descent	211		
	8.3	Backward propagation of errors	213		
	8.4	Implementing backpropagation	216		
	8.5	Recognizing handwritten digits	224		
	8.6	(*) Improving SGD and regularization	226		
	8.7	(\star) Classification with neural networks	232		
	8.8	(*) Convolutional neural networks	239		
	8.9	Implementation and notes	249		
	8.10	Application: Image classification with EMNIST	249		
	8.11	Exercises	259		
9	Dim	ensionality Reduction	26 1		
	9.1	Unsupervised learning	261		
	9.2	Kernel functions	262		
	9.3	Kernel principal component analysis	266		
	9.4	Spectral clustering	272		
	9.5	t-Distributed stochastic neighbor embedding (t-SNE)	277		
	9.6	Autoencoders	282		
	9.7	Implementation and notes	283		
	9.8	Application: Classifying and visualizing fashion MNIST	284		
	9.9	Exercises	295		
10		nputation in Practice	297		
	10.1	Reference implementations	297		
	10.2	Sparse matrices	298		
		Sparse generalized linear models	304		
	10.4	Computation on row chunks	307		
	10.5	Feature hashing	311		
	10.6	Data quality issues	318		
		Implementation and notes	320		
	10.8	Application	321		
	10.9	Exercises	329		
A	Linear algebra and matrices				
		Vector spaces	331		
	A.2	Matrices	333		
\mathbf{B}	Floating Point Arithmetic and Numerical Computation				
	B.1	Floating point arithmetic	337		
	B.2	Computational effort	340		
Bibliography 343					
Index					