Deep Learning

Ian Goodfellow Yoshua Bengio Aaron Courville

Contents

Website Acknowledgments Notation			vii	
			viii	
			xi	
1	Intro 1.1 1.2	Oduction Who Should Read This Book?	1 8 11	
Ι	Appl	lied Math and Machine Learning Basics	29	
2	Line	ar Algebra	31	
	2.1	Scalars, Vectors, Matrices and Tensors	31	
	2.2	Multiplying Matrices and Vectors	34	
	2.3	Identity and Inverse Matrices	36	
	2.4	Linear Dependence and Span	37	
	2.5	Norms	39	
	2.6	Special Kinds of Matrices and Vectors	40	
	2.7	Eigendecomposition	42	
	2.8	Singular Value Decomposition	44	
	2.9	The Moore-Penrose Pseudoinverse	45	
	2.10	The Trace Operator	46	
	2.11	The Determinant	47	
	2.12	Example: Principal Components Analysis	48	
3	Prob	pability and Information Theory	53	
	3.1	Why Probability?	54	

	3.2	Random Variables	. 56
	3.3	Probability Distributions	
	3.4	Marginal Probability	. 58
	3.5	Conditional Probability	. 59
	3.6	The Chain Rule of Conditional Probabilities	. 59
	3.7	Independence and Conditional Independence	. 60
	3.8	Expectation, Variance and Covariance	. 60
	3.9	Common Probability Distributions	. 62
	3.10	Useful Properties of Common Functions	. 67
	3.11	Bayes' Rule	. 70
	3.12	Technical Details of Continuous Variables	. 71
	3.13	Information Theory	. 73
	3.14	Structured Probabilistic Models	. 75
4	Nun	nerical Computation	80
	4.1	Overflow and Underflow	. 80
	4.2	Poor Conditioning	. 82
	4.3	Gradient-Based Optimization	. 82
	4.4	Constrained Optimization	
	4.5	Example: Linear Least Squares	. 96
5	Mac	hine Learning Basics	98
	5.1	Learning Algorithms	. 99
	5.2	Capacity, Overfitting and Underfitting	. 110
	5.3	Hyperparameters and Validation Sets	. 120
	5.4	Estimators, Bias and Variance	. 122
	5.5	Maximum Likelihood Estimation	. 131
	5.6	Bayesian Statistics	. 135
	5.7	Supervised Learning Algorithms	. 140
	5.8	Unsupervised Learning Algorithms	. 146
	5.9	Stochastic Gradient Descent	. 151
	5.10	Building a Machine Learning Algorithm	. 153
	5.11	Challenges Motivating Deep Learning	. 155
II	Dee	p Networks: Modern Practices	166
6	_	p Feedforward Networks	168
	6.1	Example: Learning XOR	
	6.2	Gradient-Based Learning	. 177

	6.3	Hidden Units		
	6.4	Architecture Design		
	6.5	Back-Propagation and Other Differentiation Algorithms 204		
	6.6	Historical Notes		
7	Regularization for Deep Learning 228			
	7.1	Parameter Norm Penalties		
	7.2	Norm Penalties as Constrained Optimization		
	7.3	Regularization and Under-Constrained Problems		
	7.4	Dataset Augmentation		
	7.5	Noise Robustness		
	7.6	Semi-Supervised Learning		
	7.7	Multi-Task Learning		
	7.8	Early Stopping		
	7.9	Parameter Tying and Parameter Sharing		
	7.10	Sparse Representations		
	7.11	Bagging and Other Ensemble Methods		
	7.12	Dropout		
	7.13	Adversarial Training		
	7.14	Tangent Distance, Tangent Prop, and Manifold Tangent Classifier 270		
8	Optimization for Training Deep Models 274			
	8.1	How Learning Differs from Pure Optimization		
	8.2	Challenges in Neural Network Optimization		
	8.3	Basic Algorithms		
	8.4	Parameter Initialization Strategies		
	8.5	Algorithms with Adaptive Learning Rates		
	8.6	Approximate Second-Order Methods		
	8.7	Optimization Strategies and Meta-Algorithms		
9	Convolutional Networks 330			
	9.1	The Convolution Operation		
	9.2	Motivation		
	9.3	Pooling		
	9.4	Convolution and Pooling as an Infinitely Strong Prior		
	9.5	Variants of the Basic Convolution Function		
	9.6	Structured Outputs		
	9.7	Data Types		
	9.8	Efficient Convolution Algorithms		
	9.9	Random or Unsupervised Features		

	9.10	The Neuroscientific Basis for Convolutional Networks 364		
	9.11	Convolutional Networks and the History of Deep Learning 371		
10	Sequence Modeling: Recurrent and Recursive Nets 373			
	10.1	Unfolding Computational Graphs		
	10.2	Recurrent Neural Networks		
	10.3	Bidirectional RNNs		
	10.4	Encoder-Decoder Sequence-to-Sequence Architectures 396		
	10.5	Deep Recurrent Networks		
	10.6	Recursive Neural Networks		
	10.7	The Challenge of Long-Term Dependencies		
	10.8	Echo State Networks		
	10.9	Leaky Units and Other Strategies for Multiple Time Scales 406		
	10.10	The Long Short-Term Memory and Other Gated RNNs 408		
	10.11	Optimization for Long-Term Dependencies		
	10.12	Explicit Memory		
11	Pract	tical Methodology 421		
	11.1	Performance Metrics		
	11.2	Default Baseline Models		
	11.3	Determining Whether to Gather More Data 426		
	11.4	Selecting Hyperparameters		
	11.5	Debugging Strategies		
	11.6	Example: Multi-Digit Number Recognition		
12	Applications 443			
	12.1	Large-Scale Deep Learning		
	12.2	Computer Vision		
	12.3	Speech Recognition		
	12.4	Natural Language Processing		
	12.5	Other Applications		
ш	Dee	ep Learning Research 486		
13		ar Factor Models 489		
	13.1	Probabilistic PCA and Factor Analysis		
	13.2	Independent Component Analysis (ICA)		
	13.3	Slow Feature Analysis		
	13.4	Sparse Coding 496		

	13.5	Manifold Interpretation of PCA	499
14	Auto	pencoders	502
	14.1	Undercomplete Autoencoders	503
	14.2	Regularized Autoencoders	504
	14.3	Representational Power, Layer Size and Depth	508
	14.4	Stochastic Encoders and Decoders	509
	14.5	Denoising Autoencoders	510
	14.6	Learning Manifolds with Autoencoders	515
	14.7	Contractive Autoencoders	521
	14.8	Predictive Sparse Decomposition	523
	14.9	Applications of Autoencoders	524
15	Repi	resentation Learning	526
	15.1^{-}	Greedy Layer-Wise Unsupervised Pretraining	528
	15.2	Transfer Learning and Domain Adaptation	
	15.3	Semi-Supervised Disentangling of Causal Factors	
	15.4	Distributed Representation	
	15.5	Exponential Gains from Depth	
	15.6	Providing Clues to Discover Underlying Causes	554
16	Structured Probabilistic Models for Deep Learning 558		
	16.1	The Challenge of Unstructured Modeling	559
	16.2	Using Graphs to Describe Model Structure	563
	16.3	Sampling from Graphical Models	580
	16.4	Advantages of Structured Modeling	582
	16.5	Learning about Dependencies	582
	16.6	Inference and Approximate Inference	584
	16.7	The Deep Learning Approach to Structured Probabilistic Models	585
17	Mon	te Carlo Methods	590
	17.1	Sampling and Monte Carlo Methods	590
	17.2	Importance Sampling	592
	17.3	Markov Chain Monte Carlo Methods	595
	17.4	Gibbs Sampling	599
	17.5	The Challenge of Mixing between Separated Modes	599
18	Conf	fronting the Partition Function	605
	18.1	The Log-Likelihood Gradient	606
	18.2	Stochastic Maximum Likelihood and Contrastive Divergence	607

	18.3	Pseudolikelihood	615
	18.4	Score Matching and Ratio Matching	617
	18.5	Denoising Score Matching	619
	18.6	Noise-Contrastive Estimation	620
	18.7	Estimating the Partition Function	623
19	Appr	roximate Inference	631
	19.1	Inference as Optimization	633
	19.2	Expectation Maximization	634
	19.3	MAP Inference and Sparse Coding	635
	19.4	Variational Inference and Learning	638
	19.5	Learned Approximate Inference	651
20	Deep	Generative Models	654
	20.1	Boltzmann Machines	654
	20.2	Restricted Boltzmann Machines	656
	20.3	Deep Belief Networks	660
	20.4	Deep Boltzmann Machines	663
	20.5	Boltzmann Machines for Real-Valued Data	
	20.6	Convolutional Boltzmann Machines	683
	20.7	Boltzmann Machines for Structured or Sequential Outputs	685
	20.8	Other Boltzmann Machines	686
	20.9	Back-Propagation through Random Operations	687
	20.10	Directed Generative Nets	692
	20.11	Drawing Samples from Autoencoders	711
	20.12	Generative Stochastic Networks	714
	20.13	Other Generation Schemes	716
	20.14	Evaluating Generative Models	717
	20.15	Conclusion	720
Bibliography			721
Index			777

Website

www.deeplearningbook.org

This book is accompanied by the above website. The website provides a variety of supplementary material, including exercises, lecture slides, corrections of mistakes, and other resources that should be useful to both readers and instructors.