## 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?	
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	
	2.3	Identity and Inverse Matrices	
	2.4	Linear Dependence and Span	
	2.5	Norms	
	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	
	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
	3.3	Probability Distributions
	3.4	Marginal Probability
	3.5	Conditional Probability
	3.6	The Chain Rule of Conditional Probabilities
	3.7	Independence and Conditional Independence
	3.8	Expectation, Variance and Covariance
	3.9	Common Probability Distributions
	3.10	Useful Properties of Common Functions
	3.11	Bayes' Rule
	3.12	Technical Details of Continuous Variables
	3.13	Information Theory
	3.14	Structured Probabilistic Models
4	Num	nerical Computation 80
	4.1	Overflow and Underflow
	4.2	Poor Conditioning
	4.3	Gradient-Based Optimization
	4.4	Constrained Optimization
	4.5	Example: Linear Least Squares
5	Mac	hine Learning Basics 98
	5.1	Learning Algorithms
	5.2	Capacity, Overfitting and Underfitting
	5.3	Hyperparameters and Validation Sets
	5.4	Estimators, Bias and Variance
	5.5	Maximum Likelihood Estimation
	5.6	Bayesian Statistics
	5.7	Supervised Learning Algorithms
	5.8	Unsupervised Learning Algorithms
	5.9	Stochastic Gradient Descent
	5.10	Building a Machine Learning Algorithm
	5.11	Challenges Motivating Deep Learning
II	Doo	p Networks: Modern Practices 165
11		
6	Deep	Feedforward Networks 167
	6.1	Example: Learning XOR
	6.2	Gradient-Based Learning 176

	6.3	Hidden Units			
	6.4	Architecture Design			
	6.5	Back-Propagation and Other Differentiation Algorithms 203			
	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	<u>Dropout</u>			
	7.13	Adversarial Training			
	7.14	Tangent Distance, Tangent Prop, and Manifold Tangent Classifier 268			
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 331				
	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         361			
	9.8	Efficient Convolution Algorithms			
	9.9	Random or Unsupervised Features 364			

	9.10	The Neuroscientific Basis for Convolutional Networks		
	9.11	Convolutional Networks and the History of Deep Learning 37	<sup>7</sup> 2	
10	Sequence Modeling: Recurrent and Recursive Nets 37			
	10.1	Unfolding Computational Graphs	<b>7</b> 6	
	10.2	Recurrent Neural Networks	79	
	10.3	Bidirectional RNNs	<b>)</b> 6	
	10.4	Encoder-Decoder Sequence-to-Sequence Architectures 39	)7	
	10.5	Deep Recurrent Networks	)9	
	10.6	Recursive Neural Networks	)1	
	10.7	The Challenge of Long-Term Dependencies	)3	
	10.8	Echo State Networks	)6	
	10.9	Leaky Units and Other Strategies for Multiple Time Scales 40	)9	
	10.10	The Long Short-Term Memory and Other Gated RNNs 41	11	
	10.11	Optimization for Long-Term Dependencies	.5	
	10.12	Explicit Memory	.9	
11	Pract	tical methodology 42	4	
	11.1	Performance Metrics	25	
	11.2	Default Baseline Models	28	
	11.3	Determining Whether to Gather More Data		
	11.4	Selecting Hyperparameters		
	11.5	Debugging Strategies	39	
	11.6	Example: Multi-Digit Number Recognition	13	
<b>12</b>	Applications 446			
		Large Scale Deep Learning	16	
	12.2	Computer Vision		
	12.3	Speech Recognition		
	12.4	Natural Language Processing		
	12.5	Other Applications		
<b>TTT</b>	Doc	an I samina Dagaanda		
III	Dee	ep Learning Research 48	9	
<b>13</b>		ar Factor Models 49		
	13.1	Probabilistic PCA and Factor Analysis		
	13.2	Independent Component Analysis (ICA)		
	13.3	Slow Feature Analysis		
	13.4	Sparse Coding 49	14	

	13.5	Manifold Interpretation of PCA	. 502
14	Auto	pencoders	505
	14.1	Undercomplete Autoencoders	. 506
	14.2	Regularized Autoencoders	
	14.3	Representational Power, Layer Size and Depth	
	14.4	Stochastic Encoders and Decoders	
	14.5	Denoising Autoencoders	
	14.6	Learning Manifolds with Autoencoders	
	14.7	Contractive Autoencoders	
	14.8	Predictive Sparse Decomposition	
	14.9	Applications of Autoencoders	
<b>15</b>	Rep	resentation Learning	<b>529</b>
	15.1	Greedy Layer-Wise Unsupervised Pretraining	. 531
	15.2	Transfer Learning and Domain Adaptation	. 539
	15.3	Semi-Supervised Disentangling of Causal Factors	. 544
	15.4	Distributed Representation	. 549
	15.5	Exponential Gains from Depth	. 556
	15.6	Providing Clues to Discover Underlying Causes	. 557
<b>16</b>	Stru	ctured Probabilistic Models for Deep Learning	561
	16.1	The Challenge of Unstructured Modeling	. 562
	16.2	Using Graphs to Describe Model Structure	. 566
	16.3	Sampling from Graphical Models	. 583
	16.4	Advantages of Structured Modeling	. 584
	16.5	Learning about Dependencies	. 585
	16.6	Inference and Approximate Inference	. 586
	16.7	The Deep Learning Approach to Structured Probabilistic Models	587
<b>17</b>	Mon	te Carlo Methods	593
	17.1	Sampling and Monte Carlo Methods	
	17.2	Importance Sampling	
	17.3	Markov Chain Monte Carlo Methods	. 598
	17.4	Gibbs Sampling	
	17.5	The Challenge of Mixing between Separated Modes	. 602
18		fronting the Partition Function	608
	18.1	The Log-Likelihood Gradient	
	18 2	Stochastic Maximum Likelihood and Contrastive Divergence	610

	18.3	Pseudolikelihood	618
	18.4	Score Matching and Ratio Matching	620
	18.5	Denoising Score Matching	622
	18.6	Noise-Contrastive Estimation	
	18.7	Estimating the Partition Function	626
19	Appr	oximate inference	634
	19.1	Inference as Optimization	636
	19.2	Expectation Maximization	637
	19.3	MAP Inference and Sparse Coding	638
	19.4	Variational Inference and Learning	641
	19.5	Learned Approximate Inference	653
20	Deep	Generative Models	656
	20.1	Boltzmann Machines	656
	20.2	Restricted Boltzmann Machines	658
	20.3	Deep Belief Networks	662
	20.4	Deep Boltzmann Machines	665
	20.5	Boltzmann Machines for Real-Valued Data	678
	20.6	Convolutional Boltzmann Machines	685
	20.7	Boltzmann Machines for Structured or Sequential Outputs	687
	20.8	Other Boltzmann Machines	688
	20.9	Back-Propagation through Random Operations	689
	20.10	Directed Generative Nets	694
	20.11	Drawing Samples from Autoencoders	712
	20.12	Generative Stochastic Networks	716
	20.13	Other Generation Schemes	717
	20.14	Evaluating Generative Models	719
	20.15	Conclusion	721
Bil	oliogra	aphy	723
Index			780

## 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.