
Outlier Analysis

Charu C. Aggarwal

Outlier Analysis

Second Edition

 Springer

Charu C. Aggarwal
IBM T.J. Watson Research Center
Yorktown Heights, New York, USA

ISBN 978-3-319-47577-6 ISBN 978-3-319-47578-3 (eBook)
DOI 10.1007/978-3-319-47578-3

Library of Congress Control Number: 2016961247

© Springer International Publishing AG 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To my wife, my daughter Sayani,
and my late parents Dr. Prem Sarup and Mrs. Pushplata Aggarwal.

Contents

- 1 An Introduction to Outlier Analysis** **1**
- 1.1 Introduction 1
- 1.2 The Data Model is Everything 5
 - 1.2.1 Connections with Supervised Models 8
- 1.3 The Basic Outlier Detection Models 10
 - 1.3.1 Feature Selection in Outlier Detection 10
 - 1.3.2 Extreme-Value Analysis 11
 - 1.3.3 Probabilistic and Statistical Models 12
 - 1.3.4 Linear Models 13
 - 1.3.4.1 Spectral Models 14
 - 1.3.5 Proximity-Based Models 14
 - 1.3.6 Information-Theoretic Models 16
 - 1.3.7 High-Dimensional Outlier Detection 17
- 1.4 Outlier Ensembles 18
 - 1.4.1 Sequential Ensembles 19
 - 1.4.2 Independent Ensembles 20
- 1.5 The Basic Data Types for Analysis 21
 - 1.5.1 Categorical, Text, and Mixed Attributes 21
 - 1.5.2 When the Data Values have Dependencies 21
 - 1.5.2.1 Times-Series Data and Data Streams 22
 - 1.5.2.2 Discrete Sequences 24
 - 1.5.2.3 Spatial Data 24
 - 1.5.2.4 Network and Graph Data 25
- 1.6 Supervised Outlier Detection 25
- 1.7 Outlier Evaluation Techniques 26
 - 1.7.1 Interpreting the ROC AUC 29
 - 1.7.2 Common Mistakes in Benchmarking 30
- 1.8 Conclusions and Summary 31
- 1.9 Bibliographic Survey 31
- 1.10 Exercises 33

2	Probabilistic Models for Outlier Detection	35
2.1	Introduction	35
2.2	Statistical Methods for Extreme-Value Analysis	37
2.2.1	Probabilistic Tail Inequalities	37
2.2.1.1	Sum of Bounded Random Variables	38
2.2.2	Statistical-Tail Confidence Tests	43
2.2.2.1	t -Value Test	43
2.2.2.2	Sum of Squares of Deviations	45
2.2.2.3	Visualizing Extreme Values with Box Plots	45
2.3	Extreme-Value Analysis in Multivariate Data	46
2.3.1	Depth-Based Methods	47
2.3.2	Deviation-Based Methods	48
2.3.3	Angle-Based Outlier Detection	49
2.3.4	Distance Distribution-based Techniques: The Mahalanobis Method	51
2.3.4.1	Strengths of the Mahalanobis Method	53
2.4	Probabilistic Mixture Modeling for Outlier Analysis	54
2.4.1	Relationship with Clustering Methods	57
2.4.2	The Special Case of a Single Mixture Component	58
2.4.3	Other Ways of Leveraging the EM Model	58
2.4.4	An Application of EM for Converting Scores to Probabilities	59
2.5	Limitations of Probabilistic Modeling	60
2.6	Conclusions and Summary	61
2.7	Bibliographic Survey	61
2.8	Exercises	62
3	Linear Models for Outlier Detection	65
3.1	Introduction	65
3.2	Linear Regression Models	68
3.2.1	Modeling with Dependent Variables	70
3.2.1.1	Applications of Dependent Variable Modeling	73
3.2.2	Linear Modeling with Mean-Squared Projection Error	74
3.3	Principal Component Analysis	75
3.3.1	Connections with the Mahalanobis Method	78
3.3.2	Hard PCA versus Soft PCA	79
3.3.3	Sensitivity to Noise	79
3.3.4	Normalization Issues	80
3.3.5	Regularization Issues	80
3.3.6	Applications to Noise Correction	80
3.3.7	How Many Eigenvectors?	81
3.3.8	Extension to Nonlinear Data Distributions	83
3.3.8.1	Choice of Similarity Matrix	85
3.3.8.2	Practical Issues	86
3.3.8.3	Application to Arbitrary Data Types	88
3.4	One-Class Support Vector Machines	88
3.4.1	Solving the Dual Optimization Problem	92
3.4.2	Practical Issues	92
3.4.3	Connections to Support Vector Data Description and Other Kernel Models	93
3.5	A Matrix Factorization View of Linear Models	95

3.5.1	Outlier Detection in Incomplete Data	96
3.5.1.1	Computing the Outlier Scores	98
3.6	Neural Networks: From Linear Models to Deep Learning	98
3.6.1	Generalization to Nonlinear Models	101
3.6.2	Replicator Neural Networks and Deep Autoencoders	102
3.6.3	Practical Issues	105
3.6.4	The Broad Potential of Neural Networks	106
3.7	Limitations of Linear Modeling	106
3.8	Conclusions and Summary	107
3.9	Bibliographic Survey	108
3.10	Exercises	109
4	Proximity-Based Outlier Detection	111
4.1	Introduction	111
4.2	Clusters and Outliers: The Complementary Relationship	112
4.2.1	Extensions to Arbitrarily Shaped Clusters	115
4.2.1.1	Application to Arbitrary Data Types	118
4.2.2	Advantages and Disadvantages of Clustering Methods	118
4.3	Distance-Based Outlier Analysis	118
4.3.1	Scoring Outputs for Distance-Based Methods	119
4.3.2	Binary Outputs for Distance-Based Methods	121
4.3.2.1	Cell-Based Pruning	122
4.3.2.2	Sampling-Based Pruning	124
4.3.2.3	Index-Based Pruning	126
4.3.3	Data-Dependent Similarity Measures	128
4.3.4	ODIN: A Reverse Nearest Neighbor Approach	129
4.3.5	Intensional Knowledge of Distance-Based Outliers	130
4.3.6	Discussion of Distance-Based Methods	131
4.4	Density-Based Outliers	131
4.4.1	LOF: Local Outlier Factor	132
4.4.1.1	Handling Duplicate Points and Stability Issues	134
4.4.2	LOCI: Local Correlation Integral	135
4.4.2.1	LOCI Plot	136
4.4.3	Histogram-Based Techniques	137
4.4.4	Kernel Density Estimation	138
4.4.4.1	Connection with Harmonic k -Nearest Neighbor Detector	139
4.4.4.2	Local Variations of Kernel Methods	140
4.4.5	Ensemble-Based Implementations of Histograms and Kernel Methods	140
4.5	Limitations of Proximity-Based Detection	141
4.6	Conclusions and Summary	142
4.7	Bibliographic Survey	142
4.8	Exercises	146
5	High-Dimensional Outlier Detection	149
5.1	Introduction	149
5.2	Axis-Parallel Subspaces	152
5.2.1	Genetic Algorithms for Outlier Detection	153
5.2.1.1	Defining Abnormal Lower-Dimensional Projections	153
5.2.1.2	Defining Genetic Operators for Subspace Search	154

5.2.2	Finding Distance-Based Outlying Subspaces	157
5.2.3	Feature Bagging: A Subspace Sampling Perspective	157
5.2.4	Projected Clustering Ensembles	158
5.2.5	Subspace Histograms in Linear Time	160
5.2.6	Isolation Forests	161
5.2.6.1	Further Enhancements for Subspace Selection	163
5.2.6.2	Early Termination	163
5.2.6.3	Relationship to Clustering Ensembles and Histograms	164
5.2.7	Selecting High-Contrast Subspaces	164
5.2.8	Local Selection of Subspace Projections	166
5.2.9	Distance-Based Reference Sets	169
5.3	Generalized Subspaces	170
5.3.1	Generalized Projected Clustering Approach	171
5.3.2	Leveraging Instance-Specific Reference Sets	172
5.3.3	Rotated Subspace Sampling	175
5.3.4	Nonlinear Subspaces	176
5.3.5	Regression Modeling Techniques	178
5.4	Discussion of Subspace Analysis	178
5.5	Conclusions and Summary	180
5.6	Bibliographic Survey	181
5.7	Exercises	184
6	Outlier Ensembles	185
6.1	Introduction	185
6.2	Categorization and Design of Ensemble Methods	188
6.2.1	Basic Score Normalization and Combination Methods	189
6.3	Theoretical Foundations of Outlier Ensembles	191
6.3.1	What is the Expectation Computed Over?	195
6.3.2	Relationship of Ensemble Analysis to Bias-Variance Trade-Off	195
6.4	Variance Reduction Methods	196
6.4.1	Parametric Ensembles	197
6.4.2	Randomized Detector Averaging	199
6.4.3	Feature Bagging: An Ensemble-Centric Perspective	199
6.4.3.1	Connections to Representational Bias	200
6.4.3.2	Weaknesses of Feature Bagging	202
6.4.4	Rotated Bagging	202
6.4.5	Isolation Forests: An Ensemble-Centric View	203
6.4.6	Data-Centric Variance Reduction with Sampling	205
6.4.6.1	Bagging	205
6.4.6.2	Subsampling	206
6.4.6.3	Variable Subsampling	207
6.4.6.4	Variable Subsampling with Rotated Bagging (VR)	209
6.4.7	Other Variance Reduction Methods	209
6.5	Flying Blind with Bias Reduction	211
6.5.1	Bias Reduction by Data-Centric Pruning	211
6.5.2	Bias Reduction by Model-Centric Pruning	212
6.5.3	Combining Bias and Variance Reduction	213
6.6	Model Combination for Outlier Ensembles	214
6.6.1	Combining Scoring Methods with Ranks	215

6.6.2	Combining Bias and Variance Reduction	216
6.7	Conclusions and Summary	217
6.8	Bibliographic Survey	217
6.9	Exercises	218
7	Supervised Outlier Detection	219
7.1	Introduction	219
7.2	Full Supervision: Rare Class Detection	221
7.2.1	Cost-Sensitive Learning	223
7.2.1.1	MetaCost: A Relabeling Approach	223
7.2.1.2	Weighting Methods	225
7.2.2	Adaptive Re-sampling	228
7.2.2.1	Relationship between Weighting and Sampling	229
7.2.2.2	Synthetic Over-sampling: SMOTE	229
7.2.3	Boosting Methods	230
7.3	Semi-Supervision: Positive and Unlabeled Data	231
7.4	Semi-Supervision: Partially Observed Classes	232
7.4.1	One-Class Learning with Anomalous Examples	233
7.4.2	One-Class Learning with Normal Examples	234
7.4.3	Learning with a Subset of Labeled Classes	234
7.5	Unsupervised Feature Engineering in Supervised Methods	235
7.6	Active Learning	236
7.7	Supervised Models for Unsupervised Outlier Detection	239
7.7.1	Connections with PCA-Based Methods	242
7.7.2	Group-wise Predictions for High-Dimensional Data	243
7.7.3	Applicability to Mixed-Attribute Data Sets	244
7.7.4	Incorporating Column-wise Knowledge	244
7.7.5	Other Classification Methods with Synthetic Outliers	244
7.8	Conclusions and Summary	245
7.9	Bibliographic Survey	245
7.10	Exercises	247
8	Categorical, Text, and Mixed Attribute Data	249
8.1	Introduction	249
8.2	Extending Probabilistic Models to Categorical Data	250
8.2.1	Modeling Mixed Data	253
8.3	Extending Linear Models to Categorical and Mixed Data	254
8.3.1	Leveraging Supervised Regression Models	254
8.4	Extending Proximity Models to Categorical Data	255
8.4.1	Aggregate Statistical Similarity	256
8.4.2	Contextual Similarity	257
8.4.2.1	Connections to Linear Models	258
8.4.3	Issues with Mixed Data	259
8.4.4	Density-Based Methods	259
8.4.5	Clustering Methods	259
8.5	Outlier Detection in Binary and Transaction Data	260
8.5.1	Subspace Methods	260
8.5.2	Novelties in Temporal Transactions	262
8.6	Outlier Detection in Text Data	262

8.6.1	Probabilistic Models	262
8.6.2	Linear Models: Latent Semantic Analysis	264
8.6.2.1	Probabilistic Latent Semantic Analysis (PLSA)	265
8.6.3	Proximity-Based Models	268
8.6.3.1	First Story Detection	269
8.7	Conclusions and Summary	270
8.8	Bibliographic Survey	270
8.9	Exercises	272
9	Time Series and Streaming Outlier Detection	273
9.1	Introduction	273
9.2	Predictive Outlier Detection in Streaming Time-Series	276
9.2.1	Autoregressive Models	276
9.2.2	Multiple Time Series Regression Models	279
9.2.2.1	Direct Generalization of Autoregressive Models	279
9.2.2.2	Time-Series Selection Methods	281
9.2.2.3	Principal Component Analysis and Hidden Variable-Based Models	282
9.2.3	Relationship between Unsupervised Outlier Detection and Prediction	284
9.2.4	Supervised Point Outlier Detection in Time Series	284
9.3	Time-Series of Unusual Shapes	286
9.3.1	Transformation to Other Representations	287
9.3.1.1	Numeric Multidimensional Transformations	288
9.3.1.2	Discrete Sequence Transformations	290
9.3.1.3	Leveraging Trajectory Representations of Time Series	291
9.3.2	Distance-Based Methods	293
9.3.2.1	Single Series versus Multiple Series	295
9.3.3	Probabilistic Models	295
9.3.4	Linear Models	295
9.3.4.1	Univariate Series	295
9.3.4.2	Multivariate Series	296
9.3.4.3	Incorporating Arbitrary Similarity Functions	297
9.3.4.4	Leveraging Kernel Methods with Linear Models	298
9.3.5	Supervised Methods for Finding Unusual Time-Series Shapes	298
9.4	Multidimensional Streaming Outlier Detection	298
9.4.1	Individual Data Points as Outliers	299
9.4.1.1	Proximity-Based Algorithms	299
9.4.1.2	Probabilistic Algorithms	301
9.4.1.3	High-Dimensional Scenario	301
9.4.2	Aggregate Change Points as Outliers	301
9.4.2.1	Velocity Density Estimation Method	302
9.4.2.2	Statistically Significant Changes in Aggregate Distributions	304
9.4.3	Rare and Novel Class Detection in Multidimensional Data Streams	305
9.4.3.1	Detecting Rare Classes	305
9.4.3.2	Detecting Novel Classes	306
9.4.3.3	Detecting Infrequently Recurring Classes	306
9.5	Conclusions and Summary	307
9.6	Bibliographic Survey	307
9.7	Exercises	310

10	Outlier Detection in Discrete Sequences	311
10.1	Introduction	311
10.2	Position Outliers	313
10.2.1	Rule-Based Models	315
10.2.2	Markovian Models	316
10.2.3	Efficiency Issues: Probabilistic Suffix Trees	318
10.3	Combination Outliers	320
10.3.1	A Primitive Model for Combination Outlier Detection	322
10.3.1.1	Model-Specific Combination Issues	323
10.3.1.2	Easier Special Cases	323
10.3.1.3	Relationship between Position and Combination Outliers	324
10.3.2	Distance-Based Models	324
10.3.2.1	Combining Anomaly Scores from Comparison Units	326
10.3.2.2	Some Observations on Distance-Based Methods	327
10.3.2.3	Easier Special Case: Short Sequences	327
10.3.3	Frequency-Based Models	327
10.3.3.1	Frequency-Based Model with User-Specified Comparison Unit	327
10.3.3.2	Frequency-Based Model with Extracted Comparison Units	328
10.3.3.3	Combining Anomaly Scores from Comparison Units	329
10.3.4	Hidden Markov Models	329
10.3.4.1	Design Choices in a Hidden Markov Model	331
10.3.4.2	Training and Prediction with HMMs	333
10.3.4.3	Evaluation: Computing the Fit Probability for Observed Sequences	334
10.3.4.4	Explanation: Determining the Most Likely State Sequence for Observed Sequence	334
10.3.4.5	Training: Baum-Welch Algorithm	335
10.3.4.6	Computing Anomaly Scores	336
10.3.4.7	Special Case: Short Sequence Anomaly Detection	337
10.3.5	Kernel-Based Methods	337
10.4	Complex Sequences and Scenarios	338
10.4.1	Multivariate Sequences	338
10.4.2	Set-Based Sequences	339
10.4.3	Online Applications: Early Anomaly Detection	340
10.5	Supervised Outliers in Sequences	340
10.6	Conclusions and Summary	342
10.7	Bibliographic Survey	342
10.8	Exercises	344
11	Spatial Outlier Detection	345
11.1	Introduction	345
11.2	Spatial Attributes are Contextual	349
11.2.1	Neighborhood-Based Algorithms	349
11.2.1.1	Multidimensional Methods	350
11.2.1.2	Graph-Based Methods	351
11.2.1.3	The Case of Multiple Behavioral Attributes	351
11.2.2	Autoregressive Models	352
11.2.3	Visualization with Variogram Clouds	353
11.2.4	Finding Abnormal Shapes in Spatial Data	355

11.2.4.1	Contour Extraction Methods	356
11.2.4.2	Extracting Multidimensional Representations	360
11.2.4.3	Multidimensional Wavelet Transformation	360
11.2.4.4	Supervised Shape Discovery	360
11.2.4.5	Anomalous Shape Change Detection	361
11.3	Spatiotemporal Outliers with Spatial and Temporal Context	362
11.4	Spatial Behavior with Temporal Context: Trajectories	363
11.4.1	Real-Time Anomaly Detection	363
11.4.2	Unusual Trajectory Shapes	363
11.4.2.1	Segment-wise Partitioning Methods	363
11.4.2.2	Tile-Based Transformations	364
11.4.2.3	Similarity-Based Transformations	365
11.4.3	Supervised Outliers in Trajectories	365
11.5	Conclusions and Summary	366
11.6	Bibliographic Survey	366
11.7	Exercises	367
12	Outlier Detection in Graphs and Networks	369
12.1	Introduction	369
12.2	Outlier Detection in Many Small Graphs	371
12.2.1	Leveraging Graph Kernels	371
12.3	Outlier Detection in a Single Large Graph	372
12.3.1	Node Outliers	372
12.3.1.1	Leveraging the Mahalanobis Method	374
12.3.2	Linkage Outliers	374
12.3.2.1	Matrix Factorization Methods	374
12.3.2.2	Spectral Methods and Embeddings	378
12.3.2.3	Clustering Methods	379
12.3.2.4	Community Linkage Outliers	380
12.3.3	Subgraph Outliers	381
12.4	Node Content in Outlier Analysis	382
12.4.1	Shared Matrix Factorization	382
12.4.2	Relating Feature Similarity to Tie Strength	383
12.4.3	Heterogeneous Markov Random Fields	384
12.5	Change-Based Outliers in Temporal Graphs	384
12.5.1	Discovering Node Hotspots in Graph Streams	385
12.5.2	Streaming Detection of Linkage Anomalies	386
12.5.3	Outliers Based on Community Evolution	388
12.5.3.1	Integrating Clustering Maintenance with Evolution Analysis	388
12.5.3.2	Online Analysis of Community Evolution in Graph Streams	390
12.5.3.3	GraphScope	390
12.5.4	Outliers Based on Shortest Path Distance Changes	392
12.5.5	Matrix Factorization and Latent Embedding Methods	392
12.6	Conclusions and Summary	393
12.7	Bibliographic Survey	394
12.8	Exercises	396

13 Applications of Outlier Analysis	399
13.1 Introduction	399
13.2 Quality Control and Fault Detection Applications	401
13.3 Financial Applications	404
13.4 Web Log Analytics	406
13.5 Intrusion and Security Applications	407
13.6 Medical Applications	410
13.7 Text and Social Media Applications	411
13.8 Earth Science Applications	413
13.9 Miscellaneous Applications	415
13.10 Guidelines for the Practitioner	416
13.10.1 Which Unsupervised Algorithms Work Best?	418
13.11 Resources for the Practitioner	421
13.12 Conclusions and Summary	422

Preface

“All things excellent are as difficult as they are rare.”– Baruch Spinoza

First Edition

Most of the earliest work on outlier detection was performed by the statistics community. While statistical methods are mathematically more precise, they have several shortcomings, such as simplified assumptions about data representations, poor algorithmic scalability, and a low focus on interpretability. With the increasing advances in hardware technology for *data collection*, and advances in software technology (databases) for *data organization*, computer scientists have increasingly been participating in the latest advancements of this field. Computer scientists approach this field based on their practical experiences in managing large amounts of data, and with far fewer assumptions– the data can be of any type, structured or unstructured, and may be extremely large. Furthermore, issues such as computational efficiency and intuitive analysis of the data are generally considered more important by computer scientists than mathematical precision, though the latter is important as well. This is the approach of professionals from the field of data mining, an area of computer science that was founded about 20 years ago. This has led to the formation of multiple academic communities on the subject, which have remained separated, partially because of differences in technical style and opinions about the importance of different problems and approaches to the subject. At this point, data mining professionals (with a computer science background) are much more actively involved in this area as compared to statisticians. This seems to be a major change in the research landscape. This book presents outlier detection from an integrated perspective, though the focus is towards computer science professionals. Special emphasis was placed on relating the methods from different communities with one another.

The key advantage of writing the book at this point in time is that the vast amount of work done by computer science professionals in the last two decades has remained largely untouched by a formal book on the subject. The classical books relevant to outlier analysis are as follows:

- P. Rousseeuw and A. Leroy. Robust Regression and Outlier Detection, *Wiley*, 2003.
- V. Barnett and T. Lewis. Outliers in Statistical Data, *Wiley*, 1994.
- D. Hawkins. Identification of Outliers, *Chapman and Hall*, 1980.

We note that these books are quite outdated, and the most recent among them is a decade old. Furthermore, this (most recent) book is really focused on the relationship between regression and outlier analysis, rather than the latter. Outlier analysis is a much broader area, in which regression analysis is only a small part. The other books are even older, and are between 15 and 25 years old. They are exclusively targeted to the statistics community. This is not surprising, given that the first mainstream computer science conference in data mining (KDD) was organized in 1995. Most of the work in the data-mining community was performed after the writing of these books. Therefore, many key topics of interest to the broader data mining community are not covered in these books. Given that outlier analysis has been explored by a much broader community, including databases, data mining, statistics, and machine learning, we feel that our book incorporates perspectives from a much broader audience and brings together different points of view.

The chapters of this book have been organized carefully, with a view of covering the area extensively in a natural order. Emphasis was placed on simplifying the content, so that students and practitioners can also benefit from the book. While we did not originally intend to create a textbook on the subject, it evolved during the writing process into a work that can also be used as a teaching aid. Furthermore, it can also be used as a reference book, since each chapter contains extensive bibliographic notes. Therefore, this book serves a dual purpose, providing a comprehensive exposition of the topic of outlier detection from multiple points of view.

Additional Notes for the Second Edition

The second edition of this book is a significant enhancement over the first edition. In particular, most of the chapters have been upgraded with new material and recent techniques. More explanations have been added at several places and newer techniques have also been added. An entire chapter on outlier ensembles has been added. Many new topics have been added to the book such as feature selection, one-class support vector machines, one-class neural networks, matrix factorization, spectral methods, wavelet transforms, and supervised learning. Every chapter has been updated with the latest algorithms on the topic.

Last but not least, the first edition was classified by the publisher as a monograph, whereas the second edition is formally classified as a textbook. The writing style has been enhanced to be easily understandable to students. Many algorithms have been described in greater detail, as one might expect from a textbook. It is also accompanied with a solution manual for classroom teaching.

Acknowledgments

First Edition

I would like to thank my wife and daughter for their love and support during the writing of this book. The writing of a book requires significant time that is taken away from family members. This book is the result of their patience with me during this time. I also owe my late parents a debt of gratitude for instilling in me a love of education, which has played an important inspirational role in my book-writing efforts.

I would also like to thank my manager Nagui Halim for providing the tremendous support necessary for the writing of this book. His professional support has been instrumental for my many book efforts in the past and present.

Over the years, I have benefited from the insights of numerous collaborators. An incomplete list of these long-term collaborators in alphabetical order is Tarek F. Abdelzaher, Jiawei Han, Thomas S. Huang, Latifur Khan, Mohammad M. Masud, Spiros Papadimitriou, Guojun Qi, and Philip S. Yu. I would like to thank them for their collaborations and insights over the course of many years.

I would also like to specially thank my advisor James B. Orlin for his guidance during my early years as a researcher. While I no longer work in the same area, the legacy of what I learned from him is a crucial part of my approach to research. In particular, he taught me the importance of intuition and simplicity of thought in the research process. These are more important aspects of research than is generally recognized. This book is written in a simple and intuitive style, and is meant to improve accessibility of this area to both researchers and practitioners.

Finally, I would like to thank Lata Aggarwal for helping me with some of the figures created using PowerPoint graphics in this book.

Acknowledgments for Second Edition

I received significant feedback from various colleagues during the writing of the second edition. In particular, I would like to acknowledge Leman Akoglu, Chih-Jen Lin, Saket Sathe, Jiliang Tang, and Suhang Wang. Leman and Saket provided detailed feedback on several sections and chapters of this book.

Author Biography

Charu C. Aggarwal is a Distinguished Research Staff Member (DRSM) at the IBM T. J. Watson Research Center in Yorktown Heights, New York. He completed his undergraduate degree in Computer Science from the Indian Institute of Technology at Kanpur in 1993 and his Ph.D. from the Massachusetts Institute of Technology in 1996.



He has worked extensively in the field of data mining. He has published more than 300 papers in refereed conferences and journals and authored over 80 patents. He is the author or editor of 15 books, including a textbook on data mining and a comprehensive book on outlier analysis. Because of the commercial value of his patents, he has thrice been designated a Master Inventor at IBM. He is a recipient of an IBM Corporate Award (2003) for his work on bio-terrorist threat detection in data streams, a recipient of the IBM Outstanding Innovation Award (2008) for his scientific contributions to privacy technology, a recipient of two IBM Outstanding Technical Achievement Awards (2009, 2015) for his work on data streams and high-dimensional data, respectively. He received the EDBT 2014 Test of Time Award for his work on condensation-based privacy-preserving data mining. He is also a recipient of the IEEE ICDM Research Contributions Award (2015), which is one of the two highest awards for influential research contributions in the field of data mining.

He has served as the general co-chair of the IEEE Big Data Conference (2014) and as the program co-chair of the ACM CIKM Conference (2015), the IEEE ICDM Conference (2015), and the ACM KDD Conference (2016). He served as an associate editor of the IEEE Transactions on Knowledge and Data Engineering from 2004 to 2008. He is an associate editor of the ACM Transactions on Knowledge Discovery from Data, an associate editor of the IEEE Transactions on Big Data, an action editor of the Data Mining and Knowledge Discovery Journal, editor-in-chief of the ACM SIGKDD Explorations, and an associate editor of the Knowledge and Information Systems Journal. He serves on the advisory board of the Lecture Notes on Social Networks, a publication by Springer. He has served as the vice-president of the SIAM Activity Group on Data Mining and is a member of the SIAM industry committee. He is a fellow of the SIAM, ACM, and the IEEE, for “contributions to knowledge discovery and data mining algorithms.”