

# Contents

<b>1</b>	<b>What is Data Science?</b>	<b>1</b>
1.1	Computer Science, Data Science, and Real Science . . . . .	2
1.2	Asking Interesting Questions from Data . . . . .	4
1.2.1	The Baseball Encyclopedia . . . . .	5
1.2.2	The Internet Movie Database (IMDb) . . . . .	7
1.2.3	Google Ngrams . . . . .	10
1.2.4	New York Taxi Records . . . . .	11
1.3	Properties of Data . . . . .	14
1.3.1	Structured vs. Unstructured Data . . . . .	14
1.3.2	Quantitative vs. Categorical Data . . . . .	15
1.3.3	Big Data vs. Little Data . . . . .	15
1.4	Classification and Regression . . . . .	16
1.5	Data Science Television: The Quant Shop . . . . .	17
1.5.1	Kaggle Challenges . . . . .	19
1.6	About the War Stories . . . . .	19
1.7	War Story: Answering the Right Question . . . . .	21
1.8	Chapter Notes . . . . .	22
1.9	Exercises . . . . .	23
<b>2</b>	<b>Mathematical Preliminaries</b>	<b>27</b>
2.1	Probability . . . . .	27
2.1.1	Probability vs. Statistics . . . . .	29
2.1.2	Compound Events and Independence . . . . .	30
2.1.3	Conditional Probability . . . . .	31
2.1.4	Probability Distributions . . . . .	32
2.2	Descriptive Statistics . . . . .	34
2.2.1	Centrality Measures . . . . .	34
2.2.2	Variability Measures . . . . .	36
2.2.3	Interpreting Variance . . . . .	37
2.2.4	Characterizing Distributions . . . . .	39
2.3	Correlation Analysis . . . . .	40
2.3.1	Correlation Coefficients: Pearson and Spearman Rank . . . . .	41
2.3.2	The Power and Significance of Correlation . . . . .	43
2.3.3	Correlation Does Not Imply Causation! . . . . .	45

2.3.4	Detecting Periodicities by Autocorrelation . . . . .	46
2.4	Logarithms . . . . .	47
2.4.1	Logarithms and Multiplying Probabilities . . . . .	48
2.4.2	Logarithms and Ratios . . . . .	48
2.4.3	Logarithms and Normalizing Skewed Distributions . . . . .	49
2.5	War Story: Fitting Designer Genes . . . . .	50
2.6	Chapter Notes . . . . .	52
2.7	Exercises . . . . .	53
<b>3</b>	<b>Data Munging</b> . . . . .	<b>57</b>
3.1	Languages for Data Science . . . . .	57
3.1.1	The Importance of Notebook Environments . . . . .	59
3.1.2	Standard Data Formats . . . . .	61
3.2	Collecting Data . . . . .	64
3.2.1	Hunting . . . . .	64
3.2.2	Scraping . . . . .	67
3.2.3	Logging . . . . .	68
3.3	Cleaning Data . . . . .	69
3.3.1	Errors vs. Artifacts . . . . .	69
3.3.2	Data Compatibility . . . . .	72
3.3.3	Dealing with Missing Values . . . . .	76
3.3.4	Outlier Detection . . . . .	78
3.4	War Story: Beating the Market . . . . .	79
3.5	Crowdsourcing . . . . .	80
3.5.1	The Penny Demo . . . . .	81
3.5.2	When is the Crowd Wise? . . . . .	82
3.5.3	Mechanisms for Aggregation . . . . .	83
3.5.4	Crowdsourcing Services . . . . .	84
3.5.5	Gamification . . . . .	88
3.6	Chapter Notes . . . . .	90
3.7	Exercises . . . . .	90
<b>4</b>	<b>Scores and Rankings</b> . . . . .	<b>95</b>
4.1	The Body Mass Index (BMI) . . . . .	96
4.2	Developing Scoring Systems . . . . .	99
4.2.1	Gold Standards and Proxies . . . . .	99
4.2.2	Scores vs. Rankings . . . . .	100
4.2.3	Recognizing Good Scoring Functions . . . . .	101
4.3	Z-scores and Normalization . . . . .	103
4.4	Advanced Ranking Techniques . . . . .	104
4.4.1	Elo Rankings . . . . .	104
4.4.2	Merging Rankings . . . . .	108
4.4.3	Digraph-based Rankings . . . . .	109
4.4.4	PageRank . . . . .	111
4.5	War Story: Clyde's Revenge . . . . .	111
4.6	Arrow's Impossibility Theorem . . . . .	114

4.7	War Story: Who's Bigger? . . . . .	115
4.8	Chapter Notes . . . . .	118
4.9	Exercises . . . . .	119
<b>5</b>	<b>Statistical Analysis</b>	<b>121</b>
5.1	Statistical Distributions . . . . .	122
5.1.1	The Binomial Distribution . . . . .	123
5.1.2	The Normal Distribution . . . . .	124
5.1.3	Implications of the Normal Distribution . . . . .	126
5.1.4	Poisson Distribution . . . . .	127
5.1.5	Power Law Distributions . . . . .	129
5.2	Sampling from Distributions . . . . .	132
5.2.1	Random Sampling beyond One Dimension . . . . .	133
5.3	Statistical Significance . . . . .	135
5.3.1	The Significance of Significance . . . . .	135
5.3.2	The T-test: Comparing Population Means . . . . .	137
5.3.3	The Kolmogorov-Smirnov Test . . . . .	139
5.3.4	The Bonferroni Correction . . . . .	141
5.3.5	False Discovery Rate . . . . .	142
5.4	War Story: Discovering the Fountain of Youth? . . . . .	143
5.5	Permutation Tests and P-values . . . . .	145
5.5.1	Generating Random Permutations . . . . .	147
5.5.2	DiMaggio's Hitting Streak . . . . .	148
5.6	Bayesian Reasoning . . . . .	150
5.7	Chapter Notes . . . . .	151
5.8	Exercises . . . . .	151
<b>6</b>	<b>Visualizing Data</b>	<b>155</b>
6.1	Exploratory Data Analysis . . . . .	156
6.1.1	Confronting a New Data Set . . . . .	156
6.1.2	Summary Statistics and Anscombe's Quartet . . . . .	159
6.1.3	Visualization Tools . . . . .	160
6.2	Developing a Visualization Aesthetic . . . . .	162
6.2.1	Maximizing Data-Ink Ratio . . . . .	163
6.2.2	Minimizing the Lie Factor . . . . .	164
6.2.3	Minimizing Chartjunk . . . . .	165
6.2.4	Proper Scaling and Labeling . . . . .	167
6.2.5	Effective Use of Color and Shading . . . . .	168
6.2.6	The Power of Repetition . . . . .	169
6.3	Chart Types . . . . .	170
6.3.1	Tabular Data . . . . .	170
6.3.2	Dot and Line Plots . . . . .	174
6.3.3	Scatter Plots . . . . .	177
6.3.4	Bar Plots and Pie Charts . . . . .	179
6.3.5	Histograms . . . . .	183
6.3.6	Data Maps . . . . .	187

6.4	Great Visualizations . . . . .	189
6.4.1	Marey's Train Schedule . . . . .	189
6.4.2	Snow's Cholera Map . . . . .	191
6.4.3	New York's Weather Year . . . . .	192
6.5	Reading Graphs . . . . .	192
6.5.1	The Obscured Distribution . . . . .	193
6.5.2	Overinterpreting Variance . . . . .	193
6.6	Interactive Visualization . . . . .	195
6.7	War Story: TextMapping the World . . . . .	196
6.8	Chapter Notes . . . . .	198
6.9	Exercises . . . . .	199
<b>7</b>	<b>Mathematical Models</b>	<b>201</b>
7.1	Philosophies of Modeling . . . . .	201
7.1.1	Occam's Razor . . . . .	201
7.1.2	Bias-Variance Trade-Offs . . . . .	202
7.1.3	What Would Nate Silver Do? . . . . .	203
7.2	A Taxonomy of Models . . . . .	205
7.2.1	Linear vs. Non-Linear Models . . . . .	206
7.2.2	Blackbox vs. Descriptive Models . . . . .	206
7.2.3	First-Principle vs. Data-Driven Models . . . . .	207
7.2.4	Stochastic vs. Deterministic Models . . . . .	208
7.2.5	Flat vs. Hierarchical Models . . . . .	209
7.3	Baseline Models . . . . .	210
7.3.1	Baseline Models for Classification . . . . .	210
7.3.2	Baseline Models for Value Prediction . . . . .	212
7.4	Evaluating Models . . . . .	212
7.4.1	Evaluating Classifiers . . . . .	213
7.4.2	Receiver-Operator Characteristic (ROC) Curves . . . . .	218
7.4.3	Evaluating Multiclass Systems . . . . .	219
7.4.4	Evaluating Value Prediction Models . . . . .	221
7.5	Evaluation Environments . . . . .	224
7.5.1	Data Hygiene for Evaluation . . . . .	225
7.5.2	Amplifying Small Evaluation Sets . . . . .	226
7.6	War Story: 100% Accuracy . . . . .	228
7.7	Simulation Models . . . . .	229
7.8	War Story: Calculated Bets . . . . .	230
7.9	Chapter Notes . . . . .	233
7.10	Exercises . . . . .	234
<b>8</b>	<b>Linear Algebra</b>	<b>237</b>
8.1	The Power of Linear Algebra . . . . .	237
8.1.1	Interpreting Linear Algebraic Formulae . . . . .	238
8.1.2	Geometry and Vectors . . . . .	240
8.2	Visualizing Matrix Operations . . . . .	241
8.2.1	Matrix Addition . . . . .	242

8.2.2	Matrix Multiplication . . . . .	243
8.2.3	Applications of Matrix Multiplication . . . . .	244
8.2.4	Identity Matrices and Inversion . . . . .	248
8.2.5	Matrix Inversion and Linear Systems . . . . .	250
8.2.6	Matrix Rank . . . . .	251
8.3	Factoring Matrices . . . . .	252
8.3.1	Why Factor Feature Matrices? . . . . .	252
8.3.2	LU Decomposition and Determinants . . . . .	254
8.4	Eigenvalues and Eigenvectors . . . . .	255
8.4.1	Properties of Eigenvalues . . . . .	255
8.4.2	Computing Eigenvalues . . . . .	256
8.5	Eigenvalue Decomposition . . . . .	257
8.5.1	Singular Value Decomposition . . . . .	258
8.5.2	Principal Components Analysis . . . . .	260
8.6	War Story: The Human Factors . . . . .	262
8.7	Chapter Notes . . . . .	263
8.8	Exercises . . . . .	263
<b>9</b>	<b>Linear and Logistic Regression</b> . . . . .	<b>267</b>
9.1	Linear Regression . . . . .	268
9.1.1	Linear Regression and Duality . . . . .	268
9.1.2	Error in Linear Regression . . . . .	269
9.1.3	Finding the Optimal Fit . . . . .	270
9.2	Better Regression Models . . . . .	272
9.2.1	Removing Outliers . . . . .	272
9.2.2	Fitting Non-Linear Functions . . . . .	273
9.2.3	Feature and Target Scaling . . . . .	274
9.2.4	Dealing with Highly-Correlated Features . . . . .	277
9.3	War Story: Taxi Driver . . . . .	277
9.4	Regression as Parameter Fitting . . . . .	279
9.4.1	Convex Parameter Spaces . . . . .	280
9.4.2	Gradient Descent Search . . . . .	281
9.4.3	What is the Right Learning Rate? . . . . .	283
9.4.4	Stochastic Gradient Descent . . . . .	285
9.5	Simplifying Models through Regularization . . . . .	286
9.5.1	Ridge Regression . . . . .	286
9.5.2	LASSO Regression . . . . .	287
9.5.3	Trade-Offs between Fit and Complexity . . . . .	288
9.6	Classification and Logistic Regression . . . . .	289
9.6.1	Regression for Classification . . . . .	290
9.6.2	Decision Boundaries . . . . .	291
9.6.3	Logistic Regression . . . . .	292
9.7	Issues in Logistic Classification . . . . .	295
9.7.1	Balanced Training Classes . . . . .	295
9.7.2	Multi-Class Classification . . . . .	297
9.7.3	Hierarchical Classification . . . . .	298

9.7.4	Partition Functions and Multinomial Regression . . . . .	299
9.8	Chapter Notes . . . . .	300
9.9	Exercises . . . . .	301
<b>10</b>	<b>Distance and Network Methods</b>	<b>303</b>
10.1	Measuring Distances . . . . .	303
10.1.1	Distance Metrics . . . . .	304
10.1.2	The $L_k$ Distance Metric . . . . .	305
10.1.3	Working in Higher Dimensions . . . . .	307
10.1.4	Dimensional Egalitarianism . . . . .	308
10.1.5	Points vs. Vectors . . . . .	309
10.1.6	Distances between Probability Distributions . . . . .	310
10.2	Nearest Neighbor Classification . . . . .	311
10.2.1	Seeking Good Analogies . . . . .	312
10.2.2	$k$ -Nearest Neighbors . . . . .	313
10.2.3	Finding Nearest Neighbors . . . . .	315
10.2.4	Locality Sensitive Hashing . . . . .	317
10.3	Graphs, Networks, and Distances . . . . .	319
10.3.1	Weighted Graphs and Induced Networks . . . . .	320
10.3.2	Talking About Graphs . . . . .	321
10.3.3	Graph Theory . . . . .	323
10.4	PageRank . . . . .	325
10.5	Clustering . . . . .	327
10.5.1	$k$ -means Clustering . . . . .	330
10.5.2	Agglomerative Clustering . . . . .	336
10.5.3	Comparing Clusterings . . . . .	341
10.5.4	Similarity Graphs and Cut-Based Clustering . . . . .	341
10.6	War Story: Cluster Bombing . . . . .	344
10.7	Chapter Notes . . . . .	345
10.8	Exercises . . . . .	346
<b>11</b>	<b>Machine Learning</b>	<b>351</b>
11.1	Naive Bayes . . . . .	354
11.1.1	Formulation . . . . .	354
11.1.2	Dealing with Zero Counts (Discounting) . . . . .	356
11.2	Decision Tree Classifiers . . . . .	357
11.2.1	Constructing Decision Trees . . . . .	359
11.2.2	Realizing Exclusive Or . . . . .	361
11.2.3	Ensembles of Decision Trees . . . . .	362
11.3	Boosting and Ensemble Learning . . . . .	363
11.3.1	Voting with Classifiers . . . . .	363
11.3.2	Boosting Algorithms . . . . .	364
11.4	Support Vector Machines . . . . .	366
11.4.1	Linear SVMs . . . . .	369
11.4.2	Non-linear SVMs . . . . .	369
11.4.3	Kernels . . . . .	371

11.5	Degrees of Supervision . . . . .	372
11.5.1	Supervised Learning . . . . .	372
11.5.2	Unsupervised Learning . . . . .	372
11.5.3	Semi-supervised Learning . . . . .	374
11.5.4	Feature Engineering . . . . .	375
11.6	Deep Learning . . . . .	377
11.6.1	Networks and Depth . . . . .	378
11.6.2	Backpropagation . . . . .	382
11.6.3	Word and Graph Embeddings . . . . .	383
11.7	War Story: The Name Game . . . . .	385
11.8	Chapter Notes . . . . .	387
11.9	Exercises . . . . .	388
<b>12</b>	<b>Big Data: Achieving Scale</b>	<b>391</b>
12.1	What is Big Data? . . . . .	392
12.1.1	Big Data as Bad Data . . . . .	392
12.1.2	The Three Vs . . . . .	394
12.2	War Story: Infrastructure Matters . . . . .	395
12.3	Algorithmics for Big Data . . . . .	397
12.3.1	Big Oh Analysis . . . . .	397
12.3.2	Hashing . . . . .	399
12.3.3	Exploiting the Storage Hierarchy . . . . .	401
12.3.4	Streaming and Single-Pass Algorithms . . . . .	402
12.4	Filtering and Sampling . . . . .	403
12.4.1	Deterministic Sampling Algorithms . . . . .	404
12.4.2	Randomized and Stream Sampling . . . . .	406
12.5	Parallelism . . . . .	406
12.5.1	One, Two, Many . . . . .	407
12.5.2	Data Parallelism . . . . .	409
12.5.3	Grid Search . . . . .	409
12.5.4	Cloud Computing Services . . . . .	410
12.6	MapReduce . . . . .	410
12.6.1	Map-Reduce Programming . . . . .	412
12.6.2	MapReduce under the Hood . . . . .	414
12.7	Societal and Ethical Implications . . . . .	416
12.8	Chapter Notes . . . . .	419
12.9	Exercises . . . . .	419
<b>13</b>	<b>Coda</b>	<b>423</b>
13.1	Get a Job! . . . . .	423
13.2	Go to Graduate School! . . . . .	424
13.3	Professional Consulting Services . . . . .	425
<b>14</b>	<b>Bibliography</b>	<b>427</b>