Contents

About the Author xxi

PREAMBLE 1

1 Financial Machine Learning as a Distinct Subject 3

1.1 Motivation, 3
1.2 The Main Reason Financial Machine Learning Projects Usually Fail, 4
1.2.1 The Sisyphus Paradigm, 4
1.2.2 The Meta-Strategy Paradigm, 5
1.3 Book Structure, 6
1.3.1 Structure by Production Chain, 6
1.3.2 Structure by Strategy Component, 9
1.3.3 Structure by Common Pitfall, 12
1.4 Target Audience, 12
1.5 Requisites, 13
1.6 FAQs, 14
1.7 Acknowledgments, 18
Exercises, 19
References, 20
Bibliography, 20

PART 1 DATA ANALYSIS 21

2 Financial Data Structures 23

2.1 Motivation, 23

2.2 Essential Types of Financial Data, 23
2.2.1 Fundamental Data, 23
2.2.2 Market Data, 24
2.2.3 Analytics, 25
2.2.4 Alternative Data, 25
2.3 Bars, 25
2.3.1 Standard Bars, 26
2.3.2 Information-Driven Bars, 29
2.4 Dealing with Multi-Product Series, 32
2.4.1 The ETF Trick, 33
2.4.2 PCA Weights, 35
2.4.3 Single Future Roll, 36
2.5 Sampling Features, 38
2.5.1 Sampling for Reduction, 38
2.5.2 Event-Based Sampling, 38
Exercises, 40
References, 41

3 Labeling 43
3.1 Motivation, 43
3.2 The Fixed-Time Horizon Method, 43
3.3 Computing Dynamic Thresholds, 44
3.4 The Triple-Barrier Method, 45
3.5 Learning Side and Size, 48
3.6 Meta-Labeling, 50
3.7 How to Use Meta-Labeling, 51
3.8 The Quantamental Way, 53
3.9 Dropping Unnecessary Labels, 54
Exercises, 55
Bibliography, 56

4 Sample Weights 59
4.1 Motivation, 59
4.2 Overlapping Outcomes, 59
4.3 Number of Concurrent Labels, 60
4.4 Average Uniqueness of a Label, 61
4.5 Bagging Classifiers and Uniqueness, 62
4.5.1 Sequential Bootstrap, 63
4.5.2 Implementation of Sequential Bootstrap, 64

4.5.3 A Numerical Example, 65
4.5.4 Monte Carlo Experiments, 66
4.6 Return Attribution, 68
4.7 Time Decay, 70
4.8 Class Weights, 71
Exercises, 72
References, 73
Bibliography, 73

5 Fractionally Differentiated Features 75

5.1 Motivation, 75
5.2 The Stationarity vs. Memory Dilemma, 75
5.3 Literature Review, 76
5.4 The Method, 77
5.4.1 Long Memory, 77
5.4.2 Iterative Estimation, 78
5.4.3 Convergence, 80
5.5 Implementation, 80
5.5.1 Expanding Window, 80
5.5.2 Fixed-Width Window Fracdiff, 82
5.6 Stationarity with Maximum Memory Preservation, 84
5.7 Conclusion, 88
Exercises, 88
References, 89
Bibliography, 89

PART 2 MODELLING 91

6 Ensemble Methods 93

6.1 Motivation, 93
6.2 The Three Sources of Errors, 93
6.3 Bootstrap Aggregation, 94
6.3.1 Variance Reduction, 94
6.3.2 Improved Accuracy, 96
6.3.3 Observation Redundancy, 97
6.4 Random Forest, 98
6.5 Boosting, 99

6.6 Bagging vs. Boosting in Finance, 100
6.7 Bagging for Scalability, 101
Exercises, 101
References, 102
Bibliography, 102

7 Cross-Validation in Finance 103

7.1 Motivation, 103
7.2 The Goal of Cross-Validation, 103
7.3 Why K-Fold CV Fails in Finance, 104
7.4 A Solution: Purged K-Fold CV, 105
7.4.1 Purging the Training Set, 105
7.4.2 Embargo, 107
7.4.3 The Purged K-Fold Class, 108
7.5 Bugs in Sklearn's Cross-Validation, 109
Exercises, 110
Bibliography, 111

8 Feature Importance 113

8.1 Motivation, 113
8.2 The Importance of Feature Importance, 113
8.3 Feature Importance with Substitution Effects, 114
8.3.1 Mean Decrease Impurity, 114
8.3.2 Mean Decrease Accuracy, 116
8.4 Feature Importance without Substitution Effects, 117
8.4.1 Single Feature Importance, 117
8.4.2 Orthogonal Features, 118
8.5 Parallelized vs. Stacked Feature Importance, 121
8.6 Experiments with Synthetic Data, 122
Exercises, 127
References, 127

9 Hyper-Parameter Tuning with Cross-Validation 129

9.1 Motivation, 129
9.2 Grid Search Cross-Validation, 129
9.3 Randomized Search Cross-Validation, 131
9.3.1 Log-Uniform Distribution, 132
9.4 Scoring and Hyper-parameter Tuning, 134

Exercises, 135
References, 136
Bibliography, 137

PART 3 BACKTESTING 139

10 Bet Sizing 141
10.1 Motivation, 141
10.2 Strategy-Independent Bet Sizing Approaches, 141
10.3 Bet Sizing from Predicted Probabilities, 142
10.4 Averaging Active Bets, 144
10.5 Size Discretization, 144
10.6 Dynamic Bet Sizes and Limit Prices, 145
Exercises, 148
References, 149
Bibliography, 149

11 The Dangers of Backtesting 151
11.1 Motivation, 151
11.2 Mission Impossible: The Flawless Backtest, 151
11.3 Even If Your Backtest Is Flawless, It Is Probably Wrong, 152
11.4 Backtesting Is Not a Research Tool, 153
11.5 A Few General Recommendations, 153
11.6 Strategy Selection, 155
Exercises, 158
References, 158
Bibliography, 159

12 Backtesting through Cross-Validation 161
12.1 Motivation, 161
12.2 The Walk-Forward Method, 161
12.2.1 Pitfalls of the Walk-Forward Method, 162
12.3 The Cross-Validation Method, 162
12.4 The Combinatorial Purged Cross-Validation Method, 163
12.4.1 Combinatorial Splits, 164
12.4.2 The Combinatorial Purged Cross-Validation Backtesting Algorithm, 165
12.4.3 A Few Examples, 165

12.5 How Combinatorial Purged Cross-Validation Addresses Backtest Overfitting, 166
Exercises, 167
References, 168

13 Backtesting on Synthetic Data 169

13.1 Motivation, 169
13.2 Trading Rules, 169
13.3 The Problem, 170
13.4 Our Framework, 172
13.5 Numerical Determination of Optimal Trading Rules, 173
13.5.1 The Algorithm, 173
13.5.2 Implementation, 174
13.6 Experimental Results, 176
13.6.1 Cases with Zero Long-Run Equilibrium, 177
13.6.2 Cases with Positive Long-Run Equilibrium, 180
13.6.3 Cases with Negative Long-Run Equilibrium, 182
13.7 Conclusion, 192
Exercises, 192
References, 193

14 Backtest Statistics 195

14.1 Motivation, 195
14.2 Types of Backtest Statistics, 195
14.3 General Characteristics, 196
14.4 Performance, 198
14.4.1 Time-Weighted Rate of Return, 198
14.5 Runs, 199
14.5.1 Returns Concentration, 199
14.5.2 Drawdown and Time under Water, 201
14.5.3 Runs Statistics for Performance Evaluation, 201
14.6 Implementation Shortfall, 202
14.7 Efficiency, 203
14.7.1 The Sharpe Ratio, 203
14.7.2 The Probabilistic Sharpe Ratio, 203
14.7.3 The Deflated Sharpe Ratio, 204
14.7.4 Efficiency Statistics, 205
14.8 Classification Scores, 206
14.9 Attribution, 207

Exercises, 208
References, 209
Bibliography, 209

15 Understanding Strategy Risk 211

15.1 Motivation, 211
15.2 Symmetric Payouts, 211
15.3 Asymmetric Payouts, 213
15.4 The Probability of Strategy Failure, 216
15.4.1 Algorithm, 217
15.4.2 Implementation, 217
Exercises, 219
References, 220

16 Machine Learning Asset Allocation 221

16.1 Motivation, 221
16.2 The Problem with Convex Portfolio Optimization, 221
16.3 Markowitz's Curse, 222
16.4 From Geometric to Hierarchical Relationships, 223
16.4.1 Tree Clustering, 224
16.4.2 Quasi-Diagonalization, 229
16.4.3 Recursive Bisection, 229
16.5 A Numerical Example, 231
16.6 Out-of-Sample Monte Carlo Simulations, 234
16.7 Further Research, 236
16.8 Conclusion, 238
Appendices, 239
16.A.1 Correlation-based Metric, 239
16.A.2 Inverse Variance Allocation, 239
16.A.3 Reproducing the Numerical Example, 240
16.A.4 Reproducing the Monte Carlo Experiment, 242
Exercises, 244
References, 245

PART 4 USEFUL FINANCIAL FEATURES 247

17 Structural Breaks 249

17.1 Motivation, 249
17.2 Types of Structural Break Tests, 249

17.3 CUSUM Tests, 250
17.3.1 Brown-Durbin-Evans CUSUM Test on Recursive Residuals, 250
17.3.2 Chu-Stinchcombe-White CUSUM Test on Levels, 251
17.4 Explosiveness Tests, 251
17.4.1 Chow-Type Dickey-Fuller Test, 251
17.4.2 Supremum Augmented Dickey-Fuller, 252
17.4.3 Sub- and Super-Martingale Tests, 259
Exercises, 261
References, 261

18 Entropy Features 263
18.1 Motivation, 263
18.2 Shannon's Entropy, 263
18.3 The Plug-in (or Maximum Likelihood) Estimator, 264
18.4 Lempel-Ziv Estimators, 265
18.5 Encoding Schemes, 269
18.5.1 Binary Encoding, 270
18.5.2 Quantile Encoding, 270
18.5.3 Sigma Encoding, 270
18.6 Entropy of a Gaussian Process, 271
18.7 Entropy and the Generalized Mean, 271
18.8 A Few Financial Applications of Entropy, 275
18.8.1 Market Efficiency, 275
18.8.2 Maximum Entropy Generation, 275
18.8.3 Portfolio Concentration, 275
18.8.4 Market Microstructure, 276
Exercises, 277
References, 278
Bibliography, 279

19 Microstructural Features 281
19.1 Motivation, 281
19.2 Review of the Literature, 281
19.3 First Generation: Price Sequences, 282
19.3.1 The Tick Rule, 282
19.3.2 The Roll Model, 282

19.3.3 High-Low Volatility Estimator, 283
19.3.4 Corwin and Schultz, 284
19.4 Second Generation: Strategic Trade Models, 286
19.4.1 Kyle's Lambda, 286
19.4.2 Amihud's Lambda, 288
19.4.3 Hasbrouck's Lambda, 289
19.5 Third Generation: Sequential Trade Models, 290
19.5.1 Probability of Information-based Trading, 290
19.5.2 Volume-Synchronized Probability of Informed Trading, 292
19.6 Additional Features from Microstructural Datasets, 293
19.6.1 Distibution of Order Sizes, 293
19.6.2 Cancellation Rates, Limit Orders, Market Orders, 293
19.6.3 Time-Weighted Average Price Execution Algorithms, 294
19.6.4 Options Markets, 295
19.6.5 Serial Correlation of Signed Order Flow, 295
19.7 What Is Microstructural Information?, 295
Exercises, 296
References, 298

PART 5 HIGH-PERFORMANCE COMPUTING RECIPES 301

20 Multiprocessing and Vectorization 303

20.1 Motivation, 303
20.2 Vectorization Example, 303
20.3 Single-Thread vs. Multithreading vs. Multiprocessing, 304
20.4 Atoms and Molecules, 306
20.4.1 Linear Partitions, 306
20.4.2 Two-Nested Loops Partitions, 307
20.5 Multiprocessing Engines, 309
20.5.1 Preparing the Jobs, 309
20.5.2 Asynchronous Calls, 311
20.5.3 Unwrapping the Callback, 312
20.5.4 Pickle/Unpickle Objects, 313
20.5.5 Output Reduction, 313
20.6 Multiprocessing Example, 315
Exercises, 316

Reference, 317
Bibliography, 317

21 Brute Force and Quantum Computers 319

21.1 Motivation, 319
21.2 Combinatorial Optimization, 319
21.3 The Objective Function, 320
21.4 The Problem, 321
21.5 An Integer Optimization Approach, 321
21.5.1 Pigeonhole Partitions, 321
21.5.2 Feasible Static Solutions, 323
21.5.3 Evaluating Trajectories, 323
21.6 A Numerical Example, 325
21.6.1 Random Matrices, 325
21.6.2 Static Solution, 326
21.6.3 Dynamic Solution, 327
Exercises, 327
References, 328

22 High-Performance Computational Intelligence and Forecasting Technologies 329
Kesheng Wu and Horst D. Simon

22.1 Motivation, 329
22.2 Regulatory Response to the Flash Crash of 2010, 329
22.3 Background, 330
22.4 HPC Hardware, 331
22.5 HPC Software, 335
22.5.1 Message Passing Interface, 335
22.5.2 Hierarchical Data Format 5, 336
22.5.3 *In Situ* Processing, 336
22.5.4 Convergence, 337
22.6 Use Cases, 337
22.6.1 Supernova Hunting, 337
22.6.2 Blobs in Fusion Plasma, 338
22.6.3 Intraday Peak Electricity Usage, 340
22.6.4 The Flash Crash of 2010, 341
22.6.5 Volume-synchronized Probability of Informed Trading Calibration, 346

22.6.6 Revealing High Frequency Events with Non-uniform Fast Fourier Transform, 347

22.7 Summary and Call for Participation, 349

22.8 Acknowledgments, 350

References, 350

Index 353