

---

# Contents

---

<b>Preface</b>	<b>xi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Before You Start	1
1.2 Initial Data Analysis	2
1.3 When to Use Linear Modeling	7
1.4 History	8
<b>2 Estimation</b>	<b>13</b>
2.1 Linear Model	13
2.2 Matrix Representation	14
2.3 Estimating $\beta$	15
2.4 Least Squares Estimation	16
2.5 Examples of Calculating $\hat{\beta}$	17
2.6 Example	17
2.7 QR Decomposition	20
2.8 Gauss–Markov Theorem	22
2.9 Goodness of Fit	23
2.10 Identifiability	26
2.11 Orthogonality	28
<b>3 Inference</b>	<b>33</b>
3.1 Hypothesis Tests to Compare Models	33
3.2 Testing Examples	35
3.3 Permutation Tests	40
3.4 Sampling	42
3.5 Confidence Intervals for $\beta$	43
3.6 Bootstrap Confidence Intervals	46
<b>4 Prediction</b>	<b>51</b>
4.1 Confidence Intervals for Predictions	51
4.2 Predicting Body Fat	52
4.3 Autoregression	54
4.4 What Can Go Wrong with Predictions?	56

<b>5</b>	<b>Explanation</b>	<b>59</b>
5.1	Simple Meaning	59
5.2	Causality	61
5.3	Designed Experiments	62
5.4	Observational Data	63
5.5	Matching	65
5.6	Covariate Adjustment	68
5.7	Qualitative Support for Causation	69
<b>6</b>	<b>Diagnostics</b>	<b>73</b>
6.1	Checking Error Assumptions	73
6.1.1	Constant Variance	73
6.1.2	Normality	78
6.1.3	Correlated Errors	81
6.2	Finding Unusual Observations	83
6.2.1	Leverage	83
6.2.2	Outliers	85
6.2.3	Influential Observations	89
6.3	Checking the Structure of the Model	92
6.4	Discussion	96
<b>7</b>	<b>Problems with the Predictors</b>	<b>99</b>
7.1	Errors in the Predictors	99
7.2	Changes of Scale	103
7.3	Collinearity	106
<b>8</b>	<b>Problems with the Error</b>	<b>113</b>
8.1	Generalized Least Squares	113
8.2	Weighted Least Squares	116
8.3	Testing for Lack of Fit	119
8.4	Robust Regression	123
8.4.1	M-Estimation	123
8.4.2	Least Trimmed Squares	126
<b>9</b>	<b>Transformation</b>	<b>133</b>
9.1	Transforming the Response	133
9.2	Transforming the Predictors	137
9.3	Broken Stick Regression	137
9.4	Polynomials	139
9.5	Splines	141
9.6	Additive Models	144
9.7	More Complex Models	145

CONTENTS	ix
<b>10 Model Selection</b>	<b>149</b>
10.1 Hierarchical Models	150
10.2 Testing-Based Procedures	151
10.3 Criterion-Based Procedures	153
10.4 Summary	159
<b>11 Shrinkage Methods</b>	<b>161</b>
11.1 Principal Components	161
11.2 Partial Least Squares	172
11.3 Ridge Regression	174
11.4 Lasso	177
<b>12 Insurance Redlining — A Complete Example</b>	<b>183</b>
12.1 Ecological Correlation	183
12.2 Initial Data Analysis	185
12.3 Full Model and Diagnostics	188
12.4 Sensitivity Analysis	190
12.5 Discussion	194
<b>13 Missing Data</b>	<b>197</b>
13.1 Types of Missing Data	197
13.2 Deletion	198
13.3 Single Imputation	200
13.4 Multiple Imputation	202
<b>14 Categorical Predictors</b>	<b>205</b>
14.1 A Two-Level Factor	205
14.2 Factors and Quantitative Predictors	209
14.3 Interpretation with Interaction Terms	212
14.4 Factors With More Than Two Levels	213
14.5 Alternative Codings of Qualitative Predictors	219
<b>15 One Factor Models</b>	<b>223</b>
15.1 The Model	223
15.2 An Example	224
15.3 Diagnostics	227
15.4 Pairwise Comparisons	228
15.5 False Discovery Rate	230
<b>16 Models with Several Factors</b>	<b>235</b>
16.1 Two Factors with No Replication	235
16.2 Two Factors with Replication	239
16.3 Two Factors with an Interaction	243
16.4 Larger Factorial Experiments	246

<b>17 Experiments with Blocks</b>	<b>251</b>
17.1 Randomized Block Design	252
17.2 Latin Squares	256
17.3 Balanced Incomplete Block Design	259
<b>A About R</b>	<b>265</b>
<b>Bibliography</b>	<b>267</b>
<b>Index</b>	<b>271</b>