

# Contents

<b>1 Programming Primer</b>	<b>1</b>
1.1 Programming Fundamentals . . . . .	1
1.1.1 Compiled vs. Interpreted . . . . .	1
1.1.2 Some Fundamental Concepts . . . . .	2
1.1.3 Code Components . . . . .	4
1.1.4 Designing With Pseudo-Code . . . . .	7
1.1.5 From Pseudo-Code to Code . . . . .	9
1.1.6 Debugging . . . . .	10
1.1.7 R/Python . . . . .	10
1.2 Introduction to R . . . . .	12
1.2.1 Why Use R . . . . .	12
1.2.2 Installing R / RStudio . . . . .	12
1.2.3 Test, Test, Test! . . . . .	13
1.2.4 Customizing RStudio . . . . .	14
1.2.5 Upgrading R / RStudio . . . . .	15
1.2.6 Basics of R . . . . .	15
1.3 More Programming in R . . . . .	27
1.3.1 Help and Documentation . . . . .	27
1.3.2 Simple Data Manipulation . . . . .	29
1.3.3 Exploring Data . . . . .	34
1.3.4 A Word About NAs . . . . .	39
1.3.5 Loops and Conditions . . . . .	40
1.4 The tidyverse . . . . .	40
1.4.1 Pipeline Operator . . . . .	41
1.4.2 Tidy Data . . . . .	42
1.4.3 The dplyr Package . . . . .	44
1.5 Basics of Python . . . . .	47
1.5.1 IDE for Python . . . . .	48
1.5.2 Introduction to Python . . . . .	48
1.5.3 NumPy and Arrays . . . . .	67
1.6 Python for Data Science . . . . .	72
1.6.1 Pandas and Data Frames . . . . .	72
1.6.2 Data Wrangling . . . . .	78
1.6.3 Data Aggregation . . . . .	83
1.6.4 Combining Python with R . . . . .	85
1.7 Getting Started with SQL . . . . .	86
1.7.1 Basics . . . . .	86
1.7.2 SQL Syntax . . . . .	87
1.7.3 Key Query Operators . . . . .	88
1.7.4 Examples . . . . .	96
1.8 Exercises . . . . .	98
Chapter References . . . . .	106

<b>2 Multivariate Calculus for Data Analysis</b>	<b>107</b>
2.1 Points, Vectors, Coordinates . . . . .	107
2.1.1 One Dimension . . . . .	108
2.1.2 Two and Three Dimensions . . . . .	108
2.1.3 More Dimensions . . . . .	108
2.2 Functions . . . . .	109
2.3 Graphical Representation . . . . .	111
2.3.1 One Variable . . . . .	111
2.3.2 Two Variables . . . . .	111
2.3.3 Three or More Variables . . . . .	114
2.3.4 Scalars and Vector Fields . . . . .	115
2.4 Derivatives . . . . .	116
2.4.1 Difference Quotients . . . . .	116
2.4.2 Rules of Differentiation . . . . .	117
2.4.3 Partial Derivatives . . . . .	118
2.4.4 Gradients . . . . .	121
2.4.5 Directional Derivatives . . . . .	122
2.5 Optimization . . . . .	125
2.5.1 Critical Points . . . . .	125
2.5.2 Local vs. Global . . . . .	127
2.5.3 Local Extrema . . . . .	127
2.5.4 Global Extrema . . . . .	130
2.5.5 Lagrange Multipliers . . . . .	132
2.6 Riemann Integrals . . . . .	135
2.6.1 Local Densities, Total Sums . . . . .	136
2.6.2 One Variable . . . . .	137
2.6.3 Fundamental Theorem . . . . .	137
2.6.4 Finding Antiderivatives . . . . .	138
2.6.5 Several Variables . . . . .	139
2.6.6 Applications to Statistics . . . . .	140
2.7 Exercises . . . . .	143
Chapter References . . . . .	146
<b>3 Overview of Linear Algebra</b>	<b>147</b>
3.1 Vector Spaces . . . . .	147
3.1.1 Practical Definition . . . . .	147
3.1.2 Linear Combinations . . . . .	149
3.1.3 Bases and Dimension . . . . .	150
3.1.4 Vector Subspaces . . . . .	151
3.1.5 Spanning Sets . . . . .	153
3.1.6 Dot Product . . . . .	153
3.1.7 Cross Product in $\mathbb{R}^3$ . . . . .	154
3.2 Linear Transformations . . . . .	155
3.3 Matrix Algebra . . . . .	157
3.3.1 Matrix Operations . . . . .	157
3.3.2 Square Matrices . . . . .	159
3.3.3 Determinants . . . . .	160
3.4 Linear Systems . . . . .	162
3.4.1 Gauss-Jordan Elimination . . . . .	165
3.4.2 Linear Systems & Matrices . . . . .	167
3.5 Matrix Diagonalization . . . . .	168

3.5.1	Eigenvalues & Eigenvectors . . . . .	168
3.5.2	Similar Matrices . . . . .	174
3.5.3	Diagonalization . . . . .	175
3.6	Exercises . . . . .	177
	Chapter References . . . . .	180
<b>4</b>	<b>Basics of Numerical Methods</b>	<b>181</b>
4.1	Basic Concepts . . . . .	181
4.1.1	Round-Off Error . . . . .	182
4.2	Equations With 1 Variable . . . . .	185
4.2.1	Bisection Method . . . . .	185
4.2.2	Golden Ratio Method . . . . .	191
4.2.3	Fixed Point Method . . . . .	193
4.2.4	Newton's Method . . . . .	203
4.2.5	Secant Method . . . . .	207
4.3	Systems of Equations . . . . .	208
4.3.1	Linear Systems . . . . .	208
4.3.2	Non-Linear Systems . . . . .	221
4.4	Exercises . . . . .	223
	Chapter References . . . . .	226
<b>5</b>	<b>A Survey of Optimization</b>	<b>227</b>
5.1	Beginnings . . . . .	227
5.2	Single-Objective Problems . . . . .	228
5.2.1	Feasible/Optimal Solutions . . . . .	229
5.2.2	Unsolvable Problems . . . . .	230
5.2.3	Possible Tasks . . . . .	230
5.3	Problems Types . . . . .	231
5.3.1	Classification . . . . .	231
5.3.2	Algorithms . . . . .	232
5.4	Linear Programming . . . . .	233
5.4.1	LP Duality . . . . .	235
5.4.2	Solving LP Problems . . . . .	237
5.5	Mixed-Integer LP . . . . .	238
5.5.1	Cutting Planes . . . . .	241
5.6	Useful Techniques . . . . .	241
5.6.1	Activation . . . . .	242
5.6.2	Disjunction . . . . .	242
5.6.3	Soft Constraints . . . . .	242
5.7	Software Solvers . . . . .	243
5.8	Data Envelopment Analysis . . . . .	244
5.8.1	Challenges and Pitfalls . . . . .	246
5.8.2	Pros and Cons . . . . .	247
5.8.3	DEA Solvers . . . . .	247
5.8.4	Case Study: Schools . . . . .	248
5.9	Exercises . . . . .	252
	Chapter References . . . . .	252
<b>6</b>	<b>Probability and Applications</b>	<b>253</b>
6.1	Basic Notions . . . . .	253
6.1.1	Sample Spaces and Events . . . . .	253

6.1.2	Counting Techniques . . . . .	254
6.1.3	Ordered Samples . . . . .	255
6.1.4	Unordered Samples . . . . .	257
6.1.5	Probability of an Event . . . . .	257
6.1.6	Conditionality Probability . . . . .	260
6.1.7	Bayes' Theorem . . . . .	266
6.2	Discrete Distributions . . . . .	272
6.2.1	Random Variables . . . . .	272
6.2.2	Expectation . . . . .	275
6.2.3	Binomial R.V. . . . .	277
6.2.4	Geometric R.V. . . . .	282
6.2.5	Negative Binomial R.V. . . . .	282
6.2.6	Poisson R.V. . . . .	283
6.2.7	Other Discrete R.V. . . . .	288
6.3	Continuous Distributions . . . . .	288
6.3.1	Continuous R.V. . . . .	288
6.3.2	Expectation . . . . .	294
6.3.3	Normal R.V. . . . .	296
6.3.4	Exponential R.V. . . . .	301
6.3.5	Gamma R.V. . . . .	304
6.3.6	Binomial Approximations . . . . .	305
6.3.7	Other Continuous R.V. . . . .	307
6.4	Joint Distributions . . . . .	307
6.5	CLT/Sampling Distributions . . . . .	313
6.5.1	Sampling Distributions . . . . .	313
6.5.2	Central Limit Theorem . . . . .	316
6.5.3	Sampling Distributions II . . . . .	323
6.6	Exercises . . . . .	327
	Chapter References . . . . .	336
<b>7</b>	<b>Introductory Statistical Analysis</b>	<b>337</b>
7.1	Introduction . . . . .	337
7.2	Descriptive Statistics . . . . .	337
7.2.1	Data Descriptions . . . . .	338
7.2.2	Outliers . . . . .	343
7.2.3	Visual Summaries . . . . .	343
7.2.4	Coefficient of Correlation . . . . .	346
7.3	Estimation . . . . .	349
7.3.1	Standard Error . . . . .	349
7.3.2	C.I. for $\mu$ With $\sigma$ Known . . . . .	351
7.3.3	Confidence Level . . . . .	356
7.3.4	Sample Size . . . . .	358
7.3.5	C.I. for $\mu$ With $\sigma$ Unknown . . . . .	359
7.3.6	C.I. for a Proportion . . . . .	362
7.4	Hypothesis Testing . . . . .	363
7.4.1	Generalities . . . . .	367
7.4.2	Critical Regions . . . . .	369
7.4.3	Test for a Mean . . . . .	372
7.4.4	Test for a Proportion . . . . .	378
7.4.5	Two-Sample Tests . . . . .	379
7.4.6	Difference of 2 Proportions . . . . .	383

7.4.7	Hypothesis Testing with R . . . . .	384
7.5	Additional Topics . . . . .	389
7.5.1	Analysis of Variance . . . . .	389
7.5.2	Analysis of Covariance . . . . .	394
7.5.3	Multivariate Statistics . . . . .	397
7.5.4	Goodness-of-Fit Test . . . . .	401
7.6	Exercises . . . . .	402
	Chapter References . . . . .	408
<b>8</b>	<b>Classical Regression Analysis</b>	<b>409</b>
8.1	Preliminaries . . . . .	409
8.1.1	Random Variables . . . . .	409
8.1.2	Multivariate Calculus . . . . .	416
8.1.3	Matrix Algebra . . . . .	417
8.1.4	Quadratic Forms . . . . .	417
8.1.5	Optimization . . . . .	419
8.2	Simple Linear Regression . . . . .	419
8.2.1	Least Squares Estimation . . . . .	421
8.2.2	Inference . . . . .	429
8.2.3	Estimation and Prediction . . . . .	437
8.2.4	Significance of Regression . . . . .	444
8.2.5	SLR in R . . . . .	446
8.3	Multiple Linear Regression . . . . .	447
8.3.1	Least Squares Estimation . . . . .	448
8.3.2	Inference . . . . .	451
8.3.3	Power of a Test . . . . .	460
8.3.4	Determination Coefficients . . . . .	461
8.3.5	Diagnostics . . . . .	461
8.4	Extensions of OLS . . . . .	468
8.4.1	Multicollinearity . . . . .	468
8.4.2	Polynomial Regression . . . . .	471
8.4.3	Interaction Effects . . . . .	474
8.4.4	Categorical Variables . . . . .	477
8.4.5	Weighted Least Squares . . . . .	477
8.4.6	Other Extensions . . . . .	480
8.5	OLS and Outliers . . . . .	481
8.5.1	Leverage and Extrapolation . . . . .	481
8.5.2	Deleted Residuals . . . . .	483
8.5.3	Influential Observations . . . . .	484
8.5.4	Cook's Distance . . . . .	485
8.6	Exercises . . . . .	486
	Chapter References . . . . .	490
<b>9</b>	<b>Time Series and Forecasting</b>	<b>491</b>
9.1	Introduction . . . . .	491
9.1.1	Simple Examples . . . . .	492
9.1.2	Pre-Processing . . . . .	493
9.1.3	Stationary Models . . . . .	504
9.1.4	Partial Autocorrelation . . . . .	508
9.2	Estimating Parameters . . . . .	510
9.2.1	Sample Statistics . . . . .	510

9.2.2	Examples . . . . .	511
9.3	ARMA Models . . . . .	516
9.3.1	Linear Processes . . . . .	516
9.3.2	ARMA in General . . . . .	518
9.3.3	Stationarity and Causality . . . . .	519
9.3.4	Linear Representation . . . . .	521
9.3.5	ACVF . . . . .	523
9.3.6	PACF . . . . .	526
9.4	Forecasting . . . . .	530
9.4.1	Yule-Walker Procedure . . . . .	530
9.4.2	Durbin-Levinson Algorithm . . . . .	533
9.4.3	Forecast Limits . . . . .	535
9.4.4	Example . . . . .	535
9.5	ARMA Estimation . . . . .	543
9.5.1	Mean: I.I.D. Case . . . . .	543
9.5.2	Mean: Time Series . . . . .	544
9.5.3	Yule-Walker Estimators . . . . .	545
9.5.4	Example . . . . .	548
9.6	Diagnostic Tests . . . . .	551
9.6.1	Ljung-Box Test . . . . .	552
9.6.2	Example . . . . .	553
9.7	MLE Estimation . . . . .	556
9.7.1	I.I.D. Random Variables . . . . .	556
9.7.2	Time Series Model . . . . .	558
9.7.3	Order Selection . . . . .	560
9.7.4	Examples . . . . .	560
9.8	Nonlinear Time Series . . . . .	575
9.8.1	ARCH Model . . . . .	575
9.8.2	GARCH Model . . . . .	576
9.8.3	Example . . . . .	577
9.9	Miscellenea . . . . .	580
9.9.1	Seasonality . . . . .	581
9.9.2	Asymptotic Normality . . . . .	584
9.10	Exercises . . . . .	590
	Chapter References . . . . .	598
<b>10</b>	<b>Survey Sampling Methods</b>	<b>599</b>
10.1	Background . . . . .	599
10.1.1	Sampling Generalities . . . . .	602
10.1.2	Survey Frames . . . . .	604
10.1.3	Fundamental Concepts . . . . .	604
10.1.4	Data Collection Basics . . . . .	607
10.1.5	Sampling Types . . . . .	607
10.2	Questionnaire Design . . . . .	610
10.2.1	Basic Concepts . . . . .	610
10.2.2	Question Types . . . . .	611
10.2.3	Design Considerations . . . . .	612
10.2.4	Question Order . . . . .	613
10.3	Simple Random Sampling . . . . .	615
10.3.1	Basic Notions . . . . .	619
10.3.2	Estimators and C.I. . . . .	622

10.3.3	Sample Size . . . . .	635
10.4	Stratified Sampling . . . . .	637
10.4.1	Estimators and C.I. . . . .	644
10.4.2	Sample Size and Allocation . . . . .	654
10.4.3	Comparison: SRS and STS . . . . .	661
10.5	Auxiliary Information . . . . .	663
10.5.1	Ratio Estimation . . . . .	663
10.5.2	Regression Estimation . . . . .	674
10.5.3	Difference Estimation . . . . .	681
10.5.4	Comparisons . . . . .	684
10.6	Cluster Sampling . . . . .	688
10.6.1	Estimators and C.I. . . . .	688
10.6.2	Sample Size . . . . .	704
10.6.3	Comparison: SRS and CLS . . . . .	706
10.7	Special Topics . . . . .	707
10.7.1	Systematic Sampling . . . . .	707
10.7.2	Sampling with PPS . . . . .	713
10.7.3	Multi-Stage Sampling . . . . .	716
10.7.4	Multi-Phase Sampling . . . . .	720
10.7.5	Miscellaneous . . . . .	722
10.8	Exercises . . . . .	730
	Chapter References . . . . .	731
<b>11</b>	<b>The Design of Experiments</b>	<b>733</b>
11.1	Basic Notions . . . . .	733
11.1.1	Experiments . . . . .	734
11.1.2	Useful Distributions . . . . .	737
11.2	Hypothesis Testing . . . . .	740
11.2.1	Inference on $\mu$ . . . . .	740
11.2.2	Inference on $\mu_1 - \mu_2$ . . . . .	745
11.2.3	Inference on $\sigma^2$ . . . . .	751
11.2.4	Inference on $\sigma_1^2/\sigma_2^2$ . . . . .	753
11.3	One-Way Classification . . . . .	754
11.3.1	Randomized Designs . . . . .	754
11.3.2	1-Way Model . . . . .	756
11.3.3	Analysis of Variance . . . . .	757
11.3.4	Estimation of Parameters . . . . .	761
11.3.5	Unbalanced Designs . . . . .	762
11.3.6	Contrasts . . . . .	763
11.3.7	Multiple Comparisons . . . . .	765
11.3.8	Model Validation . . . . .	773
11.3.9	Power and Sample Size . . . . .	776
11.4	Random Effects . . . . .	778
11.4.1	Estimation of Parameters . . . . .	779
11.4.2	Analysis of Variance . . . . .	780
11.4.3	Inference on $\sigma^2, \sigma_T^2, \mu$ . . . . .	782
11.4.4	Power . . . . .	783
11.5	Randomized Block Designs . . . . .	784
11.5.1	Analysis of Variance . . . . .	785
11.5.2	Estimation of Parameters . . . . .	789
11.5.3	Multiple Comparisons . . . . .	789

11.5.4	Power and Sample Size . . . . .	790
11.5.5	Model Validation . . . . .	790
11.6	Factorial Designs . . . . .	791
11.6.1	2-Way Factorial Experiments . . . . .	791
11.6.2	Model Validation . . . . .	798
11.6.3	Model Without Interaction . . . . .	799
11.6.4	Multiple Comparisons . . . . .	800
11.6.5	$n$ -Way Factorial Designs . . . . .	801
11.7	Exercises . . . . .	801
	Chapter References . . . . .	802
<b>12</b>	<b>Simulations and Modeling</b>	<b>803</b>
12.1	Introduction . . . . .	803
12.1.1	Static Models . . . . .	805
12.1.2	Dynamic Models . . . . .	808
12.1.3	Uses, Data, Contrast . . . . .	809
12.1.4	Simulation Types . . . . .	813
12.2	Modeling Strategies . . . . .	815
12.2.1	Information Gathering . . . . .	815
12.2.2	Conceptual Model . . . . .	816
12.2.3	Building the Model . . . . .	818
12.2.4	Verification and Validation . . . . .	818
12.2.5	Analysis of Results . . . . .	818
12.3	Practical Considerations . . . . .	820
12.3.1	Computational Complexity . . . . .	820
12.3.2	Applications . . . . .	820
12.3.3	Software . . . . .	822
12.4	Case Study: NWMO . . . . .	822
12.5	Exercise . . . . .	825
	Chapter References . . . . .	825

## List of Figures

1.1	An example of a computer program . . . . .	2
1.2	Lexical rules of the programming language C . . . . .	4
1.3	Computer code elements in action, for the scripting language R . . . . .	5
1.4	The first stage of pseudo-coding . . . . .	8
1.5	RStudio interface . . . . .	14
1.6	Database diagram for the toy example . . . . .	87
2.1	Intervals on the real line . . . . .	107
2.2	The real line $\mathbb{R}$ . . . . .	108
2.3	The real plane $\mathbb{R}^2$ and space $\mathbb{R}^3$ . . . . .	108
2.4	An illustration of a simple 2D vector field . . . . .	115
2.5	Difference quotient and slope of the tangent at $x = a$ . . . . .	116
2.6	Tangent plane . . . . .	119

2.7	Tangent planes at a cone's vertex . . . . .	120
2.8	Illustration of Clairaut's theorem . . . . .	121
2.9	Gradient and level sets . . . . .	122
2.10	Illustration of gradient descent . . . . .	124
2.11	Critical points for continuous functions of a single real variable . . . . .	132
2.12	Monthly profit function for the gadgets and gizmos example . . . . .	133
2.13	Charts related to the gadgets and gizmos example . . . . .	133
2.14	Graphical illustration of the Riemann integral . . . . .	137
4.1	Schematics of scientific computing . . . . .	182
5.1	Graphical solution for the lemonade and lemon juice optimization problem . . . . .	234
5.2	Excel's numerical solver for unit $D$ . . . . .	248
5.3	Results of the re-allocation process in the Barcelona public school dataset . . . . .	251
6.1	Failure probability for the 2-engine and 3-engine planes . . . . .	262
6.2	Conceptual model of air traffic control security system . . . . .	262
6.3	Decomposition of $B$ via $A$ . . . . .	265
6.4	The Monty Hall set-up . . . . .	268
6.5	P.m.f. and c.m.f. for a discrete r.v. . . . .	274
6.6	Uniform distributions . . . . .	277
6.7	Tabulated c.d.f. values for the binomial distribution with $n = 12$ . . . . .	279
6.8	P.d.f. and c.d.f. for a continuous r.v. . . . .	290
6.9	P.d.f. and c.d.f. for a continuous r.v., with event $A$ . . . . .	291
6.10	P.d.f. and c.d.f. for a continuous r.v., with $\lambda = 0.2$ . . . . .	292
6.11	Probability of $X > 10.2$ , for a continuous r.v. $X$ , with $\lambda = 0.2$ . . . . .	293
6.12	Probability of $X > 10.2$ , for a continuous r.v. $X$ , with $\lambda = 2$ . . . . .	293
6.13	P.d.f. and c.d.f. for the Cauchy distribution, with area under the curve . . . . .	295
6.14	P.d.f. and c.d.f. for the standard normal distribution . . . . .	296
6.15	P.d.f. and c.d.f. for the exponential distribution . . . . .	302
6.16	Conditional and marginal probabilities in the dice example . . . . .	309
6.17	Support for the joint distribution of $X$ and $Y$ – example . . . . .	310
6.18	Illustration of the central limit theorem . . . . .	317
6.19	Chi-squared distribution with 8 degrees of freedom . . . . .	324
6.20	Student $t$ -distribution with $r$ degrees of freedom . . . . .	325
7.1	Mean, median, and mode in various skewness scenarios . . . . .	340
7.2	Normal distributions with various means and standard deviations . . . . .	340
7.3	Boxplot with one (suspected) outlier . . . . .	343
7.4	Boxplot of positively skewed datasets . . . . .	344
7.5	Histogram and boxplot of the Sydney accident dataset . . . . .	345
7.6	Strong links that are not detected by the coefficient of correlation . . . . .	348
7.7	The 68-96-99.7 rule . . . . .	351
7.8	Frequentist interpretation of confidence intervals . . . . .	353
7.9	Quantiles of the standard normal distribution . . . . .	356
7.10	Two-sided quantiles of the standard normal distribution . . . . .	357
7.11	Two-sided quantiles of the standard normal distribution, for confidence level 0.05 . . . . .	357
7.12	Estimation error . . . . .	358
7.13	Critical value $t(4; 0.05)$ . . . . .	360
7.14	Binomial distribution for 10 trials, with probability of success 1/2 . . . . .	363
7.15	Binomial distribution for 100 trials, with probability of success 1/2 . . . . .	364
7.16	Critical test region, left-sided test . . . . .	373

7.17	Critical test region, right-sided test . . . . .	373
7.18	Critical test region, two-sided test . . . . .	373
7.19	Critical test regions for the right-sided test; $n = 10$ observations . . . . .	380
7.20	Confidence region for a bivariate normal random sample . . . . .	399
8.1	C.d.f. of Student's distribution . . . . .	413
8.2	C.d.f. of Fisher's distribution . . . . .	414
8.3	Response and predictor in the Gapminder dataset . . . . .	420
8.4	Illustrations of failed SLRM assumptions. . . . .	421
8.5	Line of best fit and deviations . . . . .	421
8.6	Total deviation decomposition . . . . .	426
8.7	Illustration of the Spearman correlation . . . . .	427
8.8	Various $R^2$ for nonlinear datasets . . . . .	429
8.9	Confidence interval for the mean response . . . . .	437
8.10	Prediction interval for a new response . . . . .	439
8.11	Joint confidence interval for the mean response . . . . .	443
8.12	Examples of non-significant regressions . . . . .	444
8.13	Geometrical interpretation of multiple linear regression . . . . .	453
8.14	Power function . . . . .	460
8.15	Illustration of non-linearity using residuals and fitted values . . . . .	462
8.16	Illustration of the Brown-Forsythe test . . . . .	464
8.17	White House COVID-19 projections . . . . .	473
8.18	Model scope in two-dimensional predictor space . . . . .	482
8.19	X-outlier and Y-outlier in a dataset . . . . .	483
8.20	Influential observation in a dataset . . . . .	484
9.1	Simple time series examples . . . . .	493
9.2	Time series; CV by year . . . . .	495
9.4	Diagnostic plots and adjusted plots . . . . .	496
9.3	Continuous CV; estimation summary . . . . .	496
10.1	Various populations and samples in the sampling model . . . . .	603
10.2	Dewey vs Truman . . . . .	609
10.3	Schematics of various sampling designs . . . . .	610
10.4	2021 Census – How do I complete the questionnaire? . . . . .	614
10.5	Schematics of SRS . . . . .	615
10.6	Health and wealth of nations for the 2011 Gapminder data . . . . .	616
10.7	Schematics of STS . . . . .	644
10.8	Gapminder data with line of best fit . . . . .	674
10.9	Scatterplot of X and Y for difference estimation example . . . . .	682
10.10	Schematics of CLS . . . . .	689
10.11	Schematics of SYS . . . . .	707
10.12	Various populations and systematic samplings . . . . .	710
10.13	Schematics of SRS2S . . . . .	717
10.14	Schematics of SRS2P . . . . .	721
12.1	Example of analogical reasoning . . . . .	804
12.2	A to-scale architectural model . . . . .	807
12.3	An example of a data model . . . . .	807
12.4	Possible solutions of the $n$ -body problem . . . . .	812
12.5	Harvard orrery; flight simulator . . . . .	814
12.6	A school of fish – the target system for a fish school simulation . . . . .	816

12.7	Some information about fish perceptual mechanics . . . . .	816
12.8	Representing the fish school in the simulation . . . . .	817
12.9	Representing the physical characteristics of individual fish . . . . .	818
12.10	Fish school simulation pseudo-code . . . . .	819
12.11	A screen shot of the 3D fish school simulation . . . . .	819
12.12	A sketch of computational complexity . . . . .	821

## List of Tables

5.5	Sample from the Barcelona public school dataset . . . . .	249
10.2	Sampling weights for Canadian provinces . . . . .	656
11.5	The four possible outcomes for hypothesis testing . . . . .	741
11.11	ANOVA table for equality of treatment means in one-way classification . . . . .	760
11.19	ANOVA table for equality of treatment means in a RCBD . . . . .	787
11.21	Two-way factorial design treatment structure . . . . .	791
11.25	ANOVA table for two-way factorial design . . . . .	794
11.29	ANOVA table for two-way factorial design with no interactions . . . . .	799