## Contents

Pı	Preface					
1	A b	A brief introduction to R				
	1.1	An ov	1 1			
		1.1.1	A short R session	1		
		1.1.2	The uses of R	5		
		1.1.3	Online help	6		
		1.1.4	Further steps in learning R	8		
	1.2	Data i	input, packages and the search list	8		
		1.2.1	Reading data from a file	8		
		1.2.2	R packages	9		
	1.3	Vector	rs, factors and univariate time series	10		
		1.3.1	Vectors in R	10		
		1.3.2	Concatenation – joining vector objects	10		
		1.3.3	Subsets of vectors	11		
		1.3.4	Patterned data	11		
		1.3.5	Missing values	12		
		1.3.6	Factors	13		
		1.3.7	Time series	14		
	1.4	Data f	frames and matrices	14		
		1.4.1	The attaching of data frames	16		
		1.4.2	Aggregation, stacking and unstacking	17		
		1.4.3*	Data frames and matrices	17		
	1.5	Functi	ions, operators and loops	18		
		1.5.1	Built-in functions	18		
		1.5.2	Generic functions and the class of an object	20		
		1.5.3	User-written functions	21		
		1.5.4	Relational and logical operators and operations	22		
		1.5.5	Selection and matching	23		
		1.5.6	Functions for working with missing values	23		
		1.5.7*	Looping	24		
	1.6	-	ics in R	24		
		1.6.1	The function plot ( ) and allied functions	25		
		1.6.2	The use of color	27		

X Contents

		1.0.5	The importance of aspect ratio	21
		1.6.4	Dimensions and other settings for graphics devices	28
		1.6.5	The plotting of expressions and mathematical symbols	28
		1.6.6	Identification and location on the figure region	29
		1.6.7	Plot methods for objects other than vectors	29
		1.6.8	Lattice graphics versus base graphics – xyplot() versus plot()	30
		1.6.9	Further information on graphics	30
		1.6.10	Good and bad graphs	30
	1.7		(trellis) graphics	31
	1.8	Additio	nal points on the use of R	33
	1.9	Recap		36
	1.10		r reading	36
		1.10.1	References for further reading	37
	1.11	Exercis	es	37
2	Style	s of data	a analysis	43
	2.1	Reveali	ng views of the data	43
		2.1.1	Views of a single sample	44
		2.1.2	Patterns in univariate time series	48
		2.1.3	Patterns in bivariate data	50
		2.1.4	Patterns in grouped data	52
		2.1.5*	Multiple variables and times	54
		2.1.6	Scatterplots, broken down by multiple factors	56
		2.1.7	What to look for in plots	58
	2.2	Data su	ummary	59
		2.2.1	Counts	60
		2.2.2	Summaries of information from data frames	63
		2.2.3	Standard deviation and inter-quartile range	66
		2.2.4	Correlation	68
	2.3	Statistic	cal analysis questions, aims and strategies	69
		2.3.1	How relevant and how reliable are the data?	70
		2.3.2	Helpful and unhelpful questions	70
		2.3.3	How will results be used?	71
		2.3.4	Formal and informal assessments	72
		2.3.5	Statistical analysis strategies	73
			Planning the formal analysis	73
		2.3.7	Changes to the intended plan of analysis	74
	2.4	Recap		74
	2.5		reading	75
		2.5.1	References for further reading	75
	2.6	Exercise	es	75
3	Statis	stical mo	dels	78
	3.1	Regular		79
		3.1.1	Deterministic models	79

Contents xi

		3.1.2 M	odels that include a random component	79
			tting models – the model formula	82
	3.2	Distributio	ons: models for the random component	83
		3.2.1 D	iscrete distributions	84
		3.2.2 Co	ontinuous distributions	86
	3.3	The uses of	of random numbers	88
		3.3.1 Si	mulation	88
		3.3.2 Sa	ampling from populations	89
	3.4	Model ass	rumptions	90
		3.4.1 Ra	andom sampling assumptions - independence	91
		3.4.2 CI	hecks for normality	92
		3.4.3 CI	hecking other model assumptions	95
		3.4.4 A	re non-parametric methods the answer?	95
		3.4.5 W	hy models matter – adding across contingency tables	95
	3.5	Recap		96
	3.6	Further re	eading	97
		3.6.1 Re	eferences for further reading	97
	3.7	Exercises		97
4	A == -	introductio	n to formal informac	101
4	4.1		on to formal inference	101
	7.1		cepts of estimation equippopulation parameters and sample statistics	101 101
			ampling distributions	101
			ssessing accuracy – the standard error	102
			ne standard error for the difference of means	102
			ne standard error for the difference of means	103
			ne sampling distribution of the <i>t</i> -statistic	104
	4.2		e intervals and hypothesis tests	104
	7.2	=	ne- and two-sample intervals and tests for means	107
			onfidence intervals and tests for proportions	113
			onfidence intervals and tests for proportions	113
			onfidence intervals versus hypothesis tests	114
	4.3	Contingen		115
	,,,,	0	are and endangered plant species	117
			Iditional notes	119
	4.4		unstructured comparisons	120
			splaying means for the one-way layout	123
			ultiple comparisons	124
			ata with a two-way structure, that is, two factors	125
			esentation issues	126
	4.5	Response of		126
		-	a nested variation structure	127
	-		egrees of freedom considerations	128
			eneral multi-way analysis of variance designs	129

xii Contents

	4./		pling methods for standard errors, tests and confidence	
		interva		129
		4.7.1	The one-sample permutation test	129
		4.7.2	The two-sample permutation test	130
		4.7.3*	<i>C</i>	131
		4.7.4	Bootstrap estimates of confidence intervals	133
	4.8*		es of inference	134
		4.8.1	Maximum likelihood estimation	135
			Bayesian estimation	136
		4.8.3	If there is strong prior information, use it!	136
	4.9	Recap		137
	4.10		er reading	138
			References for further reading	138
	4.11	Exerci.	ses	139
5	Regr	ession w	vith a single predictor	144
	5.1	Fitting	a line to data	144
		5.1.1	Lawn roller example	145
		5.1.2	Calculating fitted values and residuals	146
		5.1.3	Residual plots	147
		5.1.4	Iron slag example: is there a pattern in the residuals?	148
		5.1.5	The analysis of variance table	150
	5.2	Outlier	rs, influence and robust regression	151
	5.3	Standa	rd errors and confidence intervals	153
		5.3.1	Confidence intervals and tests for the slope	153
		5.3.2	SEs and confidence intervals for predicted values	154
		5.3.3*	Implications for design	155
	5.4	Regres	sion versus qualitative anova comparisons	157
		5.4.1	Issues of power	157
		5.4.2	The pattern of change	158
	5.5	Assessi	ing predictive accuracy	158
		5.5.1	Training/test sets and cross-validation	158
		5.5.2	Cross-validation – an example	159
		5.5.3*	Bootstrapping	161
	5.6*	A note	e on power transformations	164
		5.6.1*	General power transformations	164
	5.7	Size an	nd shape data	165
		5.7.1	Allometric growth	166
		5.7.2	There are two regression lines!	167
	5.8	The mo	odel matrix in regression	168
	5.9	Recap		169
	5.10	Method	lological references	170
	5.11	Exercis	ses	170

Contents	xiii

6	Mult	tiple line	ear regression	173		
	6.1	Basic i	ideas: book weight and brain weight examples	173		
		6.1.1	Omission of the intercept term	176		
		6.1.2	Diagnostic plots	176		
		6.1.3	Example: brain weight	178		
		6.1.4	Plots that show the contribution of individual terms	180		
	6.2	Multip	le regression assumptions and diagnostics	182		
		6.2.1	Influential outliers and Cook's distance	183		
		6.2.2	Influence on the regression coefficients	184		
		6.2.3*	Additional diagnostic plots	185		
		6.2.4	Robust and resistant methods	185		
		6.2.5	The uses of model diagnostics	185		
	6.3	A strat	tegy for fitting multiple regression models	186		
		6.3.1	Preliminaries	186		
		6.3.2	Model fitting	187		
		6.3.3	An example – the Scottish hill race data	187		
	6.4	Measu	res for the assessment and comparison of regression			
		models	7	193		
		6.4.1	$R^2$ and adjusted $R^2$	193		
		6.4.2	AIC and related statistics	194		
		6.4.3	How accurately does the equation predict?	194		
	6.5	Interpr	reting regression coefficients	196		
		6.5.1	Book dimensions and book weight	196		
	6.6	Proble	ms with many explanatory variables	199		
		6.6.1	Variable selection issues	200		
	6.7	Multice	ollinearity	202		
		6.7.1	A contrived example	202		
		6.7.2	The variance inflation factor	206		
		6.7.3	Remedies for multicollinearity	206		
	6.8	Multip	le regression models – additional points	207		
		6.8.1	Errors in x	207		
		6.8.2	Confusion between explanatory and response variables	210		
		6.8.3		210		
		6.8.4*	The use of transformations	212		
		6.8.5*	Non-linear methods – an alternative to transformation?	212		
	6.9	Recap		214		
	6.10		r reading	214		
			References for further reading	215		
	6.11	Exercis	<u> </u>	216		
7	Exploiting the linear model framework 21					
	7.1	Levels	of a factor – using indicator variables	220		
		7.1.1	Example – sugar weight	220		
		7.1.2	Different choices for the model matrix when there are			
			factors	223		

xiv Contents

	7.2	Block	designs and balanced incomplete block designs	224
		7.2.1	Analysis of the rice data, allowing for block effects	224
		7.2.2	A balanced incomplete block design	226
	7.3	Fitting	multiple lines	227
	7.4	Polyno	omial regression	231
		7.4.1	Issues in the choice of model	233
	<i>7.5</i> *	Metho	ds for passing smooth curves through data	234
		7.5.1	Scatterplot smoothing – regression splines	235
		7.5.2*	Penalized splines and generalized additive models	239
		7.5.3	Other smoothing methods	239
	7.6	Smoot	hing terms in additive models	241
		7.6.1*	The fitting of penalized spline terms	243
	7.7	Furthe	er reading	243
		7.7.1	References for further reading	243
	7.8	Exerci	ses	243
8	Gene	eralized	linear models and survival analysis	246
•	8.1		alized linear models	246
		8.1.1	Transformation of the expected value on the left	246
		8.1.2	Noise terms need not be normal	247
		8.1.3	Log odds in contingency tables	247
		8.1.4	Logistic regression with a continuous explanatory variable	248
	8.2		ic multiple regression	251
		8.2.1	Selection of model terms and fitting the model	253
		8.2.2	A plot of contributions of explanatory variables	256
		8.2.3	Cross-validation estimates of predictive accuracy	257
	8.3		ic models for categorical data – an example	258
	8.4		n and quasi-Poisson regression	260
		8.4.1	Data on aberrant crypt foci	260
		8.4.2	Moth habitat example	263
	8.5		onal notes on generalized linear models	269
	•••		Residuals, and estimating the dispersion	269
		8.5.2	Standard errors and z- or t-statistics for binomial models	270
		8.5.3	Leverage for binomial models	270
	8.6		s with an ordered categorical or categorical response	270
	0.0		Ordinal regression models	271
			Loglinear models	
	8.7		al analysis	274 275
	0.,	8.7.1	Analysis of the Aids2 data	
		8.7.2	Right censoring prior to the termination of the study	276
		8.7.3	The survival curve for male homosexuals	278
		8.7.4	Hazard rates	279
		8.7.5	The Cox proportional hazards model	279
	8.8		formations for count data	280
	8.9		r reading	282 283
	0.,	C	· · · · · · · · · · · · · · · · · · ·	2X 3

Contents xv

		8.9.1	References for further reading	283
	8.10	Exercis	es	284
9	Time	series m	odels	280
	9.1	Time se	eries – some basic ideas	286
		9.1.1	Preliminary graphical explorations	286
		9.1.2	The autocorrelation function	287
		9.1.3	Autoregressive models	288
		9.1.4*	Autoregressive moving average models – theory	290
	9.2*	Regress	sion modeling with moving average errors	291
	9.3*	Non-lin	ear time series	297
	9.4	Other to	ime series packages	298
	9.5	Further	reading	298
		9.5.1	Spatial statistics	299
		9.5.2	References for further reading	299
	9.6	Exercise	es	299
10	Multi	-level mo	odels and repeated measures	301
	10.1	A one-w	vay random effects model	302
		10.1.1	Analysis with aov()	303
		10.1.2	A more formal approach	306
		10.1.3	Analysis using 1mer()	308
	10.2	Survey	data, with clustering	311
		10.2.1	Alternative models	311
		10.2.2	Instructive, though faulty, analyses	316
		10.2.3	Predictive accuracy	317
	10.3	A multi-	level experimental design	317
		10.3.1	The anova table	319
		10.3.2	Expected values of mean squares	320
		10.3.3*	The sums of squares breakdown	321
		10.3.4	The variance components	324
		10.3.5	The mixed model analysis	325
		10.3.6	Predictive accuracy	327
		10.3.7	Different sources of variance – complication or focus	
			of interest?	327
	10.4	Within-	and between-subject effects	328
		10.4.1	Model selection	329
		10.4.2	Estimates of model parameters	330
	10.5	Repeate	d measures in time	332
		10.5.1	Example - random variation between profiles	334
		10.5.2	Orthodontic measurements on children	339
	10.6	Error st	ructure considerations	343
		10.6.1	Predictions from models with a complex error	
			structure	343
		10.6.2	Error structure in explanatory variables	344

xvi Contents

	10.7	Furthe	er notes on multi-level and other models with correlated	
		errors		344
		10.7.1	An historical perspective on multi-level models	344
		10.7.2	Meta-analysis	346
		10.7.3	Functional data analysis	346
	10.8	Recap		346
	10.9	Furthe	er reading	347
		10.9.1	References for further reading	347
	10.10	Exerci.	ses	348
11	Tree-l	ased cl	assification and regression	350
	11.1	The us	res of tree-based methods	351
		11.1.1	Problems for which tree-based regression may be used	351
	11.2	Detecti	ing email spam – an example	352
		11.2.1	Choosing the number of splits	355
	11.3	Termin	nology and methodology	355
		11.3.1	Choosing the split – regression trees	355
		11.3.2	Within and between sums of squares	356
		11.3.3	Choosing the split – classification trees	357
		11.3.4	Tree-based regression versus loess regression smoothing	358
	11.4	Predict	tive accuracy and the cost-complexity tradeoff	360
		11.4.1	Cross-validation	361
		11.4.2	The cost–complexity parameter	361
		11.4.3	Prediction error versus tree size	362
	11.5	Data fe	or female heart attack patients	363
		11.5.1	The one-standard-deviation rule	365
		11.5.2	Printed information on each split	365
	11.6	Detecti	ing email spam – the optimal tree	366
	11.7	The rai	ndomForest package	368
	11.8	Additio	onal notes on tree-based methods	371
		11.8.1	The combining of tree-based methods with other approaches	371
		11.8.2	Models with a complex error structure	372
		11.8.3	Pruning as variable selection	372
		11.8.4	Other types of tree	372
		11.8.5	Factors as predictors	372
		11.8.6	Summary of pluses and minuses of tree-based methods	372
	11.9	Further	r reading	373
		11.9.1	References for further reading	373
	11.10	Exercis	ses	374
12	Multiv	ariate d	lata exploration and discrimination	375
	12.1		ariate exploratory data analysis	376
		12.1.1	Scatterplot matrices	376
		12.1.2	Principal components analysis	377
		12.1.3	Multi-dimensional scaling	383

Contents	xvii

	12.2	Discrir	ninant analysis	384
		12.2.1	Example – plant architecture	384
		12.2.2	Logistic discriminant analysis	386
		12.2.3	Linear discriminant analysis	387
		12.2.4	An example with more than two groups	388
	12.3*	High-d	limensional data, classification and plots	390
		12.3.1	Classifications and associated graphs	392
		12.3.2	Flawed graphs	393
		12.3.3	Accuracies and scores for test data	397
		12.3.4	Graphs derived from the cross-validation process	403
	12.4	Further	r reading	405
		12.4.1	References for further reading	406
	12.5	Exercis	ses	406
13	Regre	ession or	n principal component or discriminant scores	408
	13.1	Princip	pal component scores in regression	408
	13.2*	Propen	sity scores in regression comparisons – labor	
		trainin	g data	412
		13.2.1	Regression analysis, using all covariates	415
		13.2.2	The use of propensity scores	417
	13.3	Further	r reading	419
		13.3.1	References for further reading	419
	13.4	Exercis	res	420
14	The I	R system	– additional topics	421
	14.1	Workin	g directories, workspaces and the search list	421
		14.1.1*	The search path	421
		14.1.2	Workspace management	421
		14.1.3	Utility functions	423
	14.2	Data in	aput and output	423
		14.2.1	Input of data	424
		14.2.2	Data output	428
	14.3	Functio	ons and operators – some further details	429
		14.3.1	Function arguments	430
		14.3.2	Character string and vector functions	431
		14.3.3	Anonymous functions	431
		14.3.4	Functions for working with dates (and times)	432
		14.3.5	Creating groups	433
		14.3.6	Logical operators	434
	14.4	Factors	7	434
	14.5	_	g values	437
	14.6*	Matrice	es and arrays	439
		14.6.1	Matrix arithmetic	440
		14.6.2	Outer products	441
		14.6.3	Arrays	442

xviii Contents

14.7	Manipul	lations with lists, data frames and matrices	443
	14.7.1	Lists – an extension of the notion of "vector"	443
	14.7.2	Changing the shape of data frames	445
	14.7.3*	Merging data frames – merge ()	445
	14.7.4	Joining data frames, matrices and vectors – cbind()	446
	14.7.5	The apply family of functions	446
	14.7.6	Splitting vectors and data frames into lists - split()	448
	14.7.7	Multivariate time series	448
14.8	Classes	and methods	449
	14.8.1	Printing and summarizing model objects	449
	14.8.2	Extracting information from model objects	450
	14.8.3	S4 classes and methods	450
14.9	Manipul	ation of language constructs	451
	14.9.1	Model and graphics formulae	451
	14.9.2	The use of a list to pass parameter values	452
	14.9.3	Expressions	453
	14.9.4	Environments	453
	14.9.5	Function environments and lazy evaluation	455
14.10	Docume	nt preparation — Sweave()	456
14.11	Graphs i	in R	457
	14.11.1	Hardcopy graphics devices	457
	14.11.2	Multiple graphs on a single graphics page	457
	14.11.3	Plotting characters, symbols, line types and colors	457
14.12		raphics and the grid package	462
	14.12.1	Interaction with plots	464
	14.12.2*	Use of grid.text() to label points	464
	14.12.3*	Multiple lattice graphs on a graphics page	465
14.13	Further i	reading	466
	14.13.1	Vignettes	466
	14.13.2	References for further reading	466
14.14	Exercises	S	467
Epilogue	– models		470
Reference	References		
Index of 1	R Symbols	s and Functions	485
Index of	Terms		491
Index of	Authors		501
Color Pla	tes after I	Page 502	