

A Handbook of Statistical Analyses Using R

Brian S. Everitt and Torsten Hothorn

Preface

This book is intended as a guide to data analysis with the R system for statistical computing. R is an environment incorporating an implementation of the S programming language, which is powerful, flexible and has excellent graphical facilities (R Development Core Team, 2005). In the Handbook we aim to give relatively brief and straightforward descriptions of how to conduct a range of statistical analyses using R. Each chapter deals with the analysis appropriate for one or several data sets. A brief account of the relevant statistical background is included in each chapter along with appropriate references, but our prime focus is on how to use R and how to interpret results. We hope the book will provide students and researchers in many disciplines with a self-contained means of using R to analyse their data. R is an open-source project developed by dozens of volunteers for more than ten years now and is available from the Internet under the General Public Licence. R has become the *lingua franca* of statistical computing. Increasingly, implementations of new statistical methodology first appear as R add-on packages. In some communities, such as in bioinformatics, R already is the primary workhorse for statistical analyses. Because the sources of the R system are open and available to everyone without restrictions and because of its powerful language and graphical capabilities, R has started to become the main computing engine for reproducible statistical research (Leisch, 2002a,b, 2003, Leisch and Rossini, 2003, Gentleman, 2005). For a reproducible piece of research, the original observations, all data preprocessing steps, the statistical analysis as well as the scientific report form a unity and all need to be available for inspection, reproduction and modification by the readers. Reproducibility is a natural requirement for textbooks such as the ‘Handbook of Statistical Analyses Using R’ and therefore this book is fully reproducible using an R version greater or equal to 2.5.0. All analyses and results, including figures and tables, can be reproduced by the reader without having to retype a single line of R code. The data sets presented in this book are collected in a dedicated add-on package called *HSAUR* accompanying this book. The package can be installed from the Comprehensive R Archive Network (CRAN) via

```
R> install.packages("HSAUR")  
and its functionality is attached by  
R> library("HSAUR")
```

The relevant parts of each chapter are available as a *vignette*, basically a document including both the R sources and the rendered output of every

analysis contained in the book. For example, the first chapter can be inspected by

```
R> vignette("Ch_introduction_to_R", package = "HSAUR")
```

and the R sources are available for reproducing our analyses by

```
R> edit(vignette("Ch_introduction_to_R", package = "HSAUR"))
```

An overview on all chapter vignettes included in the package can be obtained from

```
R> vignette(package = "HSAUR")
```

We welcome comments on the R package *HSAUR*, and where we think these add to or improve our analysis of a data set we will incorporate them into the package and, hopefully at a later stage, into a revised or second edition of the book. Plots and tables of results obtained from R are all labelled as ‘Figures’ in the text. For the graphical material, the corresponding figure also contains the ‘essence’ of the R code used to produce the figure, although this code may differ a little from that given in the *HSAUR* package, since the latter may include some features, for example thicker line widths, designed to make a basic plot more suitable for publication. We would like to thank the R Development Core Team for the R system, and authors of contributed add-on packages, particularly Uwe Ligges and Vince Carey for helpful advice on *scatterplot3d* and *gee*. Kurt Hornik, Ludwig A. Hothorn, Fritz Leisch and Rafael Weißbach provided good advice with some statistical and technical problems. We are also very grateful to Achim Zeileis for reading the entire manuscript, pointing out inconsistencies or even bugs and for making many suggestions which have led to improvements. Lastly we would like to thank the CRC Press staff, in particular Rob Calver, for their support during the preparation of the book. Any errors in the book are, of course, the joint responsibility of the two authors.

Brian S. Everitt and Torsten Hothorn
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An Introduction to R

1.1 What is R?

The R system for statistical computing is an environment for data analysis and graphics. The root of R is the S language, developed by John Chambers and colleagues (Becker et al., 1988, Chambers and Hastie, 1992, Chambers, 1998) at Bell Laboratories (formerly AT&T, now owned by Lucent Technologies) starting in the 1960s. The S language was designed and developed as a programming language for data analysis tasks but in fact it is a full-featured programming language in its current implementations. The development of the R system for statistical computing is heavily influenced by the open source idea: The base distribution of R and a large number of user contributed extensions are available under the terms of the Free Software Foundation's GNU General Public License in source code form. This licence has two major implications for the data analyst working with R. The complete source code is available and thus the practitioner can investigate the details of the implementation of a special method, can make changes and can distribute modifications to colleagues. As a side-effect, the R system for statistical computing is available to everyone. All scientists, especially including those working in developing countries, have access to state-of-the-art tools for statistical data analysis without additional costs. With the help of the R system for statistical computing, research really becomes reproducible when both the data and the results of all data analysis steps reported in a paper are available to the readers through an R transcript file. R is most widely used for teaching undergraduate and graduate statistics classes at universities all over the world because students can freely use the statistical computing tools. The base distribution of R is maintained by a small group of statisticians, the R Development Core Team. A huge amount of additional functionality is implemented in add-on packages authored and maintained by a large group of volunteers. The main source of information about the R system is the world wide web with the official home page of the R project being

<http://www.R-project.org>

All resources are available from this page: the R system itself, a collection of add-on packages, manuals, documentation and more. The intention of this chapter is to give a rather informal introduction to basic concepts and data manipulation techniques for the R novice. Instead of a rigid treatment of the technical background, the most common tasks are illustrated by practical

examples and it is our hope that this will enable readers to get started without too many problems.

1.2 Installing R

The R system for statistical computing consists of two major parts: the base system and a collection of user contributed add-on packages. The R language is implemented in the base system. Implementations of statistical and graphical procedures are separated from the base system and are organised in the form of packages. A package is a collection of functions, examples and documentation. The functionality of a package is often focused on a special statistical methodology. Both the base system and packages are distributed via the Comprehensive R Archive Network (CRAN) accessible under

<http://CRAN.R-project.org>

1.2.1 The Base System and the First Steps

The base system is available in source form and in precompiled form for various Unix systems, Windows platforms and Mac OS X. For the data analyst, it is sufficient to download the precompiled binary distribution and install it locally. Windows users follow the link

<http://CRAN.R-project.org/bin/windows/base/release.htm>

download the corresponding file (currently named `rw2050.exe`), execute it locally and follow the instructions given by the installer. Depending on the operating system, R can be started either by typing ‘R’ on the shell (Unix systems) or by clicking on the R symbol (as shown left) created by the installer (Windows). R comes without any frills and on start up shows simply a short introductory message including the version number and a prompt ‘>’:

```
R : Copyright 2007 The R Foundation for Statistical Computing
Version 2.5.0 (2007-04-23), ISBN 3-900051-07-0
```

```
R is free software and comes with ABSOLUTELY NO WARRANTY.
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.
```

```
R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.
```

```
Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.
```

```
>
```

One can change the appearance of the prompt by

```
> options(prompt = "R> ")
```

and we will use the prompt `R>` for the display of the code examples throughout this book. Essentially, the R system evaluates commands typed on the R prompt and returns the results of the computations. The end of a command is indicated by the return key. Virtually all introductory texts on R start with an example using R as pocket calculator, and so do we:

```
R> x <- sqrt(25) + 2
```

This simple statement asks the R interpreter to calculate $\sqrt{25}$ and then to add 2. The result of the operation is assigned to an R object with variable name `x`. The assignment operator `<-` binds the value of its right hand side to a variable name on the left hand side. The value of the object `x` can be inspected simply by typing

```
R> x
```

```
[1] 7
```

which, implicitly, calls the `print` method:

```
R> print(x)
```

```
[1] 7
```

1.2.2 Packages



The base distribution already comes with some high-priority add-on packages, namely

| | | | |
|------------|----------|-----------|----------|
| KernSmooth | MASS | boot | class |
| cluster | foreign | lattice | mgcv |
| nlme | nnet | rpart | spatial |
| survival | base | codetools | datasets |
| grDevices | graphics | grid | methods |
| splines | stats | stats4 | tcltk |
| tools | utils | | |

The packages listed here implement standard statistical functionality, for example linear models, classical tests, a huge collection of high-level plotting functions or tools for survival analysis; many of these will be described and used in later chapters. Packages not included in the base distribution can be installed directly from the R prompt. At the time of writing this chapter, 1068 user contributed packages covering almost all fields of statistical methodology were available. Given that an Internet connection is available, a package is installed by supplying the name of the package to the function `install.packages`. If, for example, add-on functionality for robust estimation of covariance matrices via sandwich estimators is required (for example in Chapter ??), the *sandwich* package (Zeileis, 2004) can be downloaded and installed via

```
R> install.packages("sandwich")
```


The package functionality is available after *attaching* the package by

```
R> library("sandwich")
```

A comprehensive list of available packages can be obtained from

<http://CRAN.R-project.org/src/contrib/PACKAGES.html>

Note that on Windows operating systems, precompiled versions of packages are downloaded and installed. In contrast, packages are compiled locally before they are installed on Unix systems.

1.3 Help and Documentation

Roughly, three different forms of documentation for the R system for statistical computing may be distinguished: online help that comes with the base distribution or packages, electronic manuals and publications work in the form of books etc. The help system is a collection of manual pages describing each user-visible function and data set that comes with R. A manual page is shown in a pager or web browser when the name of the function we would like to get help for is supplied to the `help` function

```
R> help("mean")
```

or, for short,

```
R> ?mean
```

Each manual page consists of a general description, the argument list of the documented function with a description of each single argument, information about the return value of the function and, optionally, references, cross-links and, in most cases, executable examples. The function `help.search` is helpful for searching within manual pages. An overview on documented topics in an add-on package is given, for example for the *sandwich* package, by

```
R> help(package = "sandwich")
```

Often a package comes along with an additional document describing the package functionality and giving examples. Such a document is called a *vignette* (Leisch, 2003, Gentleman, 2005). The *sandwich* package vignette is opened using

```
R> vignette("sandwich", package = "sandwich")
```

More extensive documentation is available electronically from the collection of manuals at

<http://CRAN.R-project.org/manuals.html>

For the beginner, at least the first and the second document of the following four manuals (R Development Core Team, 2005a,b,c,d) are mandatory:

An Introduction to R: A more formal introduction to data analysis with R than this chapter.

R Data Import/Export: A very useful description of how to read and write various external data formats.

R Installation and Administration: Hints for installing R on special platforms.

Writing R Extensions: The authoritative source on how to write R programs and packages.

Both printed and online publications are available, the most important ones are ‘Modern Applied Statistics with S’ (Venables and Ripley, 2002), ‘Introductory Statistics with R’ (Dalgaard, 2002), ‘R Graphics’ (Murrell, 2005) and the R Newsletter, freely available from

<http://CRAN.R-project.org/doc/Rnews/>

In case the electronically available documentation and the answers to frequently asked questions (FAQ), available from

<http://CRAN.R-project.org/faqs.html>

have been consulted but a problem or question remains unsolved, the `r-help` email list is the right place to get answers to well-thought-out questions. It is helpful to read the posting guide

<http://www.R-project.org/posting-guide.html>

before starting to ask.

1.4 Data Objects in R

The data handling and manipulation techniques explained in this chapter will be illustrated by means of a data set of 2000 world leading companies, the Forbes 2000 list for the year 2004 collected by ‘Forbes Magazine’. This list is originally available from

<http://www.forbes.com>

and, as an R data object, it is part of the *HSAUR* package (*Source:* From Forbes.com, New York, New York, 2004. With permission.). In a first step, we make the data available for computations within R. The `data` function searches for data objects of the specified name (“Forbes2000”) in the package specified via the `package` argument and, if the search was successful, attaches the data object to the global environment:

```
R> data("Forbes2000", package = "HSAUR")
```

```
R> ls()
```

```
[1] "Forbes2000" "a"           "book"       "ch"
[5] "refs"       "x"
```

The output of the `ls` function lists the names of all objects currently stored in the global environment, and, as the result of the previous command, a variable named `Forbes2000` is available for further manipulation. The variable `x` arises from the pocket calculator example in Subsection 1.2.1. As one can imagine, printing a list of 2000 companies via

```
R> print(Forbes2000)
```

```

rank          name          country      category  sales
1     1      Citigroup United States    Banking  94.71
2     2  General Electric United States Conglomerates 134.19
3     3 American Intl Group United States    Insurance  76.66
profits assets marketvalue
1  17.85 1264.03   255.30
2  15.59  626.93   328.54
3   6.46  647.66   194.87
...

```

will not be particularly helpful in gathering some initial information about the data; it is more useful to look at a description of their structure found by using the following command

```
R> str(Forbes2000)
```

```

'data.frame':      2000 obs. of  8 variables:
 $ rank      : int  1 2 3 4 5 ...
 $ name      : chr  "Citigroup" "General Electric" ...
 $ country   : Factor w/ 61 levels "Africa","Australia",...: 60 60 60 6
 $ category  : Factor w/ 27 levels "Aerospace & defense",...: 2 6 16 19
 $ sales     : num   94.7 134.2 ...
 $ profits   : num   17.9 15.6 ...
 $ assets    : num   1264  627 ...
 $ marketvalue: num   255 329 ...

```

The output of the `str` function tells us that `Forbes2000` is an object of class `data.frame`, the most important data structure for handling tabular statistical data in R. As expected, information about 2000 observations, i.e., companies, are stored in this object. For each observation, the following eight variables are available:

rank: the ranking of the company,

name: the name of the company,

country: the country the company is situated in,

category: a category describing the products the company produces,

sales: the amount of sales of the company in billion US dollars,

profits: the profit of the company in billion US dollars,

assets: the assets of the company in billion US dollars,

marketvalue: the market value of the company in billion US dollars.

A similar but more detailed description is available from the help page for the `Forbes2000` object:

```
R> help("Forbes2000")
```

or

```
R> ?Forbes2000
```

All information provided by `str` can be obtained by specialised functions as well and we will now have a closer look at the most important of these. The R language is an object-oriented programming language, so every object is an instance of a class. The name of the class of an object can be determined by

```
R> class(Forbes2000)
```

```
[1] "data.frame"
```

Objects of class `data.frame` represent data the traditional table oriented way. Each row is associated with one single observation and each column corresponds to one variable. The dimensions of such a table can be extracted using the `dim` function

```
R> dim(Forbes2000)
```

```
[1] 2000    8
```

Alternatively, the numbers of rows and columns can be found using

```
R> nrow(Forbes2000)
```

```
[1] 2000
```

```
R> ncol(Forbes2000)
```

```
[1] 8
```

The results of both statements show that `Forbes2000` has 2000 rows, i.e., observations, the companies in our case, with eight variables describing the observations. The variable names are accessible from

```
R> names(Forbes2000)
```

```
[1] "rank"      "name"      "country"   "category"  
[5] "sales"    "profits"   "assets"    "marketvalue"
```

The values of single variables can be extracted from the `Forbes2000` object by their names, for example the ranking of the companies

```
R> class(Forbes2000[, "rank"])
```

```
[1] "integer"
```

is stored as an integer variable. Brackets `[]` always indicate a subset of a larger object, in our case a single variable extracted from the whole table. Because `data.frames` have two dimensions, observations and variables, the comma is required in order to specify that we want a subset of the second dimension, i.e., the variables. The rankings for all 2000 companies are represented in a *vector* structure the length of which is given by

```
R> length(Forbes2000[, "rank"])
```

```
[1] 2000
```

A *vector* is the elementary structure for data handling in R and is a set of simple elements, all being objects of the same class. For example, a simple vector of the numbers one to three can be constructed by one of the following commands

```
R> 1:3
```

```
[1] 1 2 3
```

```
R> c(1,2,3)
```

```
[1] 1 2 3
```

```
R> seq(from = 1, to = 3, by = 1)
```

```
[1] 1 2 3
```

The unique names of all 2000 companies are stored in a character vector

```
R> class(Forbes2000[,"name"])
```

```
[1] "character"
```

```
R> length(Forbes2000[,"name"])
```

```
[1] 2000
```

and the first element of this vector is

```
R> Forbes2000[,"name"][1]
```

```
[1] "Citigroup"
```

Because the companies are ranked, Citigroup is the world's largest company according to the Forbes 2000 list. Further details on vectors and subsetting are given in Section 1.6. Nominal measurements are represented by *factor* variables in R, such as the category of the company's business segment

```
R> class(Forbes2000[,"category"])
```

```
[1] "factor"
```

Objects of class *factor* and *character* basically differ in the way their values are stored internally. Each element of a vector of class *character* is stored as a *character* variable whereas an integer variable indicating the level of a *factor* is saved for *factor* objects. In our case, there are

```
R> nlevels(Forbes2000[,"category"])
```

```
[1] 27
```

different levels, i.e., business categories, which can be extracted by

```
R> levels(Forbes2000[,"category"])
```

```
[1] "Aerospace & defense"
```

```
[2] "Banking"
```

```
[3] "Business services & supplies"
```

```
...
```

As a simple summary statistic, the frequencies of the levels of such a *factor* variable can be found from

```
R> table(Forbes2000[,"category"])
```

| | |
|---|----------------|
| <i>Aerospace & defense</i> | <i>Banking</i> |
| 19 | 313 |
| <i>Business services & supplies</i> | |
| 70 | |

...

The sales, assets, profits and market value variables are of type `numeric`, the natural data type for continuous or discrete measurements, for example

```
R> class(Forbes2000[, "sales"])
```

```
[1] "numeric"
```

and simple summary statistics such as the mean, median and range can be found from

```
R> median(Forbes2000[, "sales"])
```

```
[1] 4.365
```

```
R> mean(Forbes2000[, "sales"])
```

```
[1] 9.69701
```

```
R> range(Forbes2000[, "sales"])
```

```
[1] 0.01 256.33
```

The `summary` method can be applied to a numeric vector to give a set of useful summary statistics namely the minimum, maximum, mean, median and the 25% and 75% quartiles; for example

```
R> summary(Forbes2000[, "sales"])
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
0.010  2.018   4.365   9.697   9.548 256.300
```

1.5 Data Import and Export

In the previous section, the data from the Forbes 2000 list of the world's largest companies were loaded into R from the *HSAUR* package but we will now explore practically more relevant ways to import data into the R system. The most frequent data formats the data analyst is confronted with are comma separated files, Excel spreadsheets, files in SPSS format and a variety of SQL data base engines. Querying data bases is a non-trivial task and requires additional knowledge about querying languages and we therefore refer to the 'R Data Import/Export' manual – see Section 1.3. We assume that a comma separated file containing the Forbes 2000 list is available as `Forbes2000.csv` (such a file is part of the *HSAUR* source package in directory `HSAUR/inst/rawdata`). When the fields are separated by commas and each row begins with a name (a text format typically created by Excel), we can read in the data as follows using the `read.table` function

```
R> csvForbes2000 <- read.table("Forbes2000.csv",
+   header = TRUE, sep = ",", row.names = 1)
```

The argument `header = TRUE` indicates that the entries in the first line of the text file `"Forbes2000.csv"` should be interpreted as variable names. Columns are separated by a comma (`sep = ","`), users of continental versions of Excel should take care of the character symbol coding for decimal points (by default

`dec = "."`). Finally, the first column should be interpreted as row names but not as a variable (`row.names = 1`). Alternatively, the function `read.csv` can be used to read comma separated files. The function `read.table` by default guesses the class of each variable from the specified file. In our case, character variables are stored as factors

```
R> class(csvForbes2000[, "name"])
[1] "factor"
```

which is only suboptimal since the names of the companies are unique. However, we can supply the types for each variable to the `colClasses` argument

```
R> csvForbes2000 <- read.table("Forbes2000.csv",
+   header = TRUE, sep = ",", row.names = 1,
+   colClasses = c("character", "integer", "character",
+   "factor", "factor", "numeric", "numeric", "numeric",
+   "numeric"))
R> class(csvForbes2000[, "name"])
[1] "character"
```

and check if this object is identical with our previous Forbes 2000 list object

```
R> all.equal(csvForbes2000, Forbes2000)
[1] "Component 2: 23 string mismatches"
```

The argument `colClasses` expects a character vector of length equal to the number of columns in the file. Such a vector can be supplied by the `c` function that combines the objects given in the parameter list into a *vector*

```
R> classes <- c("character", "integer", "character", "factor",
+   "factor", "numeric", "numeric", "numeric", "numeric")
R> length(classes)
[1] 9
```

```
R> class(classes)
[1] "character"
```

An R interface to the open data base connectivity standard (ODBC) is available in package *RODBC* and its functionality can be used to assess Excel and Access files directly:

```
R> library("RODBC")
R> cnct <- odbcConnectExcel("Forbes2000.xls")
R> sqlQuery(cnct, "select * from \"Forbes2000\\$\"")
```

The function `odbcConnectExcel` opens a connection to the specified Excel or Access file which can be used to send SQL queries to the data base engine and retrieve the results of the query. Files in SPSS format are read in a way similar to reading comma separated files, using the function `read.spss` from package *foreign* (which comes with the base distribution). Exporting data from R is now rather straightforward. A comma separated file readable by Excel can be constructed from a *data.frame* object via

```
R> write.table(Forbes2000, file = "Forbes2000.csv", sep = ",",
+             col.names = NA)
```

The function `write.csv` is one alternative and the functionality implemented in the *RODBC* package can be used to write data directly into Excel spreadsheets as well. Alternatively, when data should be saved for later processing in R only, R objects of arbitrary kind can be stored into an external binary file via

```
R> save(Forbes2000, file = "Forbes2000.rda")
```

where the extension `.rda` is standard. We can get the file names of all files with extension `.rda` from the working directory

```
R> list.files(pattern = "\\rda")
```

```
[1] "Forbes2000.rda"
```

and we can load the contents of the file into R by

```
R> load("Forbes2000.rda")
```

1.6 Basic Data Manipulation

The examples shown in the previous section have illustrated the importance of *data.frames* for storing and handling tabular data in R. Internally, a *data.frame* is a *list* of vectors of a common length n , the number of rows of the table. Each of those vectors represents the measurements of one variable and we have seen that we can access such a variable by its name, for example the names of the companies

```
R> companies <- Forbes2000[, "name"]
```

Of course, the `companies` vector is of class *character* and of length 2000. A subset of the elements of the vector `companies` can be extracted using the `[]` subset operator. For example, the largest of the 2000 companies listed in the Forbes 2000 list is

```
R> companies[1]
```

```
[1] "Citigroup"
```

and the top three companies can be extracted utilising an integer vector of the numbers one to three:

```
R> 1:3
```

```
[1] 1 2 3
```

```
R> companies[1:3]
```

```
[1] "Citigroup"           "General Electric"
[3] "American Intl Group"
```

In contrast to indexing with positive integers, negative indexing returns all elements which are *not* part of the index vector given in brackets. For example, all companies except those with numbers four to two-thousand, i.e., the top three companies, are again


```
R> companies[-(4:2000)]
```

```
[1] "Citigroup"           "General Electric"
[3] "American Intl Group"
```

The complete information about the top three companies can be printed in a similar way. Because *data.frames* have a concept of rows and columns, we need to separate the subsets corresponding to rows and columns by a comma. The statement

```
R> Forbes2000[1:3, c("name", "sales", "profits", "assets")]
```

```
           name sales profits assets
1      Citigroup  94.71  17.85 1264.03
2  General Electric 134.19  15.59  626.93
3 American Intl Group  76.66   6.46  647.66
```

extracts the variables `name`, `sales`, `profits` and `assets` for the three largest companies. Alternatively, a single variable can be extracted from a *data.frame* by

```
R> companies <- Forbes2000$name
```

which is equivalent to the previously shown statement

```
R> companies <- Forbes2000[, "name"]
```

We might be interested in extracting the largest companies with respect to an alternative ordering. The three top selling companies can be computed along the following lines. First, we need to compute the ordering of the companies' sales

```
R> order_sales <- order(Forbes2000$sales)
```

which returns the indices of the ordered elements of the numeric vector `sales`. Consequently the three companies with the lowest sales are

```
R> companies[order_sales[1:3]]
```

```
[1] "Custodia Holding"           "Central European Media"
[3] "Minara Resources"
```

The indices of the three top sellers are the elements 1998, 1999 and 2000 of the integer vector `order_sales`

```
R> Forbes2000[order_sales[c(2000, 1999, 1998)],
+           c("name", "sales", "profits", "assets")]
```

```
           name sales profits assets
10 Wal-Mart Stores 256.33   9.05 104.91
5      BP          232.57  10.27 177.57
4  ExxonMobil    222.88  20.96 166.99
```

Another way of selecting vector elements is the use of a logical vector being `TRUE` when the corresponding element is to be selected and `FALSE` otherwise. The companies with assets of more than 1000 billion US dollars are

```
R> Forbes2000[Forbes2000$assets > 1000,
+           c("name", "sales", "profits", "assets")]
```

```

              name sales profits assets
1          Citigroup 94.71  17.85 1264.03
9          Fannie Mae 53.13   6.48 1019.17
403 Mizuho Financial 24.40 -20.11 1115.90

```

where the expression `Forbes2000$assets > 1000` indicates a logical vector of length 2000 with

```

R> table(Forbes2000$assets > 1000)

FALSE  TRUE
 1997      3

```

elements being either `FALSE` or `TRUE`. In fact, for some of the companies the measurement of the `profits` variable are missing. In R, missing values are treated by a special symbol, `NA`, indicating that this measurement is not available. The observations with profit information missing can be obtained via

```

R> na_profits <- is.na(Forbes2000$profits)
R> table(na_profits)

```

```

na_profits
FALSE  TRUE
 1995      5

```

```

R> Forbes2000[na_profits,
+             c("name", "sales", "profits", "assets")]

```

```

              name sales profits assets
772             AMP  5.40      NA  42.94
1085            HHG  5.68      NA  51.65
1091            NTL  3.50      NA  10.59
1425    US Airways Group 5.50      NA   8.58
1909 Laidlaw International 4.48      NA   3.98

```

where the function `is.na` returns a logical vector being `TRUE` when the corresponding element of the supplied vector is `NA`. A more comfortable approach is available when we want to remove all observations with at least one missing value from a *data.frame* object. The function `complete.cases` takes a *data.frame* and returns a logical vector being `TRUE` when the corresponding observation does not contain any missing value:

```

R> table(complete.cases(Forbes2000))

FALSE  TRUE
   5 1995

```

Subsetting *data.frames* driven by logical expressions may induce a lot of typing which can be avoided. The `subset` function takes a *data.frame* as first argument and a logical expression as second argument. For example, we can select a subset of the Forbes 2000 list consisting of all companies situated in the United Kingdom by

```

R> UKcomp <- subset(Forbes2000, country == "United Kingdom")
R> dim(UKcomp)

```

[1] 137 8

i.e., 137 of the 2000 companies are from the UK. Note that it is not necessary to extract the variable `country` from the `data.frame` `Forbes2000` when formulating the logical expression.

1.7 Simple Summary Statistics

Two functions are helpful for getting an overview about R objects: `str` and `summary`, where `str` is more detailed about data types and `summary` gives a collection of sensible summary statistics. For example, applying the `summary` method to the `Forbes2000` data set,

```
R> summary(Forbes2000)
```

results in the following output

```

      rank          name          country
Min.   : 1.0   Length:2000   United States :751
1st Qu.: 500.8 Class :character   Japan         :316
Median :1000.5 Mode  :character   United Kingdom:137
Mean   :1000.5          Germany      : 65
3rd Qu.:1500.2          France       : 63
Max.   :2000.0          Canada      : 56
                                (Other)      :612

      category          sales
Banking           : 313   Min.   : 0.010
Diversified financials: 158 1st Qu.: 2.018
Insurance         : 112   Median : 4.365
Utilities         : 110   Mean    : 9.697
Materials         :  97   3rd Qu.: 9.547
Oil & gas operations :  90   Max.    :256.330
(Other)           :1120

      profits          assets          marketvalue
Min.   : -25.8300   Min.   : 0.270   Min.   : 0.02
1st Qu.:  0.0800   1st Qu.: 4.025   1st Qu.: 2.72
Median :  0.2000   Median : 9.345   Median : 5.15
Mean   :  0.3811   Mean    :34.042   Mean    :11.88
3rd Qu.:  0.4400   3rd Qu.:22.793   3rd Qu.:10.60
Max.   : 20.9600   Max.    :1264.030 Max.    :328.54
NA's   :  5.0000

```

From this output we can immediately see that most of the companies are situated in the US and that most of the companies are working in the banking sector as well as that negative profits, or losses, up to 26 billion US dollars occur. Internally, `summary` is a so-called *generic function* with methods for a multitude of classes, i.e., `summary` can be applied to objects of different classes and will report sensible results. Here, we supply a `data.frame` object to `summary` where it is natural to apply `summary` to each of the variables in this `data.frame`. Because a `data.frame` is a *list* with each variable being an element of that *list*, the same effect can be achieved by

```
R> lapply(Forbes2000, summary)
```

The members of the `apply` family help to solve recurring tasks for each element of a *data.frame*, *matrix*, *list* or for each level of a factor. It might be interesting to compare the profits in each of the 27 categories. To do so, we first compute the median profit for each category from

```
R> mprofits <- tapply(Forbes2000$profits,
+                   Forbes2000$category, median, na.rm = TRUE)
```

a command that should be read as follows. For each level of the factor `category`, determine the corresponding elements of the numeric vector `profits` and supply them to the `median` function with additional argument `na.rm = TRUE`. The latter one is necessary because `profits` contains missing values which would lead to a non-sensible result of the `median` function

```
R> median(Forbes2000$profits)
```

```
[1] NA
```

The three categories with highest median profit are computed from the vector of sorted median profits

```
R> rev(sort(mprofits))[1:3]
```

| | |
|--|----------------------------------|
| <i>Oil & gas operations</i> | <i>Drugs & biotechnology</i> |
| 0.35 | 0.35 |
| <i>Household & personal products</i> | |
| 0.31 | |

where `rev` rearranges the vector of median profits `sorted` from smallest to largest. Of course, we can replace the `median` function with `mean` or whatever is appropriate in the call to `tapply`. In our situation, `mean` is not a good choice, because the distributions of profits or sales are naturally skewed. Simple graphical tools for the inspection of distributions are introduced in the next section.

1.7.1 Simple Graphics

The degree of skewness of a distribution can be investigated by constructing histograms using the `hist` function. (More sophisticated alternatives such as smooth density estimates will be considered in Chapter ??.) For example, the code for producing Figure 1.1 first divides the plot region into two equally spaced rows (the `layout` function) and then plots the histograms of the raw market values in the upper part using the `hist` function. The lower part of the figure depicts the histogram for the log transformed market values which appear to be more symmetric. Bivariate relationships of two continuous variables are usually depicted as scatterplots. In R, regression relationships are specified by so-called *model formulae* which, in a simple bivariate case, may look like

```
R> fm <- marketvalue ~ sales
R> class(fm)
```

```
R> layout(matrix(1:2, nrow = 2))
R> hist(Forbes2000$marketvalue)
R> hist(log(Forbes2000$marketvalue))
```

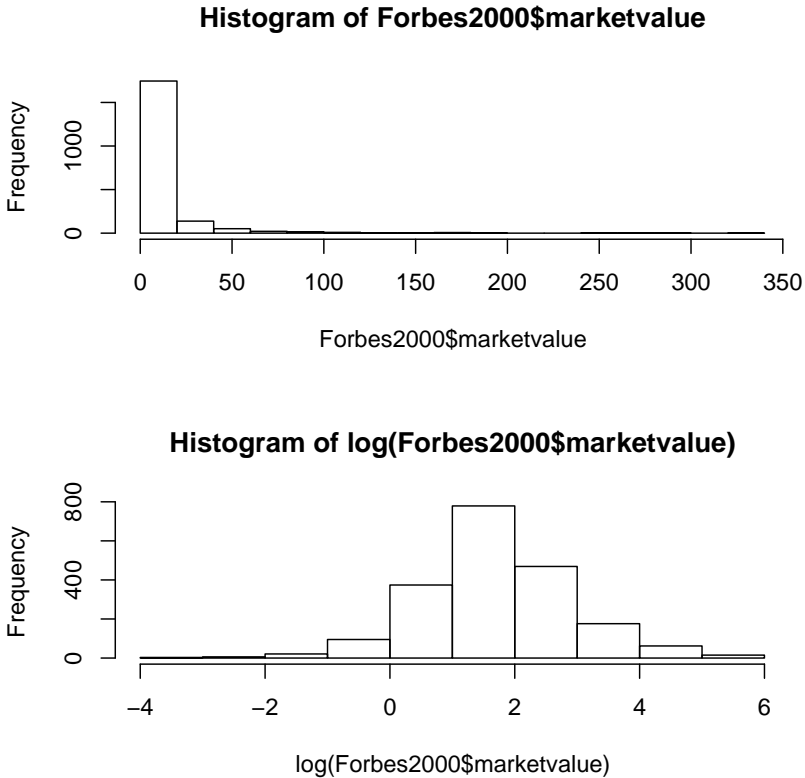


Figure 1.1 Histograms of the market value and the logarithm of the market value for the companies contained in the Forbes 2000 list.

```
[1] "formula"
```

with the dependent variable on the left hand side and the independent variable on the right hand side. The tilde separates left and right hand side. Such a model formula can be passed to a model function (for example to the linear model function as explained in Chapter ??). The `plot` generic function implements a *formula* method as well. Because the distributions of both market value and sales are skewed we choose to depict their logarithms. A raw scatterplot of 2000 data points (Figure 1.2) is rather uninformative due to areas with very high density. This problem can be avoided by choosing a transparent color for the dots (currently only possible with the PDF graphics device) as

```
R> plot(log(marketvalue) ~ log(sales), data = Forbes2000,  
+       pch = ".")
```

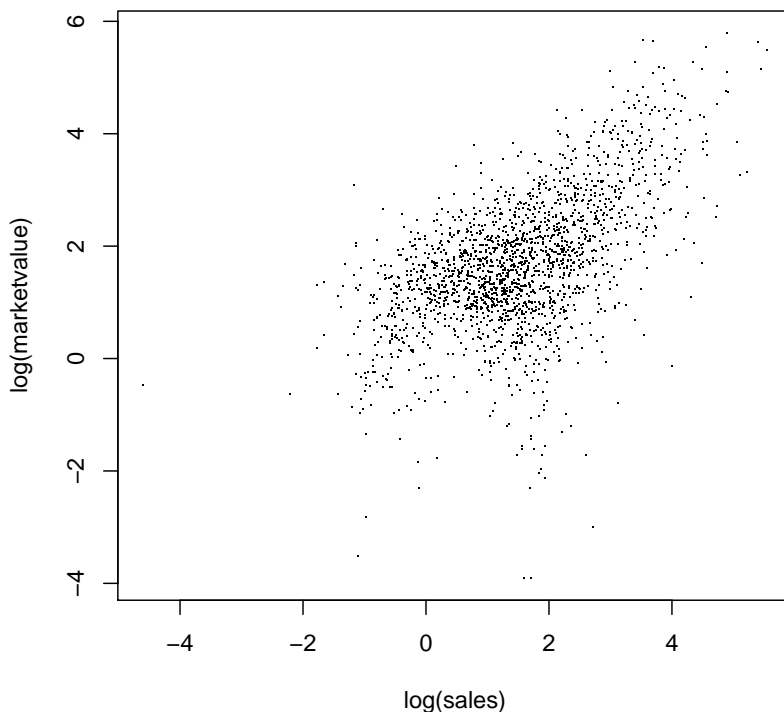


Figure 1.2 Raw scatterplot of the logarithms of market value and sales.

shown in Figure 1.3. If the independent variable is a factor, a boxplot representation is a natural choice. For four selected countries, the distributions of the logarithms of the market value may be visually compared in Figure 1.4. Here, the width of the boxes are proportional to the square root of the number of companies for each country and extremely large or small market values are depicted by single points.

1.8 Organising an Analysis

Although it is possible to perform an analysis typing all commands directly on the R prompt it is much more comfortable to maintain a separate text file collecting all steps necessary to perform a certain data analysis task. Such

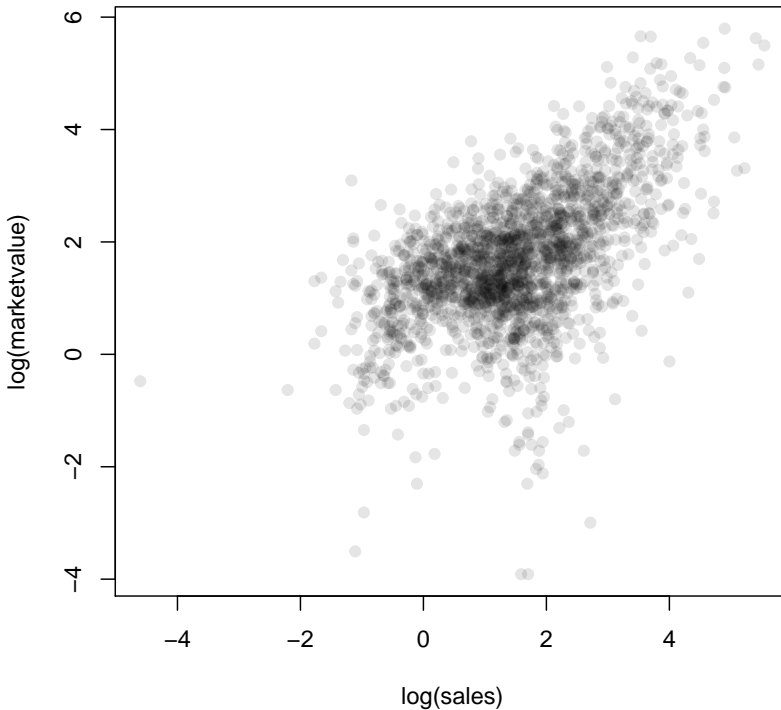


Figure 1.3 Scatterplot with transparent shading of points of the logarithms of market value and sales.

an R transcript file, for example `analysis.R` created with your favourite text editor, can be sourced into R using the `source` command

```
R> source("analysis.R", echo = TRUE)
```

When all steps of a data analysis, i.e., data preprocessing, transformations, simple summary statistics and plots, model building and inference as well as reporting, are collected in such an R transcript file, the analysis can be reproduced at any time, maybe with modified data as it frequently happens in our consulting practice.

1.9 Summary

Reading data into R is possible in many different ways, including direct connections to data base engines. Tabular data are handled by *data.frames* in R, and the usual data manipulation techniques such as sorting, ordering or sub-

```
R> boxplot(log(marketvalue) ~ country, data =
+         subset(Forbes2000, country %in% c("United Kingdom",
+         "Germany", "India", "Turkey")),
+         ylab = "log(marketvalue)", varwidth = TRUE)
```

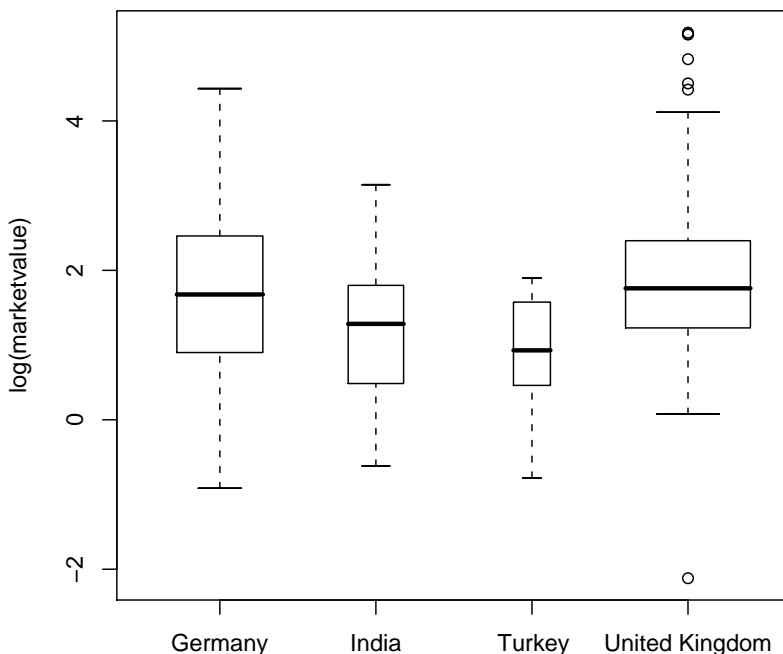


Figure 1.4 Boxplots of the logarithms of the market value for four selected countries, the width of the boxes is proportional to the square-roots of the number of companies.

setting can be performed by simple R statements. An overview on data stored in a *data.frame* is given mainly by two functions: `summary` and `str`. Simple graphics such as histograms and scatterplots can be constructed by applying the appropriate R functions (`hist` and `plot`) and we shall give many more examples of these functions and those that produce more interesting graphics in later chapters.

Exercises

- Ex. 1.1 Calculate the median profit for the companies in the United States and the median profit for the companies in the UK, France and Germany.
- Ex. 1.2 Find all German companies with negative profit.
- Ex. 1.3 Which business category are most of the companies situated at the Bermuda island working in?
- Ex. 1.4 For the 50 companies in the Forbes data set with the highest profits, plot sales against assets (or some suitable transformation of each variable), labelling each point with the appropriate country name which may need to be abbreviated (using `abbreviate`) to avoid making the plot look too ‘messy’.
- Ex. 1.5 Find the average value of sales for the companies in each country in the Forbes data set, and find the number of companies in each country with profits above 5 billion US dollars.

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Simple Inference: Guessing Lengths, Wave Energy, Water Hardness, Piston Rings, and Rearrests of Juveniles

2.1 Introduction

2.2 Statistical Tests

2.3 Analysis Using R

2.3.1 Estimating the Width of a Room

The data shown in Table ?? are available as `roomwidth data.frame` from the `HSAUR` package and can be attached by using

```
R> data("roomwidth", package = "HSAUR")
```

If we convert the estimates of the room width in metres into feet by multiplying each by 3.28 then we would like to test the hypothesis that the mean of the population of ‘metre’ estimates is equal to the mean of the population of ‘feet’ estimates. We shall do this first by using an independent samples *t*-test, but first it is good practice to, informally at least, check the normality and equal variance assumptions. Here we can use a combination of numerical and graphical approaches. The first step should be to convert the metre estimates into feet, i.e., by a factor

```
R> convert <- ifelse(roomwidth$unit == "feet", 1, 3.28)
```

which equals one for all feet measurements and 3.28 for the measurements in metres. Now, we get the usual summary statistics and standard deviations of each set of estimates using

```
R> tapply(roomwidth$width * convert, roomwidth$unit, summary)
```

\$feet

| <i>Min.</i> | <i>1st Qu.</i> | <i>Median</i> | <i>Mean</i> | <i>3rd Qu.</i> | <i>Max.</i> |
|-------------|----------------|---------------|-------------|----------------|-------------|
| 24.0 | 36.0 | 42.0 | 43.7 | 48.0 | 94.0 |

\$metres

| <i>Min.</i> | <i>1st Qu.</i> | <i>Median</i> | <i>Mean</i> | <i>3rd Qu.</i> | <i>Max.</i> |
|-------------|----------------|---------------|-------------|----------------|-------------|
| 26.24 | 36.08 | 49.20 | 52.55 | 55.76 | 131.20 |

```
R> tapply(roomwidth$width * convert, roomwidth$unit, sd)
```

| <i>feet</i> | <i>metres</i> |
|-------------|---------------|
| 12.49742 | 23.43444 |

where `tapply` applies `summary`, or `sd`, to the converted widths for both groups of measurements given by `roomwidth$unit`. A boxplot of each set of estimates might be useful and is depicted in Figure 2.1. The `layout` function (line 1 in Figure 2.1) divides the plotting area in three parts. The `boxplot` function produces a boxplot in the upper part and the two `qqnorm` statements in lines 8 and 11 set up the normal probability plots that can be used to assess the normality assumption of the t -test. The boxplots indicate that both sets of estimates contain a number of outliers and also that the estimates made in metres are skewed and more variable than those made in feet, a point underlined by the numerical summary statistics above. Both normal probability plots depart from linearity, suggesting that the distributions of both sets of estimates are not normal. The presence of outliers, the apparently different variances and the evidence of non-normality all suggest caution in applying the t -test, but for the moment we shall apply the usual version of the test using the `t.test` function in R. The two-sample test problem is specified by a *formula*, here by

$$I(\text{width} * \text{convert}) \sim \text{unit}$$

where the response, `width`, on the left hand side needs to be converted first and, because the star has a special meaning in formulae as will be explained in Chapter 4, the conversion needs to be embedded by `I`. The factor `unit` on the right hand side specifies the two groups to be compared.

2.3.2 Wave Energy Device Mooring

The data from Table ?? are available as *data.frame* `waves`

```
R> data("waves", package = "HSAUR")
```

and requires the use of a matched pairs t -test to answer the question of interest. This test assumes that the differences between the matched observations have a normal distribution so we can begin by checking this assumption by constructing a boxplot and a normal probability plot – see Figure 2.5.

2.3.3 Mortality and Water Hardness

There is a wide range of analyses we could apply to the data in Table ?? available from

```
R> data("water", package = "HSAUR")
```

But to begin we will construct a scatterplot of the data enhanced somewhat by the addition of information about the marginal distributions of water hardness (calcium concentration) and mortality, and by adding the estimated linear regression fit (see Chapter 5) for mortality on hardness. The plot and the required R code is given along with Figure 2.8. In line 1 of Figure 2.8, we divide the plotting region into four areas of different size. The scatterplot

```

1 R> layout(matrix(c(1,2,1,3), nrow = 2, ncol = 2, byrow = FALSE))
2 R> boxplot(I(width * convert) ~ unit, data = roomwidth,
3 +         ylab = "Estimated width (feet)",
4 +         varwidth = TRUE, names = c("Estimates in feet",
5 +         "Estimates in metres (converted to feet)"))
6 R> feet <- roomwidth$unit == "feet"
7 R> qqnorm(roomwidth$width[feet],
8 +         ylab = "Estimated width (feet)")
9 R> qqline(roomwidth$width[feet])
10 R> qqnorm(roomwidth$width[!feet],
11 +         ylab = "Estimated width (metres)")
12 R> qqline(roomwidth$width[!feet])

```

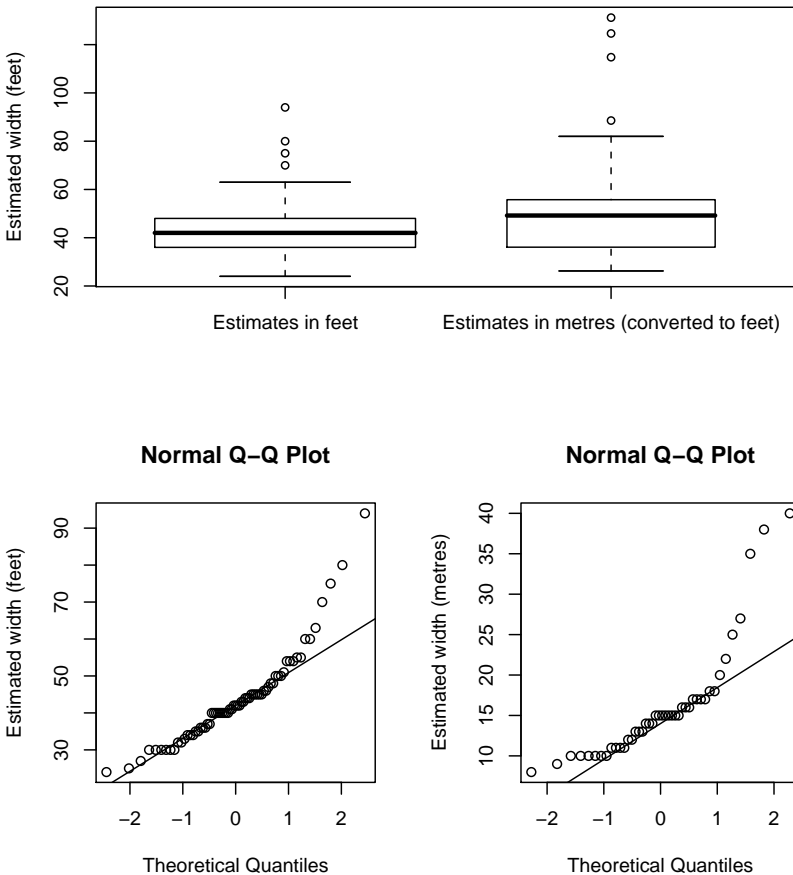


Figure 2.1 Boxplots of estimates of width of room in feet and metres (after conversion to feet) and normal probability plots of estimates of room width made in feet and in metres.

```
R> t.test(I(width * convert) ~ unit, data = roomwidth,
+        var.equal = TRUE)

      Two Sample t-test

data:  I(width * convert) by unit
t = -2.6147, df = 111, p-value = 0.01017
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -15.572734  -2.145052
sample estimates:
 mean in group feet mean in group metres
      43.69565          52.55455
```

Figure 2.2 R output of the independent samples *t*-test for the roomwidth data.

```
R> t.test(I(width * convert) ~ unit, data = roomwidth,
+        var.equal = FALSE)

      Welch Two Sample t-test

data:  I(width * convert) by unit
t = -2.3071, df = 58.788, p-value = 0.02459
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -16.54308  -1.17471
sample estimates:
 mean in group feet mean in group metres
      43.69565          52.55455
```

Figure 2.3 R output of the independent samples Welch test for the roomwidth data.

(line 3) uses a plotting symbol depending on the location of the city (by the `pch` argument), a legend for the location is added in line 6. We add a least squares fit (see Chapter 5) to the scatterplot and, finally, depict the marginal distributions by means of a boxplot and a histogram. The scatterplot shows that as hardness increases mortality decreases, and the histogram for the water hardness shows it has a rather skewed distribution.

2.3.4 Piston-ring Failures

Rather than looking at the simple differences of observed and expected values for each cell which would be unsatisfactory since a difference of fixed size is clearly more important for smaller samples, it is preferable to consider a *standardised residual* given by dividing the observed minus expected difference by the square root of the appropriate expected value. The X^2 statistic for

```
R> wilcox.test(I(width * convert) ~ unit, data = roomwidth,
+             conf.int = TRUE)

      Wilcoxon rank sum test with continuity correction

data:  I(width * convert) by unit
W = 1145, p-value = 0.02815
alternative hypothesis: true location shift is not equal to 0
95 percent confidence interval:
 -9.3599953 -0.8000423
sample estimates:
difference in location
      -5.279955
```

Figure 2.4 R output of the Wilcoxon rank sum test for the roomwidth data.

assessing independence is simply the sum, over all the cells in the table, of the squares of these terms. We can find these values extracting the `residuals` element of the object returned by the `chisq.test` function

```
R> chisq.test(pistonrings)$residuals

      leg
compressor  North      Centre      South
C1  0.6036154  1.6728267 -1.7802243
C2  0.1429031  0.2975200 -0.3471197
C3 -0.3251427 -0.4522620  0.6202463
C4 -0.4157886 -1.4666936  1.4635235
```

A graphical representation of these residuals is called *association plot* and is available via the `assoc` function from package *vcd* (Meyer et al., 2006) applied to the contingency table of the two categorical variables. Figure 2.11 depicts the residuals for the piston ring data. The deviations from independence are largest for C1 and C4 compressors in the centre and south leg.

2.3.5 Rearrests of Juveniles

The data in Table ?? are available as *table* object via

```
R> data("rearrests", package = "HSAUR")
R> rearrests
```

```
      Juvenile court
Adult court Rearrest No rearrest
Rearrest    158      515
No rearrest  290     1134
```

and in `rearrests` the counts in the four cells refer to the matched pairs of subjects; for example, in 158 pairs both members of the pair were rearrested. Here we need to use McNemar's test to assess whether rearrest is associated

```

R> mooringdiff <- waves$method1 - waves$method2
R> layout(matrix(1:2, ncol = 2))
R> boxplot(mooringdiff, ylab = "Differences (Newton metres)",
+         main = "Boxplot")
R> abline(h = 0, lty = 2)
R> qqnorm(mooringdiff, ylab = "Differences (Newton metres)")
R> qqline(mooringdiff)

```

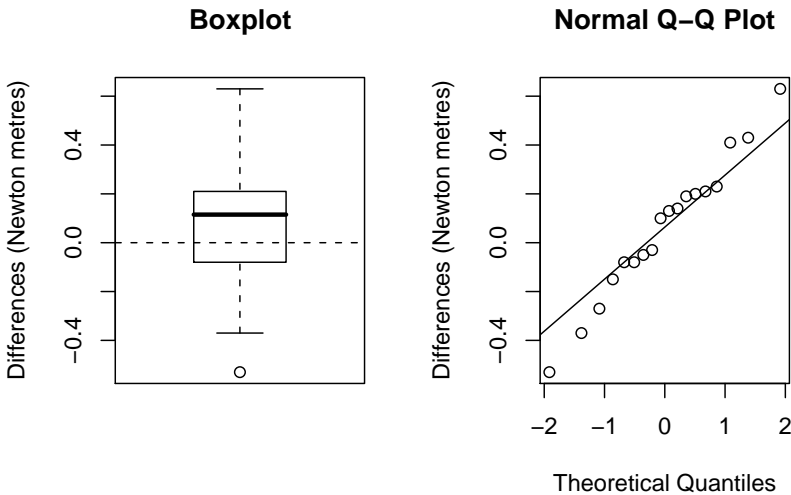


Figure 2.5 Boxplot and normal probability plot for differences between the two mooring methods.

with type of court where the juvenile was tried. We can use the R function `mcnemar.test`. The test statistic shown in Figure 2.12 is 62.888 with a single degree of freedom – the associated p -value is extremely small and there is strong evidence that type of court and the probability of rearrest are related. It appears that trial at a juvenile court is less likely to result in rearrest (see Exercise 2.4). An exact version of McNemar's test can be obtained by testing whether b and c are equal using a binomial test (see Figure 2.13).

```
R> t.test(mooringdiff)

      One Sample t-test

data:  mooringdiff
t = 0.9019, df = 17, p-value = 0.3797
alternative hypothesis: true mean is not equal to 0
95 percent confidence interval:
 -0.08258476  0.20591810
sample estimates:
 mean of x
0.06166667
```

Figure 2.6 R output of the paired t -test for the `waves` data.

```
R> wilcox.test(mooringdiff)

      Wilcoxon signed rank test with continuity correction

data:  mooringdiff
V = 109, p-value = 0.3165
alternative hypothesis: true location is not equal to 0
```

Figure 2.7 R output of the Wilcoxon signed rank test for the `waves` data.

```

1 R> nf <- layout(matrix(c(2, 0, 1, 3), 2, 2, byrow = TRUE),
2 +                     c(2, 1), c(1, 2), TRUE)
3 R> psymb <- as.numeric(water$location)
4 R> plot(mortality ~ hardness, data = water, pch = psymb)
5 R> abline(lm(mortality ~ hardness, data = water))
6 R> legend("topright", legend = levels(water$location),
7 +       pch = c(1,2), bty = "n")
8 R> hist(water$hardness)
9 R> boxplot(water$mortality)

```

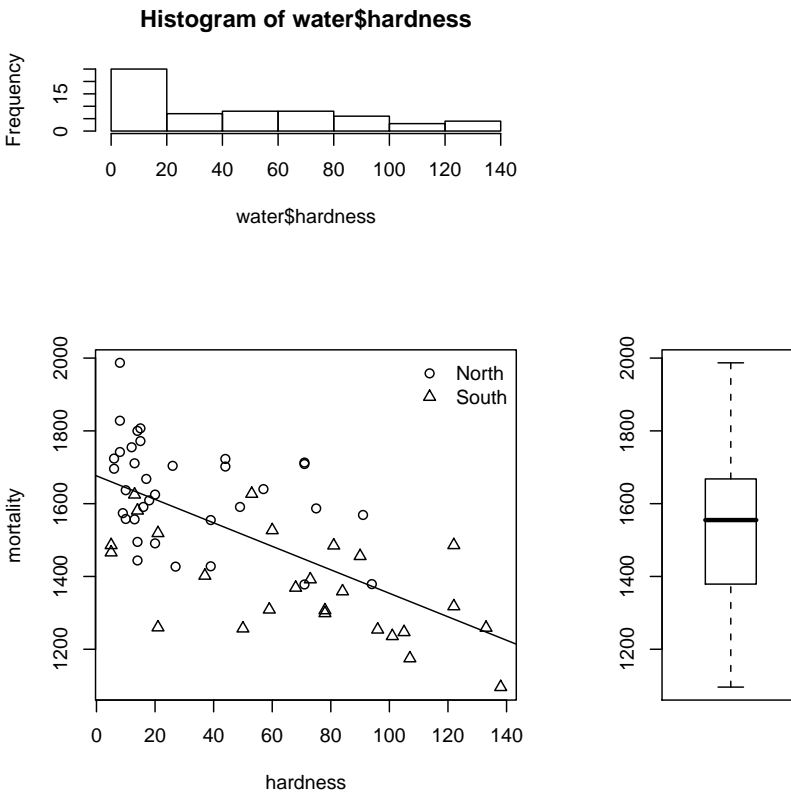


Figure 2.8 Enhanced scatterplot of water hardness and mortality, showing both the joint and the marginal distributions and, in addition, the location of the city by different plotting symbols.

```
R> cor.test(~ mortality + hardness, data = water)
      Pearson's product-moment correlation

data: mortality and hardness
t = -6.6555, df = 59, p-value = 1.033e-08
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.7783208 -0.4826129
sample estimates:
      cor
-0.6548486
```

Figure 2.9 R output of Pearsons' correlation coefficient for the `water` data.

```
R> data("pistonrings", package = "HSAUR")
R> chisq.test(pistonrings)
      Pearson's Chi-squared test

data: pistonrings
X-squared = 11.7223, df = 6, p-value = 0.06846
```

Figure 2.10 R output of the chi-squared test for the `pistonrings` data.

```
R> library("vcd")
R> assoc(pistonrings)
```

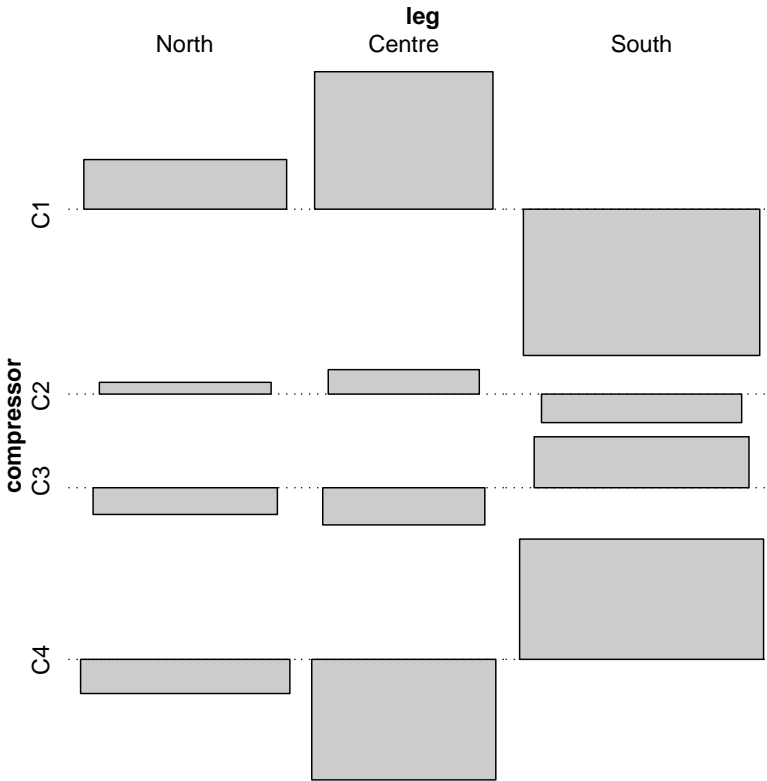


Figure 2.11 Association plot of the residuals for the pistonrings data.

```
R> mcnemar.test(rearrests, correct = FALSE)
```

McNemar's Chi-squared test

data: rearrests

McNemar's chi-squared = 62.8882, df = 1, p-value = 2.188e-15

Figure 2.12 R output of McNemar's test for the rearrests data.

```
R> binom.test(rearrests[2], n = sum(rearrests[c(2,3)]))  
      Exact binomial test  
  
data:  rearrests[2] and sum(rearrests[c(2, 3)])  
number of successes = 290, number of trials = 805,  
p-value = 1.918e-15  
alternative hypothesis: true probability of success is not equal to 0.5  
95 percent confidence interval:  
 0.3270278 0.3944969  
sample estimates:  
probability of success  
 0.3602484
```

Figure 2.13 R output of an exact version of McNemar's test for the `rearrests` data computed via a binomial test.

Bibliography

Meyer, D., Zeileis, A., Karatzoglou, A., and Hornik, K. (2006), *vcd: Visualizing Categorical Data*, URL <http://CRAN.R-project.org>, R package version 1.0-2.

Conditional Inference: Guessing Lengths, Suicides, Gastrointestinal Damage, and Newborn Infants

3.1 Introduction

3.2 Conditional Test Procedures

3.3 Analysis Using R

3.3.1 Estimating the Width of a Room Revised

The unconditional analysis of the room width estimated by two groups of students in Chapter ?? lead to the conclusion that the estimates in metres are slightly larger than the estimates in feet. Here, we reanalyse these data in a conditional framework. First, we convert metres into feet and store the vector of observations in a variable y :

```
R> data("roomwidth", package = "HSAUR")
R> convert <- ifelse(roomwidth$unit == "feet", 1, 3.28)
R> feet <- roomwidth$unit == "feet"
R> metre <- !feet
R> y <- roomwidth$width * convert
```

The test statistic is simply the difference in means

```
R> T <- mean(y[feet]) - mean(y[metre])
R> T
```

```
[1] -8.858893
```

In order to approximate the conditional distribution of the test statistic T we compute 9999 test statistics for shuffled y values. A permutation of the y vector can be obtained from the `sample` function.

```
R> meandiffs <- double(9999)
R> for (i in 1:length(meandiffs)) {
+   sy <- sample(y)
+   meandiffs[i] <- mean(sy[feet]) - mean(sy[metre])
+ }
```

The distribution of the test statistic T under the null hypothesis of independence of room width estimates and groups is depicted in Figure 3.1. Now, the value of the test statistic T for the original unshuffled data can be compared

```
R> hist(meandiffs)
R> abline(v = T, lty = 2)
R> abline(v = -T, lty = 2)
```

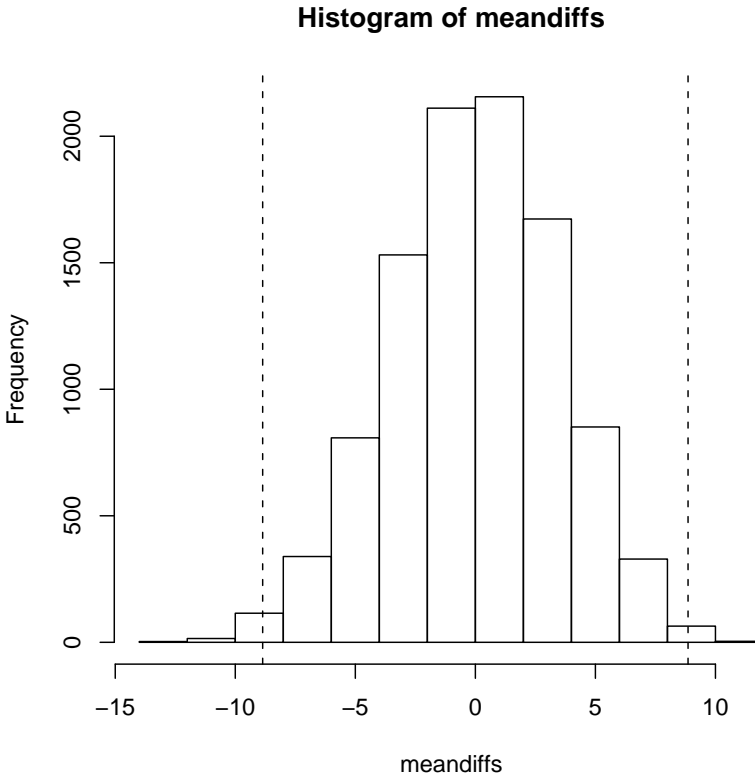


Figure 3.1 Approximated conditional distribution of the difference of mean `roomwidth` estimates in the feet and metres group under the null hypothesis. The vertical lines show the negative and positive absolute value of the test statistic T obtained from the original data.

with the distribution of T under the null hypothesis (the vertical lines in Figure 3.1). The p -value, i.e., the proportion of test statistics T larger than 8.859 or smaller than -8.859 is

```
R> greater <- abs(meandiffs) > abs(T)
R> mean(greater)
```

```
[1] 0.0080008
```

with a confidence interval of

```
R> binom.test(sum(greater), length(greater))$conf.int
```



```
[1] 0.006349087 0.009947933
attr(,"conf.level")
[1] 0.95
```

Note that the approximated conditional p -value is roughly the same as the p -value reported by the t -test in Chapter 2.

```
R> library("coin")
R> independence_test(y ~ unit, data = roomwidth,
+                   distribution = exact())

      Exact General Independence Test

data: y by unit (feet, metres)
Z = -2.5491, p-value = 0.008492
alternative hypothesis: two.sided
```

Figure 3.2 R output of the exact permutation test applied to the `roomwidth` data.

```
R> wilcox_test(y ~ unit, data = roomwidth,
+             distribution = exact())

      Exact Wilcoxon Mann-Whitney Rank Sum Test

data: y by unit (feet, metres)
Z = -2.1981, p-value = 0.02763
alternative hypothesis: true mu is not equal to 0
```

Figure 3.3 R output of the exact conditional Wilcoxon rank sum test applied to the `roomwidth` data.

3.3.2 *Crowds and Threatened Suicide*

3.3.3 *Gastrointestinal Damages*

Here we are interested in the comparison of two groups of patients, where one group received a placebo and the other one Misoprostol. In the trials shown here, the response variable is measured on an ordered scale – see Table ???. Data from four clinical studies are available and thus the observations are naturally grouped together. From the *data.frame* `Lanza` we can construct a three-way table as follows:

```
R> data("Lanza", package = "HSAUR")
R> xtabs(~ treatment + classification + study, data = Lanza)
```

```
R> data("suicides", package = "HSAUR")
R> fisher.test(suicides)

      Fisher's Exact Test for Count Data

data:  suicides
p-value = 0.0805
alternative hypothesis: true odds ratio is not equal to 1
95 percent confidence interval:
 0.7306872 91.0288231
sample estimates:
odds ratio
 6.302622
```

Figure 3.4 R output of Fisher's exact test for the suicides data.

```
, , study = I

      classification
treatment  1  2  3  4  5
Misoprostol 21  2  4  2  0
Placebo     2  2  4  9 13

, , study = II

      classification
treatment  1  2  3  4  5
Misoprostol 20  4  6  0  0
Placebo     8  4  9  4  5

, , study = III

      classification
treatment  1  2  3  4  5
Misoprostol 20  4  3  1  2
Placebo     0  2  5  5 17

, , study = IV

      classification
treatment  1  2  3  4  5
Misoprostol 1  4  5  0  0
Placebo     0  0  0  4  6
```

For the first study, the null hypothesis of independence of treatment and gastrointestinal damage, i.e., of no treatment effect of Misoprostol, is tested by

```
R> library("coin")
R> cmh_test(classification ~ treatment, data = Lanza,
+           scores = list(classification = c(0, 1, 6, 17, 30)),
+           subset = Lanza$study == "I")
      Asymptotic Linear-by-Linear Association Test

data:  classification (ordered) by treatment (Misoprostol, Placebo)
chi-squared = 28.8478, df = 1, p-value = 7.83e-08
```

and, by default, the conditional distribution is approximated by the corresponding limiting distribution. The p -value indicates a strong treatment effect. For the second study, the asymptotic p -value is a little bit larger

```
R> cmh_test(classification ~ treatment, data = Lanza,
+           scores = list(classification = c(0, 1, 6, 17, 30)),
+           subset = Lanza$study == "II")
      Asymptotic Linear-by-Linear Association Test

data:  classification (ordered) by treatment (Misoprostol, Placebo)
chi-squared = 12.0641, df = 1, p-value = 0.000514
```

and we make sure that the implied decision is correct by calculating a confidence interval for the exact p -value

```
R> p <- cmh_test(classification ~ treatment, data = Lanza,
+               scores = list(classification = c(0, 1, 6, 17, 30)),
+               subset = Lanza$study == "II", distribution =
+               approximate(B = 19999))
R> pvalue(p)
[1] 5.00025e-05
99 percent confidence interval:
 2.506396e-07 3.714653e-04
```

The third and fourth study indicate a strong treatment effect as well

```
R> cmh_test(classification ~ treatment, data = Lanza,
+           scores = list(classification = c(0, 1, 6, 17, 30)),
+           subset = Lanza$study == "III")
      Asymptotic Linear-by-Linear Association Test

data:  classification (ordered) by treatment (Misoprostol, Placebo)
chi-squared = 28.1587, df = 1, p-value = 1.118e-07

R> cmh_test(classification ~ treatment, data = Lanza,
+           scores = list(classification = c(0, 1, 6, 17, 30)),
+           subset = Lanza$study == "IV")
      Asymptotic Linear-by-Linear Association Test

data:  classification (ordered) by treatment (Misoprostol, Placebo)
chi-squared = 15.7414, df = 1, p-value = 7.262e-05
```

At the end, a separate analysis for each study is unsatisfactory. Because the design of the four studies is the same, we can use `study` as a block variable and perform a global linear-association test investigating the treatment effect of Misoprostol in all four studies. The block variable can be incorporated into the *formula* by the `|` symbol.

```
R> cmh_test(classification ~ treatment | study, data = Lanza,
+           scores = list(classification = c(0, 1, 6, 17, 30)))
      Asymptotic Linear-by-Linear Association Test
```

```
data:  classification (ordered) by
       treatment (Misoprostol, Placebo)
       stratified by study
chi-squared = 83.6188, df = 1, p-value < 2.2e-16
```

Based on this result, a strong treatment effect can be established.

3.3.4 Teratogenesis

In this example, the medical doctor (MD) and the research assistant (RA) assessed the number of anomalies (0, 1, 2 or 3) for each of 395 babies:

```
R> anomalies <- c(235, 23, 3, 0, 41, 35, 8, 0,
+               20, 11, 11, 1, 2, 1, 3, 1)
R> anomalies <- as.table(matrix(anomalies,
+                               ncol = 4, dimnames = list(MD = 0:3, RA = 0:3)))
R> anomalies
```

| | | RA | | | |
|----|--|-----|----|----|---|
| MD | | 0 | 1 | 2 | 3 |
| 0 | | 235 | 41 | 20 | 2 |
| 1 | | 23 | 35 | 11 | 1 |
| 2 | | 3 | 8 | 11 | 3 |
| 3 | | 0 | 0 | 1 | 1 |

We are interested in testing whether the number of anomalies assessed by the medical doctor differs structurally from the number reported by the research assistant. Because we compare *paired* observations, i.e., one pair of measurements for each newborn, a test of marginal homogeneity (a generalisation of McNemar's test, see Chapter 2) needs to be applied:

```
R> mh_test(anomalies)
```

```
Asymptotic Marginal-Homogeneity Test
```

```
data: response by
      groups (MD, RA)
      stratified by block
chi-squared = 21.2266, df = 3, p-value = 9.446e-05
```

The p -value indicates a deviation from the null hypothesis. However, the levels of the response are not treated as ordered. Similar to the analysis of the gastrointestinal damage data above, we can take this information into account by the definition of an appropriate score. Here, the number of anomalies is a natural choice:

```
R> mh_test(anomalies, scores = list(c(0, 1, 2, 3)))
```

```
Asymptotic Marginal-Homogeneity Test for Ordered Data
```

```
data: response (ordered) by
      groups (MD, RA)
      stratified by block
chi-squared = 21.0199, df = 1, p-value = 4.545e-06
```

In our case, both versions coincide and one can conclude that the assessment of the number of anomalies differs between the medical doctor and the research assistant.

Analysis of Variance: Weight Gain, Foster Feeding in Rats, Water Hardness and Male Egyptian Skulls

4.1 Introduction

4.2 Analysis of Variance

4.3 Analysis Using R

4.3.1 Weight Gain in Rats

Before applying analysis of variance to the data in Table ?? we should try to summarise the main features of the data by calculating means and standard deviations and by producing some hopefully informative graphs. The data is available in the *data.frame* `weightgain`. The following R code produces the required summary statistics

```
R> data("weightgain", package = "HSAUR")
R> tapply(weightgain$weightgain,
+         list(weightgain$source, weightgain$type), mean)
           High  Low
Beef      100.0  79.2
Cereal    85.9  83.9

R> tapply(weightgain$weightgain,
+         list(weightgain$source, weightgain$type), sd)
           High      Low
Beef  15.13642 13.88684
Cereal 15.02184 15.70881
```

To apply analysis of variance to the data we can use the `aov` function in R and then the `summary` method to give us the usual analysis of variance table. The model *formula* specifies a two-way layout with interaction terms, where the first factor is `source`, and the second factor is `type`.

```
R> wg_aov <- aov(weightgain ~ source * type, data = weightgain)
```

The estimates of the intercept and the main and interaction effects can be extracted from the model fit by

```
R> coef(wg_aov)
      (Intercept)          sourceCereal          typeLow
           100.0              -14.1             -20.8
```

```
R> plot.design(weightgain)
```

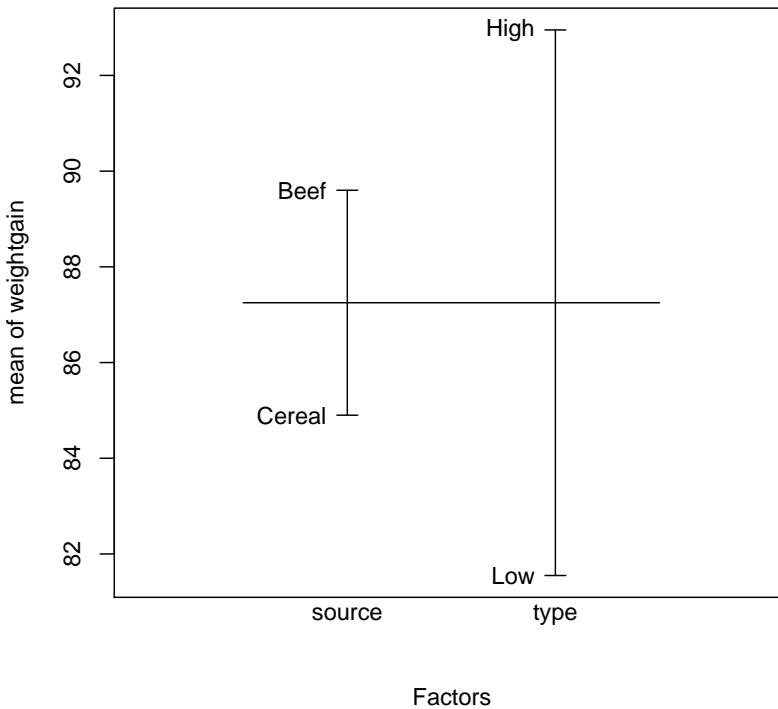


Figure 4.1 Plot of mean weight gain for each level of the two factors.

```
sourceCereal:typeLow
      18.8
```

Note that the model was fitted with the restrictions $\gamma_1 = 0$ (corresponding to Beef) and $\beta_1 = 0$ (corresponding to High) because treatment contrasts were used as default as can be seen from

```
R> options("contrasts")
```

```
$contrasts
      unordered      ordered
"contr.treatment" "contr.poly"
```

Thus, the coefficient for **source** of -14.1 can be interpreted as an estimate of the difference $\gamma_2 - \gamma_1$. Alternatively, we can use the restriction $\sum_i \gamma_i = 0$ by

```
R> coef(aov(weightgain ~ source + type + source:type,
+         data = weightgain, contrasts = list(source = contr.sum)))
```

```
R> summary(wg_aov)
```

```

              Df Sum Sq Mean Sq F value Pr(>F)
source         1  220.9    220.9  0.9879 0.32688
type           1 1299.6   1299.6  5.8123 0.02114 *
source:type    1  883.6    883.6  3.9518 0.05447 .
Residuals     36 8049.4    223.6
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

Figure 4.2 R output of the ANOVA fit for the `weightgain` data.

```

      (Intercept)          source1          typeLow
            92.95             7.05            -11.40
source1:typeLow
            -9.40

```

4.3.2 Foster Feeding of Rats of Different Genotype

As in the previous subsection we will begin the analysis of the foster feeding data in Table ?? with a plot of the mean litter weight for the different genotypes of mother and litter (see Figure 4.4). The data are in the `data.frame` `foster`

```
R> data("foster", package = "HSAUR")
```

We can derive the two analyses of variance tables for the foster feeding example by applying the R code

```
R> summary(aov(weight ~ litgen * motgen, data = foster))
```

to give

```

              Df Sum Sq Mean Sq F value Pr(>F)
litgen         3  60.16    20.05  0.3697 0.775221
motgen         3  775.08   258.36  4.7632 0.005736 **
litgen:motgen  9  824.07    91.56  1.6881 0.120053
Residuals     45 2440.82    54.24
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

and then the code

```
R> summary(aov(weight ~ motgen * litgen, data = foster))
```

to give

```

              Df Sum Sq Mean Sq F value Pr(>F)
motgen         3  771.61   257.20  4.7419 0.005869 **
litgen         3   63.63    21.21  0.3911 0.760004
motgen:litgen  9  824.07    91.56  1.6881 0.120053
Residuals     45 2440.82    54.24
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```



```
R> interaction.plot(weightgain$type, weightgain$source,
+                  weightgain$weightgain)
```

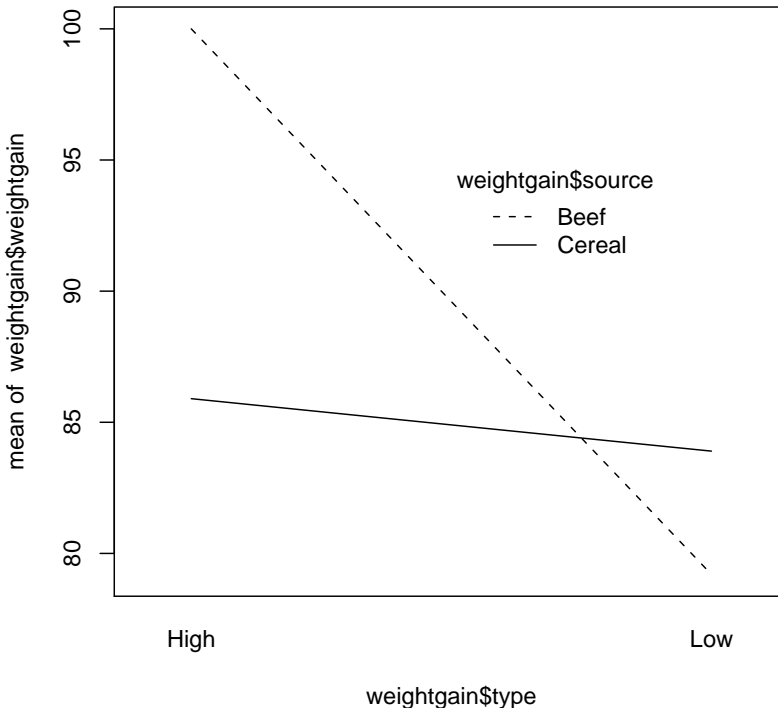


Figure 4.3 Interaction plot of type \times source.

There are (small) differences in the sum of squares for the two main effects and, consequently, in the associated F -tests and p -values. This would not be true if in the previous example in Subsection 4.3.1 we had used the code

```
R> summary(aov(weightgain ~ type * source, data = weightgain))
```

instead of the code which produced Figure 4.2 (readers should confirm that this is the case). We can investigate the effect of genotype B on litter weight in more detail by the use of *multiple comparison procedures* (see [Everitt, 1996](#)). Such procedures allow a comparison of all pairs of levels of a factor whilst maintaining the nominal significance level at its selected value and producing adjusted confidence intervals for mean differences. One such procedure is called *Tukey honest significant differences* suggested by [Tukey \(1953\)](#), see [Hochberg and Tamhane \(1987\)](#) also. Here, we are interested in simultaneous confidence

```
R> plot.design(foster)
```

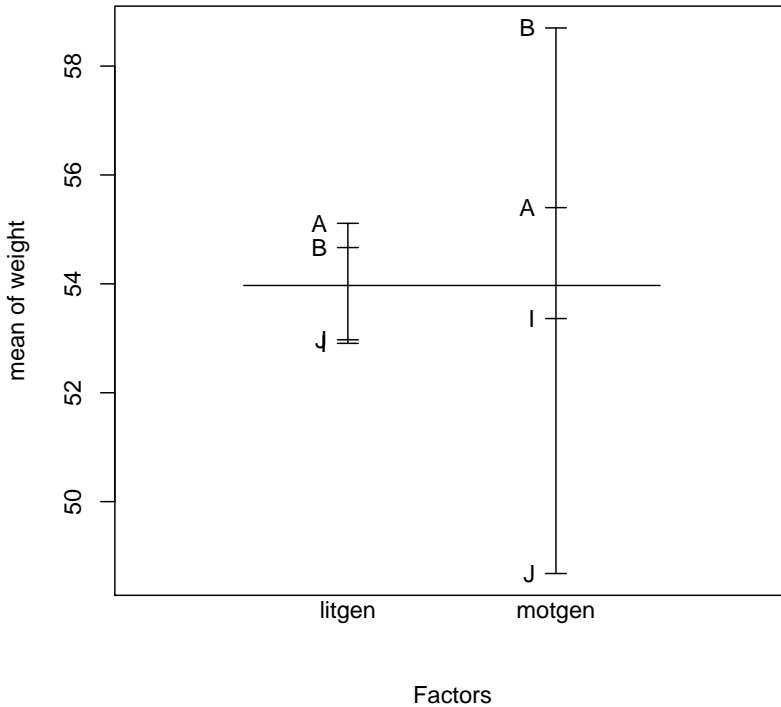


Figure 4.4 Plot of mean litter weight for each level of the two factors for the foster data.

intervals for the weight differences between all four genotypes of the mother. First, an ANOVA model is fitted

```
R> foster_aov <- aov(weight ~ litgen * motgen, data = foster)
```

which serves as the basis of the multiple comparisons, here with allpair differences by

```
R> foster_hsd <- TukeyHSD(foster_aov, "motgen")
```

```
R> foster_hsd
```

```
Tukey multiple comparisons of means  
95% family-wise confidence level
```

```
Fit: aov(formula = weight ~ litgen * motgen, data = foster)
```

```
R> plot(foster_hsd)
```

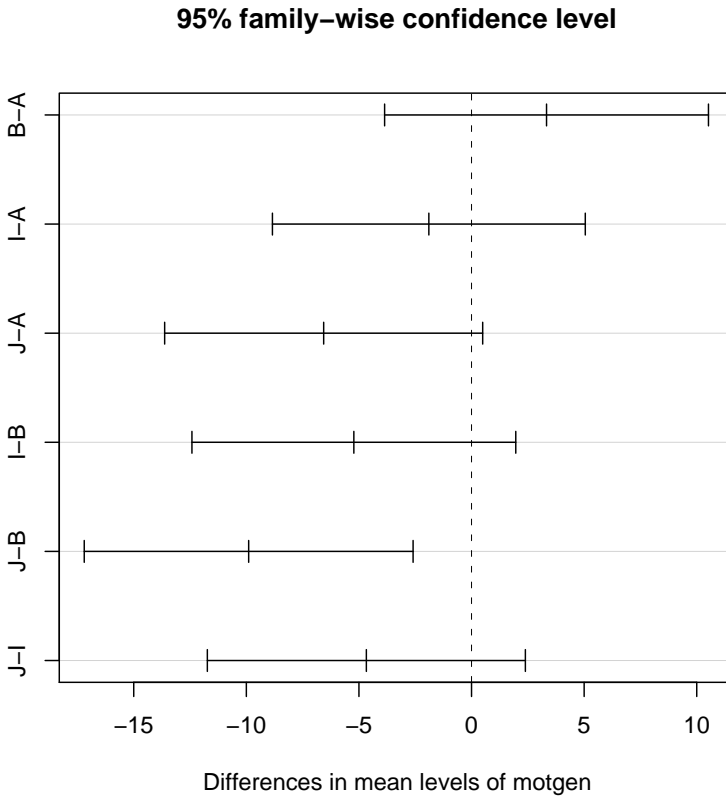


Figure 4.5 Graphical presentation of multiple comparison results for the `foster` feeding data.

```
$motgen
      diff      lwr      upr    p adj
B-A  3.330369 -3.859729 10.5204672 0.6078581
I-A -1.895574 -8.841869  5.0507207 0.8853702
J-A -6.566168 -13.627285  0.4949498 0.0767540
I-B -5.225943 -12.416041  1.9641552 0.2266493
J-B -9.896537 -17.197624 -2.5954489 0.0040509
J-I -4.670593 -11.731711  2.3905240 0.3035490
```

A convenient `plot` method exists for this object and we can get a graphical representation of the multiple confidence intervals as shown in Figure 4.5. It appears that there is only evidence for a difference in the B and J genotypes.

4.3.3 Water Hardness and Mortality

The water hardness and mortality data for 61 large towns in England and Wales (see Table 2.3) was analysed in Chapter 2 and here we will extend the analysis by an assessment of the differences of both hardness and mortality in the North or South. The hypothesis that the two-dimensional mean-vector of water hardness and mortality is the same for cities in the North and the South can be tested by *Hotelling-Lawley* test in a multivariate analysis of variance framework. The R function `manova` can be used to fit such a model and the corresponding `summary` method performs the test specified by the `test` argument

```
R> data("water", package = "HSAUR")
R> summary(manova(cbind(hardness, mortality) ~ location,
+ data = water), test = "Hotelling-Lawley")
              Df Hotelling-Lawley approx F num Df den Df      Pr(>F)
location      1              0.9002  26.1062      2    58 8.217e-09
Residuals    59

location ***
Residuals
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The `cbind` statement in the left hand side of the formula indicates that a *multivariate* response variable is to be modelled. The p -value associated with the *Hotelling-Lawley* statistic is very small and there is strong evidence that the mean vectors of the two variables are not the same in the two regions. Looking at the sample means

```
R> tapply(water$hardness, water$location, mean)
      North      South
30.40000 69.76923

R> tapply(water$mortality, water$location, mean)
      North      South
1633.600 1376.808
```

we see large differences in the two regions both in water hardness and mortality, where low mortality is associated with hard water in the South and high mortality with soft water in the North (see Figure ?? also).

4.3.4 Male Egyptian Skulls

We can begin by looking at a table of mean values for the four measurements within each of the five epochs. The measurements are available in the `data.frame` `skulls` and we can compute the means over all epochs by

```
R> data("skulls", package = "HSAUR")
R> means <- aggregate(skulls[,c("mb", "bh", "bl", "nh")],
```

```
+ list(epoch = skulls$epoch), mean)
R> means
```

| | epoch | mb | bh | bl | nh |
|---|---------|----------|----------|----------|----------|
| 1 | c4000BC | 131.3667 | 133.6000 | 99.16667 | 50.53333 |
| 2 | c3300BC | 132.3667 | 132.7000 | 99.06667 | 50.23333 |
| 3 | c1850BC | 134.4667 | 133.8000 | 96.03333 | 50.56667 |
| 4 | c200BC | 135.5000 | 132.3000 | 94.53333 | 51.96667 |
| 5 | cAD150 | 136.1667 | 130.3333 | 93.50000 | 51.36667 |

It may also be useful to look at these means graphically and this could be done in a variety of ways. Here we construct a scatterplot matrix of the means using the code attached to Figure 4.6. There appear to be quite large differences between the epoch means, at least on some of the four measurements. We can now test for a difference more formally by using MANOVA with the following R code to apply each of the four possible test criteria mentioned earlier;

```
R> skulls_manova <- manova(cbind(mb, bh, bl, nh) ~ epoch,
+ data = skulls)
R> summary(skulls_manova, test = "Pillai")
```

| | Df | Pillai | approx F | num Df | den Df | Pr(>F) |
|-----------|-----|--------|----------|--------|--------|---------------|
| epoch | 4 | 0.3533 | 3.5120 | 16 | 580 | 4.675e-06 *** |
| Residuals | 145 | | | | | |

 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
R> summary(skulls_manova, test = "Wilks")
```

| | Df | Wilks | approx F | num Df | den Df | Pr(>F) |
|-----------|-----|--------|----------|--------|--------|--------------|
| epoch | 4 | 0.6636 | 3.9009 | 16 | 434.45 | 7.01e-07 *** |
| Residuals | 145 | 0.00 | | | | |

 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
R> summary(skulls_manova, test = "Hotelling-Lawley")
```

| | Df | Hotelling-Lawley | approx F | num Df | den Df | Pr(>F) |
|-----------|-----|------------------|----------|--------|--------|--------|
| epoch | 4 | 0.4818 | 4.2310 | 16 | 562 | |
| Residuals | 145 | | | | | |

Pr(>F)
 epoch 8.278e-08 ***
 Residuals

 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
R> summary(skulls_manova, test = "Roy")
```

| | Df | Roy | approx F | num Df | den Df | Pr(>F) |
|-----------|-----|--------|----------|--------|--------|---------------|
| epoch | 4 | 0.4251 | 15.4097 | 4 | 145 | 1.588e-10 *** |
| Residuals | 145 | | | | | |

 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
R> pairs(means[,-1],
+       panel = function(x, y) {
+         text(x, y, abbreviate(levels(skulls$epoch)))
+       })
```

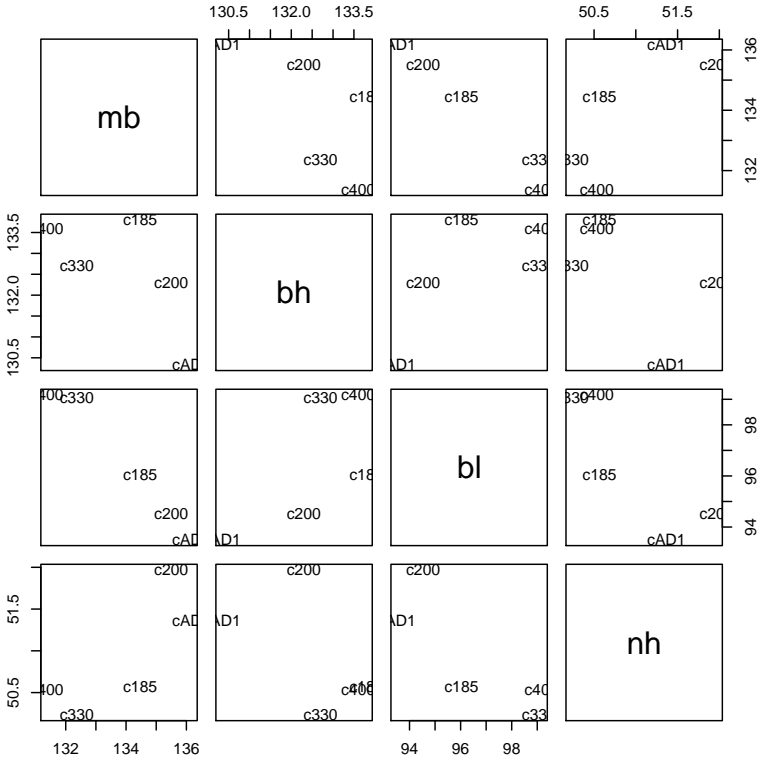


Figure 4.6 Scatterplot matrix of epoch means for Egyptian skulls data.

The p -value associated with each four test criteria is very small and there is strong evidence that the skull measurements differ between the five epochs. We might now move on to investigate which epochs differ and on which variables. We can look at the univariate F -tests for each of the four variables by using the code

```
R> summary.aov(skulls_manova)
```

```
Response mb :
          Df Sum Sq Mean Sq F value    Pr(>F)
epoch      4  502.83  125.71   5.9546 0.0001826 ***
Residuals 145 3061.07   21.11
```

```

---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Response bh :
      Df Sum Sq Mean Sq F value Pr(>F)
epoch    4  229.9    57.5  2.4474 0.04897 *
Residuals 145 3405.3    23.5
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Response bl :
      Df Sum Sq Mean Sq F value Pr(>F)
epoch    4  803.3   200.8  8.3057 4.636e-06 ***
Residuals 145 3506.0    24.2
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Response nh :
      Df Sum Sq Mean Sq F value Pr(>F)
epoch    4   61.20   15.30  1.507 0.2032
Residuals 145 1472.13   10.15

We see that the results for the maximum breadths (mb) and basialveolar length
(bl) are highly significant, with those for the other two variables, in particular
for nasal heights (nh), suggesting little evidence of a difference. To look at the
pairwise multivariate tests (any of the four test criteria are equivalent in the
case of a one-way layout with two levels only) we can use the summary method
and manova function as follows:

R> summary(manova(cbind(mb, bh, bl, nh) ~ epoch, data = skulls,
+                 subset = epoch %in% c("c4000BC", "c3300BC")))
      Df Pillai approx F num Df den Df Pr(>F)
epoch    1 0.02767  0.39135      4    55 0.814
Residuals 58

R> summary(manova(cbind(mb, bh, bl, nh) ~ epoch, data = skulls,
+                 subset = epoch %in% c("c4000BC", "c1850BC")))
      Df Pillai approx F num Df den Df Pr(>F)
epoch    1 0.1876  3.1744      4    55 0.02035 *
Residuals 58
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R> summary(manova(cbind(mb, bh, bl, nh) ~ epoch, data = skulls,
+                 subset = epoch %in% c("c4000BC", "c200BC")))
      Df Pillai approx F num Df den Df Pr(>F)
epoch    1 0.3030  5.9766      4    55 0.0004564 ***
Residuals 58
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

```
R> summary(manova(cbind(mb, bh, bl, nh) ~ epoch, data = skulls,
+                 subset = epoch %in% c("c4000BC", "cAD150")))
```

```
              Df Pillai approx F num Df den Df    Pr(>F)
epoch          1 0.3618    7.7956     4    55 4.736e-05 ***
Residuals 58
```

```
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

To keep the overall significance level for the set of all pairwise multivariate tests under some control (and still maintain a reasonable power), [Stevens \(2001\)](#) recommends setting the nominal level $\alpha = 0.15$ and carrying out each test at the α/m level where m is the number of tests performed. The results of the four pairwise tests suggest that as the epochs become further separated in time the four skull measurements become increasingly distinct.

Bibliography

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- Hochberg, Y. and Tamhane, A. C. (1987), *Multiple Comparison Procedures*, New York, USA: John Wiley & Sons.
- Stevens, J. (2001), *Applied Multivariate Statistics for the Social Sciences*, Mahwah, New Jersey, USA: Lawrence Erlbaum, 4th edition.
- Tukey, J. W. (1953), "The problem of multiple comparisons (unpublished manuscript)," in *The Collected Works of John W. Tukey VIII. Multiple Comparisons: 1948-1983*, New York, USA: Chapman & Hall.

Multiple Linear Regression: Cloud Seeding

5.1 Introduction

5.2 Multiple Linear Regression

5.3 Analysis Using R

Both the boxplots (Figure 5.1) and the scatterplots (Figure 5.2) show some evidence of outliers. The row names of the extreme observations in the `clouds` *data.frame* can be identified via

```
R> rownames(clouds)[clouds$rainfall %in% c(bxpseeding$out,
+                                       bxpecho$out)]
[1] "1" "15"
```

where `bxpseeding` and `bxpecho` are variables created by `boxplot` in Figure 5.1. For the time being we shall not remove these observations but bear in mind during the modelling process that they may cause problems.

5.3.1 Fitting a Linear Model

In this example it is sensible to assume that the effect that some of the other explanatory variables is modified by seeding and therefore consider a model that allows interaction terms for `seeding` with each of the covariates except `time`. This model can be described by the *formula*

```
R> clouds_formula <- rainfall ~ seeding * (sne + cloudcover +
+   prewetness + echomotion) + time
```

and the design matrix \mathbf{X}^* can be computed via

```
R> Xstar <- model.matrix(clouds_formula, data = clouds)
```

By default, treatment contrasts have been applied to the dummy codings of the factors `seeding` and `echomotion` as can be seen from the inspection of the `contrasts` attribute of the model matrix

```
R> attr(Xstar, "contrasts")
```

```
$seeding
[1] "contr.treatment"
```

```
$echomotion
[1] "contr.treatment"
```

```
R> data("clouds", package = "HSAUR")
R> layout(matrix(1:2, nrow = 2))
R> bxpseeding <- boxplot(rainfall ~ seeding, data = clouds,
+   ylab = "Rainfall", xlab = "Seeding")
R> bxpecho <- boxplot(rainfall ~ echomotion, data = clouds,
+   ylab = "Rainfall", xlab = "Echo Motion")
```

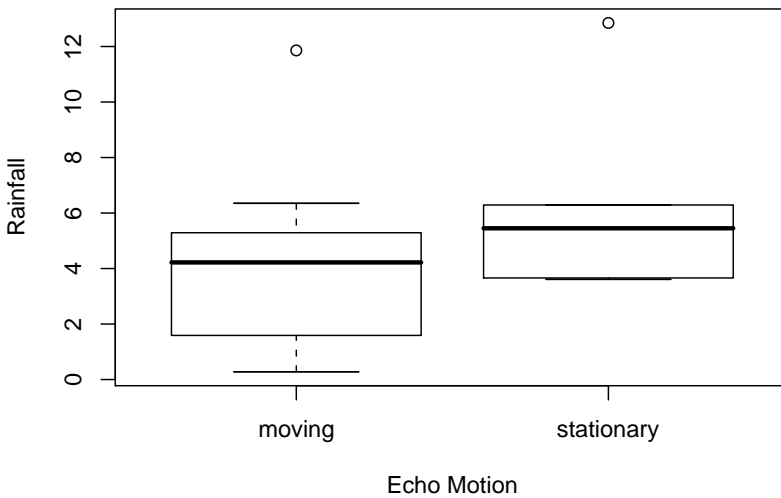
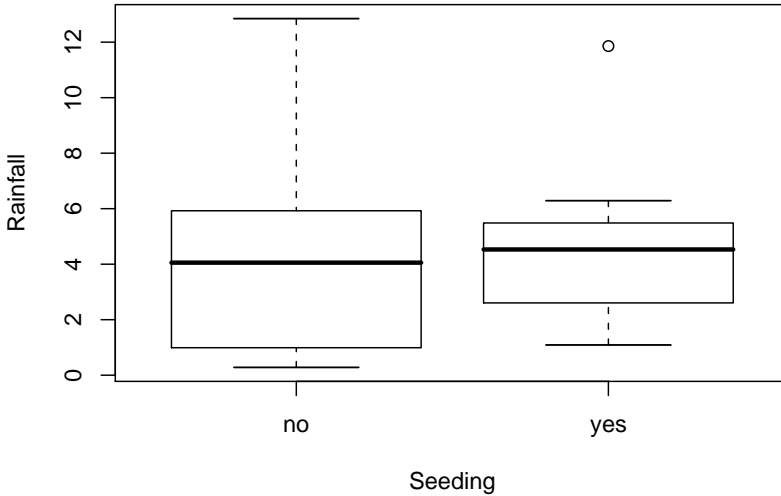


Figure 5.1 Boxplots of rainfall.

```

R> layout(matrix(1:4, nrow = 2))
R> plot(rainfall ~ time, data = clouds)
R> plot(rainfall ~ cloudcover, data = clouds)
R> plot(rainfall ~ sne, data = clouds, xlab="S-Ne criterion")
R> plot(rainfall ~ prewetness, data = clouds)

```

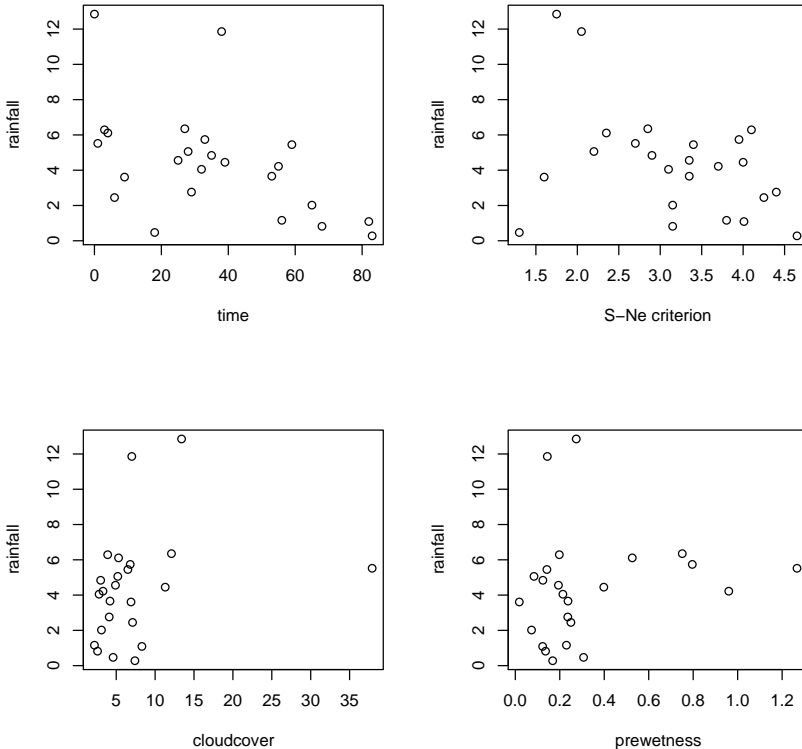


Figure 5.2 Scatterplots of `rainfall` against the continuous covariates.

The default contrasts can be changed via the `contrasts.arg` argument to `model.matrix` or the `contrasts` argument to the fitting function, for example `lm` or `aov` as shown in

Chapter 4.

However, such internals are hidden and performed by high-level model fitting functions such as `lm` which will be used to fit the linear model defined by the *formula* `clouds_formula`:

```

R> clouds_lm <- lm(clouds_formula, data = clouds)
R> class(clouds_lm)

```

```
[1] "lm"
```

The results of the model fitting is an object of class *lm* for which a `summary` method showing the conventional regression analysis output is available. The output in Figure 5.3 shows the estimates $\hat{\beta}^*$ with corresponding standard errors and *t*-statistics as well as the *F*-statistic with associated *p*-value.

Many methods are available for extracting components of the fitted model. The estimates $\hat{\beta}^*$ can be assessed via

```
R> betastar <- coef(clouds_lm)
R> betastar

      (Intercept)
      -0.34624093
      seedingyes
      15.68293481
           sne
           0.41981393
      cloudcover
           0.38786207
      prewetness
           4.10834188
echomotionstationary
           3.15281358
           time
          -0.04497427
      seedingyes:sne
          -3.19719006
      seedingyes:cloudcover
          -0.48625492
      seedingyes:prewetness
          -2.55706696
      seedingyes:echomotionstationary
          -0.56221845
```

and the corresponding covariance matrix $\text{Cov}(\hat{\beta}^*)$ is available from the `vcov` method

```
R> Vbetastar <- vcov(clouds_lm)
```

where the square roots of the diagonal elements are the standard errors as shown in Figure 5.3

```
R> sqrt(diag(Vbetastar))

      (Intercept)
      2.78773403
      seedingyes
      4.44626606
           sne
           0.84452994
      cloudcover
           0.21785501
```

```
R> summary(clouds_lm)
```

```
Call:
```

```
lm(formula = clouds_formula, data = clouds)
```

```
Residuals:
```

```
      Min       1Q   Median       3Q      Max
-2.5259 -1.1486 -0.2704  1.0401  4.3913
```

```
Coefficients:
```

| | Estimate | Std. Error | t value |
|---------------------------------|----------|------------|---------|
| (Intercept) | -0.34624 | 2.78773 | -0.124 |
| seedingyes | 15.68293 | 4.44627 | 3.527 |
| sne | 0.41981 | 0.84453 | 0.497 |
| cloudcover | 0.38786 | 0.21786 | 1.780 |
| prewetness | 4.10834 | 3.60101 | 1.141 |
| echomotionstationary | 3.15281 | 1.93253 | 1.631 |
| time | -0.04497 | 0.02505 | -1.795 |
| seedingyes:sne | -3.19719 | 1.26707 | -2.523 |
| seedingyes:cloudcover | -0.48625 | 0.24106 | -2.017 |
| seedingyes:prewetness | -2.55707 | 4.48090 | -0.571 |
| seedingyes:echomotionstationary | -0.56222 | 2.64430 | -0.213 |

```
Pr(>|t|)
```

| | |
|---------------------------------|------------|
| (Intercept) | 0.90306 |
| seedingyes | 0.00372 ** |
| sne | 0.62742 |
| cloudcover | 0.09839 . |
| prewetness | 0.27450 |
| echomotionstationary | 0.12677 |
| time | 0.09590 . |
| seedingyes:sne | 0.02545 * |
| seedingyes:cloudcover | 0.06482 . |
| seedingyes:prewetness | 0.57796 |
| seedingyes:echomotionstationary | 0.83492 |

```
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Residual standard error: 2.205 on 13 degrees of freedom
```

```
Multiple R-Squared: 0.7158, Adjusted R-squared: 0.4972
```

```
F-statistic: 3.274 on 10 and 13 DF, p-value: 0.02431
```

Figure 5.3 R output of the linear model fit for the clouds data.

```
prewetness
3.60100694
echomotionstationary
1.93252592
time
```

```
0.02505286
seedingyes:sne
1.26707204
seedingyes:cloudcover
0.24106012
seedingyes:prewetness
4.48089584
seedingyes:echomotionstationary
2.64429975
```

5.3.2 Regression Diagnostics

In order to investigate the quality of the model fit, we need access to the residuals and the fitted values. The residuals can be found by the `residuals` method and the fitted values of the response from the `fitted` (or `predict`) method

```
R> clouds_resid <- residuals(clouds_lm)
R> clouds_fitted <- fitted(clouds_lm)
```

Now the residuals and the fitted values can be used to construct diagnostic plots; for example the residual plot in Figure 5.5 where each observation is labelled by its number. Observations 1 and 15 give rather large residual values and the data should perhaps be reanalysed after these two observations are removed. The normal probability plot of the residuals shown in Figure 5.6 shows a reasonable agreement between theoretical and sample quantiles, however, observations 1 and 15 are extreme again. An index plot of the Cook's distances for each observation (and many other plots including those constructed above from using the basic functions) can be found from applying the `plot` method to the object that results from the application of the `lm` function. Figure 5.7 suggests that observations 2 and 18 have undue influence on the estimated regression coefficients, but the two outliers identified previously do not. Again it may be useful to look at the results after these two observations have been removed (see Exercise 5.2).

```

R> psymb <- as.numeric(clouds$seeding)
R> plot(rainfall ~ sne, data = clouds, pch = psymb,
+       xlab = "S-Ne criterion")
R> abline(lm(rainfall ~ sne, data = clouds,
+           subset = seeding == "no"))
R> abline(lm(rainfall ~ sne, data = clouds,
+           subset = seeding == "yes"), lty = 2)
R> legend("topright", legend = c("No seeding", "Seeding"),
+       pch = 1:2, lty = 1:2, bty = "n")

```

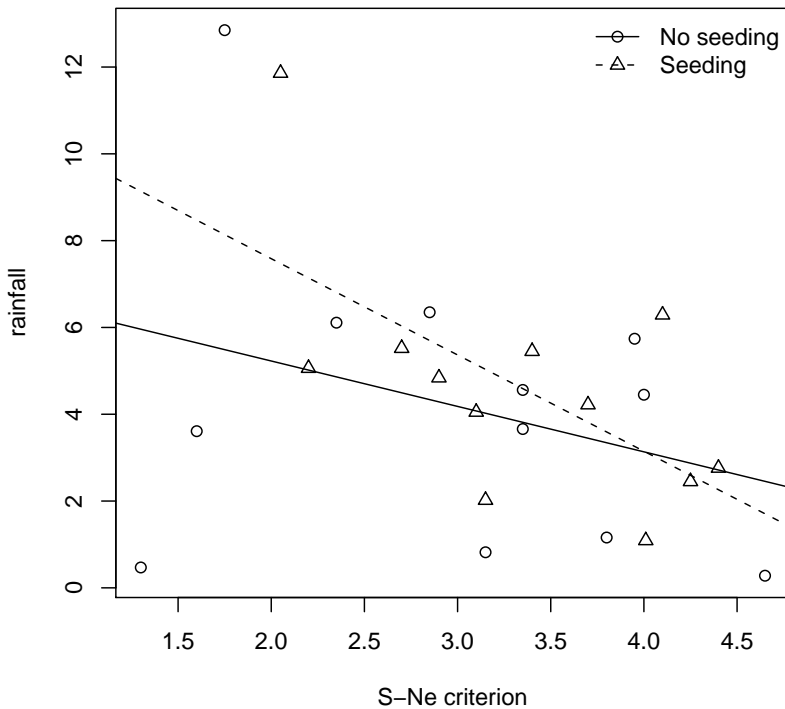


Figure 5.4 Regression relationship between S-Ne criterion and rainfall with and without seeding.


```
R> plot(clouds_fitted, clouds_resid, xlab = "Fitted values",  
+       ylab = "Residuals", type = "n",  
+       ylim = max(abs(clouds_resid)) * c(-1, 1))  
R> abline(h = 0, lty = 2)  
R> text(clouds_fitted, clouds_resid, labels = rownames(clouds))
```

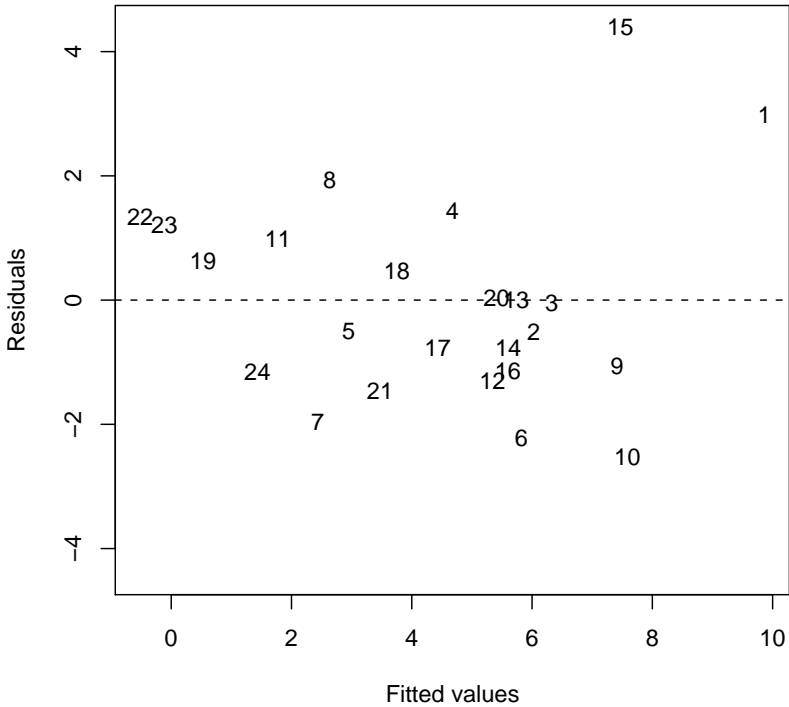


Figure 5.5 Plot of residuals against fitted values for clouds seeding data.

```
R> qqnorm(clouds_resid, ylab = "Residuals")  
R> qqline(clouds_resid)
```

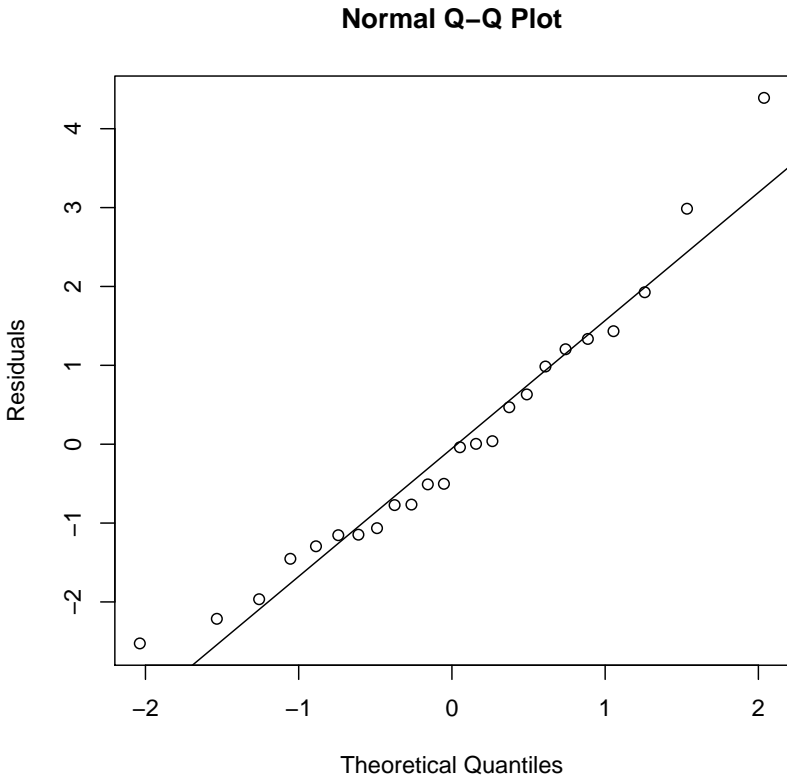


Figure 5.6 Normal probability plot of residuals from cloud seeding model `clouds_lm`.

```
R> plot(clouds_lm)
```

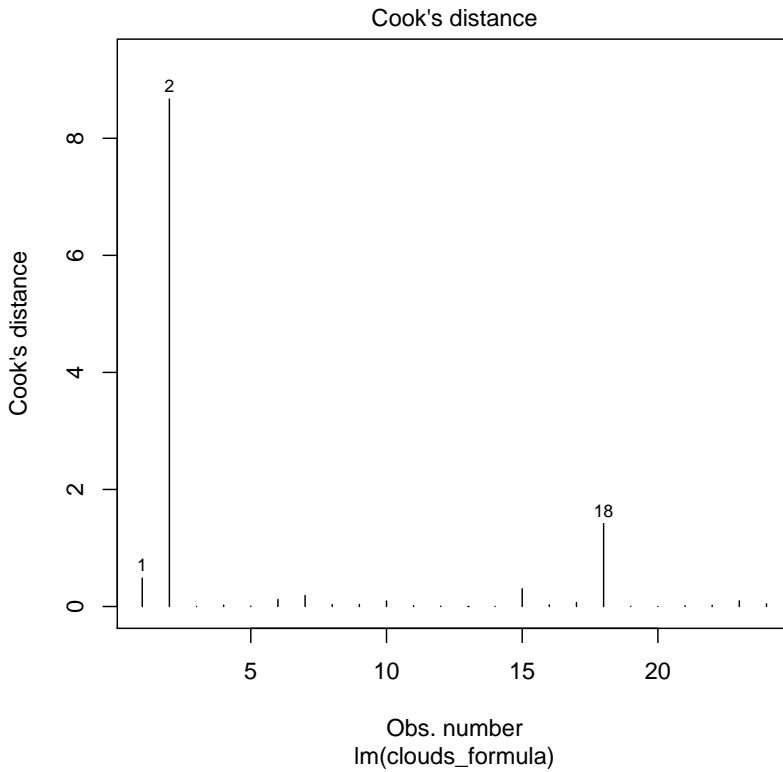


Figure 5.7 Index plot of Cook's distances for cloud seeding data.

Logistic Regression and Generalised Linear Models: Blood Screening, Women's Role in Society, and Colonic Polyps

6.1 Introduction

6.2 Logistic Regression and Generalised Linear Models

6.3 Analysis Using R

6.3.1 ESR and Plasma Proteins

We can now fit a logistic regression model to the data using the `glm` function. We start with a model that includes only a single explanatory variable, `fibrinogen`. The code to fit the model is

```
R> plasma_glm_1 <- glm(ESR ~ fibrinogen, data = plasma,
+                       family = binomial())
```

The formula implicitly defines a parameter for the global mean (the intercept term) as discussed in Chapters ?? and ?. The distribution of the response is defined by the `family` argument, a binomial distribution in our case. (The default link function when the binomial family is requested is the logistic function.)

From the results in Figure 6.2 we see that the regression coefficient for `fibrinogen` is significant at the 5% level. An increase of one unit in this variable increases the log-odds in favour of an ESR value greater than 20 by an estimated 1.83 with 95% confidence interval

```
R> confint(plasma_glm_1, parm = "fibrinogen")
      2.5 %      97.5 %
0.3389465 3.9988602
```

These values are more helpful if converted to the corresponding values for the odds themselves by exponentiating the estimate

```
R> exp(coef(plasma_glm_1)["fibrinogen"])
fibrinogen
6.215715
```

and the confidence interval

```
R> exp(confint(plasma_glm_1, parm = "fibrinogen"))
```

4 LOGISTIC REGRESSION AND GENERALISED LINEAR MODELS

```
R> data("plasma", package = "HSAUR")
R> layout(matrix(1:2, ncol = 2))
R> cdplot(ESR ~ fibrinogen, data = plasma)
R> cdplot(ESR ~ globulin, data = plasma)
```

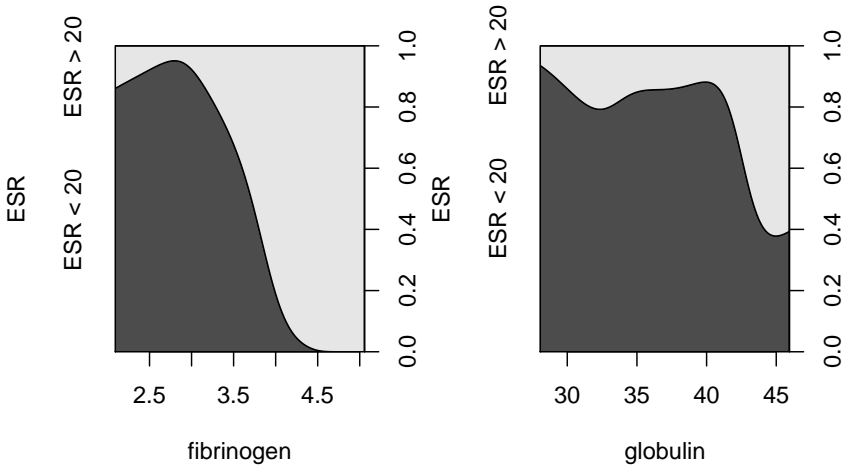


Figure 6.1 Conditional density plots of the erythrocyte sedimentation rate (ESR) given fibrinogen and globulin.

```
2.5 %    97.5 %
1.403468 54.535954
```

The confidence interval is very wide because there are few observations overall and very few where the ESR value is greater than 20. Nevertheless it seems likely that increased values of fibrinogen lead to a greater probability of an ESR value greater than 20. We can now fit a logistic regression model that includes both explanatory variables using the code

```
R> plasma_glm_2 <- glm(ESR ~ fibrinogen + globulin, data = plasma,
+                       family = binomial())
```

and the output of the `summary` method is shown in Figure 6.3. The coefficient for gamma globulin is not significantly different from zero. Subtracting the residual deviance of the second model from the corresponding value for the first model we get a value of 1.87. Tested using a χ^2 -distribution with a single degree of freedom this is not significant at the 5% level and so we conclude that gamma globulin is not associated with ESR level. In R, the task of comparing the two nested models can be performed using the `anova` function

```
R> anova(plasma_glm_1, plasma_glm_2, test = "Chisq")
```

```
R> summary(plasma_glm_1)

Call:
glm(formula = ESR ~ fibrinogen, family = binomial(), data = plasma)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.9298 -0.5399 -0.4382 -0.3356  2.4794

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  -6.8451     2.7703  -2.471  0.0135 *
fibrinogen    1.8271     0.9009   2.028  0.0425 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 30.885  on 31  degrees of freedom
Residual deviance: 24.840  on 30  degrees of freedom
AIC: 28.840

Number of Fisher Scoring iterations: 5
```

Figure 6.2 R output of the `summary` method for the logistic regression model fitted to the `plasma` data.

Analysis of Deviance Table

```
Model 1: ESR ~ fibrinogen
Model 2: ESR ~ fibrinogen + globulin
  Resid. Df Resid. Dev Df Deviance P(>|Chi|)
1      30      24.8404
2      29      22.9711  1   1.8692   0.1716
```

Nevertheless we shall use the predicted values from the second model and plot them against the values of *both* explanatory variables using a *bubble plot* to illustrate the use of the `symbols` function. The estimated conditional probability of a ESR value larger 20 for all observations can be computed, following formula (??), by

```
R> prob <- predict(plasma_glm_2, type = "response")
```

and now we can assign a larger circle to observations with larger probability as shown in Figure 6.4. The plot clearly shows the increasing probability of an ESR value above 20 (larger circles) as the values of fibrinogen, and to a lesser extent, gamma globulin, increase.

```
R> summary(plasma_glm_2)

Call:
glm(formula = ESR ~ fibrinogen + globulin, family = binomial(),
     data = plasma)

Deviance Residuals:
     Min       1Q   Median       3Q      Max
-0.9683  -0.6122  -0.3458  -0.2116   2.2636

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -12.7921     5.7963  -2.207  0.0273 *
fibrinogen    1.9104     0.9710   1.967  0.0491 *
globulin      0.1558     0.1195   1.303  0.1925
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 30.885  on 31  degrees of freedom
Residual deviance: 22.971  on 29  degrees of freedom
AIC: 28.971

Number of Fisher Scoring iterations: 5
```

Figure 6.3 R output of the `summary` method for the logistic regression model fitted to the `plasma` data.

6.3.2 Women's Role in Society

Originally the data in Table ?? would have been in a completely equivalent form to the data in Table ?? data, but here the individual observations have been grouped into counts of numbers of agreements and disagreements for the two explanatory variables, `sex` and `education`. To fit a logistic regression model to such grouped data using the `glm` function we need to specify the number of agreements and disagreements as a two-column matrix on the left hand side of the model formula. We first fit a model that includes the two explanatory variables using the code

```
R> data("womensrole", package = "HSAUR")
R> fm1 <- cbind(agree, disagree) ~ sex + education
R> womensrole_glm_1 <- glm(fm1, data = womensrole,
+                          family = binomial())
```

From the `summary` output in Figure 6.5 it appears that education has a highly significant part to play in predicting whether a respondent will agree with the statement read to them, but the respondent's sex is apparently unimportant. As years of education increase the probability of agreeing with the statement

```
R> plot(globulin ~ fibrinogen, data = plasma, xlim = c(2, 6),
+       ylim = c(25, 55), pch = ".")
R> symbols(plasma$fibrinogen, plasma$globulin, circles = prob,
+         add = TRUE)
```

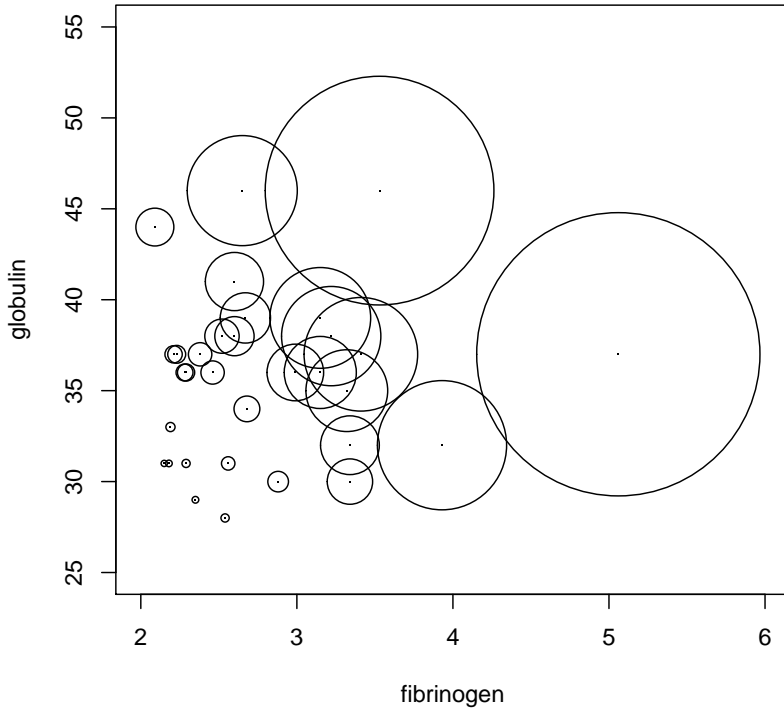


Figure 6.4 Bubble plot of fitted values for a logistic regression model fitted to the ESR data.

declines. We now are going to construct a plot comparing the observed proportions of agreeing with those fitted by our fitted model. Because we will reuse this plot for another fitted object later on, we define a function which plots years of education against some fitted probabilities, e.g.,

```
R> role.fitted1 <- predict(womensrole_glm_1, type = "response")
```

and labels each observation with the person's sex:

```
R> myplot <- function(role.fitted) {
+   f <- womensrole$sex == "Female"
+   plot(womensrole$education, role.fitted, type = "n",
```

```
R> summary(womensrole_glm_1)

Call:
glm(formula = fm1, family = binomial(), data = womensrole)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.72544  -0.86302  -0.06525   0.84340   3.13315

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  2.50937    0.18389  13.646 <2e-16 ***
sexFemale   -0.01145    0.08415  -0.136  0.892
education   -0.27062    0.01541 -17.560 <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 451.722  on 40  degrees of freedom
Residual deviance:  64.007  on 38  degrees of freedom
AIC: 208.07

Number of Fisher Scoring iterations: 4
```

Figure 6.5 R output of the `summary` method for the logistic regression model fitted to the `womensrole` data.

```
+       ylab = "Probability of agreeing",
+       xlab = "Education", ylim = c(0,1))
+     lines(womensrole$education[!f], role.fitted[!f], lty = 1)
+     lines(womensrole$education[f], role.fitted[f], lty = 2)
+     lgtxt <- c("Fitted (Males)", "Fitted (Females)")
+     legend("topright", lgtxt, lty = 1:2, bty = "n")
+     y <- womensrole$agree / (womensrole$agree +
+                             womensrole$disagree)
+     text(womensrole$education, y, ifelse(f, "\\VE", "\\MA"),
+          family = "HersheySerif", cex = 1.25)
+ }
```

The two curves for males and females in Figure 6.6 are almost the same reflecting the non-significant value of the regression coefficient for sex in `womensrole_glm_1`. But the observed values plotted on Figure 6.6 suggest that there might be an interaction of education and sex, a possibility that can be investigated by applying a further logistic regression model using

```
R> myplot(role.fitted1)
```

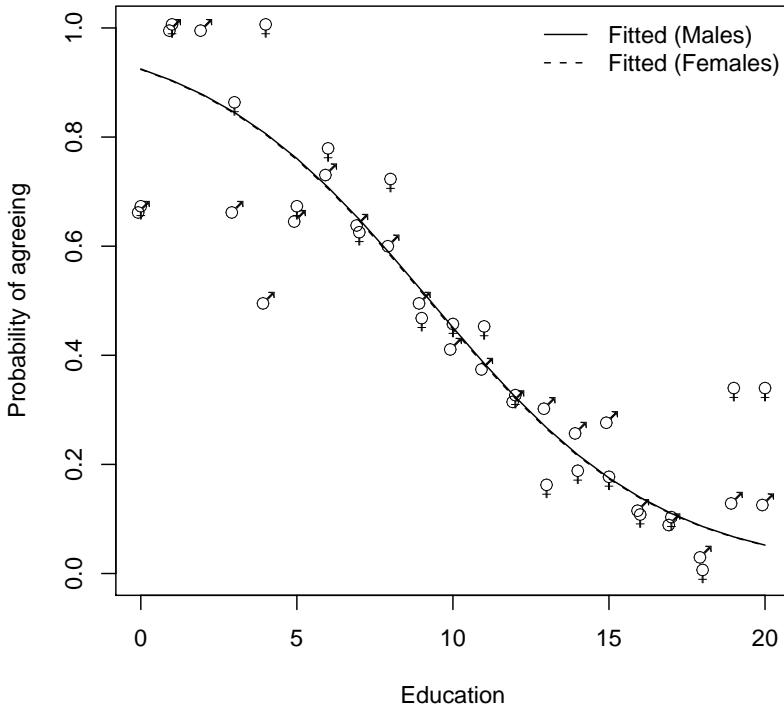


Figure 6.6 Fitted (from `womensrole_glm_1`) and observed probabilities of agreeing for the `womensrole` data.

```
R> fm2 <- cbind(agree,disagree) ~ sex * education
R> womensrole_glm_2 <- glm(fm2, data = womensrole,
+                           family = binomial())
```

The `sex` and `education` interaction term is seen to be highly significant, as can be seen from the `summary` output in Figure 6.7. We can obtain a plot of deviance residuals plotted against fitted values using the following code above Figure 6.9. The residuals fall into a horizontal band between -2 and 2 . This pattern does not suggest a poor fit for any particular observation or subset of observations.

```
R> summary(womensrole_glm_2)

Call:
glm(formula = fm2, family = binomial(), data = womensrole)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.39097  -0.88062   0.01532   0.72783   2.45262

Coefficients:
                Estimate Std. Error z value Pr(>|z|)
(Intercept)      2.09820    0.23550   8.910 < 2e-16 ***
sexFemale        0.90474    0.36007   2.513  0.01198 *
education       -0.23403    0.02019 -11.592 < 2e-16 ***
sexFemale:education -0.08138    0.03109  -2.617  0.00886 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 451.722  on 40  degrees of freedom
Residual deviance:  57.103  on 37  degrees of freedom
AIC: 203.16

Number of Fisher Scoring iterations: 4
```

Figure 6.7 R output of the `summary` method for the logistic regression model fitted to the `womensrole` data.

6.3.3 Colonic Polyps

The data on colonic polyps in Table ?? involves *count* data. We could try to model this using multiple regression but there are two problems. The first is that a response that is a count can only take positive values, and secondly such a variable is unlikely to have a normal distribution. Instead we will apply a GLM with a log link function, ensuring that fitted values are positive, and a Poisson error distribution, i.e.,

$$P(y) = \frac{e^{-\lambda} \lambda^y}{y!}.$$

This type of GLM is often known as *Poisson regression*. We can apply the model using

```
R> data("polyps", package = "HSAUR")
R> polyps_glm_1 <- glm(number ~ treat + age, data = polyps,
+                       family = poisson())
```

(The default link function when the Poisson family is requested is the log function.) We can deal with overdispersion by using a procedure known as

```
R> role.fitted2 <- predict(womensrole_glm_2, type = "response")
R> myplot(role.fitted2)
```

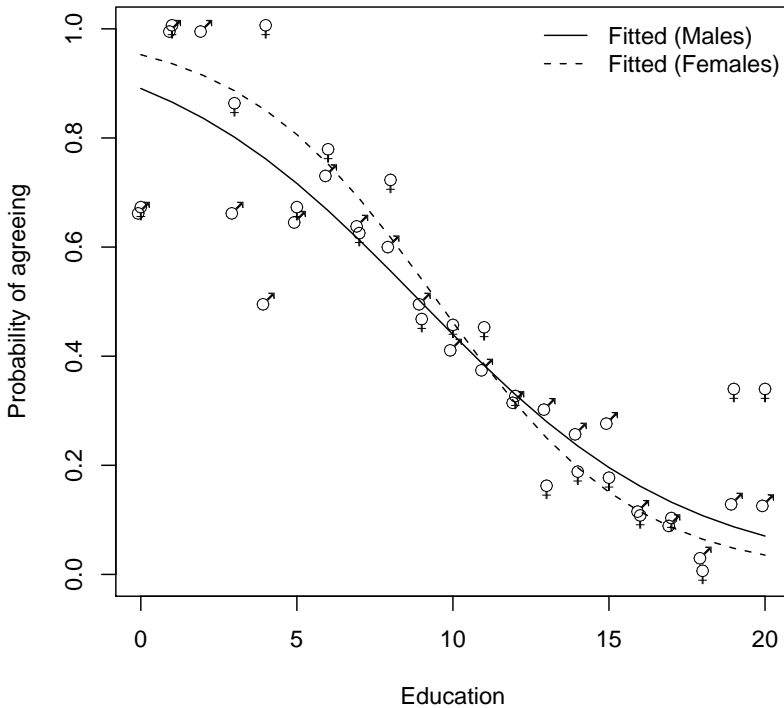


Figure 6.8 Fitted (from `womensrole_glm_2`) and observed probabilities of agreeing for the `womensrole` data.

quasi-likelihood, which allows the estimation of model parameters without fully knowing the error distribution of the response variable. [McCullagh and Nelder \(1989\)](#) give full details of the quasi-likelihood approach. In many respects it simply allows for the estimation of ϕ from the data rather than defining it to be unity for the binomial and Poisson distributions. We can apply quasi-likelihood estimation to the colonic polyps data using the following R code

```
R> polyps_glm_2 <- glm(number ~ treat + age, data = polyps,
+                      family = quasipoisson())
R> summary(polyps_glm_2)
```

Call:

```
glm(formula = number ~ treat + age, family = quasipoisson(),
```

12 LOGISTIC REGRESSION AND GENERALISED LINEAR MODELS

```
R> res <- residuals(womensrole_glm_2, type = "deviance")
R> plot(predict(womensrole_glm_2), res,
+       xlab="Fitted values", ylab = "Residuals",
+       ylim = max(abs(res)) * c(-1,1))
R> abline(h = 0, lty = 2)
```

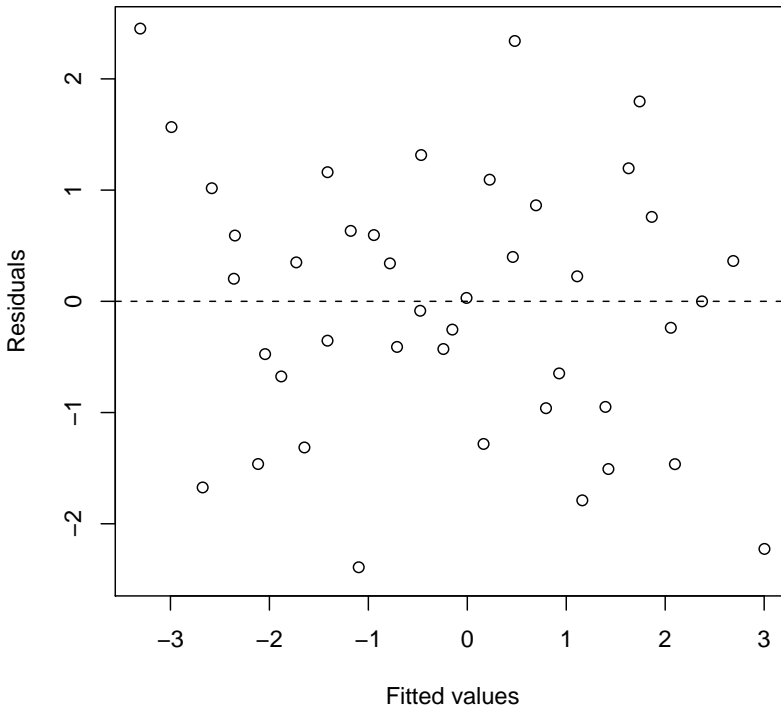


Figure 6.9 Plot of deviance residuals from logistic regression model fitted to the `womensrole` data.

```
data = polyps)
```

```
Deviance Residuals:
```

| | Min | 1Q | Median | 3Q | Max |
|--|---------|---------|---------|--------|--------|
| | -4.2212 | -3.0536 | -0.1802 | 1.4459 | 5.8301 |

```
Coefficients:
```

| | Estimate | Std. Error | t value | Pr(> t) |
|-------------|----------|------------|---------|--------------|
| (Intercept) | 4.52902 | 0.48106 | 9.415 | 3.72e-08 *** |

```
R> summary(polyps_glm_1)
```

```
Call:
```

```
glm(formula = number ~ treat + age, family = poisson(), data = polyps)
```

```
Deviance Residuals:
```

| Min | 1Q | Median | 3Q | Max |
|---------|---------|---------|--------|--------|
| -4.2212 | -3.0536 | -0.1802 | 1.4459 | 5.8301 |

```
Coefficients:
```

| | Estimate | Std. Error | z value | Pr(> z) |
|-------------|-----------|------------|---------|--------------|
| (Intercept) | 4.529024 | 0.146872 | 30.84 | < 2e-16 *** |
| treatdrug | -1.359083 | 0.117643 | -11.55 | < 2e-16 *** |
| age | -0.038830 | 0.005955 | -6.52 | 7.02e-11 *** |

```
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
(Dispersion parameter for poisson family taken to be 1)
```

```
Null deviance: 378.66 on 19 degrees of freedom
Residual deviance: 179.54 on 17 degrees of freedom
AIC: 273.88
```

```
Number of Fisher Scoring iterations: 5
```

Figure 6.10 R output of the `summary` method for the Poisson regression model fitted to the `polyps` data.

```
treatdrug  -1.35908    0.38533   -3.527  0.00259 **
age        -0.03883    0.01951   -1.991  0.06284 .
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
(Dispersion parameter for quasipoisson family taken to be 10.72805)
```

```
Null deviance: 378.66 on 19 degrees of freedom
Residual deviance: 179.54 on 17 degrees of freedom
AIC: NA
```

```
Number of Fisher Scoring iterations: 5
```

The regression coefficients for both explanatory variables remain significant but their estimated standard errors are now much greater than the values given in Figure 6.10. A possible reason for overdispersion in these data is that polyps do not occur independently of one another, but instead may ‘cluster’ together.

Bibliography

McCullagh, P. and Nelder, J. A. (1989), *Generalized Linear Models*, London, UK: Chapman & Hall/CRC.

Density Estimation: Erupting Geysers and Star Clusters

7.1 Introduction

7.2 Density Estimation

The three kernel functions are implemented in R as shown in lines 1–3 of Figure 7.1. For some grid x , the kernel functions are plotted using the R statements in lines 5–11 (Figure 7.1). The kernel estimator \hat{f} is a sum of ‘bumps’ placed at the observations. The kernel function determines the shape of the bumps while the window width h determines their width. Figure 7.2 (redrawn from a similar plot in Silverman, 1986) shows the individual bumps $n^{-1}h^{-1}K((x - x_i)/h)$, as well as the estimate \hat{f} obtained by adding them up for an artificial set of data points

```
R> x <- c(0, 1, 1.1, 1.5, 1.9, 2.8, 2.9, 3.5)
R> n <- length(x)
```

For a grid

```
R> xgrid <- seq(from = min(x) - 1, to = max(x) + 1, by = 0.01)
```

on the real line, we can compute the contribution of each measurement in x , with $h = 0.4$, by the Gaussian kernel (defined in Figure 7.1, line 3) as follows;

```
R> h <- 0.4
R> bumps <- sapply(x, function(a) gauss((xgrid - a)/h)/(n * h))
```

A plot of the individual bumps and their sum, the kernel density estimate \hat{f} , is shown in Figure 7.2.

7.3 Analysis Using R

7.3.1 A Parametric Density Estimate for the Old Faithful Data

```
R> logL <- function(param, x) {
+   d1 <- dnorm(x, mean = param[2], sd = param[3])
+   d2 <- dnorm(x, mean = param[4], sd = param[5])
+   -sum(log(param[1] * d1 + (1 - param[1]) * d2))
+ }
R> startparam <- c(p = 0.5, mu1 = 50, sd1 = 3, mu2 = 80, sd2 = 3)
R> opp <- optim(startparam, logL, x = faithful$waiting,
```



```
1 R> rec <- function(x) (abs(x) < 1) * 0.5
2 R> tri <- function(x) (abs(x) < 1) * (1 - abs(x))
3 R> gauss <- function(x) 1/sqrt(2*pi) * exp(-(x^2)/2)
4 R> x <- seq(from = -3, to = 3, by = 0.001)
5 R> plot(x, rec(x), type = "l", ylim = c(0,1), lty = 1,
6 +       ylab = expression(K(x)))
7 R> lines(x, tri(x), lty = 2)
8 R> lines(x, gauss(x), lty = 3)
9 R> legend(-3, 0.8, legend = c("Rectangular", "Triangular",
10 + "Gaussian"), lty = 1:3, title = "kernel functions",
11 +       bty = "n")
```

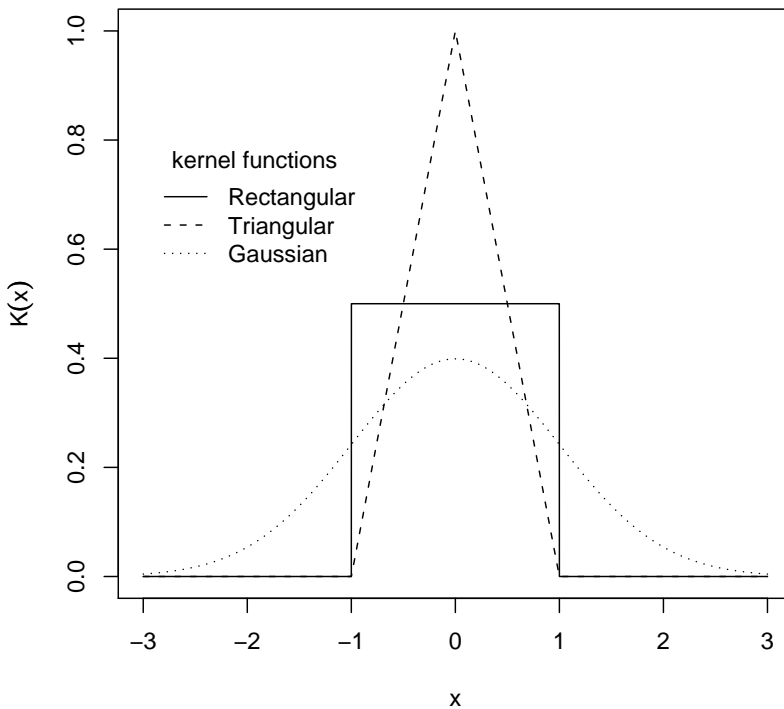


Figure 7.1 Three commonly used kernel functions.

```

1 R> plot(xgrid, rowSums(bumps), ylab = expression(hat(f)(x)),
2 +       type = "l", xlab = "x", lwd = 2)
3 R> rug(x, lwd = 2)
4 R> out <- apply(bumps, 2, function(b) lines(xgrid, b))

```

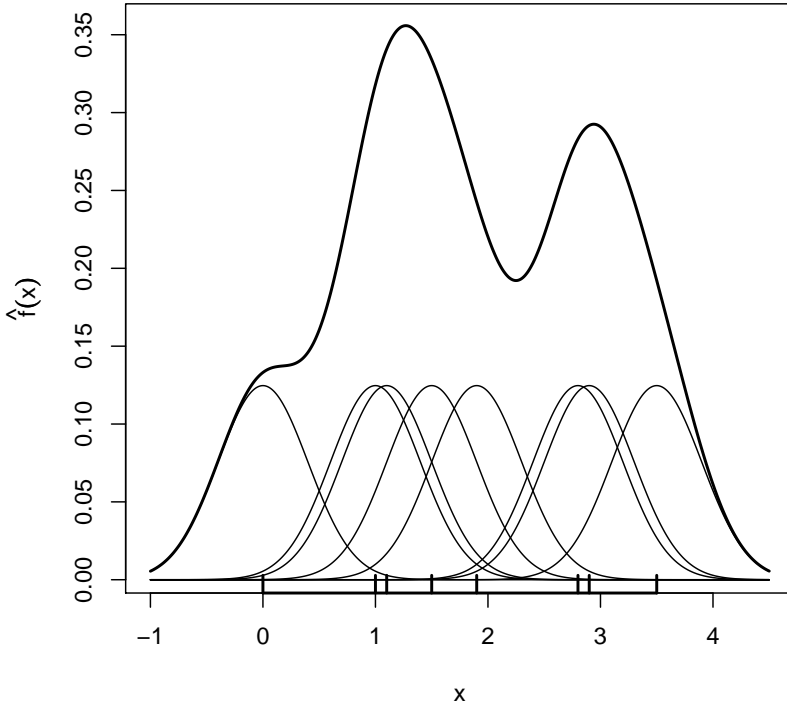


Figure 7.2 Kernel estimate showing the contributions of Gaussian kernels evaluated for the individual observations with bandwidth $h = 0.4$.

```

+           method = "L-BFGS-B",
+           lower = c(0.01, rep(1, 4)),
+           upper = c(0.99, rep(200, 4)))
R> opp
$par
      p      mu1      sd1      mu2      sd2
0.360891 54.612122 5.872379 80.093415 5.867289

$value
[1] 1034.002

```

```
R> epa <- function(x, y)
+   ((x^2 + y^2) < 1) * 2/pi * (1 - x^2 - y^2)
R> x <- seq(from = -1.1, to = 1.1, by = 0.05)
R> epavals <- sapply(x, function(a) epa(a, x))
R> persp(x = x, y = x, z = epavals, xlab = "x", ylab = "y",
+   zlab = expression(K(x, y)), theta = -35, axes = TRUE,
+   box = TRUE)
```

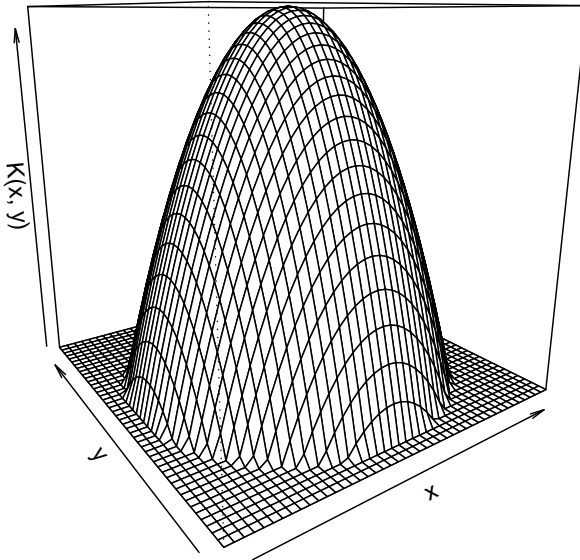


Figure 7.3 Epanechnikov kernel for a grid between $(-1.1, -1.1)$ and $(1.1, 1.1)$.

```

1 R> data("faithful", package = "datasets")
2 R> x <- faithful$waiting
3 R> layout(matrix(1:3, ncol = 3))
4 R> hist(x, xlab = "Waiting times (in min.)", ylab = "Frequency",
5 +       probability = TRUE, main = "Gaussian kernel",
6 +       border = "gray")
7 R> lines(density(x, width = 12), lwd = 2)
8 R> rug(x)
9 R> hist(x, xlab = "Waiting times (in min.)", ylab = "Frequency",
10 +     probability = TRUE, main = "Rectangular kernel",
11 +     border = "gray")
12 R> lines(density(x, width = 12, window = "rectangular"), lwd = 2)
13 R> rug(x)
14 R> hist(x, xlab = "Waiting times (in min.)", ylab = "Frequency",
15 +     probability = TRUE, main = "Triangular kernel",
16 +     border = "gray")
17 R> lines(density(x, width = 12, window = "triangular"), lwd = 2)
18 R> rug(x)

```

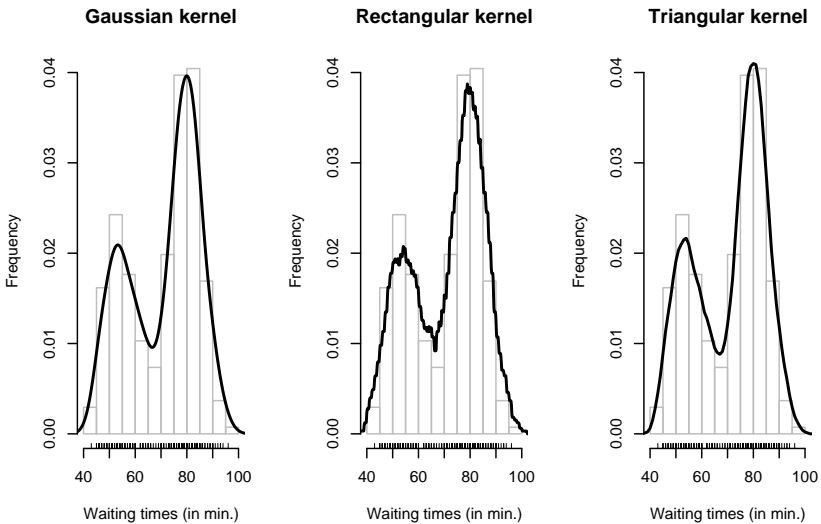


Figure 7.4 Density estimates of the geyser eruption data imposed on a histogram of the data.

```
R> library("KernSmooth")
R> data("CYGOB1", package = "HSAUR")
R> CYGOB1d <- bkde2D(CYGOB1, bandwidth = sapply(CYGOB1, dpik))
R> contour(x = CYGOB1d$x1, y = CYGOB1d$x2, z = CYGOB1d$fhat,
+         xlab = "log surface temperature",
+         ylab = "log light intensity")
```

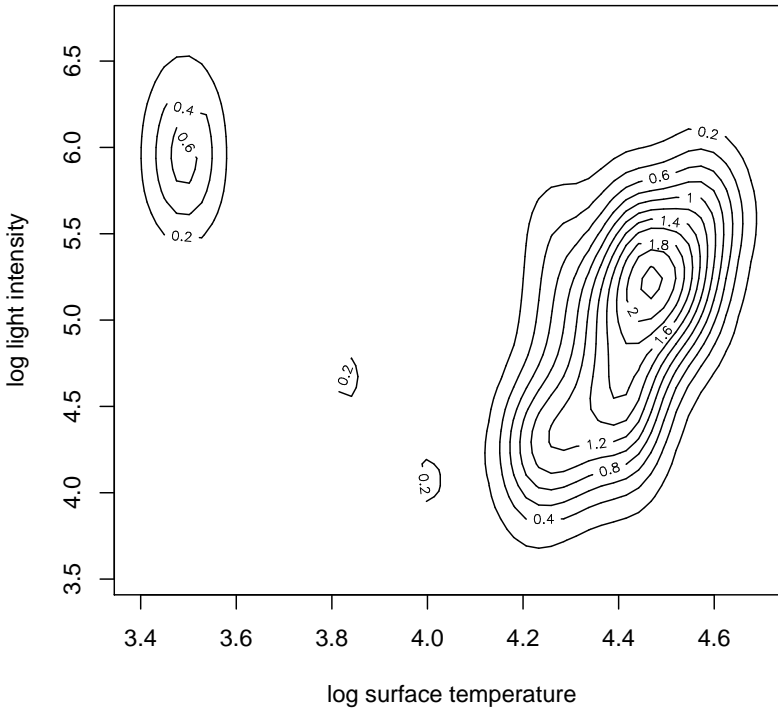


Figure 7.5 A contour plot of the bivariate density estimate of the CYGOB1 data, i.e., a two-dimensional graphical display for a three-dimensional problem.

```
R> persp(x = CYGOB1d$x1, y = CYGOB1d$x2, z = CYGOB1d$fhat,
+       xlab = "log surface temperature",
+       ylab = "log light intensity",
+       zlab = "estimated density",
+       theta = -35, axes = TRUE, box = TRUE)
```

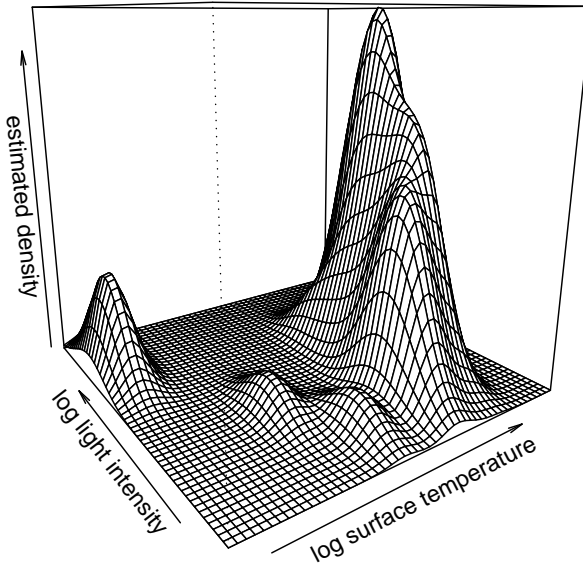


Figure 7.6 The bivariate density estimate of the CYGOB1 data, here shown in a three-dimensional fashion using the `persp` function.

```
$counts
function gradient
      55      55
```

```
$convergence
[1] 0
```

Of course, optimising the appropriate likelihood ‘by hand’ is not very convenient. In fact, (at least) two packages offer high-level functionality for esti-

mating mixture models. The first one is package *mclust* (Fraley et al., 2006) implementing the methodology described in Fraley and Raftery (2002). Here, a Bayesian information criterion (BIC) is applied to choose the form of the mixture model:

```
R> library("mclust")
R> mc <- Mclust(faithful$waiting)
R> mc
```

```
best model: E with 2 components
```

and the estimated means are

```
R> mc$parameters$mean
```

```
      1      2
54.61911 80.09384
```

with estimated standard deviation (found to be equal within both groups)

```
R> sqrt(mc$parameters$variance$sigmasq)
```

```
[1] 5.86848
```

The proportion is $\hat{p} = 0.36$. The second package is called *flexmix* whose functionality is described by Leisch (2004). A mixture of two normals can be fitted using

```
R> library("flexmix")
R> fl <- flexmix(waiting ~ 1, data = faithful, k = 2)
```

with $\hat{p} = 0.36$ and estimated parameters

```
R> parameters(fl, component = 1)
```

```
              Comp.1
coef. (Intercept) 54.628701
sigma              5.895234
```

```
R> parameters(fl, component = 2)
```

```
              Comp.2
coef. (Intercept) 80.098582
sigma              5.871749
```

We can get standard errors for the five parameter estimates by using a bootstrap approach (see Efron and Tibshirani, 1993). The original data are slightly perturbed by drawing n out of n observations *with replacement* and those artificial replications of the original data are called *bootstrap samples*. Now, we can fit the mixture for each bootstrap sample and assess the variability of the estimates, for example using confidence intervals. Some suitable R code based on the *Mclust* function follows. First, we define a function that, for a bootstrap sample *indx*, fits a two-component mixture model and returns \hat{p} and the estimated means (note that we need to make sure that we always get an estimate of p , not $1 - p$):

```

R> opar <- as.list(opp$par)
R> rx <- seq(from = 40, to = 110, by = 0.1)
R> d1 <- dnorm(rx, mean = opar$mu1, sd = opar$sd1)
R> d2 <- dnorm(rx, mean = opar$mu2, sd = opar$sd2)
R> f <- opar$p * d1 + (1 - opar$p) * d2
R> hist(x, probability = TRUE, xlab = "Waiting times (in min.)",
+       border = "gray", xlim = range(rx), ylim = c(0, 0.06),
+       main = "")
R> lines(rx, f, lwd = 2)
R> lines(rx, dnorm(rx, mean = mean(x), sd = sd(x)), lty = 2,
+       lwd = 2)
R> legend(50, 0.06, lty = 1:2, bty = "n",
+       legend = c("Fitted two-component mixture density",
+                 "Fitted single normal density"))

```

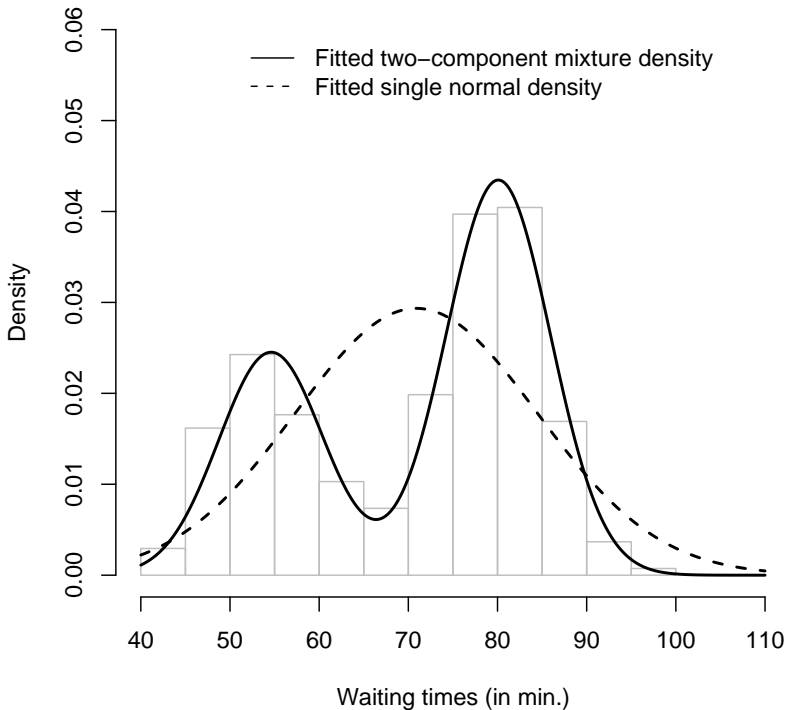


Figure 7.7 Fitted normal density and two-component normal mixture for geyser eruption data.


```
R> library("boot")
R> fit <- function(x, indx) {
+   a <- Mclust(x[indx], minG = 2, maxG = 2)$parameters
+   if (a$pro[1] < 0.5)
+     return(c(p = a$pro[1], mu1 = a$mean[1],
+             mu2 = a$mean[2]))
+   return(c(p = 1 - a$pro[1], mu1 = a$mean[2],
+           mu2 = a$mean[1]))
+ }
```

The function `fit` can now be fed into the `boot` function ([Canty and Ripley, 2006](#)) for bootstrapping (here 1000 bootstrap samples are drawn)

```
R> bootpara <- boot(faithful$waiting, fit, R = 1000)
```

We assess the variability of our estimates \hat{p} by means of adjusted bootstrap percentile (BCa) confidence intervals, which for \hat{p} can be obtained from

```
R> boot.ci(bootpara, type = "bca", index = 1)
```

BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS

Based on 1000 bootstrap replicates

CALL :

```
boot.ci(boot.out = bootpara, type = "bca", index = 1)
```

Intervals :

Level BCa

95% (0.3041, 0.4233)

Calculations and Intervals on Original Scale

We see that there is a reasonable variability in the mixture model, however, the means in the two components are rather stable, as can be seen from

```
R> boot.ci(bootpara, type = "bca", index = 2)
```

BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS

Based on 1000 bootstrap replicates

CALL :

```
boot.ci(boot.out = bootpara, type = "bca", index = 2)
```

Intervals :

Level BCa

95% (53.42, 56.07)

Calculations and Intervals on Original Scale

for $\hat{\mu}_1$ and for $\hat{\mu}_2$ from

```
R> boot.ci(bootpara, type = "bca", index = 3)
```

BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS

Based on 1000 bootstrap replicates

CALL :

```
boot.ci(boot.out = bootpara, type = "bca", index = 3)
```

```
Intervals :
```

```
Level          BCa
95%    (79.05, 81.01 )
```

```
Calculations and Intervals on Original Scale
```

Finally, we show a graphical representation of both the bootstrap distribution of the mean estimates *and* the corresponding confidence intervals. For convenience, we define a function for plotting, namely

```
R> bootplot <- function(b, index, main = "") {
+   dens <- density(b$t[,index])
+   ci <- boot.ci(b, type = "bca", index = index)$bca[4:5]
+   est <- b$t0[index]
+   plot(dens, main = main)
+   y <- max(dens$y) / 10
+   segments(ci[1], y, ci[2], y, lty = 2)
+   points(ci[1], y, pch = "(")
+   points(ci[2], y, pch = ")")
+   points(est, y, pch = 19)
+ }
```

The element `t` of an object created by `boot` contains the bootstrap replications of our estimates, i.e., the values computed by `fit` for each of the 1000 bootstrap samples of the geyser data. First, we plot a simple density estimate and then construct a line representing the confidence interval. We apply this function to the bootstrap distributions of our estimates $\hat{\mu}_1$ and $\hat{\mu}_2$ in Figure 7.8.

```
R> layout(matrix(1:2, ncol = 2))
R> bootplot(bootpara, 2, main = expression(mu[1]))
R> bootplot(bootpara, 3, main = expression(mu[2]))
```

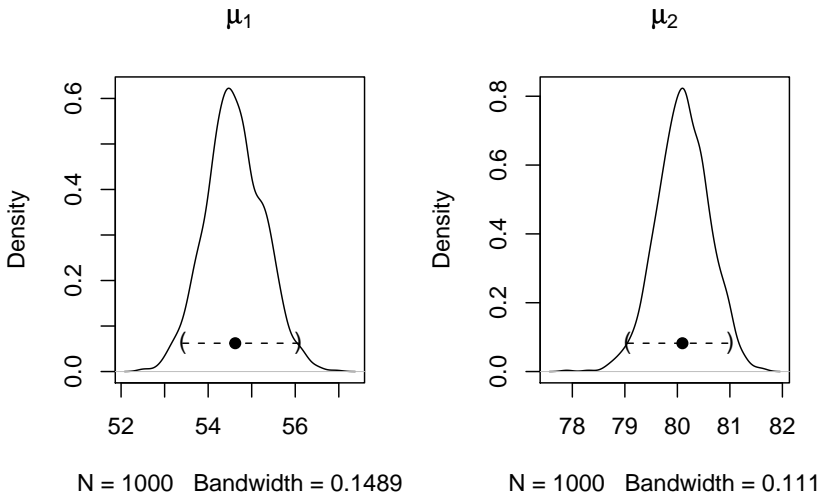


Figure 7.8 Bootstrap distribution and confidence intervals for the mean estimates of a two-component mixture for the geyser data.

Bibliography

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- Leisch, F. (2004), “FlexMix: A general framework for finite mixture models and latent class regression in R,” *Journal of Statistical Software*, 11, URL <http://www.jstatsoft.org/v11/i08/>.
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Recursive Partitioning: Large Companies and Glaucoma Diagnosis

8.1 Introduction

8.2 Recursive Partitioning

8.3 Analysis Using R

8.3.1 Forbes 2000 Data

For some observations the profit is missing and we first remove those companies from the list

```
R> data("Forbes2000", package = "HSAUR")
R> Forbes2000 <- subset(Forbes2000, !is.na(profits))
```

The `rpart` function from *rpart* can be used to grow a regression tree. The response variable and the covariates are defined by a model formula in the same way as for `lm`, say. By default, a large initial tree is grown.

```
R> library("rpart")
R> forbes_rpart <- rpart(profits ~ assets + marketvalue + sales,
+                         data = Forbes2000)
```

A `print` method for *rpart* objects is available, however, a graphical representation shown in Figure 8.1 is more convenient. Observations which satisfy the condition shown for each node go to the left and observations which don't are element of the right branch in each node. The numbers plotted in the leaves are the mean profit for those observations satisfying the conditions stated above. For example, the highest profit is observed for companies with a market value greater than 89.33 billion US dollars and with more than 91.92 US dollars sales. To determine if the tree is appropriate or if some of the branches need to be subjected to pruning we can use the `cptable` element of the *rpart* object:

```
R> print(forbes_rpart$cptable)
```

| | <i>CP</i> | <i>nsplit</i> | <i>rel error</i> | <i>xerror</i> | <i>xstd</i> |
|---|------------|---------------|------------------|---------------|-------------|
| 1 | 0.23748446 | 0 | 1.0000000 | 1.0010339 | 0.1946331 |
| 2 | 0.04600397 | 1 | 0.7625155 | 0.8397144 | 0.2174245 |
| 3 | 0.04258786 | 2 | 0.7165116 | 0.8066685 | 0.2166339 |
| 4 | 0.02030891 | 3 | 0.6739237 | 0.7625940 | 0.2089684 |
| 5 | 0.01854336 | 4 | 0.6536148 | 0.7842574 | 0.2093683 |
| 6 | 0.01102304 | 5 | 0.6350714 | 0.7925891 | 0.2106088 |

```
R> plot(forbes_rpart, uniform = TRUE, margin = 0.1, branch = 0.5,
+       compress = TRUE)
R> text(forbes_rpart)
```

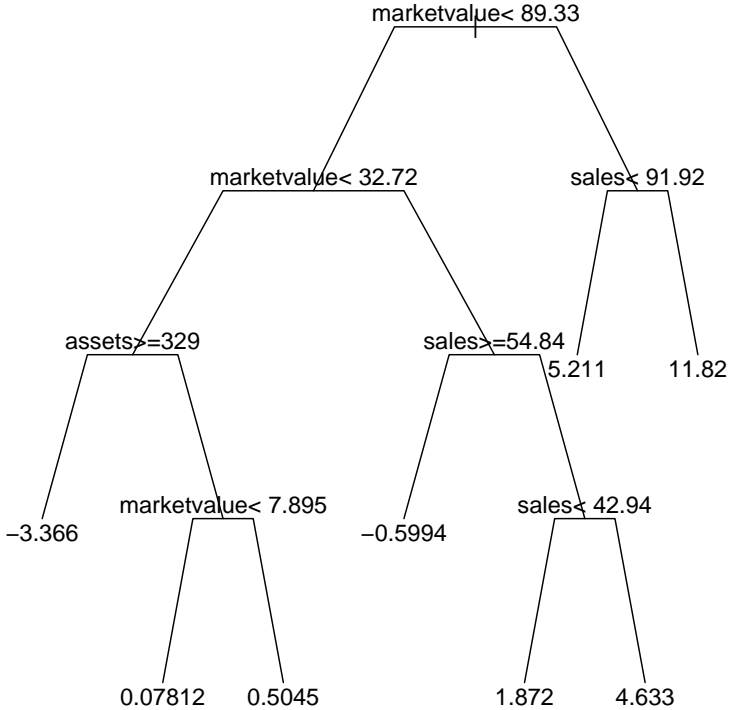


Figure 8.1 Large initial tree for Forbes 2000 data.

```
7 0.01076006      6 0.6240484 0.7931405 0.2128048
8 0.01000000      7 0.6132883 0.7902771 0.2128037
```

```
R> opt <- which.min(forbes_rpart$cptable[,"xerror"])
```

The `xerror` column contains estimates of cross-validated prediction error for different numbers of splits (`nsplit`). The best tree has three splits. Now we can prune back the large initial tree using

```
R> cp <- forbes_rpart$cptable[opt, "CP"]
R> forbes_prune <- prune(forbes_rpart, cp = cp)
```

The result is shown in Figure 8.2. This tree is much smaller. From the sample sizes and boxplots shown for each leaf we see that the majority of companies

is grouped together. However, a large market value, more than 32.72 billion US dollars, seems to be a good indicator of large profits.

8.3.2 Glaucoma Diagnosis

```
R> data("GlaucomaM", package = "ipred")
R> glaucoma_rpart <- rpart(Class ~ ., data = GlaucomaM,
+       control = rpart.control(xval = 100))
R> glaucoma_rpart$cptable
      CP nsplit rel error   xerror   xstd
1 0.65306122      0 1.0000000 1.5306122 0.06054391
2 0.07142857      1 0.3469388 0.3877551 0.05647630
3 0.01360544      2 0.2755102 0.3775510 0.05590431
4 0.01000000      5 0.2346939 0.4489796 0.05960655

R> opt <- which.min(glaucoma_rpart$cptable[, "xerror"])
R> cp <- glaucoma_rpart$cptable[opt, "CP"]
R> glaucoma_prune <- prune(glaucoma_rpart, cp = cp)
```

As we discussed earlier, the choice of the appropriate sized tree is not a trivial problem. For the glaucoma data, the above choice of three leaves is very unstable across multiple runs of cross-validation. As an illustration of this problem we repeat the very same analysis as shown above and record the optimal number of splits as suggested by the cross-validation runs.

```
R> nsplitopt <- vector(mode = "integer", length = 25)
R> for (i in 1:length(nsplitopt)) {
+   cp <- rpart(Class ~ ., data = GlaucomaM)$cptable
+   nsplitopt[i] <- cp[which.min(cp[, "xerror"]), "nsplit"]
+ }
R> table(nsplitopt)
nsplitopt
 1  2  5
14  7  4
```

Although for 14 runs of cross-validation a simple tree with one split only is suggested, larger trees would have been favored in 11 of the cases. This short analysis shows that we should not trust the tree in Figure 8.3 too much.

One way out of this dilemma is the aggregation of multiple trees via *bagging*. In R, the bagging idea can be implemented by three or four lines of code. Case count or weight vectors representing the bootstrap samples can be drawn from the multinomial distribution with parameters n and $p_1 = 1/n, \dots, p_n = 1/n$ via the `rmultinom` function. For each weight vector, one large tree is constructed without pruning and the *rpart* objects are stored in a list, here called `trees`:

```
R> trees <- vector(mode = "list", length = 25)
R> n <- nrow(GlaucomaM)
R> bootsamples <- rmultinom(length(trees), n, rep(1, n)/n)
```

```

R> layout(matrix(1:2, nc = 1))
R> plot(forbes_prune, uniform = TRUE, margin = 0.1, branch = 0.5,
+       compress = TRUE)
R> text(forbes_prune)
R> rn <- rownames(forbes_prune$frame)
R> lev <- rn[sort(unique(forbes_prune$where))]
R> where <- factor(rn[forbes_prune$where], levels = lev)
R> n <- tapply(Forbes2000$profits, where, length)
R> boxplot(Forbes2000$profits ~ where, varwidth = TRUE,
+         ylim = range(Forbes2000$profit) * 1.3,
+         pars = list(axes = FALSE),
+         ylab = "Profits in US dollars")
R> abline(h = 0, lty = 3)
R> axis(2)
R> text(1:length(n), max(Forbes2000$profit) * 1.2,
+       paste("n = ", n))

```

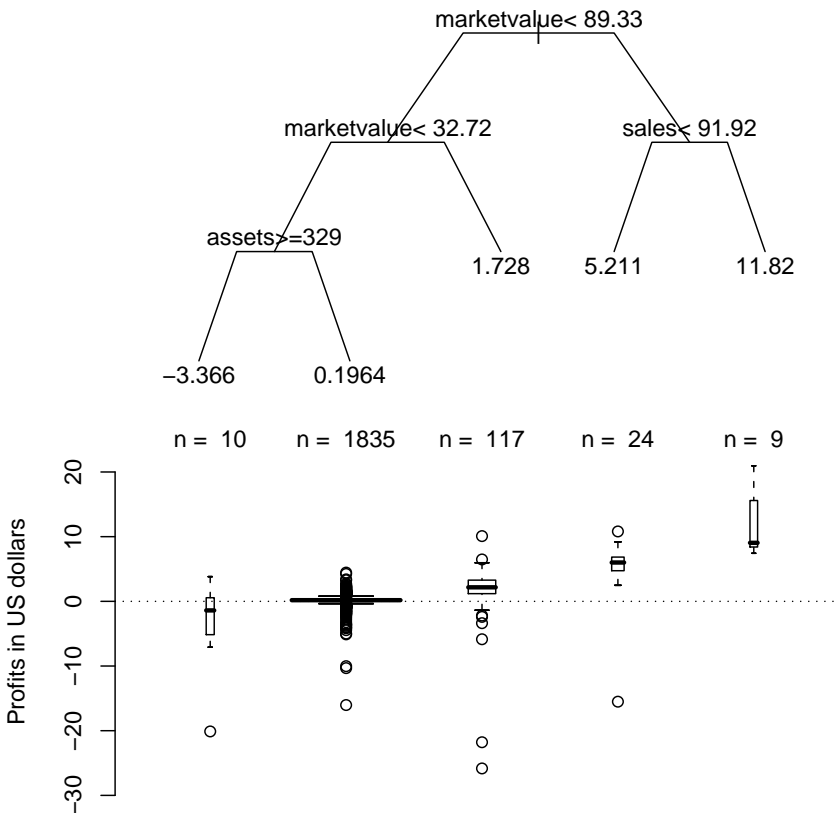


Figure 8.2 Pruned regression tree for Forbes 2000 data with the distribution of the profit in each leaf depicted by a boxplot.


```

R> layout(matrix(1:2, nc = 1))
R> plot(glaucoma_prune, uniform = TRUE, margin = 0.1, branch = 0.5,
+       compress = TRUE)
R> text(glaucoma_prune, use.n = TRUE)
R> rn <- rownames(glaucoma_prune$frame)
R> lev <- rn[sort(unique(glaucoma_prune$where))]
R> where <- factor(rn[glaucoma_prune$where], levels = lev)
R> mosaicplot(table(where, GlaucomaM$class), main = "", xlab = "",
+             las = 1)

```

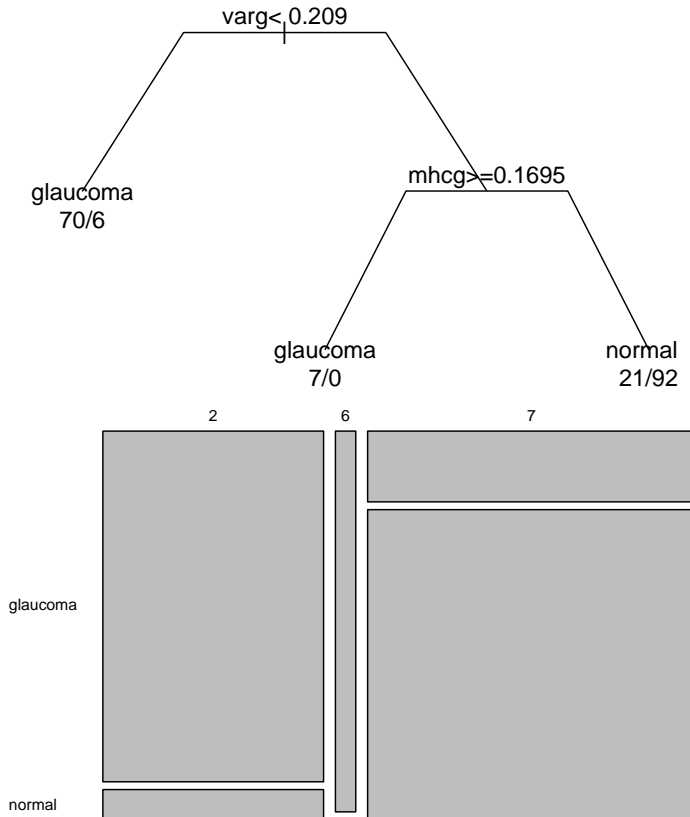


Figure 8.3 Pruned classification tree of the glaucoma data with class distribution in the leaves depicted by a mosaicplot.

```
R> mod <- rpart(Class ~ ., data = GlaucomaM,
+             control = rpart.control(xval = 0))
R> for (i in 1:length(trees))
+   trees[[i]] <- update(mod, weights = bootsamples[,i])
```

The `update` function re-evaluates the call of `mod`, however, with the weights being altered, i.e., fits a tree to a bootstrap sample specified by the weights. It is interesting to have a look at the structures of the multiple trees. For example, the variable selected for splitting in the root of the tree is not unique as can be seen by

```
R> table(sapply(trees, function(x) as.character(x$frame$var[1])))
      phcg  varg  vari  vars
      1   14    9    1
```

Although `varg` is selected most of the time, other variables such as `vari` occur as well – a further indication that the tree in Figure 8.3 is questionable and that hard decisions are not appropriate for the glaucoma data.

In order to make use of the ensemble of trees in the list `trees` we estimate the conditional probability of suffering from glaucoma given the covariates for each observation in the original data set by

```
R> classprob <- matrix(0, nrow = n, ncol = length(trees))
R> for (i in 1:length(trees)) {
+   classprob[,i] <- predict(trees[[i]],
+                           newdata = GlaucomaM)[,1]
+   classprob[bootsamples[,i] > 0,i] <- NA
+ }
```

Thus, for each observation we get 25 estimates. However, each observation has been used for growing one of the trees with probability 0.632 and thus was not used with probability 0.368. Consequently, the estimate from a tree where an observation was not used for growing is better for judging the quality of the predictions and we label the other estimates with `NA`.

Now, we can average the estimates and we vote for glaucoma when the average of the estimates of the conditional glaucoma probability exceeds 0.5. The comparison between the observed and the predicted classes does not suffer from overfitting since the predictions are computed from those trees for which each single observation was *not* used for growing.

```
R> avg <- rowMeans(classprob, na.rm = TRUE)
R> predictions <- factor(ifelse(avg > 0.5, "glaucoma", "normal"))
R> predtab <- table(predictions, GlaucomaM$Class)
R> predtab
```

```
predictions glaucoma normal
 glaucoma      78      15
 normal       20      83
```

Thus, an honest estimate of the probability of a glaucoma prediction when the patient is actually suffering from glaucoma is

```
R> round(predtab[1,1] / colSums(predtab)[1] * 100)
```

```
glaucoma
      80
```

per cent. For

```
R> round(predtab[2,2] / colSums(predtab)[2] * 100)
```

```
normal
      85
```

per cent of normal eyes, the ensemble does not predict a glaucomateous damage. The *bagging* procedure is a special case of a more general approach called *random forest* (Breiman, 2001). The package *randomForest* (Breiman et al., 2006) can be used to compute such ensembles via

```
R> library("randomForest")
```

```
R> rf <- randomForest(Class ~ ., data = GlaucomaM)
```

and we obtain out-of-bag estimates for the prediction error via

```
R> table(predict(rf), GlaucomaM$Class)
```

| | <i>glaucoma</i> | <i>normal</i> |
|-----------------|-----------------|---------------|
| <i>glaucoma</i> | 81 | 11 |
| <i>normal</i> | 17 | 87 |

For the glaucoma data, such a *conditional inference tree* can be computed using the `ctree` function

```
R> library("party")
```

```
R> glaucoma_ctree <- ctree(Class ~ ., data = GlaucomaM)
```

and a graphical representation is depicted in Figure 8.5 showing both the cutpoints and the p -values of the associated independence tests for each node. The first split is performed using a cutpoint defined with respect to the volume of the optic nerve above some reference plane, but in the inferior part of the eye only (`vari`).

```

R> library("lattice")
R> gdata <- data.frame(avg = rep(avg, 2),
+   class = rep(as.numeric(GlaucomaM$Class), 2),
+   obs = c(GlaucomaM[["varg"]], GlaucomaM[["vari"]]),
+   var = factor(c(rep("varg", nrow(GlaucomaM)),
+                 rep("vari", nrow(GlaucomaM))))))
R> panelf <- function(x, y) {
+   panel.xyplot(x, y, pch = gdata$class)
+   panel.abline(h = 0.5, lty = 2)
+ }
R> print(xyplot(avg ~ obs | var, data = gdata,
+   panel = panelf,
+   scales = "free", xlab = "",
+   ylab = "Estimated Class Probability Glaucoma"))

```

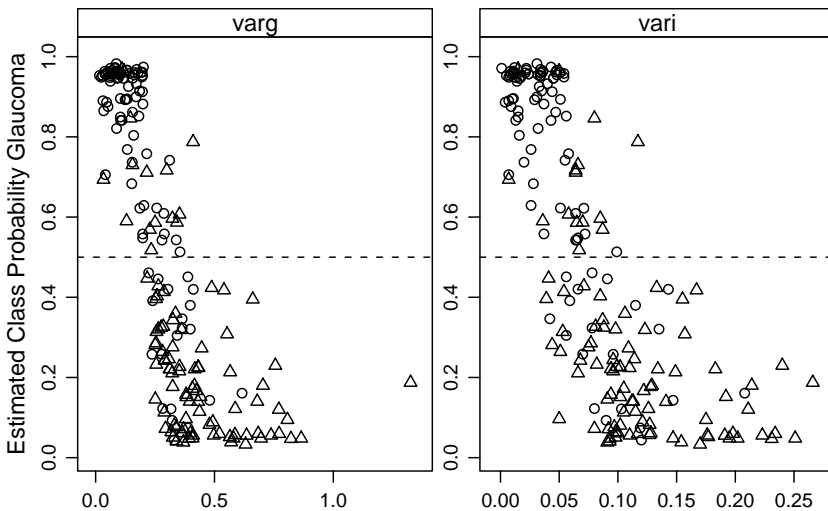


Figure 8.4 Glaucoma data: Estimated class probabilities depending on two important variables. The 0.5 cut-off for the estimated glaucoma probability is depicted as horizontal line. Glaucomatous eyes are plotted as circles and normal eyes are triangles.

```
R> plot(glaucoma_ctree)
```

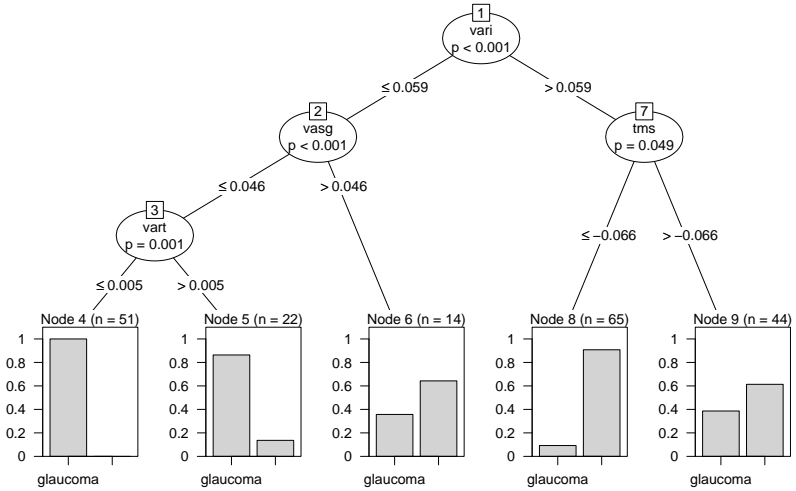


Figure 8.5 Glaucoma data: Conditional inference tree with the distribution of glaucomateous eyes shown for each terminal leaf.

Bibliography

- Breiman, L. (2001), “Random forests,” *Machine Learning*, 45, 5–32.
- Breiman, L., Cutler, A., Liaw, A., and Wiener, M. (2006), *randomForest: Breiman and Cutler’s Random Forests for Classification and Regression*, URL <http://stat-www.berkeley.edu/users/breiman/RandomForests>, R package version 4.5-16.

Survival Analysis: Glioma Treatment and Breast Cancer Survival

9.1 Introduction

9.2 Survival Analysis

9.3 Analysis Using R

9.3.1 Glioma Radioimmunotherapy

Figure 9.1 leads to the impression that patients treated with the novel radioimmunotherapy survive longer, regardless of the tumor type. In order to assess if this informal finding is reliable, we may perform a log-rank test via

```
R> survdiff(Surv(time, event) ~ group, data = g3)
```

Call:

```
survdiff(formula = Surv(time, event) ~ group, data = g3)
```

| | <i>N</i> | <i>Observed</i> | <i>Expected</i> | $(O-E)^2/E$ | $(O-E)^2/V$ |
|---------------|----------|-----------------|-----------------|-------------|-------------|
| group=Control | 6 | 4 | 1.49 | 4.23 | 6.06 |
| group=RIT | 11 | 2 | 4.51 | 1.40 | 6.06 |

Chisq= 6.1 on 1 degrees of freedom, p= 0.0138

which indicates that the survival times are indeed different in both groups. However, the number of patients is rather limited and so it might be dangerous to rely on asymptotic tests. As shown in Chapter 3, conditioning on the data and computing the distribution of the test statistics without additional assumptions is one alternative. The function `surv_test` from package *coin* (Hothorn et al., 2006b,a) can be used to compute an exact conditional test answering the question whether the survival times differ for grade III patients:

```
R> library("coin")
R> surv_test(Surv(time, event) ~ group, data = g3,
+           distribution = "exact")
```

Exact Logrank Test

```
data: Surv(time, event) by group (Control, RIT)
Z = 2.1711, p-value = 0.02877
alternative hypothesis: two.sided
```

```
R> data("glioma", package = "coin")
R> library("survival")
R> layout(matrix(1:2, ncol = 2))
R> g3 <- subset(glioma, histology == "Grade3")
R> plot(survfit(Surv(time, event) ~ group, data = g3),
+       main = "Grade III Glioma", lty = c(2, 1),
+       ylab = "Probability", xlab = "Survival Time in Month",
+       legend.bty = "n", legend.text = c("Control", "Treated"))
R> g4 <- subset(glioma, histology == "GBM")
R> plot(survfit(Surv(time, event) ~ group, data = g4),
+       main = "Grade IV Glioma", ylab = "Probability",
+       lty = c(2, 1), xlab = "Survival Time in Month",
+       xlim = c(0, max(glioma$time) * 1.05))
```

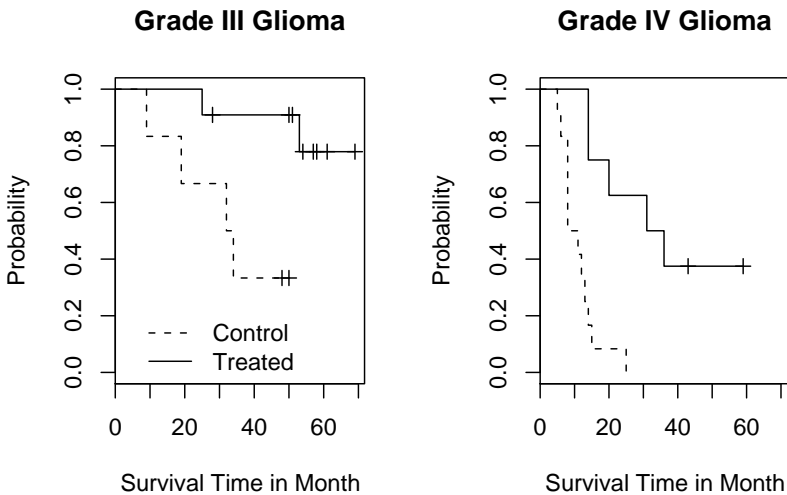


Figure 9.1 Survival times comparing treated and control patients.

which, in this case, confirms the above results. The same exercise can be performed for patients with grade IV glioma

```
R> surv_test(Surv(time, event) ~ group, data = g4,
+           distribution = "exact")
```

Exact Logrank Test

```
data: Surv(time, event) by group (Control, RIT)
Z = 3.2215, p-value = 0.0001588
alternative hypothesis: two.sided
```


which shows a difference as well. However, it might be more appropriate to answer the question whether the novel therapy is superior for both groups of tumors simultaneously. This can be implemented by *stratifying*, or *blocking*, with respect tumor grading:

```
R> surv_test(Surv(time, event) ~ group | histology, data = glioma,
+           distribution = approximate(B = 10000))
           Approximative Logrank Test

data:  Surv(time, event) by
       group (Control, RIT)
       stratified by histology
Z = 3.6704, p-value = 1e-04
alternative hypothesis: two.sided
```

Here, we need to approximate the exact conditional distribution since the exact distribution is hard to compute. The result supports the initial impression implied by Figure 9.1

9.3.2 Breast Cancer Survival

Before fitting a Cox model to the GBSG2 data, we again derive a Kaplan-Meier estimate of the survival function of the data, here stratified with respect to whether a patient received a hormonal therapy or not (see Figure 9.2). Fitting a Cox model follows roughly the same rules as shown for linear models in Chapters 4, 5 or 6 with the exception that the response variable is again coded as a *Surv* object. For the GBSG2 data, the model is fitted via

```
R> GBSG2_coxph <- coxph(Surv(time, cens) ~ ., data = GBSG2)
```

and the results as given by the `summary` method are given in Figure 9.3. Since we are especially interested in the relative risk for patients who underwent a hormonal therapy, we can compute an estimate of the relative risk and a corresponding confidence interval via

```
R> ci <- confint(GBSG2_coxph)
R> exp(cbind(coef(GBSG2_coxph), ci))["horThyes",]
           2.5 %      97.5 %
0.7073155 0.5492178 0.9109233
```

This result implies that patients treated with a hormonal therapy had a lower risk and thus survived longer compared to women who were not treated this way.

Model checking and model selection for proportional hazards models are complicated by the fact that easy to use residuals, such as those discussed in Chapter 5 for linear regression model are not available, but several possibilities do exist. A check of the proportional hazards assumption can be done by looking at the parameter estimates β_1, \dots, β_q over time. We can safely assume proportional hazards when the estimates don't vary much over time. The null hypothesis of constant regression coefficients can be tested, both globally as well as for each covariate, by using the `cox.zph` function

```
R> data("GBSG2", package = "ipred")
R> plot(survfit(Surv(time, cens) ~ horTh, data = GBSG2),
+       lty = 1:2, mark.time = FALSE, ylab = "Probability",
+       xlab = "Survival Time in Days")
R> legend(250, 0.2, legend = c("yes", "no"), lty = c(2, 1),
+       title = "Hormonal Therapy", bty = "n")
```

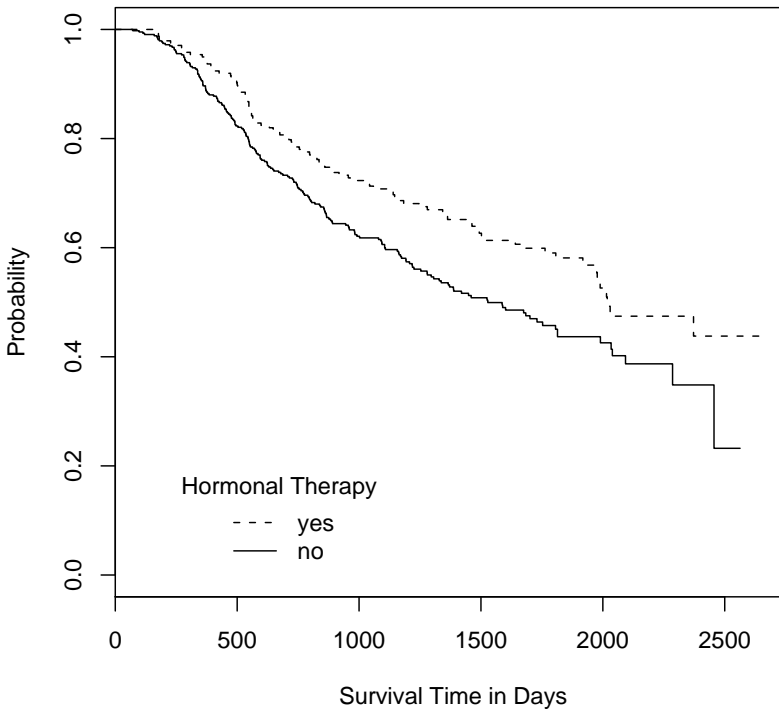


Figure 9.2 Kaplan-Meier estimates for breast cancer patients who either received a hormonal therapy or not.

```
R> GBSG2_zph <- cox.zph(GBSG2_coxph)
R> GBSG2_zph
```

| | <i>rho</i> | <i>chisq</i> | <i>p</i> |
|---------------------|------------|--------------|----------|
| <i>horThyes</i> | -2.54e-02 | 1.96e-01 | 0.65778 |
| <i>age</i> | 9.40e-02 | 2.96e+00 | 0.08552 |
| <i>menostatPost</i> | -1.19e-05 | 3.75e-08 | 0.99985 |
| <i>tsize</i> | -2.50e-02 | 1.88e-01 | 0.66436 |
| <i>tgrade.L</i> | -1.30e-01 | 4.85e+00 | 0.02772 |

```
R> summary(GBSG2_coxph)
```

```
Call:
```

```
coxph(formula = Surv(time, cens) ~ ., data = GBSG2)
```

```
n= 686
```

| | coef | exp(coef) | se(coef) | z | p |
|--------------|-----------|-----------|----------|--------|---------|
| horThyes | -0.346278 | 0.707 | 0.129075 | -2.683 | 7.3e-03 |
| age | -0.009459 | 0.991 | 0.009301 | -1.017 | 3.1e-01 |
| menostatPost | 0.258445 | 1.295 | 0.183476 | 1.409 | 1.6e-01 |
| tsize | 0.007796 | 1.008 | 0.003939 | 1.979 | 4.8e-02 |
| tgrade.L | 0.551299 | 1.736 | 0.189844 | 2.904 | 3.7e-03 |
| tgrade.Q | -0.201091 | 0.818 | 0.121965 | -1.649 | 9.9e-02 |
| pnodes | 0.048789 | 1.050 | 0.007447 | 6.551 | 5.7e-11 |
| progrec | -0.002217 | 0.998 | 0.000574 | -3.866 | 1.1e-04 |
| estrec | 0.000197 | 1.000 | 0.000450 | 0.438 | 6.6e-01 |

| | exp(coef) | exp(-coef) | lower .95 | upper .95 |
|--------------|-----------|------------|-----------|-----------|
| horThyes | 0.707 | 1.414 | 0.549 | 0.911 |
| age | 0.991 | 1.010 | 0.973 | 1.009 |
| menostatPost | 1.295 | 0.772 | 0.904 | 1.855 |
| tsize | 1.008 | 0.992 | 1.000 | 1.016 |
| tgrade.L | 1.736 | 0.576 | 1.196 | 2.518 |
| tgrade.Q | 0.818 | 1.223 | 0.644 | 1.039 |
| pnodes | 1.050 | 0.952 | 1.035 | 1.065 |
| progrec | 0.998 | 1.002 | 0.997 | 0.999 |
| estrec | 1.000 | 1.000 | 0.999 | 1.001 |

```
Rsquare= 0.142 (max possible= 0.995 )
```

```
Likelihood ratio test= 105 on 9 df, p=0
```

```
Wald test = 115 on 9 df, p=0
```

```
Score (logrank) test = 121 on 9 df, p=0
```

Figure 9.3 R output of the `summary` method for `GBSG2_coxph`.

```
tgrade.Q      3.22e-03 3.14e-03 0.95530
pnodes        5.84e-02 5.98e-01 0.43941
progrec       5.65e-02 1.20e+00 0.27351
estrec        5.46e-02 1.03e+00 0.30967
GLOBAL              NA 2.27e+01 0.00695
```

There seems to be some evidence of time-varying effects, especially for age and tumor grading. A graphical representation of the estimated regression coefficient over time is shown in Figure 9.4. We refer to [Therneau and Grambsch \(2000\)](#) for a detailed theoretical description of these topics. The tree-structured regression models applied to continuous and binary responses in Chapter 8 are applicable to censored responses in survival analysis as well. Such a simple prognostic model with only a few terminal nodes might be

```
R> plot(GBSG2_zph, var = "age")
```

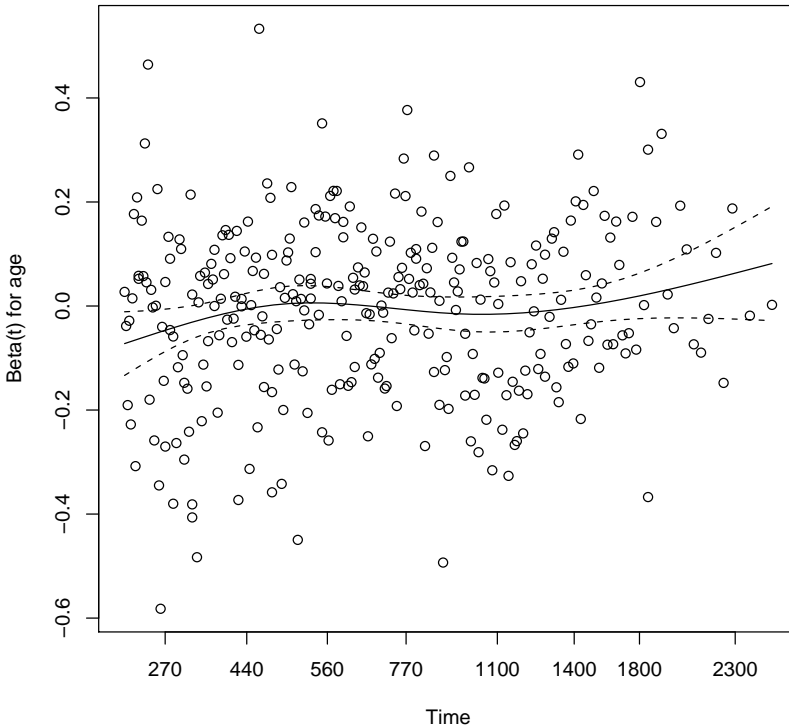


Figure 9.4 Estimated regression coefficient for `age` depending on time for the GBSG2 data.

helpful for relating the risk to certain subgroups of patients. Both `rpart` and the `ctree` function from package *party* can be applied to the GBSG2 data, where the conditional trees of the latter selects cutpoints based on log-rank statistics;

```
R> GBSG2_ctree <- ctree(Surv(time, cens) ~ ., data = GBSG2)
```

and the `plot` method applied to this tree produces the graphical representation in Figure 9.6. The number of positive lymph nodes (`pnodes`) is the most important variable in the tree, this corresponds to the p -value associated with this variable in Cox's regression, see Figure 9.3. Women with not more than three positive lymph nodes who have undergone a hormonal therapy seem to have the best prognosis whereas a large number of positive lymph nodes and a small value of the progesterone receptor indicates a bad prognosis.

```
R> layout(matrix(1:3, ncol = 3))
R> res <- residuals(GBSG2_coxph)
R> plot(res ~ age, data = GBSG2, ylim = c(-2.5, 1.5),
+       pch = ".", ylab = "Martingale Residuals")
R> abline(h = 0, lty = 3)
R> plot(res ~ pnodes, data = GBSG2, ylim = c(-2.5, 1.5),
+       pch = ".", ylab = "")
R> abline(h = 0, lty = 3)
R> plot(res ~ log(progrec), data = GBSG2, ylim = c(-2.5, 1.5),
+       pch = ".", ylab = "")
R> abline(h = 0, lty = 3)
```

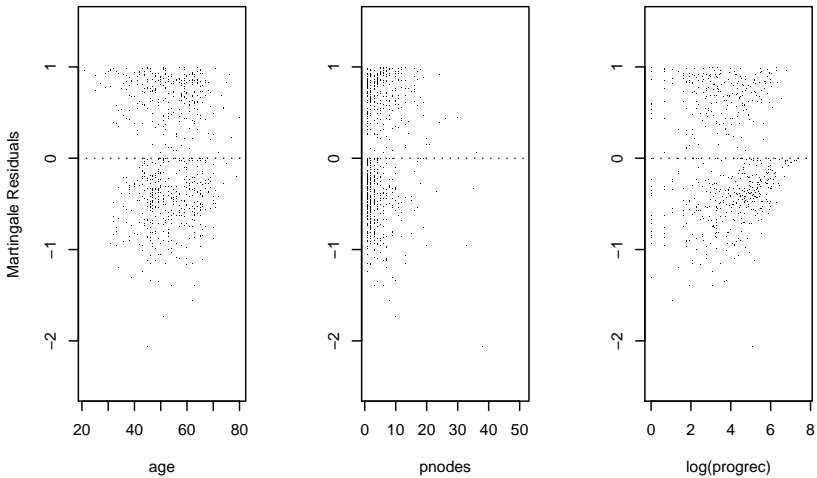


Figure 9.5 Martingale residuals for the GBSG2 data.

```
R> plot(GBSG2_ctree)
```

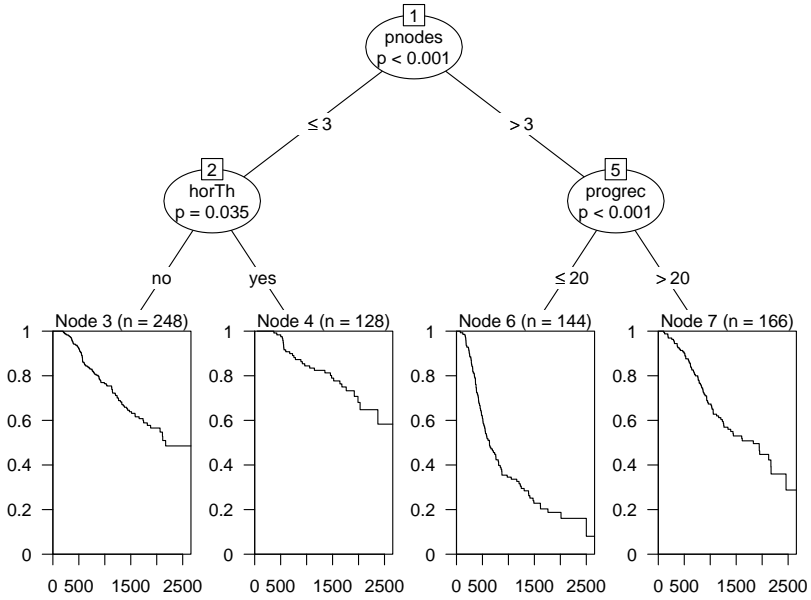


Figure 9.6 GBSG2 data: Conditional inference tree with the survival function, estimated by Kaplan-Meier, shown for every subgroup of patients identified by the tree.

Bibliography

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- Hothorn, T., Hornik, K., van de Wiel, M. A., and Zeileis, A. (2006b), “A Lego system for conditional inference,” *The American Statistician*, 60, 257–263, URL <http://statmath.wu-wien.ac.at/~zeileis/papers/Hothorn+Hornik+VanDeWiel-2006.pdf>.
- Therneau, T. M. and Grambsch, P. M. (2000), *Modeling Survival Data: Extending the Cox Model*, New York, USA: Springer.

Analysing Longitudinal Data I: Computerised Delivery of Cognitive Behavioural Therapy—Beat the Blues

10.1 Introduction

10.2 Analysing Longitudinal Data

10.3 Analysis Using R

We shall fit both random intercept and random intercept and slope models to the data including the baseline BDI values (`pre.bdi`), `treatment` group, `drug` and `length` as fixed effect covariates. Linear mixed effects models are fitted in R by using the `lmer` function contained in the `lme4` package (Bates and Sarkar, 2006, Pinheiro and Bates, 2000, Bates, 2005), but an essential first step is to rearrange the data from the ‘wide form’ in which they appear in the `BtheB` data frame into the ‘long form’ in which each separate repeated measurement and associated covariate values appear as a separate row in a *data.frame*. This rearrangement can be made using the following code:

```
R> data("BtheB", package = "HSAUR")
R> BtheB$subject <- factor(rownames(BtheB))
R> nobs <- nrow(BtheB)
R> BtheB_long <- reshape(BtheB, idvar = "subject",
+   varying = c("bdi.2m", "bdi.4m", "bdi.6m", "bdi.8m"),
+   direction = "long")
R> BtheB_long$time <- rep(c(2, 4, 6, 8), rep(nobs, 4))
```

such that the data are now in the form (here shown for the first three subjects)

```
R> subset(BtheB_long, subject %in% c("1", "2", "3"))
```

| | <i>drug</i> | <i>length</i> | <i>treatment</i> | <i>bdi.pre</i> | <i>subject</i> | <i>time</i> | <i>bdi</i> |
|------|-------------|---------------|------------------|----------------|----------------|-------------|------------|
| 1.2m | No | >6m | TAU | 29 | 1 | 2 | 2 |
| 2.2m | Yes | >6m | BtheB | 32 | 2 | 2 | 16 |
| 3.2m | Yes | <6m | TAU | 25 | 3 | 2 | 20 |
| 1.4m | No | >6m | TAU | 29 | 1 | 4 | 2 |
| 2.4m | Yes | >6m | BtheB | 32 | 2 | 4 | 24 |
| 3.4m | Yes | <6m | TAU | 25 | 3 | 4 | NA |
| 1.6m | No | >6m | TAU | 29 | 1 | 6 | NA |
| 2.6m | Yes | >6m | BtheB | 32 | 2 | 6 | 17 |
| 3.6m | Yes | <6m | TAU | 25 | 3 | 6 | NA |
| 1.8m | No | >6m | TAU | 29 | 1 | 8 | NA |


```
R> data("BtheB", package = "HSAUR")
R> layout(matrix(1:2, nrow = 1))
R> ylim <- range(BtheB[,grep("bdi", names(BtheB))],
+               na.rm = TRUE)
R> tau <- subset(BtheB, treatment == "TAU")[,
+               grep("bdi", names(BtheB))]
R> boxplot(tau, main = "Treated as usual", ylab = "BDI",
+          xlab = "Time (in months)", names = c(0, 2, 4, 6, 8),
+          ylim = ylim)
R> btheb <- subset(BtheB, treatment == "BtheB")[,
+                grep("bdi", names(BtheB))]
R> boxplot(btheb, main = "Beat the Blues", ylab = "BDI",
+          xlab = "Time (in months)", names = c(0, 2, 4, 6, 8),
+          ylim = ylim)
```

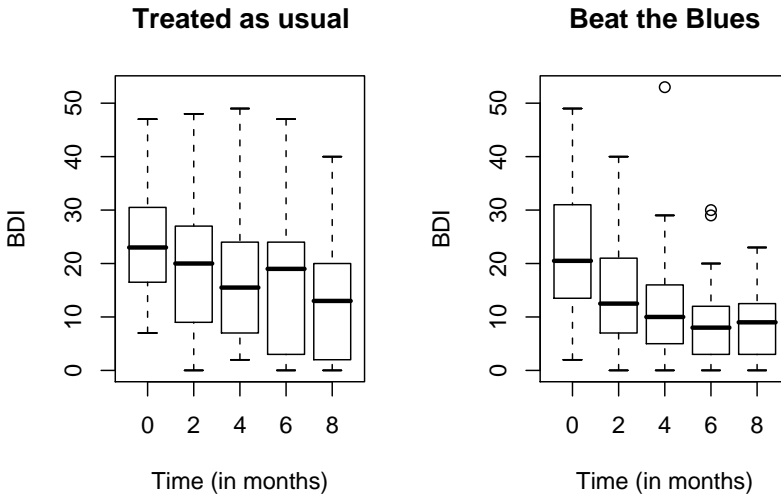


Figure 10.1 Boxplots for the repeated measures by treatment group for the `BtheB` data.

| | | | | | | | |
|------|-----|-----|--------------|----|---|---|----|
| 2.8m | Yes | >6m | <i>BtheB</i> | 32 | 2 | 8 | 20 |
| 3.8m | Yes | <6m | <i>TAU</i> | 25 | 3 | 8 | NA |

The resulting `data.frame` `BtheB_long` contains a number of missing values and in applying the `lmer` function these will be dropped. But notice it is only the missing values that are removed, *not* participants that have at least one missing value. All the available data is used in the model fitting process. The `lmer` function is used in a similar way to the `lm` function met in Chapter ?? with the addition of a random term to identify the source of the repeated

measurements, here `subject`. We can fit the two models (??) and (??) and test which is most appropriate using

```
R> library("lme4")
R> BtheB_lmer1 <- lmer(bdi ~ bdi.pre + time + treatment + drug +
+   length + (1 | subject), data = BtheB_long,
+   method = "ML", na.action = na.omit)
R> BtheB_lmer2 <- lmer(bdi ~ bdi.pre + time + treatment + drug +
+   length + (time | subject), data = BtheB_long,
+   method = "ML", na.action = na.omit)
R> anova(BtheB_lmer1, BtheB_lmer2)
```

Data: BtheB_long

Models:

BtheB_lmer1: bdi ~ bdi.pre + time + treatment + drug + length + (1 | subject)

BtheB_lmer2: bdi ~ bdi.pre + time + treatment + drug + length + (time | subject)

| | Df | AIC | BIC | logLik | Chisq | Chi | Df |
|--------------------|----|---------|---------|---------|--------|-----|----|
| <i>BtheB_lmer1</i> | 7 | 1884.62 | 1910.07 | -935.31 | | | |
| <i>BtheB_lmer2</i> | 9 | 1887.83 | 1920.54 | -934.91 | 0.7988 | | 2 |

BtheB_lmer1

BtheB_lmer2

Pr(>Chisq)

BtheB_lmer1

BtheB_lmer2 0.6707

```
R> summary(BtheB_lmer1)
Linear mixed-effects model fit by maximum likelihood
Formula: bdi ~ bdi.pre + time + treatment + drug + length + (1 | subject)
Data: BtheB_long
   AIC   BIC logLik MLdeviance REMLdeviance
1885 1910 -935.3      1871          1866
Random effects:
Groups   Name          Variance Std.Dev.
subject (Intercept) 48.299    6.9498
Residual                25.129    5.0128
number of obs: 280, groups: subject, 97

Fixed effects:
              Estimate Std. Error t value
(Intercept)    5.94372    2.24915   2.643
bdi.pre         0.63819    0.07759   8.225
time           -0.71703    0.14606  -4.909
treatmentBtheB -2.37311    1.66368  -1.426
drugYes        -2.79786    1.71993  -1.627
length>6m      0.25639    1.63213   0.157

Correlation of Fixed Effects:
              (Intr) bdi.pr time   trtmBB drugYs
bdi.pre      -0.678
time         -0.264  0.023
tretmntBthB -0.389  0.121  0.022
drugYes      -0.071 -0.237 -0.025 -0.323
length>6m   -0.238 -0.242 -0.043  0.002  0.158
```

Figure 10.2 R output of the linear mixed-effects model fit for the BtheB data.

Bibliography

- Bates, D. (2005), “Fitting linear mixed models in R,” *R News*, 5, 27–30, URL <http://CRAN.R-project.org/doc/Rnews/>.
- Bates, D. and Sarkar, D. (2006), *lme4: Linear Mixed-Effects Models Using S4 Classes*, URL <http://CRAN.R-project.org>, R package version 0.9975-10.
- Pinheiro, J. C. and Bates, D. M. (2000), *Mixed-Effects Models in S and S-PLUS*, New York, USA: Springer.

Analysing Longitudinal Data II – Generalised Estimation Equations: Treating Respiratory Illness and Epileptic Seizures

11.1 Introduction

11.2 Generalised Estimating Equations

11.3 Analysis Using R

11.3.1 *Beat the Blues Revisited*

To use the `gee` function, package *gee* (Carey et al., 2006) has to be installed and attached:

```
R> library("gee")
```

The `gee` function is used in a similar way to the `lme` function met in Chapter 10, with the addition of the features of the `glm` function that specify the appropriate error distribution for the response and the implied link function, and an argument to specify the structure of the working correlation matrix. Here we will fit an independence structure and then an exchangeable structure. The R code for fitting generalised estimation equations to the `BtheB_long` data (as constructed in Chapter 10, with identity working correlation matrix) is as follows (note that the `gee` function assumes the rows of the *data.frame* `BtheB_long` to be ordered with respect to subjects)

```
R> osub <- order(as.integer(BtheB_long$subject))
R> BtheB_long <- BtheB_long[osub,]
R> btb_gee <- gee(bdi ~ bdi.pre + treatment + length + drug,
+               data = BtheB_long, id = subject, family = gaussian,
+               corstr = "independence")
```

and with exchangeable correlation matrix

```
R> btb_gee1 <- gee(bdi ~ bdi.pre + treatment + length + drug,
+                 data = BtheB_long, id = subject, family = gaussian,
+                 corstr = "exchangeable")
```

The `summary` method can be used to inspect the fitted models; the results are shown in Figures 11.1 and 11.2

11.3.2 Respiratory Illness

The baseline status, i.e., the status for `month == 0`, will enter the models as an explanatory variable and thus we have to rearrange the *data.frame* `respiratory` in order to create a new variable `baseline`:

```
R> data("respiratory", package = "HSAUR")
R> resp <- subset(respiratory, month > "0")
R> resp$baseline <- rep(subset(respiratory, month == "0")$status, rep(4, 1))
R> resp$nstat <- as.numeric(resp$status == "good")
```

The new variable `nstat` is simply a dummy coding for a poor respiratory status. Now we can use the data `resp` to fit a logistic regression model and GEE models with an independent and an exchangeable correlation structure as follows;

```
R> resp_glm <- glm(status ~ centre + treatment + sex + baseline +
+   age, data = resp, family = "binomial")
R> resp_gee1 <- gee(nstat ~ centre + treatment + sex + baseline +
+   age, data = resp, family = "binomial", id = subject,
+   corstr = "independence", scale.fix = TRUE, scale.value = 1)
R> resp_gee2 <- gee(nstat ~ centre + treatment + sex + baseline +
+   age, data = resp, family = "binomial", id = subject,
+   corstr = "exchangeable", scale.fix = TRUE, scale.value = 1)
```

```
R> summary(btb_gee)
```

```
GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)
```

```
Model:
```

```
Link: Identity
Variance to Mean Relation: Gaussian
Correlation Structure: Independent
```

```
Call:
```

```
gee(formula = bdi ~ bdi.pre + treatment + length + drug, id = subject,
     data = BtheB_long, family = gaussian, corstr = "independence")
```

```
Summary of Residuals:
```

| | Min | 1Q | Median | 3Q | Max |
|--|-------------|------------|-----------|-----------|------------|
| | -21.6497810 | -5.8485100 | 0.1131663 | 5.5838383 | 28.1871039 |

```
Coefficients:
```

| | Estimate | Naive S.E. | Naive z | Robust S.E. |
|----------------|------------|------------|-----------|-------------|
| (Intercept) | 3.5686314 | 1.4833349 | 2.405816 | 2.26947617 |
| bdi.pre | 0.5818494 | 0.0563904 | 10.318235 | 0.09156455 |
| treatmentBtheB | -3.2372285 | 1.1295569 | -2.865928 | 1.77459534 |
| length>6m | 1.4577182 | 1.1380277 | 1.280916 | 1.48255866 |
| drugYes | -3.7412982 | 1.1766321 | -3.179667 | 1.78271179 |
| | Robust z | | | |
| (Intercept) | 1.5724472 | | | |
| bdi.pre | 6.3545274 | | | |
| treatmentBtheB | -1.8242066 | | | |
| length>6m | 0.9832449 | | | |
| drugYes | -2.0986557 | | | |

```
Estimated Scale Parameter: 79.25813
```

```
Number of Iterations: 1
```

```
Working Correlation
```

| | [,1] | [,2] | [,3] | [,4] |
|------|------|------|------|------|
| [1,] | 1 | 0 | 0 | 0 |
| [2,] | 0 | 1 | 0 | 0 |
| [3,] | 0 | 0 | 1 | 0 |
| [4,] | 0 | 0 | 0 | 1 |

Figure 11.1 R output of the `summary` method for the `btb_gee` model.

```
R> summary(btb_gee1)

GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)

Model:
Link: Identity
Variance to Mean Relation: Gaussian
Correlation Structure: Exchangeable

Call:
gee(formula = bdi ~ bdi.pre + treatment + length + drug, id = subject,
    data = BtheB_long, family = gaussian, corstr = "exchangeable")

Summary of Residuals:
      Min       1Q   Median       3Q      Max
-23.955980  -6.643864  -1.109741   4.257688  25.452310

Coefficients:
              Estimate Naive S.E.      Naive z Robust S.E.
(Intercept)  3.0231602  2.30390185   1.31219140  2.23204410
bdi.pre      0.6479276  0.08228567   7.87412417  0.08351405
treatmentBtheB -2.1692863  1.76642861  -1.22806339  1.73614385
length>6m    -0.1112910  1.73091679  -0.06429596  1.55092705
drugYes      -2.9995608  1.82569913  -1.64296559  1.73155411
              Robust z
(Intercept)  1.3544357
bdi.pre      7.7583066
treatmentBtheB -1.2494854
length>6m    -0.0717577
drugYes      -1.7322940

Estimated Scale Parameter: 81.7349
Number of Iterations: 5

Working Correlation
      [,1]      [,2]      [,3]      [,4]
[1,] 1.0000000  0.6757951  0.6757951  0.6757951
[2,] 0.6757951  1.0000000  0.6757951  0.6757951
[3,] 0.6757951  0.6757951  1.0000000  0.6757951
[4,] 0.6757951  0.6757951  0.6757951  1.0000000
```

Figure 11.2 R output of the `summary` method for the `btb_gee1` model.

```
R> summary(resp_glm)
```

```
Call:
```

```
glm(formula = status ~ centre + treatment + sex + baseline +
     age, family = "binomial", data = resp)
```

```
Deviance Residuals:
```

```
      Min       1Q   Median       3Q      Max
-2.3146 -0.8551  0.4336  0.8953  1.9246
```

```
Coefficients:
```

| | Estimate | Std. Error | z value | Pr(> z) | |
|--------------------|-----------|------------|---------|----------|-----|
| (Intercept) | -0.900171 | 0.337653 | -2.666 | 0.00768 | ** |
| centre2 | 0.671601 | 0.239567 | 2.803 | 0.00506 | ** |
| treatmenttreatment | 1.299216 | 0.236841 | 5.486 | 4.12e-08 | *** |
| sexmale | 0.119244 | 0.294671 | 0.405 | 0.68572 | |
| baselinegood | 1.882029 | 0.241290 | 7.800 | 6.20e-15 | *** |
| age | -0.018166 | 0.008864 | -2.049 | 0.04043 | * |

```
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
(Dispersion parameter for binomial family taken to be 1)
```

```
Null deviance: 608.93 on 443 degrees of freedom
Residual deviance: 483.22 on 438 degrees of freedom
AIC: 495.22
```

```
Number of Fisher Scoring iterations: 4
```

Figure 11.3 R output of the `summary` method for the `resp_glm` model.

```
R> summary(resp_gee1)
```

```
GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)
```

```
Model:
```

```
Link:                               Logit
Variance to Mean Relation: Binomial
Correlation Structure:               Independent
```

```
Call:
```

```
gee(formula = nstat ~ centre + treatment + sex + baseline + age,
     id = subject, data = resp, family = "binomial", corstr = "independence",
     scale.fix = TRUE, scale.value = 1)
```

```
Summary of Residuals:
```

| | Min | 1Q | Median | 3Q | Max |
|--|-------------|-------------|------------|------------|------------|
| | -0.93134415 | -0.30623174 | 0.08973552 | 0.33018952 | 0.84307712 |

```
Coefficients:
```

| | Estimate | Naive S.E. | Naive z |
|--------------------|-------------|-------------|-----------|
| (Intercept) | -0.90017133 | 0.337653052 | -2.665965 |
| centre2 | 0.67160098 | 0.239566599 | 2.803400 |
| treatmenttreatment | 1.29921589 | 0.236841017 | 5.485603 |
| sexmale | 0.11924365 | 0.294671045 | 0.404667 |
| baselinegood | 1.88202860 | 0.241290221 | 7.799854 |
| age | -0.01816588 | 0.008864403 | -2.049306 |

| | Robust S.E. | Robust z |
|--------------------|-------------|------------|
| (Intercept) | 0.46032700 | -1.9555041 |
| centre2 | 0.35681913 | 1.8821889 |
| treatmenttreatment | 0.35077797 | 3.7038127 |
| sexmale | 0.44320235 | 0.2690501 |
| baselinegood | 0.35005152 | 5.3764332 |
| age | 0.01300426 | -1.3969169 |

```
Estimated Scale Parameter: 1
```

```
Number of Iterations: 1
```

```
Working Correlation
```

| | [,1] | [,2] | [,3] | [,4] |
|------|------|------|------|------|
| [1,] | 1 | 0 | 0 | 0 |
| [2,] | 0 | 1 | 0 | 0 |
| [3,] | 0 | 0 | 1 | 0 |
| [4,] | 0 | 0 | 0 | 1 |

Figure 11.4 R output of the `summary` method for the `resp_gee1` model.

```
R> summary(resp_gee2)
```

```
GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)
```

```
Model:
```

```
Link:                      Logit
Variance to Mean Relation: Binomial
Correlation Structure:     Exchangeable
```

```
Call:
```

```
gee(formula = nstat ~ centre + treatment + sex + baseline + age,
     id = subject, data = resp, family = "binomial", corstr = "exchangeable",
     scale.fix = TRUE, scale.value = 1)
```

```
Summary of Residuals:
```

| | Min | 1Q | Median | 3Q | Max |
|--|-------------|-------------|------------|------------|------------|
| | -0.93134415 | -0.30623174 | 0.08973552 | 0.33018952 | 0.84307712 |

```
Coefficients:
```

| | Estimate | Naive S.E. | Naive z |
|--------------------|-------------|------------|------------|
| (Intercept) | -0.90017133 | 0.47846344 | -1.8813796 |
| centre2 | 0.67160098 | 0.33947230 | 1.9783676 |
| treatmenttreatment | 1.29921589 | 0.33561008 | 3.8712064 |
| sexmale | 0.11924365 | 0.41755678 | 0.2855747 |
| baselinegood | 1.88202860 | 0.34191472 | 5.5043802 |
| age | -0.01816588 | 0.01256110 | -1.4462014 |
| | Robust S.E. | Robust z | |
| (Intercept) | 0.46032700 | -1.9555041 | |
| centre2 | 0.35681913 | 1.8821889 | |
| treatmenttreatment | 0.35077797 | 3.7038127 | |
| sexmale | 0.44320235 | 0.2690501 | |
| baselinegood | 0.35005152 | 5.3764332 | |
| age | 0.01300426 | -1.3969169 | |

```
Estimated Scale Parameter: 1
```

```
Number of Iterations: 1
```

```
Working Correlation
```

| | [,1] | [,2] | [,3] | [,4] |
|------|-----------|-----------|-----------|-----------|
| [1,] | 1.0000000 | 0.3359883 | 0.3359883 | 0.3359883 |
| [2,] | 0.3359883 | 1.0000000 | 0.3359883 | 0.3359883 |
| [3,] | 0.3359883 | 0.3359883 | 1.0000000 | 0.3359883 |
| [4,] | 0.3359883 | 0.3359883 | 0.3359883 | 1.0000000 |

Figure 11.5 R output of the summary method for the resp_gee2 model.

The estimated treatment effect taken from the exchangeable structure GEE model is 1.299 which, using the robust standard errors, has an associated 95% confidence interval

```
R> se <- summary(resp_gee2)$coefficients["treatmenttreatment",
+                                       "Robust S.E."]
R> coef(resp_gee2)["treatmenttreatment"] +
+   c(-1, 1) * se * qnorm(0.975)
[1] 0.6117037 1.9867281
```

These values reflect effects on the log-odds scale. Interpretation becomes simpler if we exponentiate the values to get the effects in terms of odds. This gives a treatment effect of 3.666 and a 95% confidence interval of

```
R> exp(coef(resp_gee2)["treatmenttreatment"] +
+     c(-1, 1) * se * qnorm(0.975))
[1] 1.843570 7.291637
```

The odds of achieving a ‘good’ respiratory status with the active treatment is between about twice and seven times the corresponding odds for the placebo.

11.3.3 Epilepsy

Moving on to the count data in `epilepsy` from Table ??, we begin by calculating the means and variances of the number of seizures for all treatment / period interactions

```
R> data("epilepsy", package = "HSAUR")
R> itp <- interaction(epilepsy$treatment, epilepsy$period)
R> tapply(epilepsy$seizure.rate, itp, mean)
  placebo.1 Progabide.1 placebo.2 Progabide.2 placebo.3
  9.357143   8.580645   8.285714   8.419355   8.785714
Progabide.3 placebo.4 Progabide.4
  8.129032   7.964286   6.709677

R> tapply(epilepsy$seizure.rate, itp, var)
  placebo.1 Progabide.1 placebo.2 Progabide.2 placebo.3
  102.75661  332.71828   66.65608  140.65161  215.28571
Progabide.3 placebo.4 Progabide.4
  193.04946   58.18386  126.87957
```

Some of the variances are considerably larger than the corresponding means, which for a Poisson variable may suggest that overdispersion may be a problem, see Chapter ?. We can now fit a Poisson regression model to the data assuming independence using the `glm` function. We also use the GEE approach to fit an independence structure, followed by an exchangeable structure using the following R code:

```
R> per <- rep(log(2), nrow(epilepsy))
R> epilepsy$period <- as.numeric(epilepsy$period)
```

```

R> layout(matrix(1:2, nrow = 1))
R> ylim <- range(epilepsy$seizure.rate)
R> placebo <- subset(epilepsy, treatment == "placebo")
R> progabide <- subset(epilepsy, treatment == "Progabide")
R> boxplot(seizure.rate ~ period, data = placebo,
+         ylab = "Number of seizures",
+         xlab = "Period", ylim = ylim, main = "Placebo")
R> boxplot(seizure.rate ~ period, data = progabide,
+         main = "Progabide", ylab = "Number of seizures",
+         xlab = "Period", ylim = ylim)

```

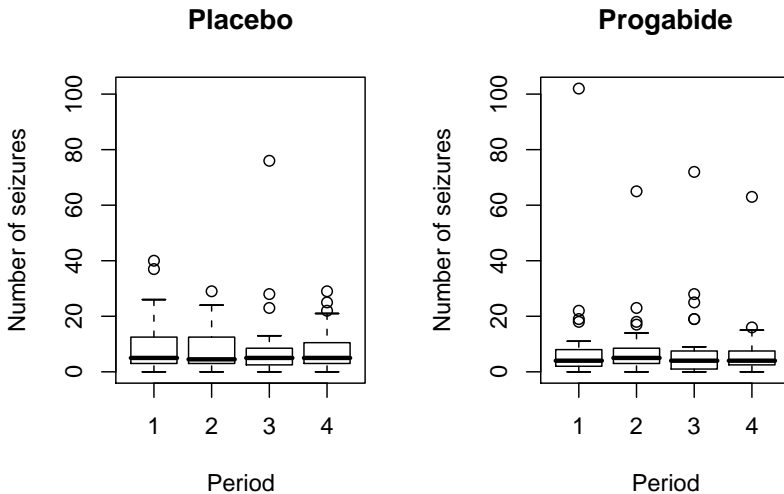


Figure 11.6 Boxplots of numbers of seizures in each two-week period post randomisation for placebo and active treatments.

```

R> fm <- seizure.rate ~ base + age + treatment + offset(per)
R> epilepsy_glm <- glm(fm, data = epilepsy, family = "poisson")
R> epilepsy_gee1 <- gee(fm, data = epilepsy, family = "poisson",
+   id = subject, corstr = "independence", scale.fix = TRUE,
+   scale.value = 1)
R> epilepsy_gee2 <- gee(fm, data = epilepsy, family = "poisson",
+   id = subject, corstr = "exchangeable", scale.fix = TRUE,
+   scale.value = 1)
R> epilepsy_gee3 <- gee(fm, data = epilepsy, family = "poisson",
+   id = subject, corstr = "exchangeable", scale.fix = FALSE,
+   scale.value = 1)

```

```
R> layout(matrix(1:2, nrow = 1))
R> ylim <- range(log(epilepsy$seizure.rate + 1))
R> boxplot(log(seizure.rate + 1) ~ period, data = placebo,
+         main = "Placebo", ylab = "Log number of seizures",
+         xlab = "Period", ylim = ylim)
R> boxplot(log(seizure.rate + 1) ~ period, data = progabide,
+         main = "Progabide", ylab = "Log number of seizures",
+         xlab = "Period", ylim = ylim)
```

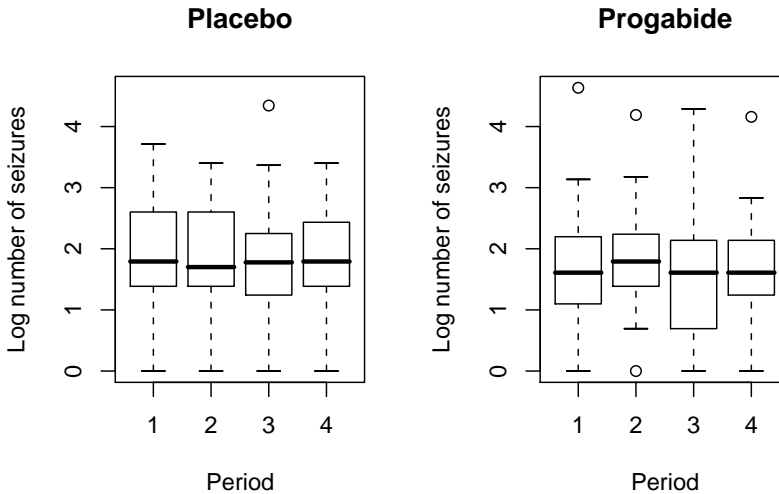


Figure 11.7 Boxplots of log of numbers of seizures in each two-week period post randomisation for placebo and active treatments.

As usual we inspect the fitted models using the `summary` method, the results are given in Figures 11.8, 11.9, 11.10, and 11.11.

```
R> summary(epilepsy_glm)

Call:
glm(formula = fm, family = "poisson", data = epilepsy)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-4.4360  -1.4034  -0.5029   0.4842  12.3223

Coefficients:
                Estimate Std. Error z value Pr(>|z|)
(Intercept)    -0.1306156  0.1356191  -0.963  0.33549
base             0.0226517  0.0005093  44.476 < 2e-16 ***
age             0.0227401  0.0040240   5.651 1.59e-08 ***
treatmentProgabide -0.1527009  0.0478051  -3.194  0.00140 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 2521.75  on 235  degrees of freedom
Residual deviance:  958.46  on 232  degrees of freedom
AIC: 1732.5

Number of Fisher Scoring iterations: 5
```

Figure 11.8 R output of the `summary` method for the `epilepsy_glm` model.

```
R> summary(epilepsy_gee1)

GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)

Model:
Link:                               Logarithm
Variance to Mean Relation: Poisson
Correlation Structure:               Independent

Call:
gee(formula = fm, id = subject, data = epilepsy, family = "poisson",
     corstr = "independence", scale.fix = TRUE, scale.value = 1)

Summary of Residuals:
      Min       1Q   Median       3Q      Max
-4.9195387  0.1808059  1.7073405  4.8850644  69.9658560

Coefficients:
              Estimate   Naive S.E.   Naive z
(Intercept)   -0.13061561  0.1356191185 -0.9631062
base           0.02265174  0.0005093011  44.4761250
age            0.02274013  0.0040239970  5.6511312
treatmentProgabide -0.15270095  0.0478051054 -3.1942393

              Robust S.E.   Robust z
(Intercept)   0.365148155 -0.3577058
base           0.001235664  18.3316325
age            0.011580405  1.9636736
treatmentProgabide 0.171108915 -0.8924196

Estimated Scale Parameter: 1
Number of Iterations: 1

Working Correlation
      [,1] [,2] [,3] [,4]
[1,]  1   0   0   0
[2,]  0   1   0   0
[3,]  0   0   1   0
[4,]  0   0   0   1
```

Figure 11.9 R output of the summary method for the epilepsy_gee1 model.

```
R> summary(epilepsy_gee2)

GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)

Model:
Link:                               Logarithm
Variance to Mean Relation: Poisson
Correlation Structure:               Exchangeable

Call:
gee(formula = fm, id = subject, data = epilepsy, family = "poisson",
    corstr = "exchangeable", scale.fix = TRUE, scale.value = 1)

Summary of Residuals:
      Min       1Q   Median       3Q      Max
-4.9195387  0.1808059  1.7073405  4.8850644 69.9658560

Coefficients:
              Estimate   Naive S.E.   Naive z
(Intercept) -0.13061561  0.2004416507 -0.651639
base         0.02265174  0.0007527342 30.092612
age          0.02274013  0.0059473665  3.823564
treatmentProgabide -0.15270095  0.0706547450 -2.161227
              Robust S.E.   Robust z
(Intercept)  0.365148155 -0.3577058
base         0.001235664 18.3316325
age          0.011580405  1.9636736
treatmentProgabide 0.171108915 -0.8924196

Estimated Scale Parameter: 1
Number of Iterations: 1

Working Correlation
      [,1]      [,2]      [,3]      [,4]
[1,] 1.0000000 0.3948033 0.3948033 0.3948033
[2,] 0.3948033 1.0000000 0.3948033 0.3948033
[3,] 0.3948033 0.3948033 1.0000000 0.3948033
[4,] 0.3948033 0.3948033 0.3948033 1.0000000
```

Figure 11.10 R output of the summary method for the epilepsy_gee2 model.

```
R> summary(epilepsy_gee3)

GEE: GENERALIZED LINEAR MODELS FOR DEPENDENT DATA
gee S-function, version 4.13 modified 98/01/27 (1998)

Model:
Link:                      Logarithm
Variance to Mean Relation: Poisson
Correlation Structure:     Exchangeable

Call:
gee(formula = fm, id = subject, data = epilepsy, family = "poisson",
    corstr = "exchangeable", scale.fix = FALSE, scale.value = 1)

Summary of Residuals:
      Min       1Q   Median       3Q      Max
-4.9195387  0.1808059  1.7073405  4.8850644  69.9658560

Coefficients:
              Estimate Naive S.E.   Naive z
(Intercept)   -0.13061561  0.452199543  -0.2888451
base           0.02265174  0.001698180  13.3388301
age            0.02274013  0.013417353   1.6948302
treatmentProgabide -0.15270095  0.159398225  -0.9579840
              Robust S.E.   Robust z
(Intercept)   0.365148155  -0.3577058
base           0.001235664  18.3316325
age            0.011580405   1.9636736
treatmentProgabide 0.171108915  -0.8924196

Estimated Scale Parameter:  5.089608
Number of Iterations:  1

Working Correlation
      [,1]      [,2]      [,3]      [,4]
[1,] 1.0000000  0.3948033  0.3948033  0.3948033
[2,] 0.3948033  1.0000000  0.3948033  0.3948033
[3,] 0.3948033  0.3948033  1.0000000  0.3948033
[4,] 0.3948033  0.3948033  0.3948033  1.0000000
```

Figure 11.11 R output of the `summary` method for the `epilepsy_gee3` model.

Bibliography

Carey, V. J., Lumley, T., and Ripley, B. D. (2006), *gee: Generalized Estimation Equation Solver*, URL <http://CRAN.R-project.org>, R package version 4.13-11.

Meta-Analysis: Nicotine Gum and Smoking Cessation and the Efficacy of BCG Vaccine in the Treatment of Tuberculosis

12.1 Introduction

12.2 Systematic Reviews and Meta-Analysis

12.3 Analysis Using R

The aim in collecting the results from the randomised trials of using nicotine gum to help smokers quit was to estimate the overall *odds ratio*, the odds of quitting smoking for those given the gum, divided by the odds of quitting for those not receiving the gum. The odds ratios and corresponding confidence intervals are computed by means of the `meta.MH` function for fixed effects meta-analysis as shown here

```
R> library("rmeta")
R> data("smoking", package = "HSAUR")
R> smokingOR <- meta.MH(smoking[["tt"]], smoking[["tc"]],
+                       smoking[["qt"]], smoking[["qc"]],
+                       names = rownames(smoking))
```

and the results can be inspected via a `summary` method – see Figure 12.1.

We shall use both the fixed effects and random effects approaches here so that we can compare results. For the fixed effects model (see Figure 12.1) the estimated overall log-odds ratio is 0.513 with a standard error of 0.066. This leads to an estimate of the overall odds ratio of 1.67, with a 95% confidence interval as given above. For the random effects model

```
R> smokingDSL <- meta.DSL(smoking[["tt"]], smoking[["tc"]],
+                         smoking[["qt"]], smoking[["qc"]],
+                         names = rownames(smoking))
R> print(smokingDSL)
```

```
Random effects ( DerSimonian-Laird ) meta-analysis
Call: meta.DSL(ntrt = smoking[["tt"]], nctrl = smoking[["tc"]], pprt =
  pctrl = smoking[["qc"]], names = rownames(smoking))
Summary OR= 1.75      95% CI ( 1.48, 2.07 )
Estimated random effects variance: 0.05
```

```
R> summary(smokingOR)
Fixed effects ( Mantel-Haenszel ) meta-analysis
Call: meta.MH(ntrt = smoking[["tt"]], nctrl = smoking[["tc"]], ptrt = s
      pctrl = smoking[["qc"]], names = rownames(smoking))
-----
              OR (lower 95% upper)
Blondal89    1.85    0.99    3.46
Campbell91   0.98    0.50    1.92
Fagerstrom82 1.76    0.80    3.89
Fee82        1.53    0.77    3.05
Garcia89     2.95    1.01    8.62
Garvey00     2.49    1.43    4.34
Gross95      2.62    1.03    6.71
Hall85       2.03    0.78    5.29
Hall87       2.82    1.33    5.99
Hall96       0.87    0.46    1.64
Hjalmarson84 2.17    1.10    4.28
Huber88      6.00    2.57   14.01
Jarvis82     3.33    1.37    8.08
Jensen91     1.43    0.84    2.44
Killen84     1.33    0.43    4.15
Killen90     1.23    0.93    1.64
Malcolm80    3.52    0.85   14.54
McGovern92   1.17    0.70    1.94
Nakamura90   3.82    1.15   12.71
Niaura94     1.34    0.35    5.19
Pirie92      1.84    1.20    2.82
Puska79      1.46    0.78    2.75
Schneider85  1.71    0.52    5.62
Tonnesen88   2.12    0.93    4.86
Villa99      1.76    0.55    5.64
Zelman92     1.46    0.68    3.14
-----
Mantel-Haenszel OR =1.67 95% CI ( 1.47,1.9 )
Test for heterogeneity: X^2( 25 ) = 34.9 ( p-value 0.09 )
```

Figure 12.1 R output of the `summary` method for `smokingOR`.

the corresponding estimate is 1.751. Both models suggest that there is clear evidence that nicotine gum increases the odds of quitting. The random effects confidence interval is considerably wider than that from the fixed effects model; here the test of homogeneity of the studies is not significant implying that we might use the fixed effects results. But the test is not particularly powerful and it is more sensible to assume a priori that heterogeneity is present and so we use the results from the random effects model.

```
R> plot(smokingOR, ylab = "")
```

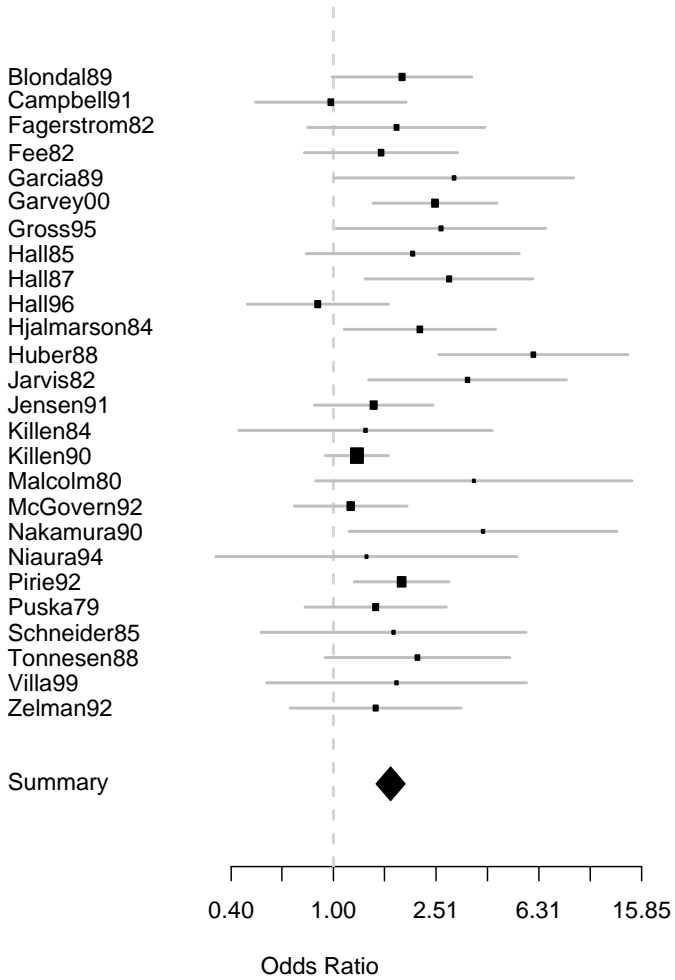


Figure 12.2 Forest plot of observed effect sizes and 95% confidence intervals for the nicotine gum studies.

12.4 Meta-Regression

The examination of heterogeneity of the effect sizes from the studies in a meta-analysis begins with the formal test for its presence, although in most meta-analyses such heterogeneity can almost be assumed to be present. There will be many possible sources of such heterogeneity and estimating how these various factors affect the observed effect sizes in the studies chosen is often of considerable interest and importance, indeed usually more important than the relatively simplistic use of meta-analysis to determine a single summary estimate of overall effect size. We can illustrate the process using the BCG vaccine data. We first find the estimate of the overall effect size from applying the fixed effects and the random effects models described previously:

```
R> data("BCG", package = "HSAUR")
R> BCG_OR <- meta.MH(BCG[["BCGVacc"]], BCG[["NoVacc"]],
+                   BCG[["BCGTB"]], BCG[["NoVaccTB"]],
+                   names = BCG$Study)
R> BCG_DSL <- meta.DSL(BCG[["BCGVacc"]], BCG[["NoVacc"]],
+                     BCG[["BCGTB"]], BCG[["NoVaccTB"]],
+                     names = BCG$Study)
```

The results are inspected using the `summary` method as shown in Figures 12.3 and 12.4.

To assess how the two covariates, latitude and year, relate to the observed effect sizes we shall use multiple linear regression but will weight each observation by $W_i = (\hat{\sigma}^2 + V_i^2)^{-1}$, $i = 1, \dots, 13$, where $\hat{\sigma}^2$ is the estimated between-study variance and V_i^2 is the estimated variance from the i th study. The required R code to fit the linear model via weighted least squares is:

```
R> studyweights <- 1 / (BCG_DSL$tau2 + BCG_DSL$selogs^2)
R> y <- BCG_DSL$logS
R> BCG_mod <- lm(y ~ Latitude + Year, data = BCG,
+               weights = studyweights)
```

and the results of the `summary` method are shown in Figure 12.5. There is some evidence that latitude is associated with observed effect size, the log-odds ratio becoming increasingly negative as latitude increases, as we can see from a scatterplot of the two variables with the added weighted regression fit seen in Figure 12.6.

12.5 Publication Bias

We can construct a funnel plot for the nicotine gum data using the R code depicted with Figure 12.8. There does not appear to be any strong evidence of publication bias here.

```
R> summary(BCG_OR)
Fixed effects ( Mantel-Haenszel ) meta-analysis
Call: meta.MH(ntrt = BCG[["BCGVacc"]], nctrl = BCG[["NoVacc"]], ptrt =
  pctrl = BCG[["NoVaccTB"]], names = BCG$Study)
-----
      OR (lower 95% upper)
1  0.39   0.12   1.26
2  0.19   0.08   0.46
3  0.25   0.07   0.91
4  0.23   0.18   0.31
5  0.80   0.51   1.26
6  0.38   0.32   0.47
7  0.20   0.08   0.50
8  1.01   0.89   1.15
9  0.62   0.39   1.00
10 0.25   0.14   0.42
11 0.71   0.57   0.89
12 1.56   0.37   6.55
13 0.98   0.58   1.66
-----
Mantel-Haenszel OR =0.62 95% CI ( 0.57,0.68 )
Test for heterogeneity: X^2( 12 ) = 163.94 ( p-value 0 )
```

Figure 12.3 R output of the summary method for BCG_OR.

```
R> summary(BCG_DSL)
```

```
Random effects ( DerSimonian-Laird ) meta-analysis
```

```
Call: meta.DSL(ntrt = BCG[["BCGVacc"]], nctrl = BCG[["NoVacc"]], ptrt =  
  pctrl = BCG[["NoVaccTB"]], names = BCG$Study)
```

```
-----  
      OR (lower 95% upper)  
1  0.39   0.12   1.26  
2  0.19   0.08   0.46  
3  0.25   0.07   0.91  
4  0.23   0.18   0.31  
5  0.80   0.51   1.26  
6  0.38   0.32   0.47  
7  0.20   0.08   0.50  
8  1.01   0.89   1.15  
9  0.62   0.39   1.00  
10 0.25   0.14   0.42  
11 0.71   0.57   0.89  
12 1.56   0.37   6.55  
13 0.98   0.58   1.66  
-----
```

```
SummaryOR= 0.47 95% CI ( 0.32,0.69 )
```

```
Test for heterogeneity:  $X^2(12) = 163.16$  ( p-value 0 )
```

```
Estimated random effects variance: 0.37
```

Figure 12.4 R output of the summary method for BCG_DSL.

```
R> summary(BCG_mod)
```

```
Call:
```

```
lm(formula = y ~ Latitude + Year, data = BCG, weights = studyweights)
```

```
Residuals:
```

```
      Min       1Q   Median       3Q      Max
-1.66012 -0.36910 -0.02937  0.31565  1.26040
```

```
Coefficients:
```

```
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -16.199115  37.605403  -0.431   0.6758
Latitude     -0.025808   0.013680  -1.887   0.0886 .
Year          0.008279   0.018972   0.436   0.6718
```

```
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Residual standard error: 0.7992 on 10 degrees of freedom
```

```
Multiple R-Squared: 0.4387, Adjusted R-squared: 0.3265
```

```
F-statistic: 3.909 on 2 and 10 DF, p-value: 0.05569
```

Figure 12.5 R output of the `summary` method for `BCG_mod`.

```
R> plot(y ~ Latitude, data = BCG, ylab = "Estimated log-OR")  
R> abline(lm(y ~ Latitude, data = BCG, weights = studyweights))
```

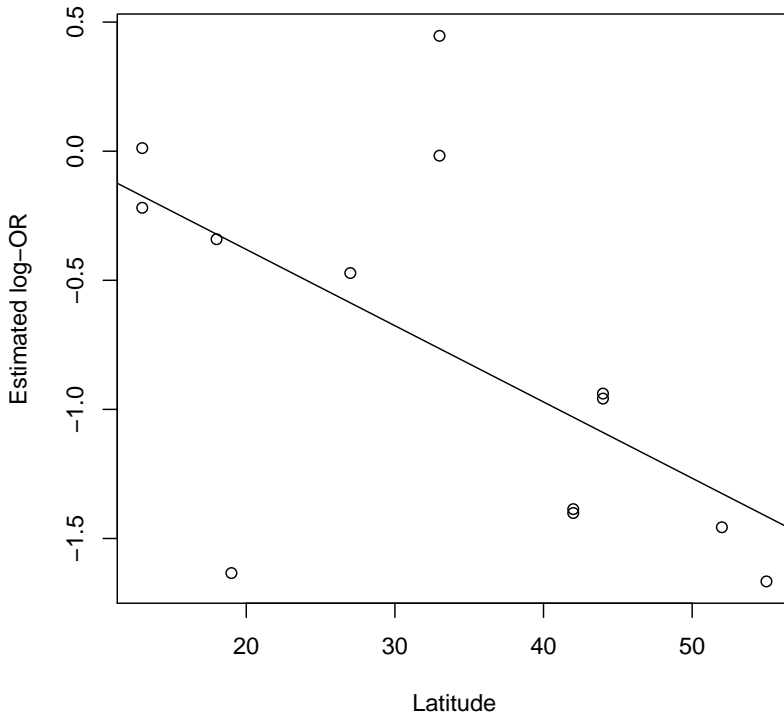


Figure 12.6 Plot of observed effect size for the BCG vaccine data against latitude, with a weighted least squares regression fit shown in addition.

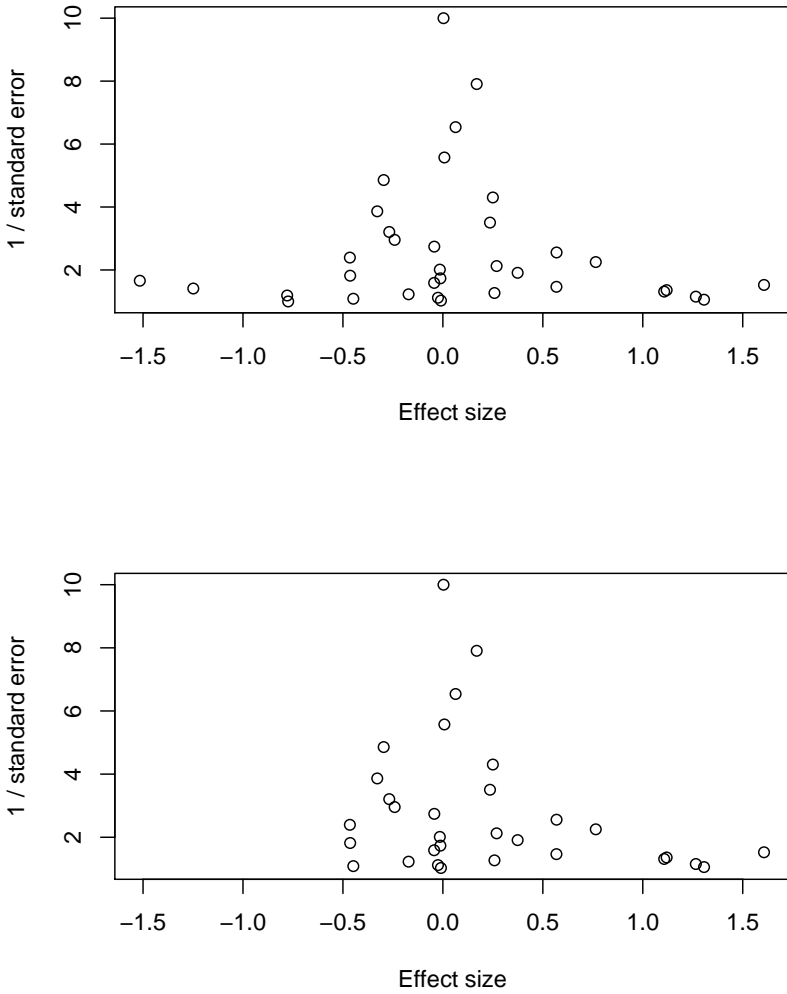


Figure 12.7 Example funnel plots from simulated data. The asymmetry in the lower plot is a hint that a publication bias might be a problem.

```
R> funnelplot(smokingDSL$logS, smokingDSL$sselogs,  
+             summ = smokingDSL$logDSL, xlim = c(-1.7, 1.7))  
R> abline(v = 0, lty = 2)
```

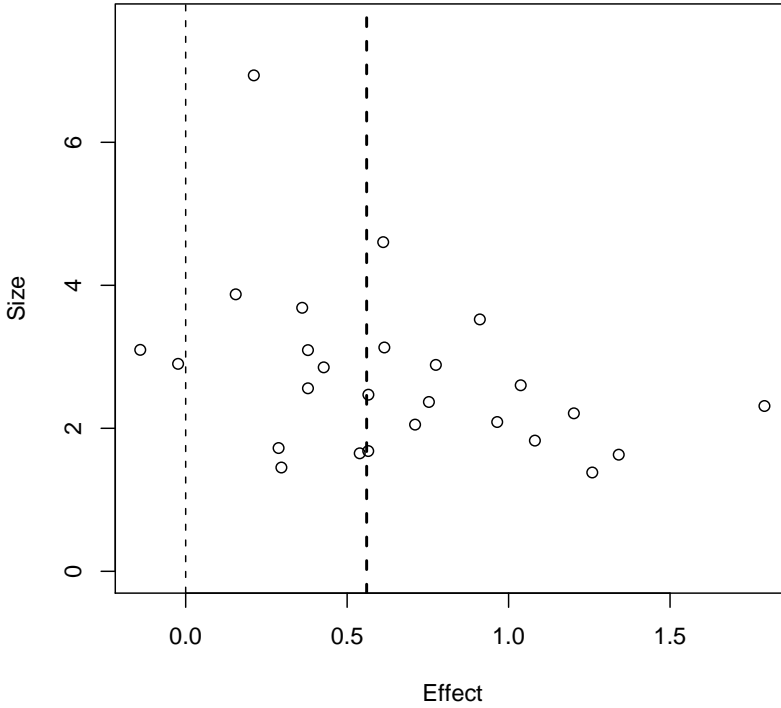


Figure 12.8 Funnel plot for nicotine gum data.

Principal Component Analysis: The Olympic Heptathlon

13.1 Introduction

13.2 Principal Component Analysis

13.3 Analysis Using R

To begin it will help to score all the seven events in the same direction, so that ‘large’ values are ‘good’. We will recode the running events to achieve this;

```
R> data("heptathlon", package = "HSAUR")
R> heptathlon$hurdles <- max(heptathlon$hurdles) -
+   heptathlon$hurdles
R> heptathlon$run200m <- max(heptathlon$run200m) -
+   heptathlon$run200m
R> heptathlon$run800m <- max(heptathlon$run800m) -
+   heptathlon$run800m
```

Figure 13.1 shows a scatterplot matrix of the results from the 25 competitors on the seven events. We see that most pairs of events are positively correlated to a greater or lesser degree. The exceptions all involve the javelin event – this is the only really ‘technical’ event and it is clear that training to become successful in the other six ‘power’-based events makes this event difficult for the majority of the competitors. We can examine the numerical values of the correlations by applying the `cor` function

```
R> round(cor(heptathlon[, -score]), 2)
```

| | <i>hurdles</i> | <i>highjump</i> | <i>shot</i> | <i>run200m</i> | <i>longjump</i> | <i>javelin</i> | <i>run800m</i> |
|-----------------|----------------|-----------------|-------------|----------------|-----------------|----------------|----------------|
| <i>hurdles</i> | 1.00 | 0.81 | 0.65 | 0.77 | 0.91 | 0.01 | 0.78 |
| <i>highjump</i> | 0.81 | 1.00 | 0.44 | 0.49 | 0.78 | 0.00 | 0.59 |
| <i>shot</i> | 0.65 | 0.44 | 1.00 | 0.68 | 0.74 | 0.27 | 0.42 |
| <i>run200m</i> | 0.77 | 0.49 | 0.68 | 1.00 | 0.82 | 0.33 | 0.62 |
| <i>longjump</i> | 0.91 | 0.78 | 0.74 | 0.82 | 1.00 | 0.07 | 0.70 |
| <i>javelin</i> | 0.01 | 0.00 | 0.27 | 0.33 | 0.07 | 1.00 | -0.02 |
| <i>run800m</i> | 0.78 | 0.59 | 0.42 | 0.62 | 0.70 | -0.02 | 1.00 |

This correlation matrix demonstrates again the points made earlier. A principal component analysis of the data can be applied using the `prcomp` function. The result is a list containing the coefficients defining each component (sometimes referred to as *loadings*), the principal component scores, etc. The required code is (omitting the `score` variable)

```
R> score <- which(colnames(heptathlon) == "score")
R> plot(heptathlon[, -score])
```

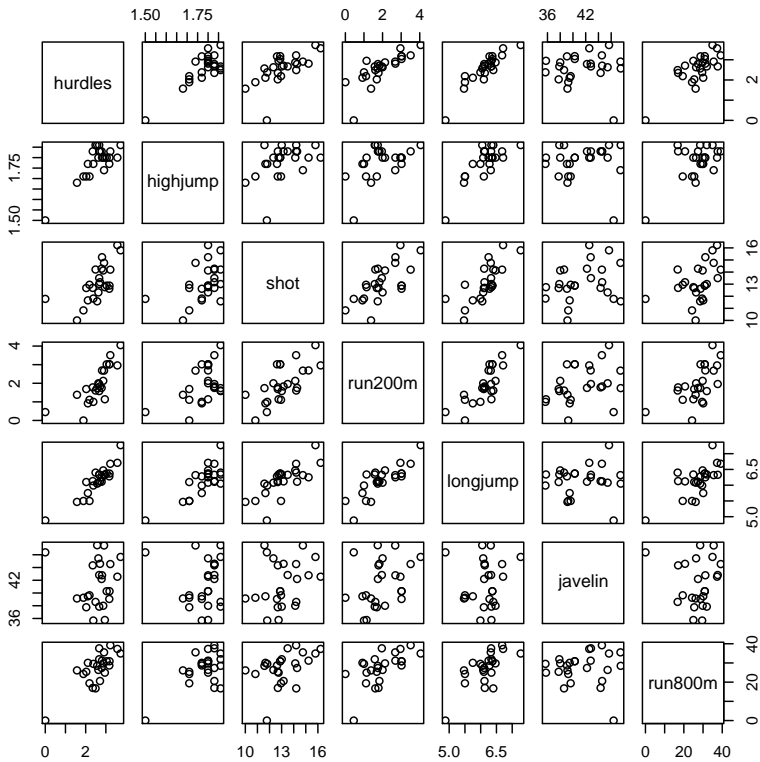


Figure 13.1 Scatterplot matrix for the heptathlon data.

```
R> heptathlon_pca <- prcomp(heptathlon[, -score], scale = TRUE)
R> print(heptathlon_pca)
```

Standard deviations:

```
[1] 2.1119364 1.0928497 0.7218131 0.6761411 0.4952441 0.2701029
[7] 0.2213617
```

Rotation:

| | PC1 | PC2 | PC3 | PC4 |
|----------|------------|-------------|-------------|-------------|
| hurdles | -0.4528710 | 0.15792058 | -0.04514996 | 0.02653873 |
| highjump | -0.3771992 | 0.24807386 | -0.36777902 | 0.67999172 |
| shot | -0.3630725 | -0.28940743 | 0.67618919 | 0.12431725 |
| run200m | -0.4078950 | -0.26038545 | 0.08359211 | -0.36106580 |
| longjump | -0.4562318 | 0.05587394 | 0.13931653 | 0.11129249 |

```

javelin  -0.0754090 -0.84169212 -0.47156016  0.12079924
run800m  -0.3749594  0.22448984 -0.39585671 -0.60341130
           PC5           PC6           PC7
hurdles  -0.09494792 -0.78334101  0.38024707
highjump  0.01879888  0.09939981 -0.43393114
shot      0.51165201 -0.05085983 -0.21762491
run200m  -0.64983404  0.02495639 -0.45338483
longjump -0.18429810  0.59020972  0.61206388
javelin  0.13510669 -0.02724076  0.17294667
run800m  0.50432116  0.15555520 -0.09830963

```

The `summary` method can be used for further inspection of the details:

```
R> summary(heptathlon_pca)
```

Importance of components:

| | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 |
|-------------------------------|-------|-------|--------|--------|--------|--------|
| <i>Standard deviation</i> | 2.112 | 1.093 | 0.7218 | 0.6761 | 0.4952 | 0.2701 |
| <i>Proportion of Variance</i> | 0.637 | 0.171 | 0.0744 | 0.0653 | 0.0350 | 0.0104 |
| <i>Cumulative Proportion</i> | 0.637 | 0.808 | 0.8822 | 0.9475 | 0.9826 | 0.9930 |
| | | | | | | |
| | PC7 | | | | | |
| <i>Standard deviation</i> | 0.221 | | | | | |
| <i>Proportion of Variance</i> | 0.007 | | | | | |
| <i>Cumulative Proportion</i> | 1.000 | | | | | |

The linear combination for the first principal component is

```
R> a1 <- heptathlon_pca$rotation[,1]
```

```
R> a1
```

```

hurdles  highjump      shot  run200m  longjump
-0.4528710 -0.3771992 -0.3630725 -0.4078950 -0.4562318
javelin  run800m
-0.0754090 -0.3749594

```

We see that the 200m and long jump competitions receive the highest weight but the javelin result is less important. For computing the first principal component, the data need to be rescaled appropriately. The center and the scaling used by `prcomp` internally can be extracted from the `heptathlon_pca` via

```
R> center <- heptathlon_pca$center
```

```
R> scale <- heptathlon_pca$scale
```

Now, we can apply the `scale` function to the data and multiply with the loadings matrix in order to compute the first principal component score for each competitor

```
R> hm <- as.matrix(heptathlon[, -score])
```

```
R> drop(scale(hm, center = center, scale = scale) %*%
```

```
+ heptathlon_pca$rotation[,1])
```

| | | |
|----------------------------|--------------------------|---------------------|
| <i>Joyner-Kersey (USA)</i> | <i>John (GDR)</i> | <i>Behmer (GDR)</i> |
| -4.121447626 | -2.882185935 | -2.649633766 |
| <i>Sablovskaitė (URS)</i> | <i>Choubenkova (URS)</i> | <i>Schulz (GDR)</i> |
| -1.343351210 | -1.359025696 | -1.043847471 |

| | | |
|-----------------------|------------------------|---------------------------|
| <i>Fleming (AUS)</i> | <i>Greiner (USA)</i> | <i>Lajbnerova (CZE)</i> |
| -1.100385639 | -0.923173639 | -0.530250689 |
| <i>Bouraga (URS)</i> | <i>Wijnsma (HOL)</i> | <i>Dimitrova (BUL)</i> |
| -0.759819024 | -0.556268302 | -1.186453832 |
| <i>Scheider (SWI)</i> | <i>Braun (FRG)</i> | <i>Ruotsalainen (FIN)</i> |
| 0.015461226 | 0.003774223 | 0.090747709 |
| <i>Yuping (CHN)</i> | <i>Hagger (GB)</i> | <i>Brown (USA)</i> |
| -0.137225440 | 0.171128651 | 0.519252646 |
| <i>Mulliner (GB)</i> | <i>Hautenaue (BEL)</i> | <i>Kytola (FIN)</i> |
| 1.125481833 | 1.085697646 | 1.447055499 |
| <i>Geremias (BRA)</i> | <i>Hui-Ing (TAI)</i> | <i>Jeong-Mi (KOR)</i> |
| 2.014029620 | 2.880298635 | 2.970118607 |
| <i>Launa (PNG)</i> | | |
| 6.270021972 | | |

or, more conveniently, by extracting the first from all precomputed principal components

```
R> predict(heptathlon_pca)[,1]
```

| | | |
|----------------------------|--------------------------|---------------------------|
| <i>Joyner-Kersey (USA)</i> | <i>John (GDR)</i> | <i>Behmer (GDR)</i> |
| -4.121447626 | -2.882185935 | -2.649633766 |
| <i>Sablovskaitė (URS)</i> | <i>Choubenkova (URS)</i> | <i>Schulz (GDR)</i> |
| -1.343351210 | -1.359025696 | -1.043847471 |
| <i>Fleming (AUS)</i> | <i>Greiner (USA)</i> | <i>Lajbnerova (CZE)</i> |
| -1.100385639 | -0.923173639 | -0.530250689 |
| <i>Bouraga (URS)</i> | <i>Wijnsma (HOL)</i> | <i>Dimitrova (BUL)</i> |
| -0.759819024 | -0.556268302 | -1.186453832 |
| <i>Scheider (SWI)</i> | <i>Braun (FRG)</i> | <i>Ruotsalainen (FIN)</i> |
| 0.015461226 | 0.003774223 | 0.090747709 |
| <i>Yuping (CHN)</i> | <i>Hagger (GB)</i> | <i>Brown (USA)</i> |
| -0.137225440 | 0.171128651 | 0.519252646 |
| <i>Mulliner (GB)</i> | <i>Hautenaue (BEL)</i> | <i>Kytola (FIN)</i> |
| 1.125481833 | 1.085697646 | 1.447055499 |
| <i>Geremias (BRA)</i> | <i>Hui-Ing (TAI)</i> | <i>Jeong-Mi (KOR)</i> |
| 2.014029620 | 2.880298635 | 2.970118607 |
| <i>Launa (PNG)</i> | | |
| 6.270021972 | | |

The first two components account for 81% of the variance. A barplot of each component's variance (see Figure 13.2) shows how the first two components dominate. A plot of the data in the space of the first two principal components, with the points labelled by the name of the corresponding competitor can be produced as shown with Figure 13.3. In addition, the first two loadings for the events are given in a second coordinate system, also illustrating the special role of the javelin event. This graphical representation is known as *biplot* (?). The correlation between the score given to each athlete by the standard scoring system used for the heptathlon and the first principal component score can be found from

```
R> cor(heptathlon$score, heptathlon_pca$x[,1])
```

```
R> plot(heptathlon_pca)
```

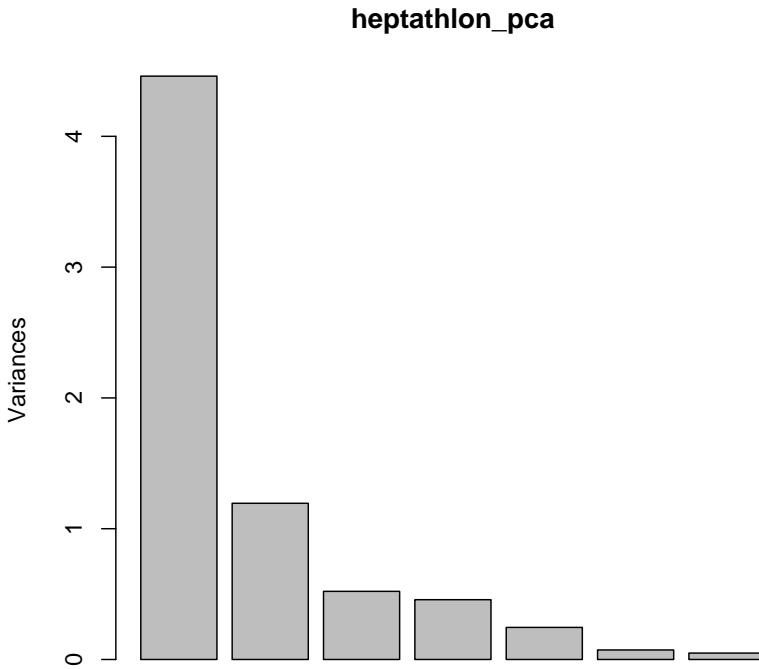


Figure 13.2 Barplot of the variances explained by the principal components.

```
[1] -0.9910978
```

This implies that the first principal component is in good agreement with the score assigned to the athletes by official Olympic rules; a scatterplot of the official score and the first principal component is given in Figure 13.4.

```
R> biplot(heptathlon_pca, col = c("gray", "black"))
```

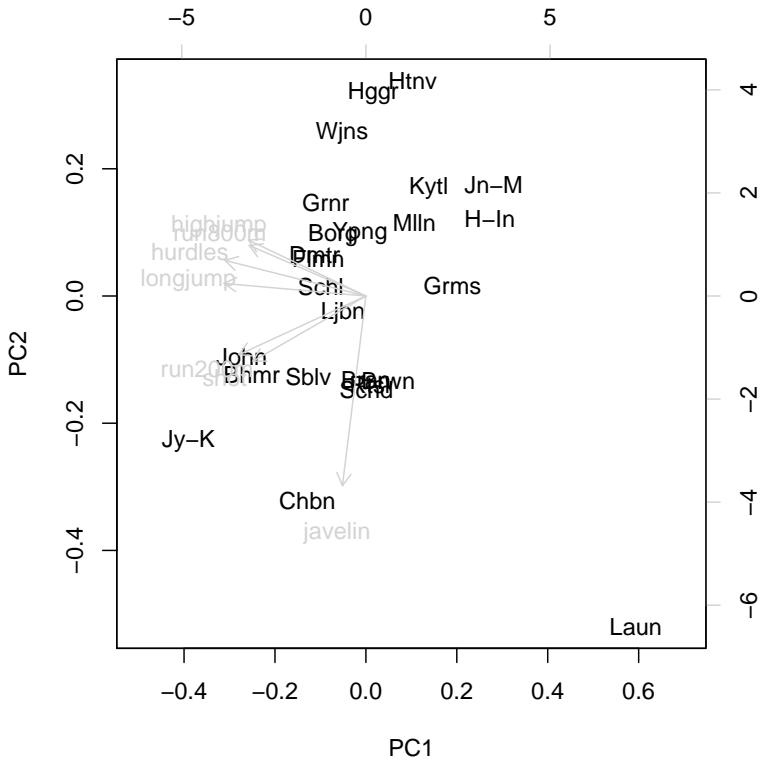


Figure 13.3 Biplot of the (scaled) first two principal components.

```
R> plot(heptathlon$score, heptathlon_pca$x[,1])
```

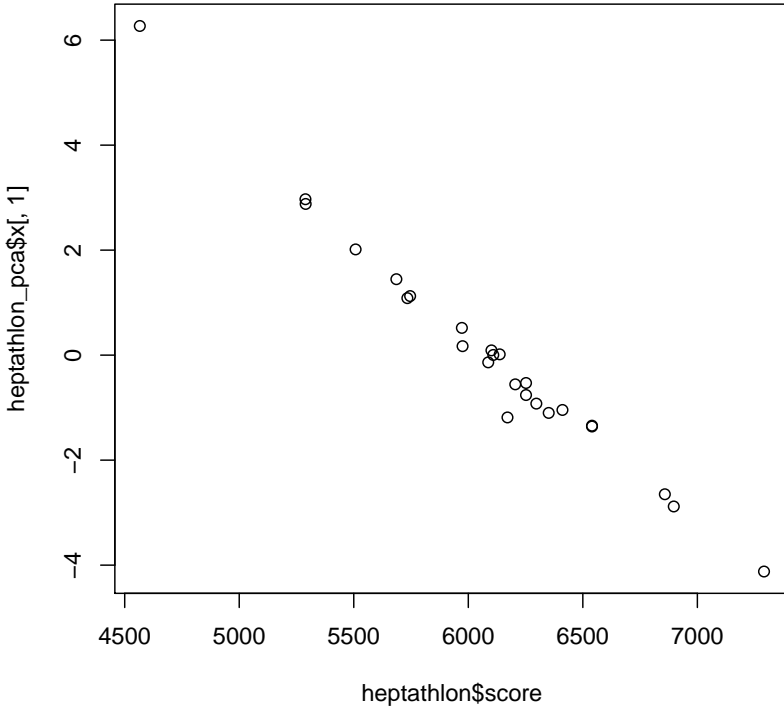


Figure 13.4 Scatterplot of the score assigned to each athlete in 1988 and the first principal component.

Multidimensional Scaling: British Water Voles and Voting in US Congress

14.1 Introduction

14.2 Multidimensional Scaling

14.3 Analysis Using R

We can apply classical scaling to the distance matrix for populations of water voles using the R function `cmdscale`. The following code finds the classical scaling solution and computes the two criteria for assessing the required number of dimensions as described above.

```
R> data("watervoles", package = "HSAUR")
R> voles_mds <- cmdscale(watervoles, k = 13, eig = TRUE)
R> voles_mds$eig

 [1]  7.359910e-01  2.626003e-01  1.492622e-01  6.990457e-02
 [5]  2.956972e-02  1.931184e-02  1.110223e-16 -1.139451e-02
 [9] -1.279569e-02 -2.849924e-02 -4.251502e-02 -5.255450e-02
[13] -7.406143e-02
```

Note that some of the eigenvalues are negative. The criterion P_2 can be computed by

```
R> sum(abs(voles_mds$eig[1:2]))/sum(abs(voles_mds$eig))

 [1] 0.6708889
```

and the criterion suggested by [Mardia et al. \(1979\)](#) is

```
R> sum((voles_mds$eig[1:2])^2)/sum((voles_mds$eig)^2)

 [1] 0.9391378
```

The two criteria for judging number of dimensions differ considerably, but both values are reasonably large, suggesting that the original distances between the water vole populations can be represented adequately in two dimensions. The two-dimensional solution can be plotted by extracting the coordinates from the `points` element of the `voles_mds` object; the plot is shown in [Figure 14.1](#).

We shall now apply non-metric scaling to the voting behaviour shown in [Table ??](#). Non-metric scaling is available with function `isoMDS` from package *MASS* ([Venables and Ripley, 2002](#)):

```
R> x <- voles_mds$points[,1]
R> y <- voles_mds$points[,2]
R> plot(x, y, xlab = "Coordinate 1", ylab = "Coordinate 2",
+       xlim = range(x)*1.2, type = "n")
R> text(x, y, labels = colnames(watervoles))
```

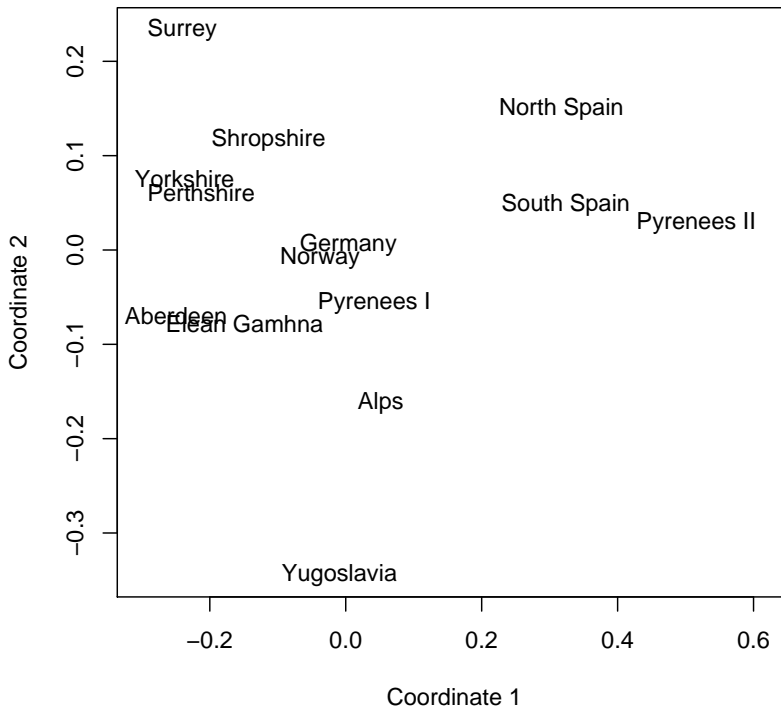


Figure 14.1 Two-dimensional solution from classical multidimensional scaling of distance matrix for water vole populations.

```
R> library("MASS")
R> data("voting", package = "HSAUR")
R> voting_mds <- isoMDS(voting)
```

and we again depict the two-dimensional solution (Figure 14.3). The Figure suggests that voting behaviour is essentially along party lines, although there is more variation among Republicans. The voting behaviour of one of the Republicans (Rinaldo) seems to be closer to his democratic colleagues rather than to the voting behaviour of other Republicans.

```

R> library("ape")
R> st <- mst(watervoles)
R> plot(x, y, xlab = "Coordinate 1", ylab = "Coordinate 2",
+       xlim = range(x)*1.2, type = "n")
R> for (i in 1:nrow(watervoles)) {
+   w1 <- which(st[i, ] == 1)
+   segments(x[i], y[i], x[w1], y[w1])
+ }
R> text(x, y, labels = colnames(watervoles))

```

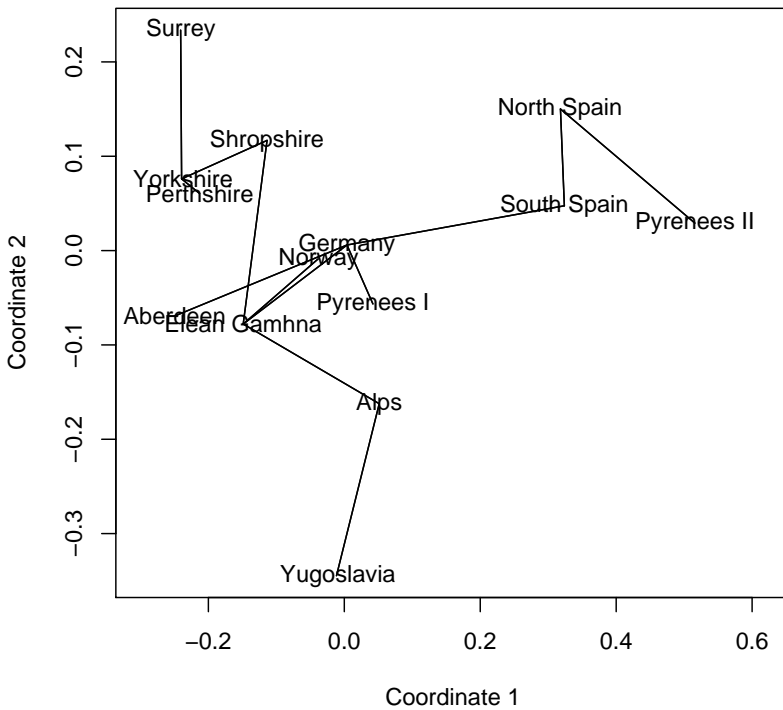


Figure 14.2 Minimum spanning tree for the `watervoles` data.

```

R> x <- voting_mds$points[,1]
R> y <- voting_mds$points[,2]
R> plot(x, y, xlab = "Coordinate 1", ylab = "Coordinate 2",
+       xlim = range(voting_mds$points[,1])*1.2, type = "n")
R> text(x, y, labels = colnames(voting))
R> voting_sh <- Shepard(voting[lower.tri(voting)],
+                      voting_mds$points)

```

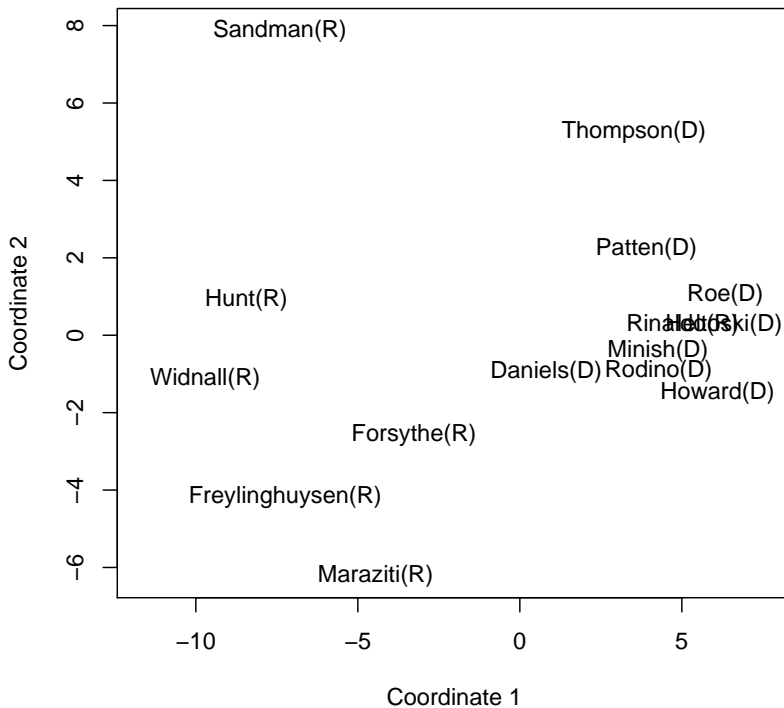


Figure 14.3 Two-dimensional solution from non-metric multidimensional scaling of distance matrix for voting matrix.


```
R> ### library("MASS")
R> ### voting_sh <- Shepard(voting[lower.tri(voting)], voting_mds$points)
R> plot(voting_sh, pch = ".", xlab = "Dissimilarity",
+       ylab = "Distance", xlim = range(voting_sh$x),
+       ylim = range(voting_sh$y))
R> lines(voting_sh$x, voting_sh$yf, type = "S")
```

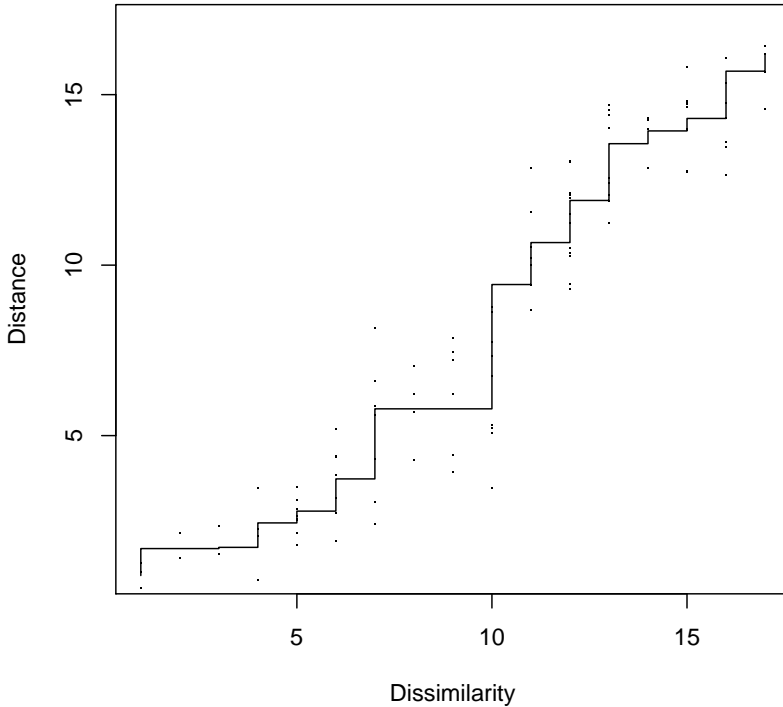


Figure 14.4 The Shepard diagram for the `voting` data shows some discrepancies between the original dissimilarities and the multidimensional scaling solution.

Bibliography

- Mardia, K. V., Kent, J. T., and Bibby, J. M. (1979), *Multivariate Analysis*, London, UK: Academic Press.
- Venables, W. N. and Ripley, B. D. (2002), *Modern Applied Statistics with S*, Springer, 4th edition, URL <http://www.stats.ox.ac.uk/pub/MASS4/>, ISBN 0-387-95457-0.

Cluster Analysis: Classifying the Exoplanets

15.1 Introduction

15.2 Cluster Analysis

15.3 Analysis Using R

Sadly Figure 15.2 gives no completely convincing verdict on the number of groups we should consider, but using a little imagination ‘little elbows’ can be spotted at the three and five group solutions. We can find the number of planets in each group using

```
R> planet_kmeans3 <- kmeans(planet.dat, centers = 3)
R> table(planet_kmeans3$cluster)
```

```
 1  2  3
28 10 63
```

The centers of the clusters for the untransformed data can be computed using a small convenience function

```
R> ccent <- function(cl) {
+   f <- function(i) colMeans(planets[cl == i,])
+   x <- sapply(sort(unique(cl)), f)
+   colnames(x) <- sort(unique(cl))
+   return(x)
+ }
```

which, applied to the three cluster solution obtained by *k*-means gets

```
R> ccent(planet_kmeans3$cluster)
```

```
           1           2           3
mass      7.0532143    3.4360    1.6540635
period 839.1644356 2420.5500 311.3897179
eccen     0.5184643    0.2718    0.1777984
```

for the three cluster solution and, for the five cluster solution using

```
R> planet_kmeans5 <- kmeans(planet.dat, centers = 5)
R> table(planet_kmeans5$cluster)
```

```
 1  2  3  4  5
28  5  7 49 12
```

```
R> ccent(planet_kmeans5$cluster)
```

```
R> data("planets", package = "HSAUR")
R> library("scatterplot3d")
R> scatterplot3d(log(planets$mass), log(planets$period),
+   log(planets$eccen), type = "h", angle = 55,
+   pch = 16, y.ticklabs = seq(0, 10, by = 2),
+   y.margin.add = 0.1, scale.y = 0.7)
```

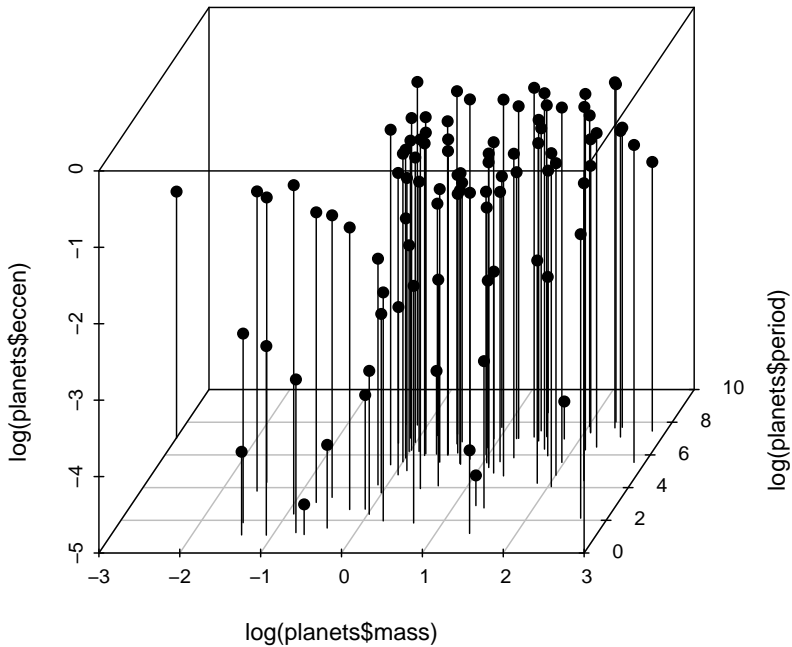


Figure 15.1 3D scatterplot of the logarithms of the three variables available for each of the exoplanets.

| | 1 | 2 | 3 | 4 | 5 |
|---------------|-------------|----------|-------------|-------------|----------|
| <i>mass</i> | 2.2617857 | 14.3480 | 2.185714 | 1.6846122 | 8.595 |
| <i>period</i> | 580.6828929 | 659.3976 | 2557.642857 | 282.2685965 | 1335.740 |
| <i>eccen</i> | 0.4910714 | 0.3268 | 0.199000 | 0.1221082 | 0.473 |

```
R> rge <- apply(planets, 2, max) - apply(planets, 2, min)
R> planet.dat <- sweep(planets, 2, rge, FUN = "/")
R> n <- nrow(planet.dat)
R> wss <- rep(0, 10)
R> wss[1] <- (n - 1) * sum(apply(planet.dat, 2, var))
R> for (i in 2:10)
+   wss[i] <- sum(kmeans(planet.dat,
+                       centers = i)$withinss)
R> plot(1:10, wss, type = "b", xlab = "Number of groups",
+       ylab = "Within groups sum of squares")
```

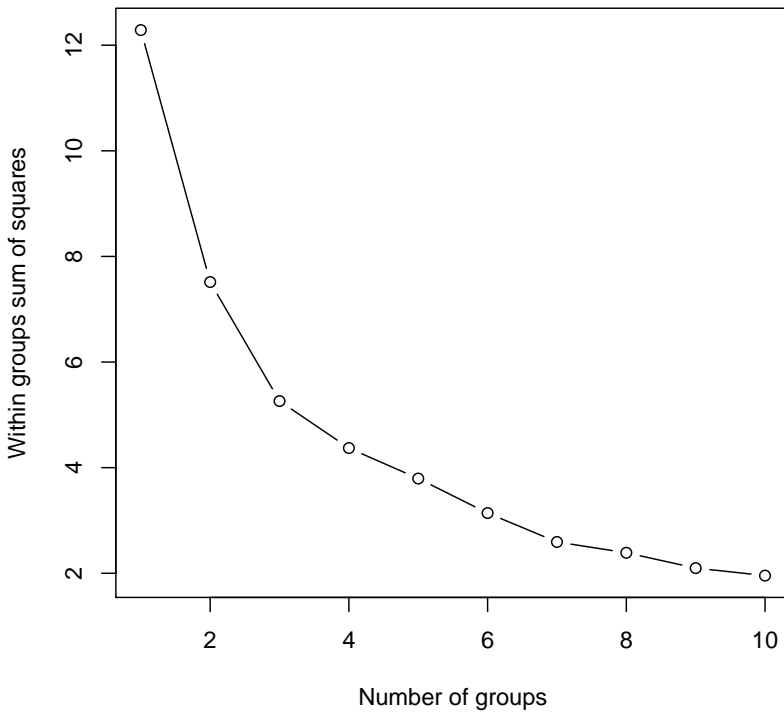


Figure 15.2 Within-cluster sum of squares for different numbers of clusters for the exoplanet data.

```
R> plot(planet_mclust, planet.dat, what = "BIC", col = "black",
+       ylab = "-BIC", ylim = c(0, 350))
```

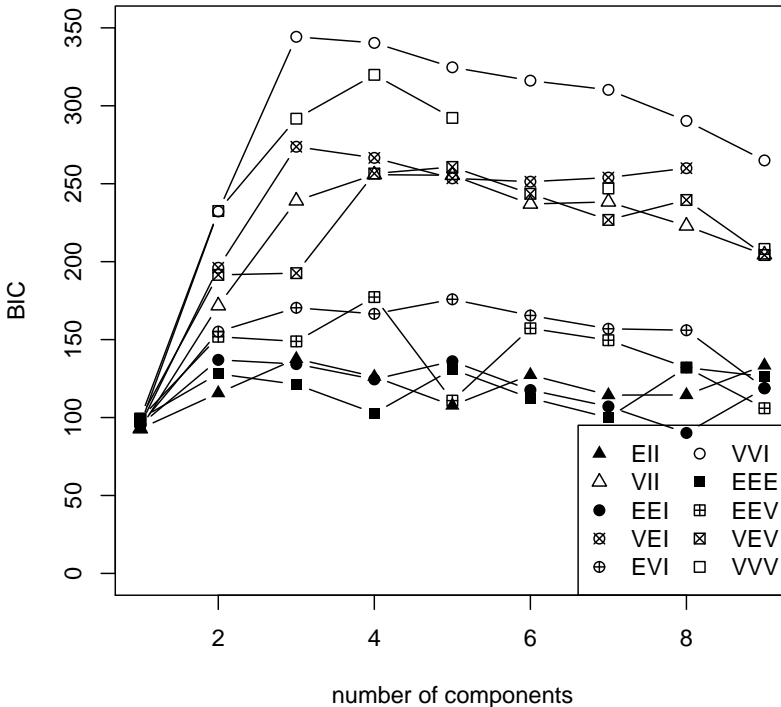


Figure 15.3 Plot of BIC values for a variety of models and a range of number of clusters.

15.3.1 Model-based Clustering in R

We now proceed to apply model-based clustering to the planets data. R functions for model-based clustering are available in package *mclust* (Fraley et al., 2006, Fraley and Raftery, 2002). Here we use the `Mclust` function since this selects both the most appropriate model for the data *and* the optimal number of groups based on the values of the BIC computed over several models and a range of values for number of groups. The necessary code is:

```
R> library("mclust")
R> planet_mclust <- Mclust(planet.dat)
```

and we first examine a plot of BIC values using The resulting diagram is

shown in Figure 15.3. In this diagram the numbers refer to different model assumptions about the shape of clusters:

1. Spherical, equal volume,
2. Spherical, unequal volume,
3. Diagonal equal volume, equal shape,
4. Diagonal varying volume, varying shape,
5. Ellipsoidal, equal volume, shape and orientation,
6. Ellipsoidal, varying volume, shape and orientation.

The BIC selects model 4 (diagonal varying volume and varying shape) with three clusters as the best solution as can be seen from the `print` output:

```
R> print(planet_mclust)
  best model: VVI with 3 components
```

This solution can be shown graphically as a scatterplot matrix. The plot is shown in Figure 15.4. Figure 15.5 depicts the clustering solution in the three-dimensional space. The number of planets in each cluster and the mean vectors of the three clusters for the untransformed data can now be inspected by using

```
R> table(planet_mclust$classification)
  1  2  3
19 41 41
```

```
R> ccent(planet_mclust$classification)
           1           2           3
mass  1.16652632  1.5797561  6.0761463
period 6.47180158 313.4127073 1325.5310048
eccen  0.03652632  0.3061463  0.3704951
```

Cluster 1 consists of planets about the same size as Jupiter with very short periods and eccentricities (similar to the first cluster of the k -means solution). Cluster 2 consists of slightly larger planets with moderate periods and large eccentricities, and cluster 3 contains the very large planets with very large periods. These two clusters do not match those found by the k -means approach.

```
R> clPairs(planet.dat,
+         classification = planet_mclust$classification,
+         symbols = 1:3, col = "black")
```

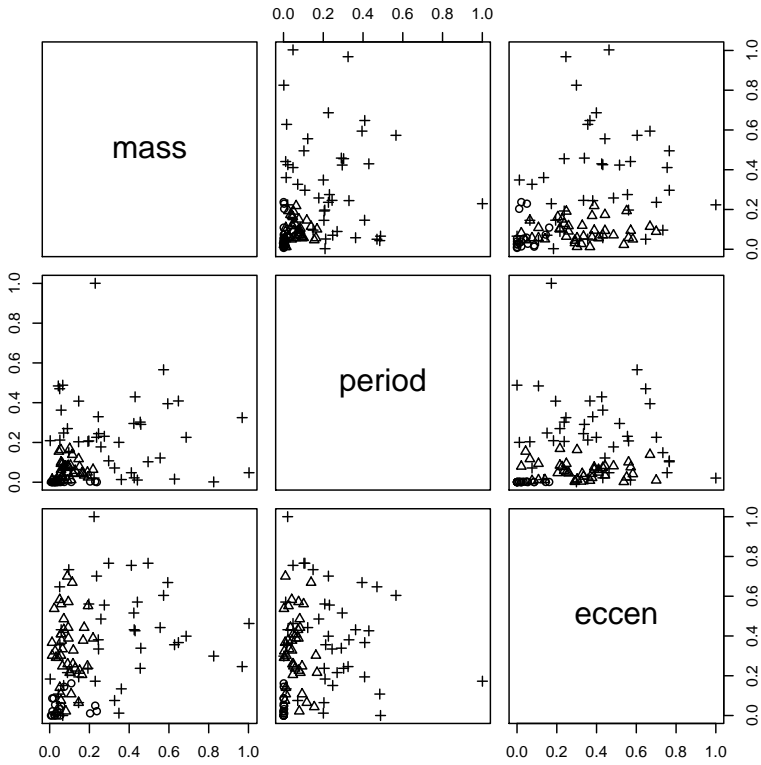


Figure 15.4 Scatterplot matrix of planets data showing a three cluster solution from Mclust.


```
R> scatterplot3d(log(planets$mass), log(planets$period),
+               log(planets$eccen), type = "h", angle = 55,
+               scale.y = 0.7, pch = planet_mclust$classification,
+               y.ticklabs = seq(0, 10, by = 2), y.margin.add = 0.1)
```

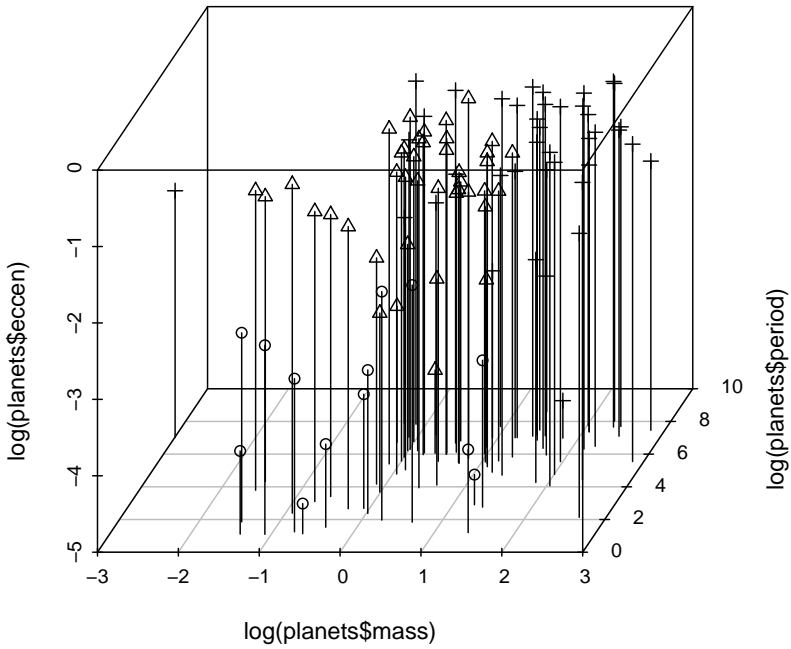


Figure 15.5 3D scatterplot of planets data showing a three cluster solution from Mclust.

Bibliography

- Fraley, C. and Raftery, A. E. (2002), “Model-based clustering, discriminant analysis, and density estimation,” *Journal of the American Statistical Association*, 97, 611–631.
- Fraley, C., Raftery, A. E., and Wehrens, R. (2006), *mclust: Model-based Cluster Analysis*, URL <http://www.stat.washington.edu/mclust>, R package version 3.0-0.

Errata

The document gives a list of typos, errors, inconsistencies etc. which have been spotted. Moreover, small numeric output differences which are due to updated packages are reported here. To get a full list of differences run R CMD check HSAUR on the source package. All issues marked with **R1**, **R2** etc have been silently fixed in first reprint, second reprint etc.

Preface

Typo in name of vignette for Chapter 1, should read

```
R> vignette("Ch_introduction_to_R", package = "HSAUR")
```

and

```
R> edit(vignette("Ch_introduction_to_R", package = "HSAUR"))
```

As of version 1.0-3, only the correctly named vignette is available (**R1**).

16.1 Introduction to R

- Typo at page 11: ‘.’ needs to be double-quoted in `list.files` (**R1**)
- Typo at page 20 (Ex. 1.5): number of companies, not number of countries (**R1**).

16.2 Simple Inference

Typo at page 31, code line 4: use argument `varwidth = TRUE`, not `var.width = TRUE` (**R1**).

16.3 Conditional Inference

- The names of the test statistics in the output have been changed from T to Z or chi-squared throughout the chapter (**R1**).
- Reference [Hothorn et al. \(2006a\)](#) updated (**R1**)

16.4 Analysis of Variance

Figure 4.3 had wrong line types in legend (Beef and Cereal interchanged) (**R2**).

16.5 Multiple Linear Regression

- Page 74, Table 5.1: The values for `cloudcover` and `sne` had to be exchanged. The corresponding coefficients and Figures in this chapter change accordingly (**R1**).
- Page 83: both `fitted` and `predict` can be used to compute fitted values, the later on can be applied to new unseen data as well (**R1**).
- Page 87: \hat{y}_i instead of \hat{y} in the definition of the standardized residual.

16.6 Logistic Regression and Generalised Linear Models

- page 97: predictions are to be computed for `plasma_glm_2`, not `plasma_glm_1` (affects Figure 6.4) (**R2**).
- Function `myplot` (page 100): the `vfont` argument in `text` has been changed to `family = "HersheySerif"` (the resulting plots remain the same) (**R1**).

16.7 Density Estimation

- Page 117: typo: in instead of is
- Page 121: small numeric differences for the output of `optim`
- update to `mclust` version 3.0-0 (new names of parameters in `mclust` objects)

16.8 Recursive Partitioning

- Page 138: the probability for glaucoma is `predict(trees[[i]], newdata = GlaucomaM)[,1]` and the code for converting average class probabilities in factors has to be reverted, too. Affects Figure 8.4. (which is now in sync with the interpretation).
- Page 139: small differences in `predtab`
- Page 140: small differences in table at bottom of this page
- Reference [Hothorn et al. \(2006b\)](#) updated (**R1**)
- Page 142, Ex. 8.1.: regression tree, not classification tree.

16.9 Survival Analysis

- The name of the test statistic in the output of `surv_test` has been changed to `chi-squared` (**R1**).
- Denominator s was missing from $h(t)$ (page 147) (**R2**).

16.10 Analysing Longitudinal Data I

Page 168, Figure 10.2: `summary` does not provide degrees of freedom and p-values in newer versions of `lme4`.

16.11 Analysing Longitudinal Data II

–nothing known–

16.12 Meta-Analysis

- Page 202: $\mu_i \sim \mathcal{N}(\mu, \tau^2)$, not $N(\mu, \tau^2)$ (**R2**).
- Page 207: square for `selogs` was missing (**R2**).

16.13 Principal Component Analysis

–nothing known–

16.14 Multidimensional Scaling

–nothing known–

16.15 Cluster Analysis

update to *mclust* version 3.0-0 (new plot method)

Thanks

We would like to thank the following people for pointing out errors, typos etc and for making suggestions for improvements:

- Tobias Verbeke
- Brian D. Ripley
- Yihui Xie
- Mike Cheung

Bibliography

- Hothorn, T., Hornik, K., van de Wiel, M. A., and Zeileis, A. (2006a), “A Lego system for conditional inference,” *The American Statistician*, 60, 257–263, URL <http://statmath.wu-wien.ac.at/~zeileis/papers/Hothorn+Hornik+VanDeWiel-2006.pdf>.
- Hothorn, T., Hornik, K., and Zeileis, A. (2006b), “Unbiased recursive partitioning: A conditional inference framework,” *Journal of Computational and Graphical Statistics*, 15, 651–674, URL <http://statmath.wu-wien.ac.at/~zeileis/papers/Hothorn+Hornik+Zeileis-2006.pdf>.