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# R for Everyone

Advanced Analytics  
and Graphics

JARED P. LANDER

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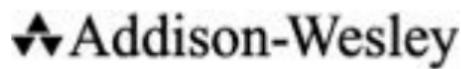
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# **R for Everyone**

## **Advanced Analytics and Graph- ics**

**Jared P. Lander**



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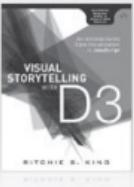
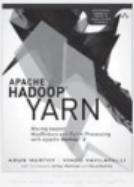
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*To my mother and father*  
❖

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# Foreword

R has had tremendous growth in popularity over the last three years. Based on that, you'd think that it was a new, up-and-coming language. But surprisingly, R has been around since 1993. Why the sudden uptick in popularity? The somewhat obvious answer seems to be the emergence of data science as a career and a field of study. But the underpinnings of data science have been around for many decades. Statistics, linear algebra, operations research, artificial intelligence, and machine learning all contribute parts to the tools that a modern data scientist uses. R, more than most languages, has been built to make most of these tools only a single function call away.

That's why I'm very excited to have this book as one of the first in the Addison-Wesley Data and Analytics Series. R is indispensable for many data science tasks. Many algorithms useful for prediction and analysis can be accessed through only a

few lines of code, which makes it a great fit for solving modern data challenges. Data science as a field isn't just about math and statistics, and it isn't just about programming and infrastructure. This book provides a well-balanced introduction to the power and expressiveness of R and is aimed at a general audience.

I can't think of a better author to provide an introduction to R than Jared Lander. Jared and I first met through the New York City machine learning community in late 2009. Back then, the New York City data community was small enough to fit in a single conference room, and many of the other data meetups had yet to be formed. Over the last four years, Jared has been at the forefront of the emerging data science profession.

Through running the Open Statistical Programming Meetup, speaking at events, and teaching a course at Columbia on R, Jared has helped grow the community by educating programmers, data scientists, journalists, and statisticians alike.

But Jared's expertise isn't limited to teaching. As an everyday practitioner, he puts these tools to use while consulting for clients big and small.

This book provides an introduction both to programming in R and to the various statistical methods and tools an everyday R programmer uses. Examples use publicly available datasets that Jared has helpfully cleaned and made accessible through his Web site. By using real data and setting up interesting problems, this book stays engaging to the end.

—*Paul Dix, Series Editor*

# Preface

With the increasing prevalence of data in our daily lives, new and better tools are needed to analyze the deluge. Traditionally there have been two ends of the spectrum: lightweight, individual analysis using tools like Excel or SPSS and heavy duty, high-performance analysis built with C++ and the like. With the increasing strength of personal computers grew a middle ground that was both interactive and robust. Analysis done by an individual on his or her own computer in an exploratory fashion could quickly be transformed into something destined for a server, underpinning advanced business processes. This area is the domain of R, Python, and other scripted languages.

R, invented by Robert Gentleman and Ross Ihaka of the University of Auckland in 1993, grew out of S, which was invented by John Chambers at Bell Labs. It is a high-level language that was originally intended to be run interactively where the

user runs a command, gets a result, and then runs another command. It has since evolved into a language that can also be embedded in systems and tackle complex problems.

In addition to transforming and analyzing data, R can produce amazing graphics and reports with ease. It is now being used as a full stack for data analysis, extracting and transforming data, fitting models, drawing inferences and making predictions, plotting and reporting results.

R's popularity has skyrocketed since the late 2000s, as it has stepped out of academia and into banking, marketing, pharmaceuticals, politics, genomics and many other fields. Its new users are often shifting from low-level, compiled languages like C++, other statistical packages such as SAS or SPSS, and from the 800-pound gorilla, Excel. This time period also saw a rapid surge in the number of add-on packages—libraries of prewritten code that extend R's functionality.

While R can sometimes be intimidating to beginners, especially for those without programming experience, I find that programming analysis, instead of pointing and clicking, soon becomes much easier, more convenient and more reliable. It is my goal to make that learning process easier and quicker.

This book lays out information in a way I wish I were taught when learning R in graduate school. Coming full circle, the content of this book was developed in conjunction with the data science course I teach at Columbia University. It is not meant to cover every minute detail of R, but rather the 20% of functionality needed to accomplish 80% of the work. The content is organized into self-contained chapters as follows.

[Chapter 1, Getting R](#): Where to download R and how to install it. This deals with the varying operating systems and 32-bit versus 64-bit versions. It also gives advice on where to install R.

[Chapter 2, The R Environment](#): An overview of using R, particularly from within RStudio.

RStudio projects and Git integration are covered as is customizing and navigating RStudio.

[Chapter 3, Packages](#): How to locate, install and load R packages.

[Chapter 4, Basics of R](#): Using R for math. Variable types such as numeric, character and Date are detailed as are vectors. There is a brief introduction to calling functions and finding documentation on functions.

[Chapter 5, Advanced Data Structures](#): The most powerful and commonly used data structure, data.frames, along with matrices and lists, are introduced.

[Chapter 6, Reading Data into R](#): Before data can be analyzed it must be read into R. There are numerous ways to ingest data, including reading from CSVs and databases.

[Chapter 7, Statistical Graphics](#): Graphics are a crucial part of preliminary data analysis and communicating results. R can make beautiful plots

using its powerful plotting utilities. Base graphics and ggplot2 are introduced and detailed here.

[Chapter 8, Writing R Functions](#): Repeatable analysis is often made easier with user-defined functions. The structure, arguments and return rules are discussed.

[Chapter 9, Control Statements](#): Controlling the flow of programs using if, ifelse and complex checks.

[Chapter 10, Loops, the Un-R Way to Iterate](#): Iterating using for and while loops. While these are generally discouraged they are important to know.

[Chapter 11, Group Manipulation](#): A better alternative to loops, vectorization does not quite iterate through data so much as operate on all elements at once. This is more efficient and is primarily performed with the apply functions and plyr package.

[Chapter 12, Data Reshaping](#): Combining multiple datasets, whether by stacking or joining, is

commonly necessary as is changing the shape of data. The plyr and reshape2 packages offer good functions for accomplishing this in addition to base tools such as rbind, cbind and merge.

[Chapter 13, Manipulating Strings](#): Most people do not associate character data with statistics but it is an important form of data. R provides numerous facilities for working with strings, including combining them and extracting information from within. Regular expressions are also detailed.

[Chapter 14, Probability Distributions](#): A thorough look at the normal, binomial and Poisson distributions. The formulas and functions for many distributions are noted.

[Chapter 15, Basic Statistics](#): These are the first statistics most people are taught, such as mean, standard deviation and t-tests.

[Chapter 16, Linear Models](#): The most powerful and common tool in statistics, linear models are extensively detailed.

[Chapter 17, Generalized Linear Models](#): Linear models are extended to include logistic and Poisson regression. Survival analysis is also covered.

[Chapter 18, Model Diagnostics](#): Determining the quality of models and variable selection using residuals, AIC, cross-validation, the bootstrap and stepwise variable selection.

[Chapter 19, Regularization and Shrinkage](#): Preventing overfitting using the Elastic Net and Bayesian methods.

[Chapter 20, Nonlinear Models](#): When linear models are inappropriate, nonlinear models are a good solution. Nonlinear least squares, splines, generalized additive models, decision trees and random forests are discussed.

[Chapter 21, Time Series and Autocorrelation](#): Methods for the analysis of univariate and multivariate time series data.

[Chapter 22, Clustering](#): Clustering, the grouping of data, is accomplished by various methods such as K-means and hierarchical clustering.

[Chapter 23, Reproducibility, Reports and Slide Shows with knitr](#): Generating reports, slide shows and Web pages from within R is made easy with knitr, LATEX and Markdown.

[Chapter 24, Building R Packages](#): R packages are great for portable, reusable code. Building these packages has been made incredibly easy with the advent of devtools and Rcpp.

[Appendix A, Real-Life Resources](#): A listing of our favorite resources for learning more about R and interacting with the community.

[Appendix B, Glossary](#): A glossary of terms used throughout this book. A good deal of the text in this book is either R code or the results of running code. Code and results are most often in a separate block of text and set in a distinctive font, as shown in the following example. The different parts of code also have different colors. Lines of code start with `>`, and if code is contin-

ued from one line to another the continued line begins with +.

```
> # this is a comment  
>  
> # now basic math  
> 10 * 10  
[1] 100  
>  
> # calling a function  
> sqrt(4)  
[1] 2
```

Certain Kindle devices do not display color so the digital edition of this book will be viewed in greyscale on those devices.

There are occasions where code is shown in-line and looks like `sqrt(4)`.

In the few places where math is necessary, the equations are indented from the margin and are numbered.

$$e^{i\pi} + 1 = 0 \tag{1}$$

Within equations, normal variables appear as italic text (*x*), vectors are bold lowercase letters

(**x**) and matrices are bold uppercase letters (**X**). Greek letters, such as  $\alpha$  and  $\beta$ , follow the same convention.

Function names will be written as `join` and package names as `plyr`. Objects generated in code that are referenced in text are written as `object1`.

Learning R is a gratifying experience that makes life so much easier for so many tasks. I hope you enjoy learning with me.

# Acknowledgments

To start, I must thank my mother, Gail Lander, for encouraging me to become a math major. Without that I would never have followed the path that led me to statistics and data science. In a similar vein, I have to thank my father, Howard Lander, for paying all those tuition bills. He has been a valuable source of advice and guidance throughout my life and someone I have aspired to emulate in many ways. While they both insist they do not understand what I do, they love that I do it and have helped me all along the way. Staying with family, I should thank my sister and brother-in-law, Aimee and Eric Schechterman, for letting me teach math to Noah, their five-year-old son.

There are many teachers who have helped shape me over the years. The first is Rochelle Lecke, who tutored me in middle school math even when my teacher told me I did not have worthwhile math skills.

Then there is Beth Edmondson, my precalc teacher at Princeton Day School. After I wasted the first half of high school as a mediocre student, she told me I had “some nerve signing up for next year’s AP Calc” given my grades. She agreed to let me take AP Calc if I went from a C to an A+ in her class, never thinking I stood a chance. Three months later, she was in shock as I not only earned the A+, but turned around my entire academic career. She changed my life and without her, I do not know where I would be today. I am forever grateful that she was my teacher.

For the first two years at Muhlenberg College, I was determined to be a business and communications major, but took math classes because they came naturally to me. My professors, Dr. Penny Dunham, Dr. Bill Dunham, and Dr. Linda McGuire, all convinced me to become a math major, a decision that has greatly shaped my life. Dr. Greg Cicconetti gave me my first glimpse of rigorous statistics, my first research opportunity

and planted the idea in my head that I should go to grad school for statistics.

While earning my M.A. at Columbia University, I was surrounded by brilliant minds in statistics and programming. Dr. David Madigan opened my eyes to modern machine learning, and Dr. Bodhi Sen got me thinking about statistical programming. I had the privilege to do research with Dr. Andrew Gelman, whose insights have been immeasurably important to me. Dr. Richard Garfield showed me how to use statistics to help people in disaster and war zones when he sent me on my first assignment to Myanmar. His advice and friendship over the years have been dear to me. Dr. Jingchen Liu allowed and encouraged me to write my thesis on New York City pizza, which has brought me an inordinate amount of attention.<sup>1</sup>

1. <http://slice.serioouseats.com/archives/2010/03/the-moneyball-of-pizza-statistician-uses-statistics-to-find-nyc-best-pizza.html>

While at Columbia, I also met my good friend—and one time TA—Dr. Ivor Cribben who filled in so many gaps in my knowledge. Through him, I met Dr. Rachel Schutt, a source of great advice, and who I am now honored to teach alongside at Columbia.

Grad school might never have happened without the encouragement and support of Shanna Lee. She helped maintain my sanity while I was incredibly overcommitted to two jobs, classes and Columbia's hockey team. I am not sure I would have made it through without her.

Steve Czetty gave me my first job in analytics at Sky IT Group and taught me about databases, while letting me experiment with off-the-wall programming. This sparked my interest in statistics and data. Joe DeSiena, Philip du Plessis, and Ed Bobrin at the Bardess Group are some of the finest people I have ever had the pleasure to work with, and I am proud to be working with them to this day. Mike Minelli, Rich Kittler, Mark Barry, David Smith, Joseph Rickert, Dr. Norman

Nie, James Peruvankal, Neera Talbert and Dave Rich at Revolution Analytics let me do one of the best jobs I could possibly imagine: explaining to people in business why they should be using R. Kirk Mettler, Richard Schultz, Dr. Bryan Lewis and Jim Winfield at Big Computing encouraged me to have fun, tackling interesting problems in R. Vincent Saulys, John Weir, and Dr. Saar Golde at Goldman Sachs made my time there both enjoyable and educational.

Throughout the course of writing this book, many people helped me with the process. First and foremost is Yin Cheung, who saw all the stress I constantly felt and supported me through many ruined nights and days.

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Numerous people have provided valuable feedback as I produced this book, including Chris Bethel, Dr. Dirk Eddelbuettel, Dr. Ramnath Vaidyanathan, Dr. Eran Bellin, Avi Fisher, Brian Ezra, Paul Puglia, Nicholas Galasinao, Aaron Schumaker, Adam Hogan, Jeffrey Arnold, and John Houston.

Last fall was my first time teaching, and I am thankful to the students from the Fall 2012 Introduction to Data Science class at Columbia

University for being the guinea pigs for the material that ultimately ended up in this book.

Thank you to everyone who helped along the way.

# About the Author

**Jared P. Lander** is the founder and CEO of Lander Analytics, a statistical consulting firm based in New York City, the organizer of the New York Open Statistical Programming Meetup, and an adjunct professor of statistics at Columbia University. He is also a tour guide for Scott's Pizza Tours and an advisor to Brewla Bars, a gourmet ice pop start-up. With an M.A. from Columbia University in statistics and a B.A. from Muhlenberg College in mathematics, he has experience in both academic research and industry. His work for both large and small organizations spans politics, tech start-ups, fund-raising, music, finance, health-care and humanitarian relief efforts.

He specializes in data management, multilevel models, machine learning, generalized linear models, visualization, data management and statistical computing.

# Chapter 1. Getting R

R is a wonderful tool for statistical analysis, visualization and reporting. Its usefulness is best seen in the wide variety of fields where it is used. We alone have used R for projects with banks, political campaigns, tech startups, food startups, international development and aid organizations, hospitals and real estate developers. Other areas where we have seen it used are online advertising, insurance, ecology, genetics and pharmaceuticals. R is used by statisticians with advanced machine learning training and by programmers familiar with other languages, and also by people who are not necessarily trained in advanced data analysis but are tired of using Excel.

Before it can be used it needs to be downloaded and installed, a process that is no more complicated than installing any other program.

## 1.1. Downloading R

The first step in using R is getting it on the computer. Unlike with languages such as C++, R must be installed in order to run.<sup>1</sup> The program is easily obtainable from the Comprehensive R Archive Network (CRAN), the maintainer of R, at <http://cran.r-project.org/>. At the top of the page are links to download R for Windows, Mac OS X and Linux.

1. Technically C++ cannot be set up on its own without a compiler, so something would still need to be installed anyway.

There are prebuilt installations available for Windows and Mac OS X while those for Linux usually compile from source. Installing R on any of these platforms is just like installing any other program.

Windows users should click the link Download R for Windows, then base and then Download R 3.x.x for Windows; the x's indicate the version of R. This changes periodically as improvements are made.

Similarly, Mac users should click Download R for (Mac) OS X and then R-3.x.x.pkg; again, the x's indicate the current version of R. This will also install both 32- and 64-bit versions.

Linux users should download R using their standard distribution mechanism whether that is apt-get (Ubuntu and Debian), zypper (SUSE) or another source. This will also build and install R.

## 1.2. R Version

As of this writing, R is at version 3.0.2, which is a big jump from the previous version, 2.15.3. CRAN follows a one-year release cycle where each major version change increases the middle of the three numbers in the version. For instance, version 3.0.0 was released in 2013. In 2014 the version will be incremented to 3.1.0 with 3.2.0 coming in 2015. The last number in the version is for minor updates to the current major version.

Most R functionality is usually backward compatible with previous versions.

## 1.3. 32-bit versus 64-bit

The choice between using 32-bit and using 64-bit comes down to whether the computer supports 64-bit—most new machines do—and the size of the data to be worked with. The 64-bit versions can address arbitrarily large amounts of memory (or RAM) so it might as well be used.

This is especially important starting with version 3.0.0, as that adds support for 64-bit integers, meaning far greater amounts of data can be stored in R objects.

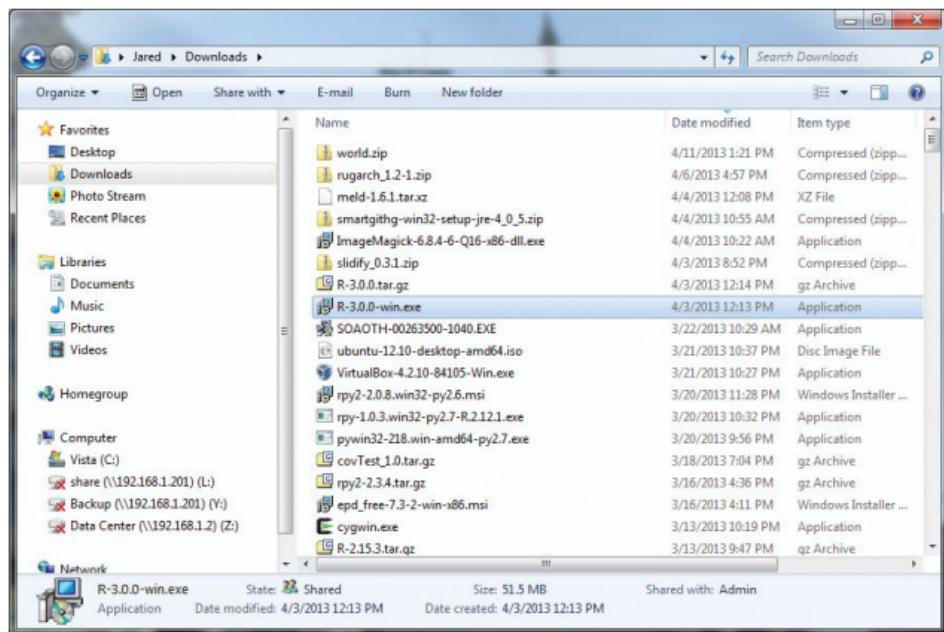
In the past, certain packages required the 32-bit version of R but that is exceedingly rare these days. The only reason for installing the 32-bit version now is to support some legacy analysis or for use on a machine with a 32-bit processor such as Intel's low-power Atom chip.

## 1.4. Installing

Installing R on Windows and Mac is just like installing any other program.

## 1.4.1. Installing on Windows

Find the appropriate installer where it was downloaded. For Windows users it will look like [Figure 1.1](#).



**Figure 1.1** Location of R installer.

R should be installed using administrator privileges. This means right-clicking the installer and then selecting Run as Administrator. This brings up a prompt where the administrator password should be entered.

The first dialog, shown in [Figure 1.2](#), offers a choice of language, defaulted at English. Choose the appropriate language and click OK.



**Figure 1.2** Language selection.

Next, the caution shown in [Figure 1.3](#) recommends that all other programs be closed. This advice is rarely followed or necessary anymore, so clicking Next is appropriate.



## Welcome to the R for Windows 3.0.0 Setup Wizard

This will install R for Windows 3.0.0 on your computer.

It is recommended that you close all other applications before continuing.

Click Next to continue, or Cancel to exit Setup.

[Next >](#)

[Cancel](#)

**Figure 1.3** With modern versions of Windows, this suggestion can be safely ignored.

The software license is then displayed, as in [Figure 1.4](#). R cannot be used without agreeing to this (important) license, so the only recourse is to click Next.

**Information**

Please read the following important information before continuing.

When you are ready to continue with Setup, click Next.

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Version 2, June 1991

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Preamble

The licenses for most software are designed to take away your  
freedom to share and change it. By contrast, the GNU General Public  
License is intended to guarantee your freedom to share and change free  
software--to make sure the software is free for all its users. This  
General Public License applies to most of the Free Software

< Back

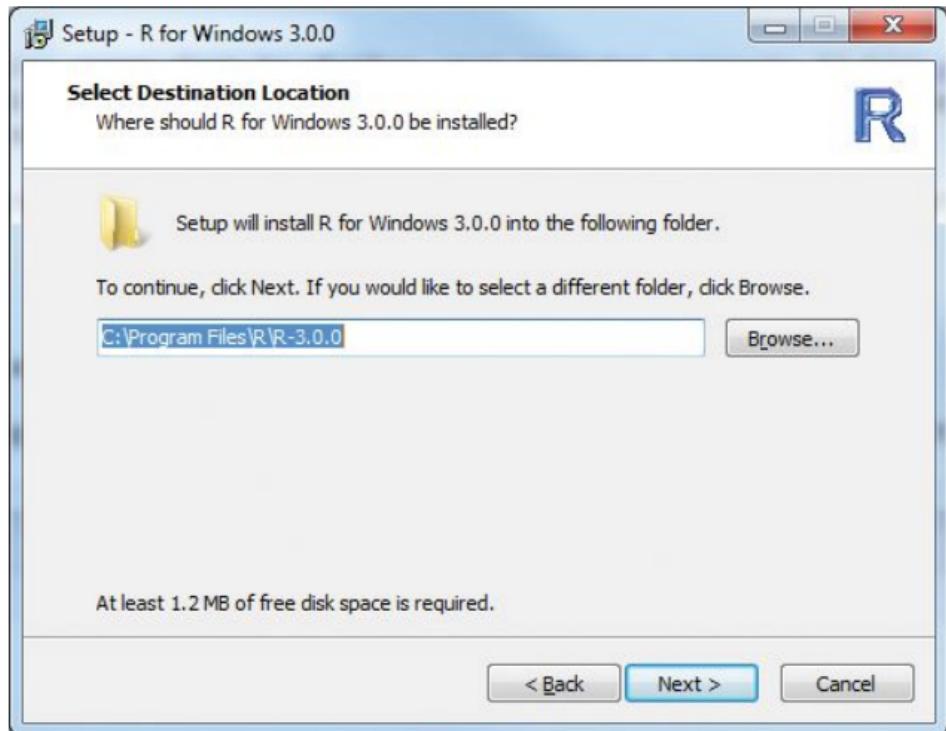
Next >

Cancel

**Figure 1.4** The license agreement must be acknowledged to use R.

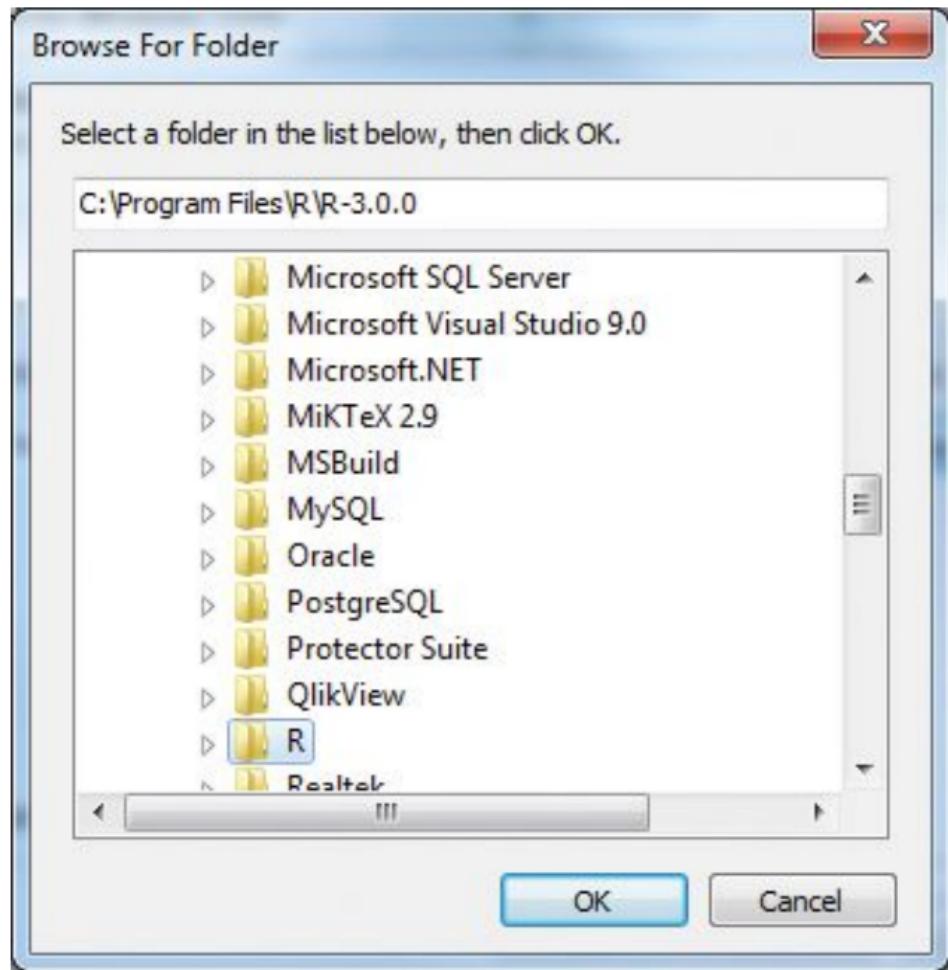
The installer then asks for a destination location. Even though the official advice from CRAN is that R should be installed in a directory with no spaces in the name, half the time the default installation directory is Program Files\R, which causes trouble if we try to build packages that re-

quire compiled code such as C++ for FORTRAN. [\*\*Figure 1.5\*\*](#) shows this dialog.



**Figure 1.5** It is important to choose a destination folder with no spaces in the name.

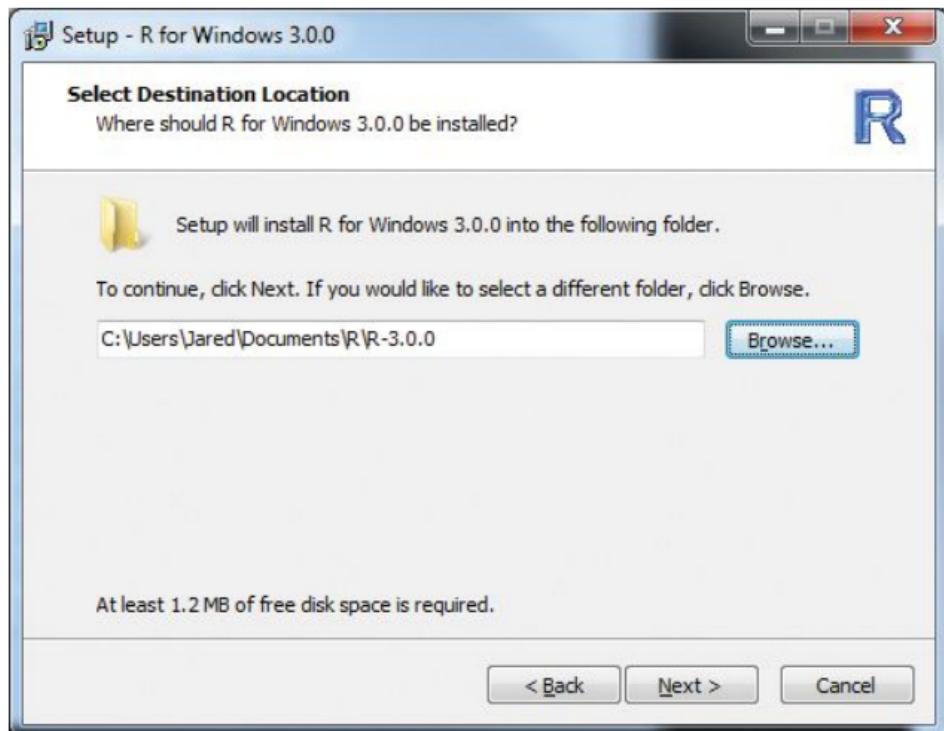
If that is the case, click the Browse button to bring up folder options like the ones shown in [\*\*Figure 1.6\*\*](#).



**Figure 1.6** This dialog is used to choose the destination folder.

It is best to choose a destination folder that is on the C: drive (or another hard disk drive) or inside My Documents, which despite that user-

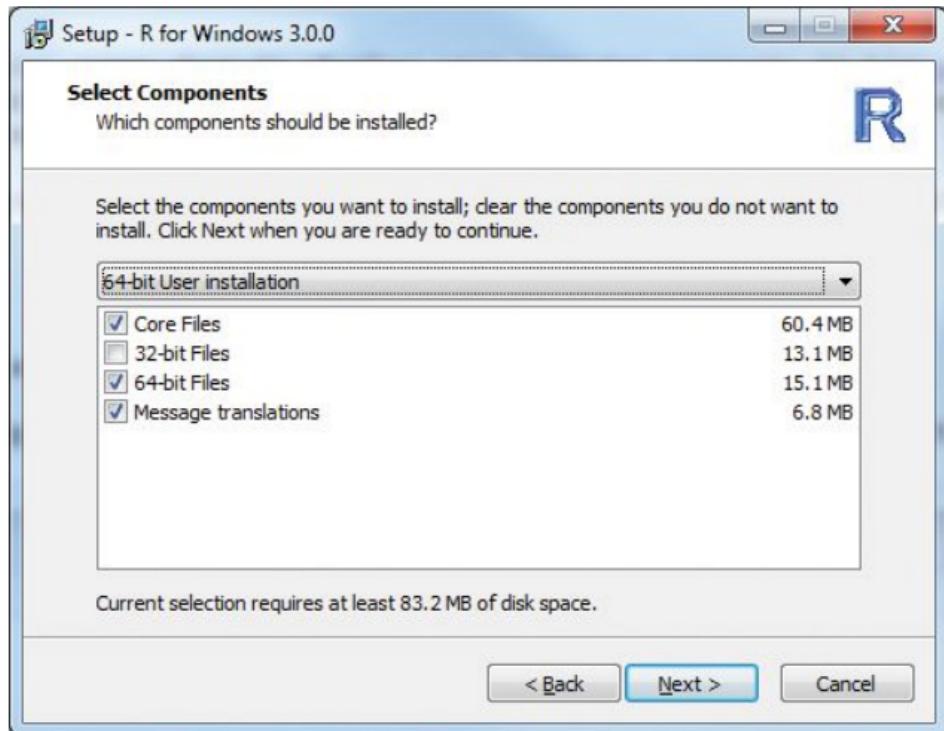
friendly name is actually located at C:\Users\UserName\Documents, which contains no spaces. [Figure 1.7](#) shows a proper destination for the installation.



**Figure 1.7** This is a proper destination, with no spaces in the name.

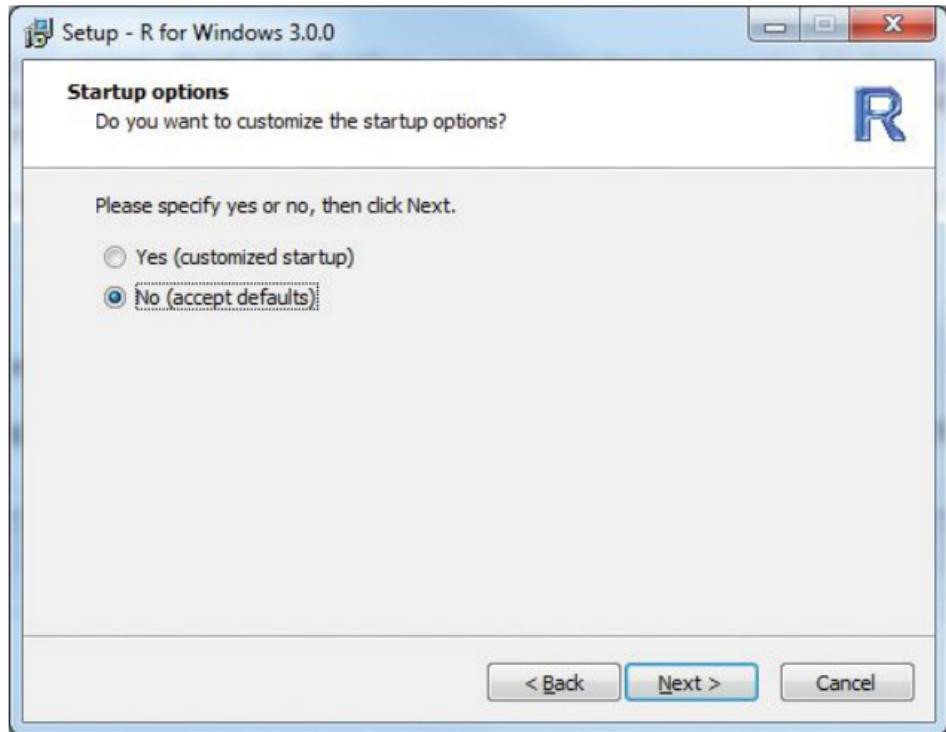
Next, [Figure 1.8](#), shows a list of components to install. Unless there is a specific need for

32-bit files, that option can be unchecked. Everything else should be selected.



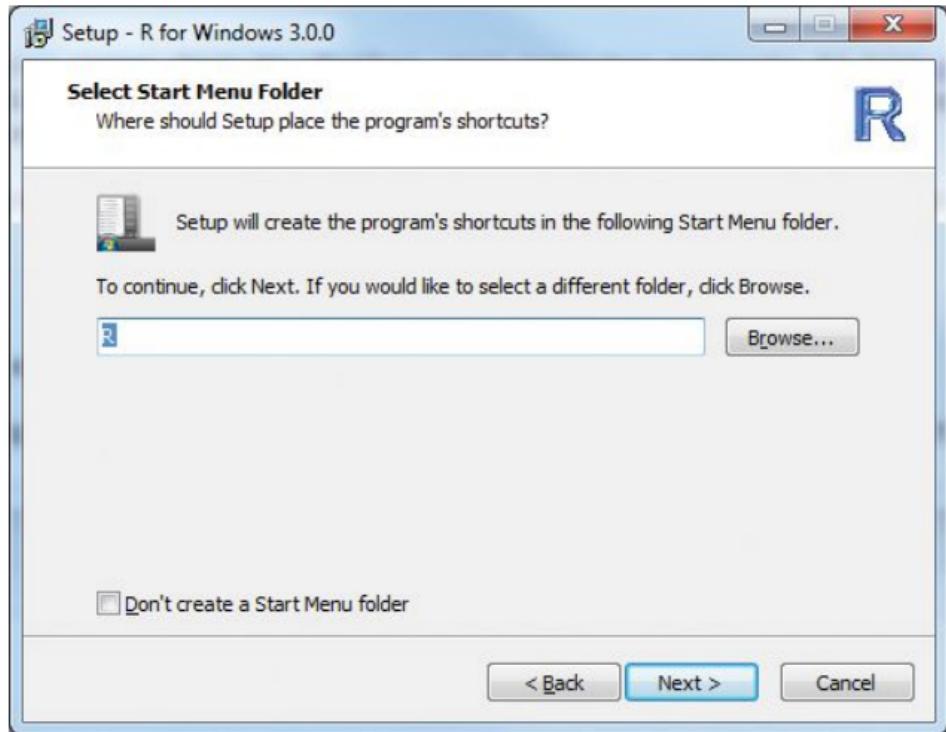
**Figure 1.8** It is best to select everything except 32-bit components.

The startup options should be left at the default, No, as in [Figure 1.9](#), because there are not a lot of options and we recommend using RStudio as the front end anyway.



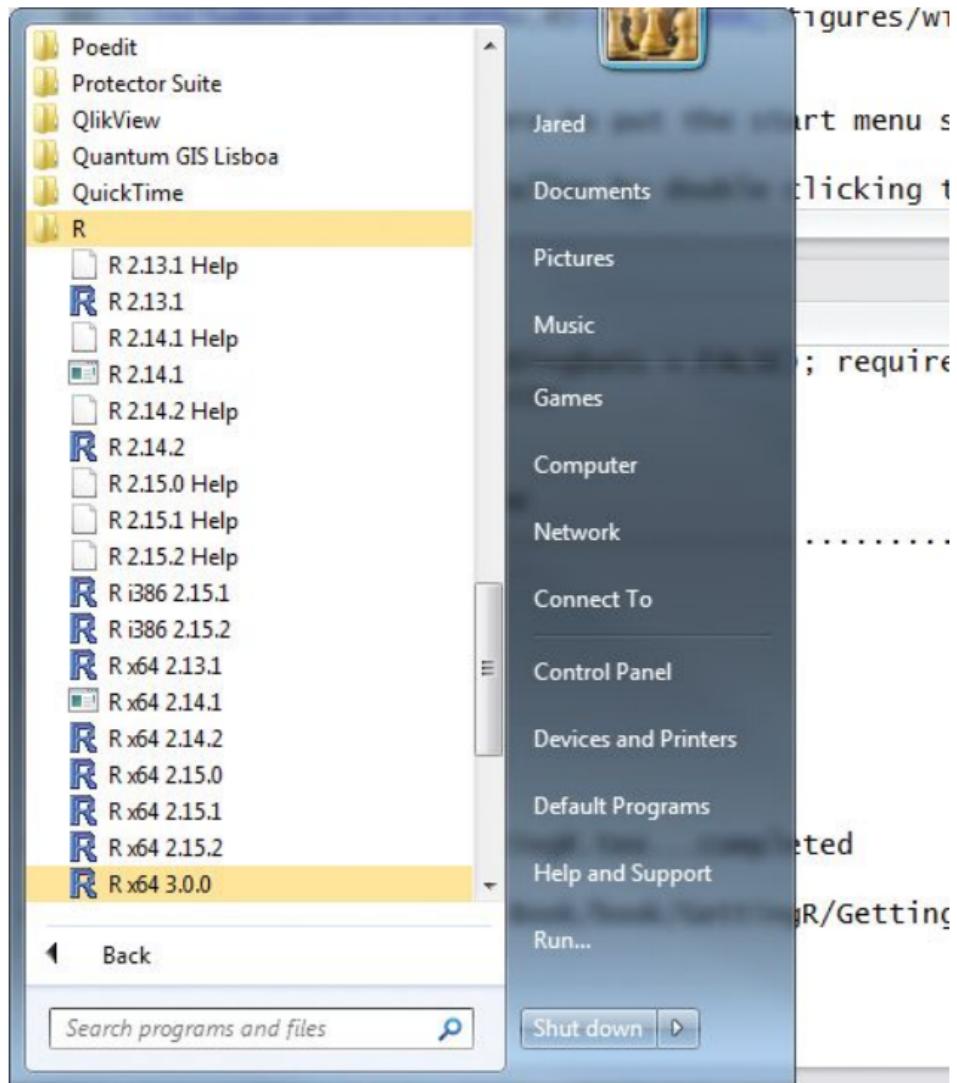
**Figure 1.9** Accept the default startup options, as we recommend using RStudio as the front end and these will not be important.

Next, choose where to put the start menu shortcuts. We recommend simply using R and putting every version in there as shown in [Figure 1.10](#).



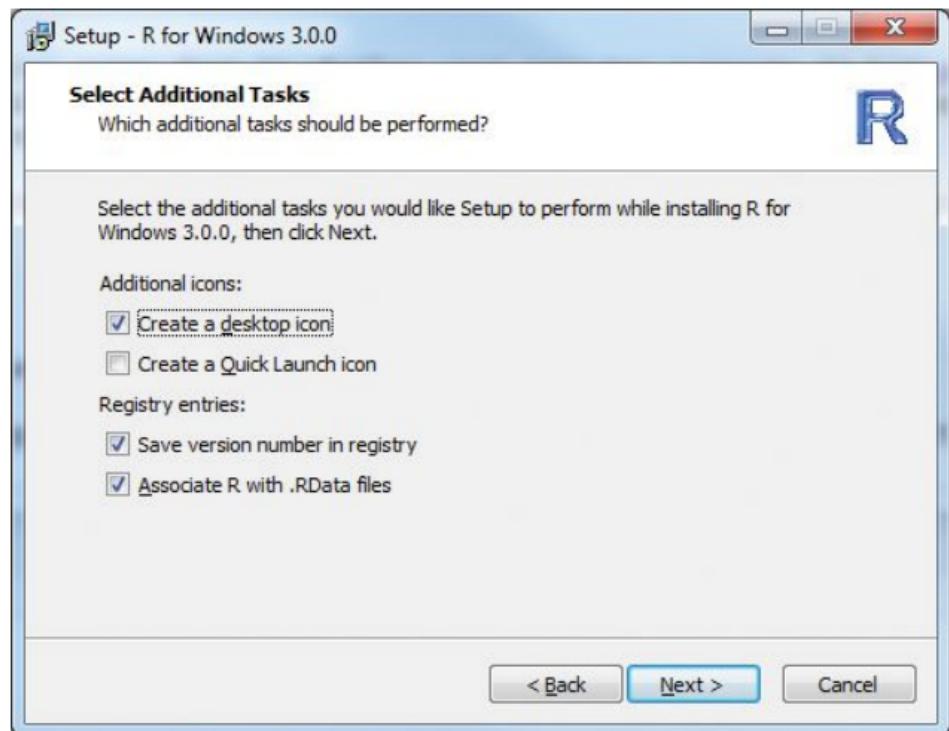
**Figure 1.10** Choose the Start Menu folder where the shortcuts will be installed.

We have many versions of R, all inside the same Start Menu folder, which allows code to be tested in different versions. This is illustrated in [Figure 1.11](#).



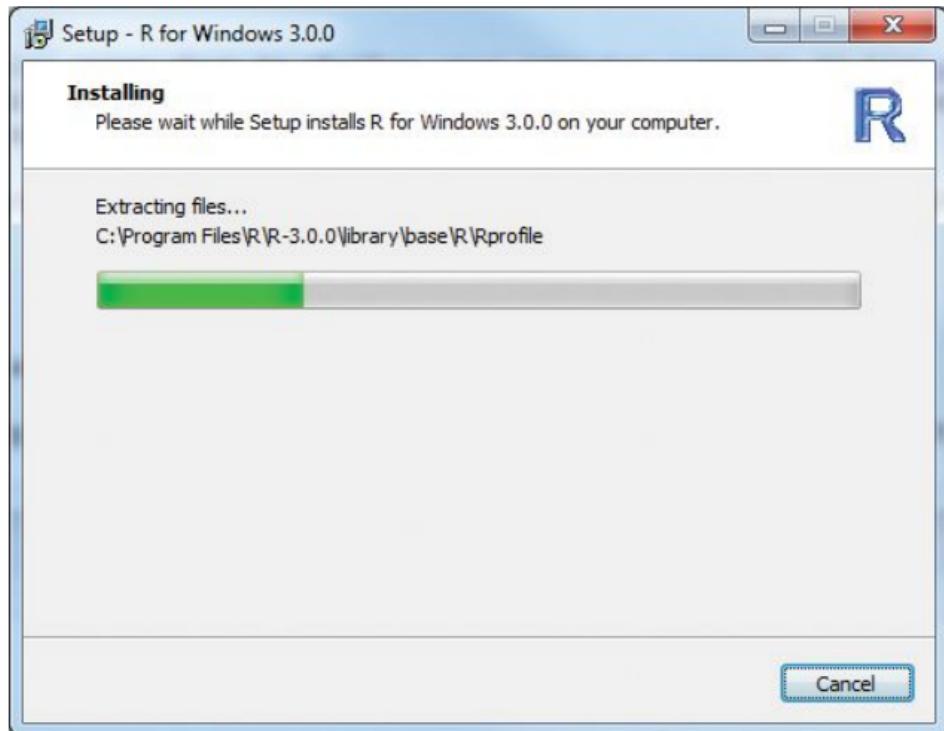
**Figure 1.11** We have multiple versions of R installed to allow development and testing with different versions.

The last option is choosing whether to complete some additional tasks such as creating a desktop icon (not too useful if using RStudio). We highly recommend saving the version number in the registry and associating R with RData files. These options are shown in [Figure 1.12](#).



**Figure 1.12** We recommend saving the version number in the registry and associating R with RData files.

Clicking Next begins installation and displays a progress bar, as shown in [Figure 1.13](#).



**Figure 1.13** A progress bar is displayed during installation.

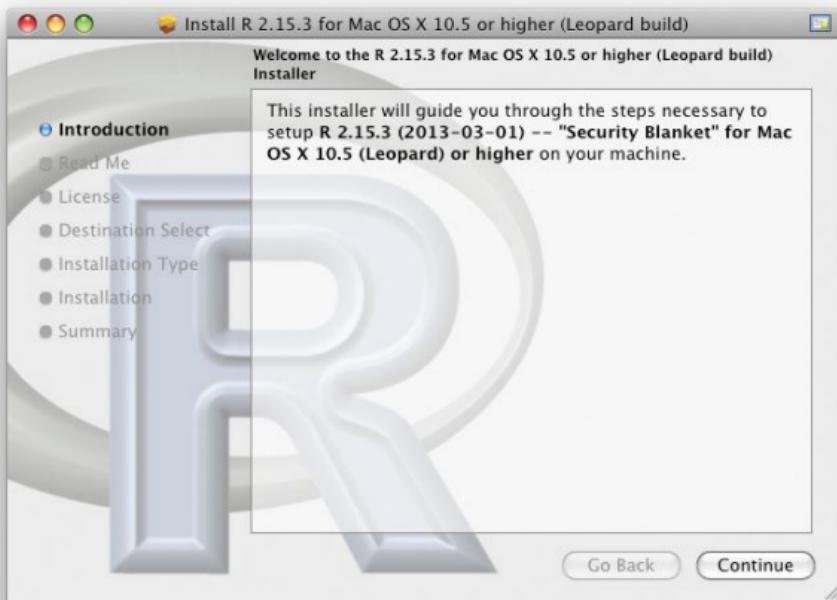
The last step, shown in [Figure 1.14](#), is to click Finish and the installation is complete.



**Figure 1.14** Confirmation that installation is complete.

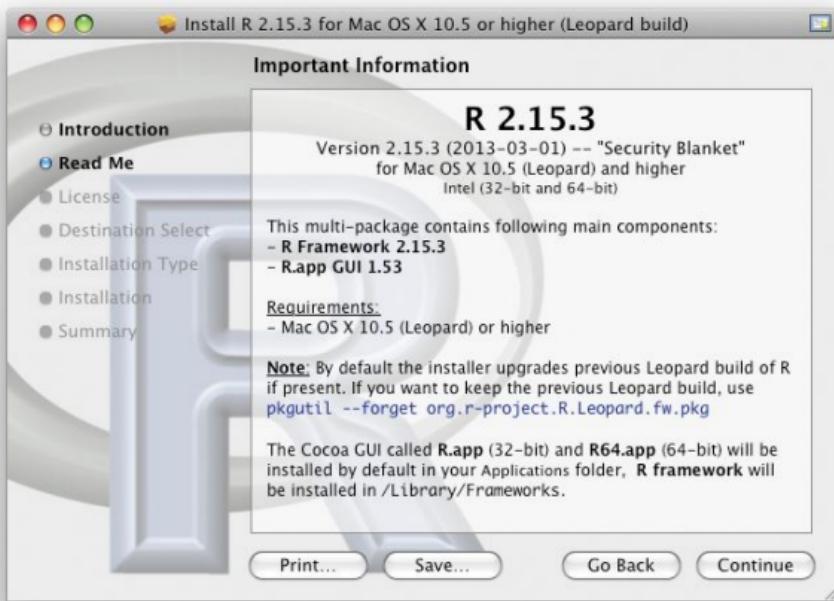
## 1.4.2. Installing on Mac OS X

Find the appropriate installer, which ends in .pkg, and launch it by double-clicking. This brings up the introduction, shown in [Figure 1.15](#). Click Continue to begin the installation process.



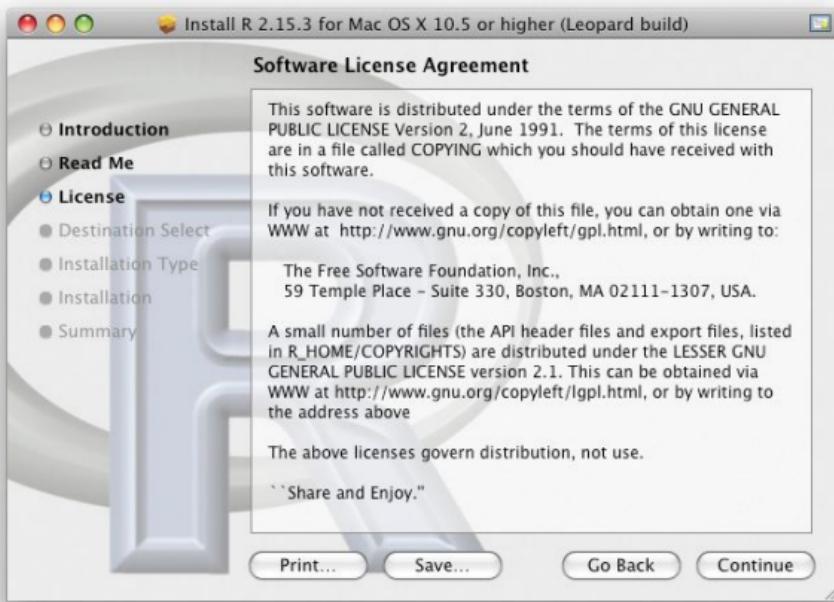
**Figure 1.15** Introductory screen for installation on a Mac.

This brings up some information about the version of R being installed. There is nothing to do except click Continue, as shown in [Figure 1.16](#).



**Figure 1.16** Version selection.

Then the license information is displayed, as in [Figure 1.17](#). Click Continue to proceed, the only viable option in order to use R.



**Figure 1.17** The license agreement, which must be acknowledged to use R.

Click Agree to confirm that the license is agreed to, which is mandatory to use R as is evidenced in [Figure 1.18](#).

To continue installing the software you must agree to the terms of the software license agreement.

Click Agree to continue or click Disagree to cancel the installation and quit the Installer.

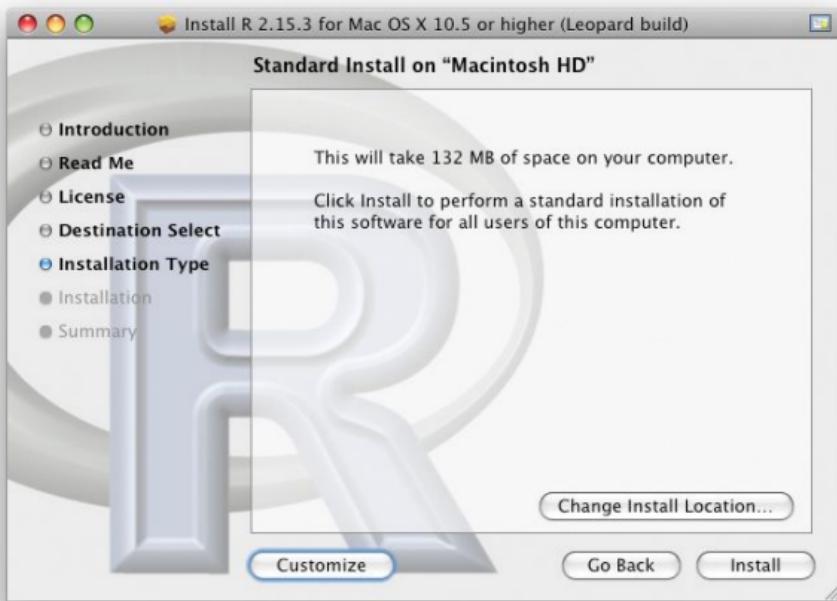
[Read License](#)

[Disagree](#)

[Agree](#)

**Figure 1.18** The license agreement must also be agreed to.

To install R for all users, click Install; otherwise, click Change Install Location to pick a different location. This is shown in [Figure 1.19](#).



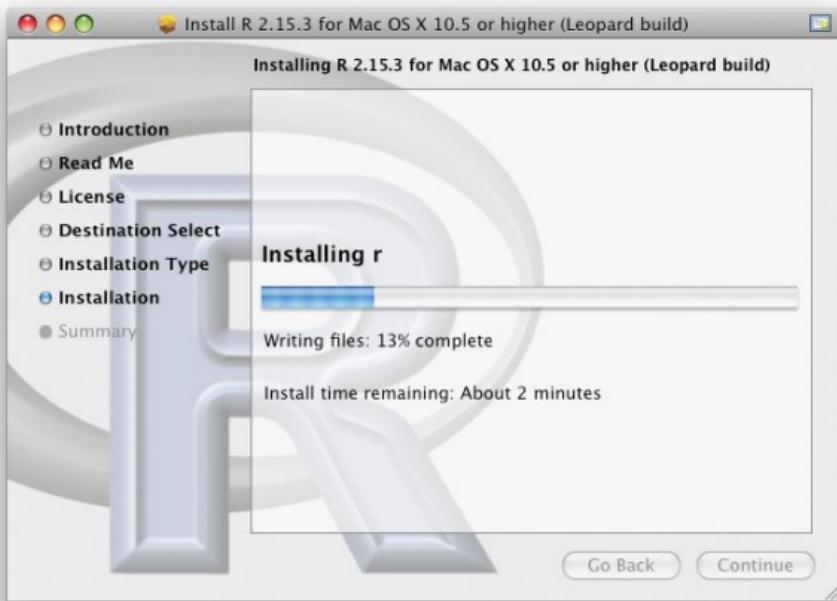
**Figure 1.19** By default R is installed for all users, although there is the option to choose a specific location.

If prompted, enter the necessary password as shown in [Figure 1.20](#).



**Figure 1.20** The administrator password might be required for installation.

This starts the installation process, which displays a progress bar as shown in [Figure 1.21](#).



**Figure 1.21** A progress bar is displayed during installation.

When done, the installer signals success as [Figure 1.22](#) shows. Click Close to finish the installation.



**Figure 1.22** This signals a successful installation.

### 1.4.3. Installing on Linux

Retrieving R from its standard distribution mechanism will download, build and install R in one step.

## 1.5. Revolution R Community Edition

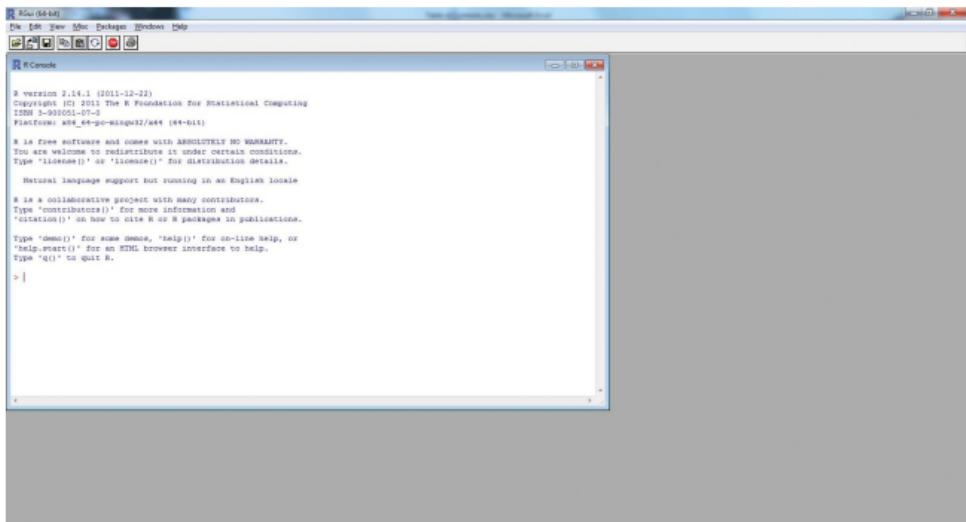
Revolution Analytics offers a community version of its build of R featuring an Integrated Development Environment based on Visual Studio and built with the Intel Matrix Kernel Library (MKL), allowing for much faster matrix computations. It is available for free at <http://www.revolutionanalytics.com/products/revolution-r.php>. They also offer a paid version that provides specialized algorithms to work on very large data. More information is available at <http://www.revolutionanalytics.com/products/revolution-enterprise.php>.

## 1.6. Conclusion

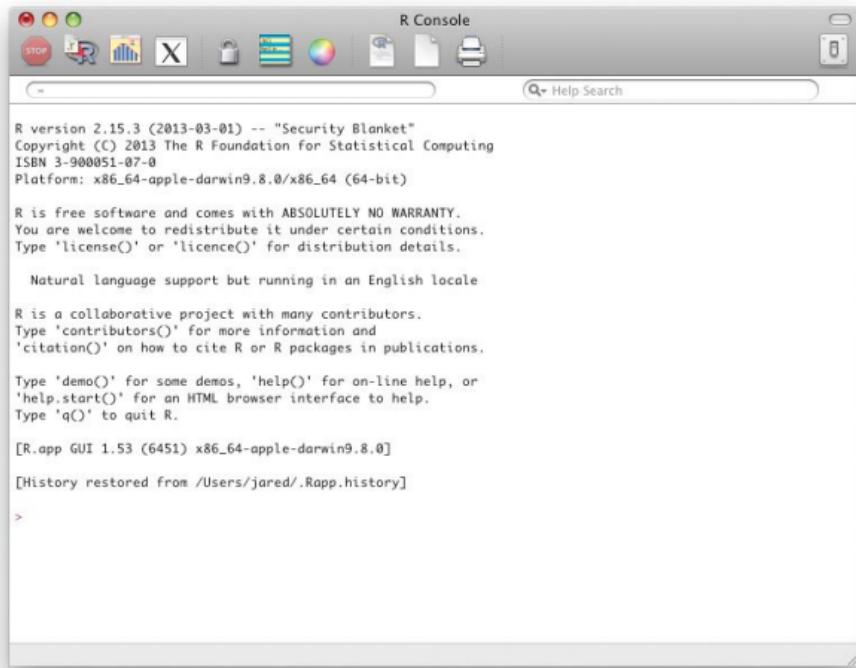
At this point R is fully usable and comes with a crude GUI. However, it is best to install RStudio and use its interface, which is detailed in [Section 2.2](#). The process involves downloading and launching an installer, just as with any other program.

# Chapter 2. The R Environment

Now that R is downloaded and installed, it is time to get familiar with how to use R. The basic R interface on Windows is fairly Spartan as seen in [Figure 2.1](#). The Mac interface ([Figure 2.2](#)) has some extra features and Linux has far fewer, being just a terminal.



**Figure 2.1** The standard R interface in Windows.



**Figure 2.2** The standard R interface on Mac OS X.

Unlike other languages, R is very interactive. That is, results can be seen one command at a time. Languages such as C++ require that an entire section of code be written, compiled and run in order to see results. The state of objects and results can be seen at any point in R. This in-

teractivity is one of the most amazing aspects of working with R.

There have been numerous Integrated Development Environments (IDEs) built for R. For the purposes of this book we will assume that RStudio is being used, which is discussed in [Section 2.2](#).

## 2.1. Command Line Interface

The command line interface is what makes R so powerful, and also frustrating to learn. There have been attempts to build point-and-click interfaces for R, such as Rcmdr, but none have truly taken off. This is a testament to how typing in commands is much better than using a mouse. That might be hard to believe, especially for those coming from Excel, but over time it becomes easier and less error prone.

For instance, fitting a regression in Excel takes at least seven mouse clicks, often more: Data >> Data Analysis >> Regression >> OK >> Input Y Range >> Input X Range >> OK. Then it

may need to be done all over again to make one little tweak or because there are new data. Even harder is walking a colleague through those steps via email. In contrast, the same command is just one line in R, which can easily be repeated and copied and pasted. This may be hard to believe initially, but after some time the command line makes life much easier.

To run a command in R, type it into the console next to the > symbol and press the Enter key. Entries can be as simple as the number 2 or complex functions, such as those seen in [Chapter 8](#).

To repeat a line of code, simply press the Up Arrow key and hit Enter again. All previous commands are saved and can be accessed by repeatedly using the Up and Down Arrow keys to cycle through them.

Interrupting a command is done with Esc in Windows and Mac and Ctrl-C in Linux.

Often when working on a large analysis it is good to have a file of the code used. Until recently, the most common way to handle this was

to use a text editor<sup>1</sup> such as TextPad or UltraEdit to write code and then copy and paste it into the R console. While this worked, it was sloppy and led to a lot of switching between programs.

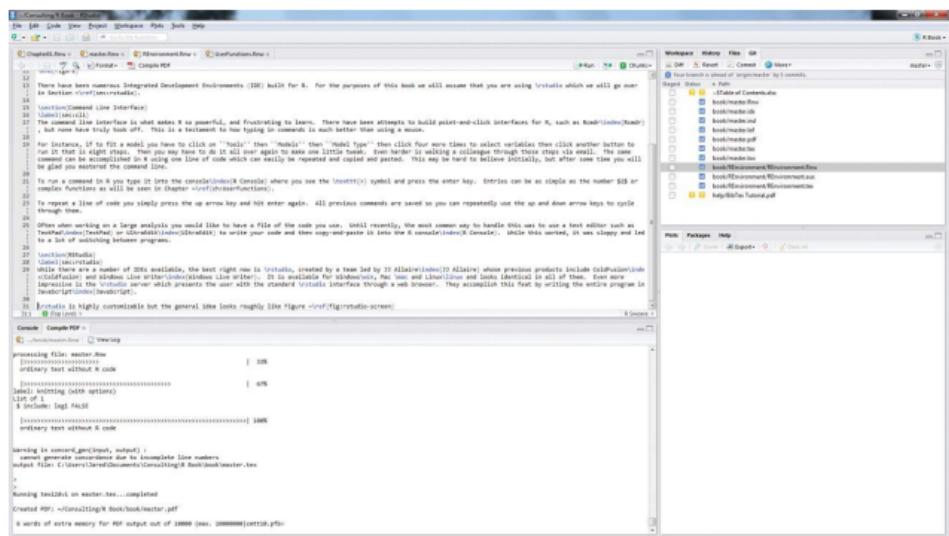
1. This means a programming text editor as opposed to a word processor such as Microsoft Word. A text editor preserves the structure of the text whereas word processors may add formatting that makes it unsuitable for insertion into the console.

## 2.2. RStudio

While there are a number of IDEs available, the best right now is RStudio, created by a team led by JJ Allaire whose previous products include ColdFusion and Windows Live Writer. It is available for Windows, Mac and Linux and looks identical in all of them. Even more impressive is the RStudio server, which runs an R instance on a Linux server and allows the user to run commands through the standard RStudio interface in a Web browser. It works with any version of R (greater than 2.11.1) including Revolution R from Revolution Analytics. RStudio has so many options that it can be a bit overwhelming. We will cover some of the most useful or frequently used features.

RStudio is highly customizable but the basic interface looks roughly like [Figure 2.3](#). In this case the lower left pane is the R console, which can be used just like the standard R console. The upper left pane takes the place of a text editor but is far more powerful. The upper right pane holds

information about the workspace, command history, files in the current folder and Git version control. The lower right pane displays plots, package information and help files.



**Figure 2.3** The general layout of RStudio.

There are a number of ways to send and execute commands from the editor to the console. To send one line place the cursor at the desired line and press Ctrl+Enter (Command+Enter on Mac). To insert a selection, simply highlight the selection and press Ctrl+Enter. To run an entire file of code, press Ctrl+Shift+S.

When typing code, such as an object name or function name, hitting Tab will autocomplete the code. If more than one object or function matches the letters typed so far, a dialog will pop up giving the matching options as shown in [Figure 2.4](#).

```
Console - Compile PDF <=
[1] > ConsultingNBook() <=
14      Yes   1
15      yes!  1
16      yes-  1
17      Yes-  1
18      Yes.  1
> 5+2+37+77+1+1
[1] 123
> 130^2/8
[1] 32.5
> 150^2/8
[1] 37.5
> 35^2/8
[1] 700
> 2.7^2/8
[1] 22
> 200^4.55
[1] 910
> 437/29
[1] eventID
> eventSize
[1]
[2]
[3]
[4]
[5]
[6]
[7]
[8]
[9]
[10] "eventID" "rsvp"    "theRSVP"
[11] 10
> even
```

**Figure 2.4** Object Name Autocomplete in RStudio.

Typing Ctrl+1 moves the cursor to the text editor area and Ctrl+2 moves it to the console. To move to the previous tab in the text editor, press Ctrl+Alt+Left in Windows, Ctrl+PageUp in Linux and Ctrl+Option+Left on Mac. To move to the next tab in the text editor, press Ctrl+Alt+Right in Windows, Ctrl+PageDown in Linux and Ctrl+Option+Right on Mac. For a

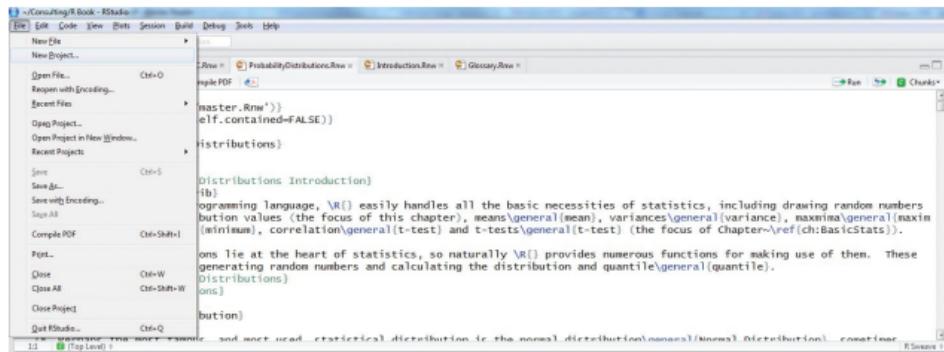
complete list of shortcuts click Help >> Keyboard Shortcuts.

## 2.2.1. RStudio Projects

A primary feature of RStudio is projects. A project is a collection of files—and possibly data, results and graphs—that are all related to each other.<sup>2</sup> Each package even has its own working directory. This is a great way to keep organized.

2. This is different from an R session, which is all the objects and work done in R and kept in memory for the current usage period, which usually resets upon restarting R.

The simplest way to start a new project is to click File >> New Project as in [Figure 2.5](#).



[Figure 2.5](#) Clicking File >> New Project begins the project creation process.

Three options are available, shown in [Figure 2.6](#): starting a new project in a new directory, associating a project with an existing directory or checking out a project from a version control repository such as Git or SVN. In all three cases a .Rproj file is put into the resulting directory and keeps track of the project.

**Create project from:****New Project**

Start a project in a new directory &gt;

**Existing Directory**

Associate a project with an existing working directory &gt;

**Version Control**

Checkout a project from a version control repository &gt;

Cancel

**Figure 2.6** Three options are available to start a new project: a new directory, associating a project with an existing directory or checking out a project from a version control repository.

Choosing to create a new directory brings up a dialog, shown in [Figure 2.7](#), that requests a project name and where to create a new directory.

 Back

## Create New Project



Type:

(Default) ▾

Directory name:

Project1

Create project as subdirectory of:

~

Browse...

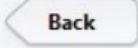
 Create a git repository for this project

Create Project

Cancel

**Figure 2.7** Dialog to choose the location of a new project directory.

Choosing an existing directory asks for the name of the directory, seen in [Figure 2.8](#).

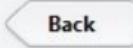
 Back**Create Project from Existing Directory**

Project working directory:

[Browse...](#)[Create Project](#)[Cancel](#)

**Figure 2.8** Dialog to choose an existing directory in which to start a project.

Choosing to use version control (we prefer Git) first asks whether to use Git or SVN as in [Figure 2.9](#).

 Back

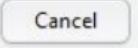
## Create Project from Version Control

**Git**

Clone a project from a Git repository

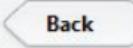
**Subversion**

Checkout a project from a Subversion repository

 Cancel

**Figure 2.9** Here is the option to choose which type of repository to start a new project from.

Selecting Git asks for a repository URL, such as <git@github.com:jaredlander/coefplot.git>, which will then fill in the project directory name, as shown in [Figure 2.10](#). As with creating a new directory, this will ask where to put this new directory.

 Back

### Clone Git Repository



Repository URL:

Project directory name:

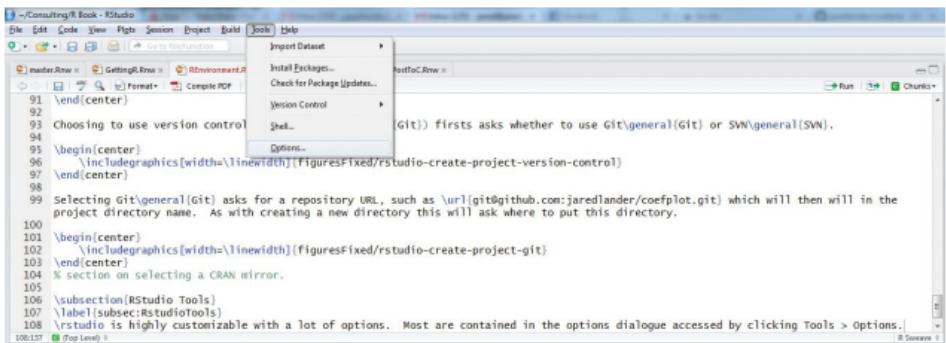
Create project as subdirectory of:

 ~[Browse...](#)[Create Project](#)[Cancel](#)

**Figure 2.10** Enter the URL for a Git repository, as well as the folder where this should be cloned to.

#### 2.2.2. RStudio Tools

RStudio is highly customizable with a lot of options. Most are contained in the Options dialog accessed by clicking Tools >> Options, as seen in [Figure 2.11](#).

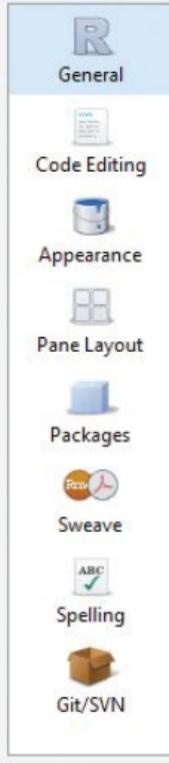


**Figure 2.11** Clicking Tools >> Options brings up RStudio options.

First are the General options, shown in [Figure 2.12](#). There is a control for selecting which version of R to use. This is a powerful tool when a computer has a number of versions of R. However, RStudio must be restarted after changing the R version. In the future, RStudio is slated to offer the ability to set different versions of R for each project. It is also a good idea to not restore or save .RData files on startup and exiting.<sup>3</sup>

3. RData files are a convenient way of saving and sharing R objects and are discussed in [Section 6.5](#).

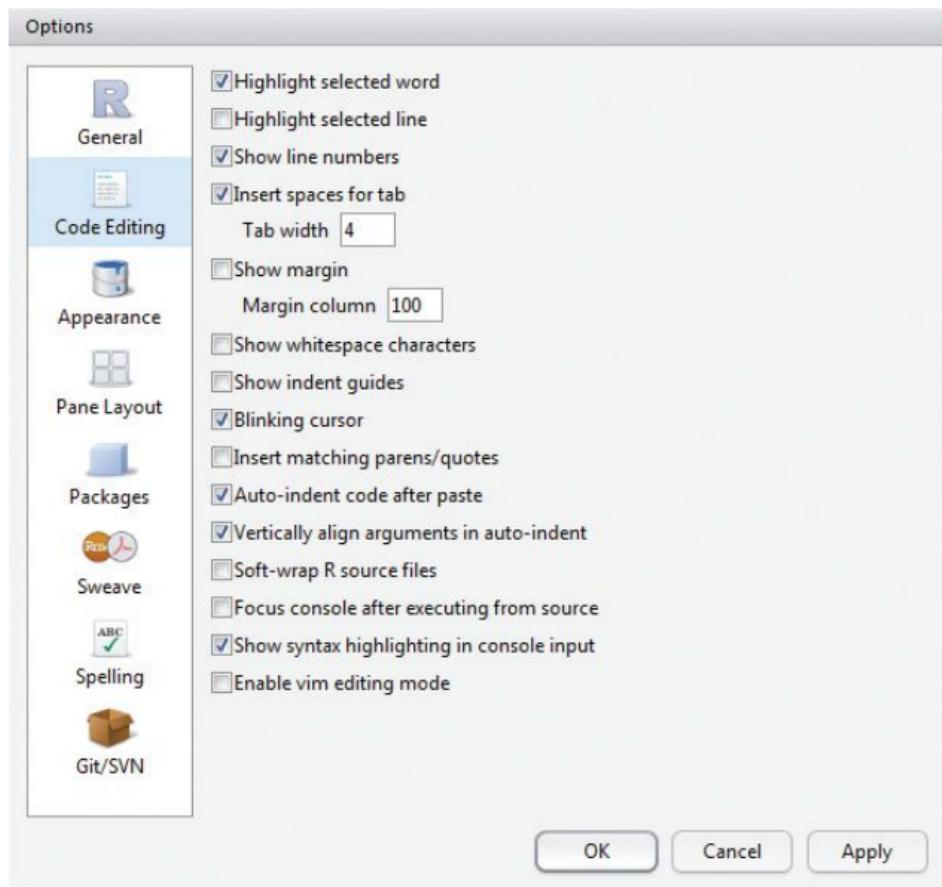
## Options



**Figure 2.12** General options in RStudio.

The Code Editing options, shown in [Figure 2.13](#), control the way code is entered and displayed in the text editor. It is generally considered good practice to replace tabs with spaces, either two or four. Some hard-core programmers will

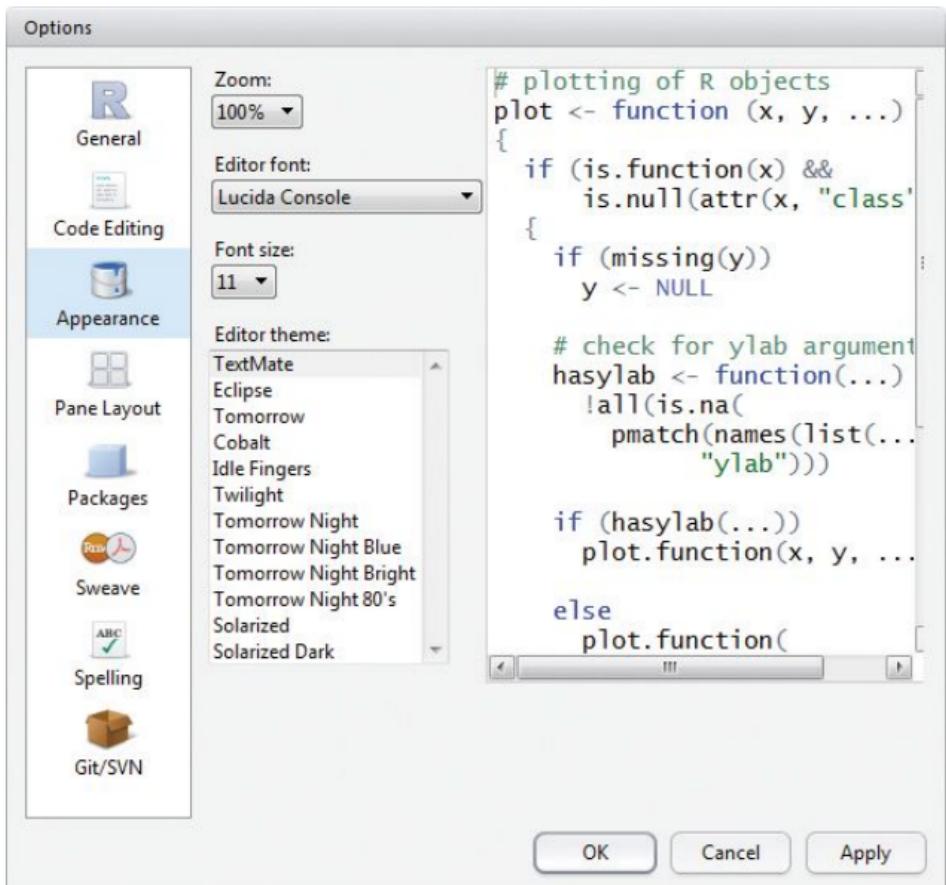
appreciate vim mode. As of now there is no Emacs mode.



**Figure 2.13** Options for customizing the code editing pane.

Appearance options, shown in [Figure 2.14](#), change the way code looks, aesthetically. The

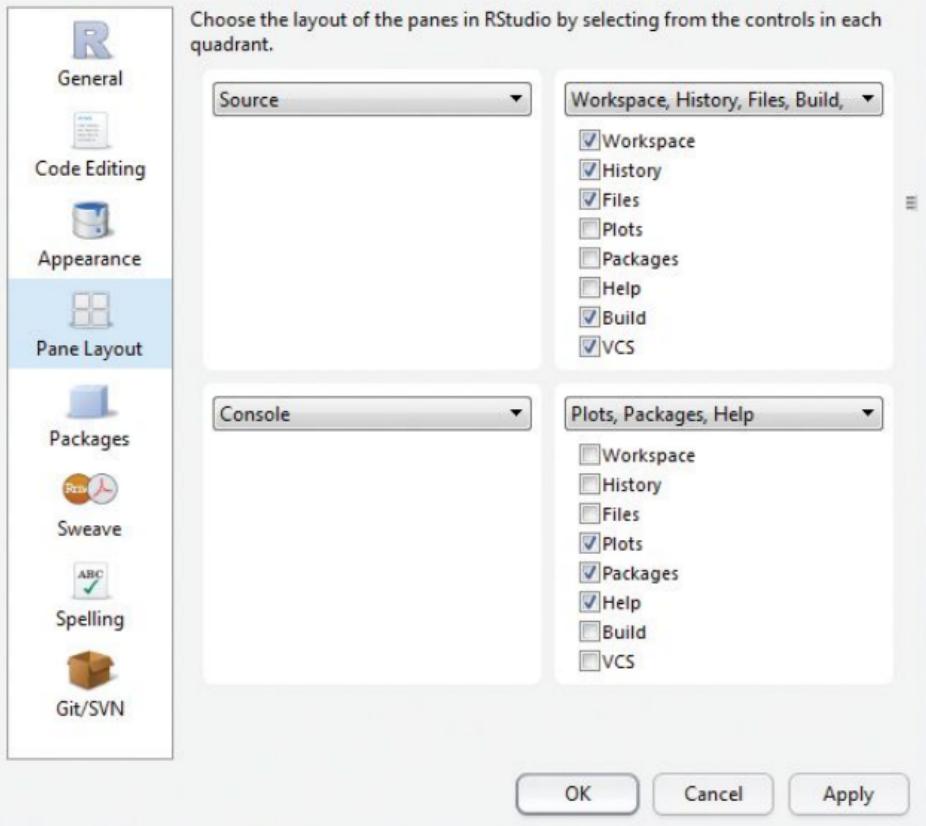
font, size and color of the background and text can all be customized here.



**Figure 2.14** Options for code appearance.

The Pane Layout options, shown in [Figure 2.15](#), simply rearrange the panes that make up RStudio.

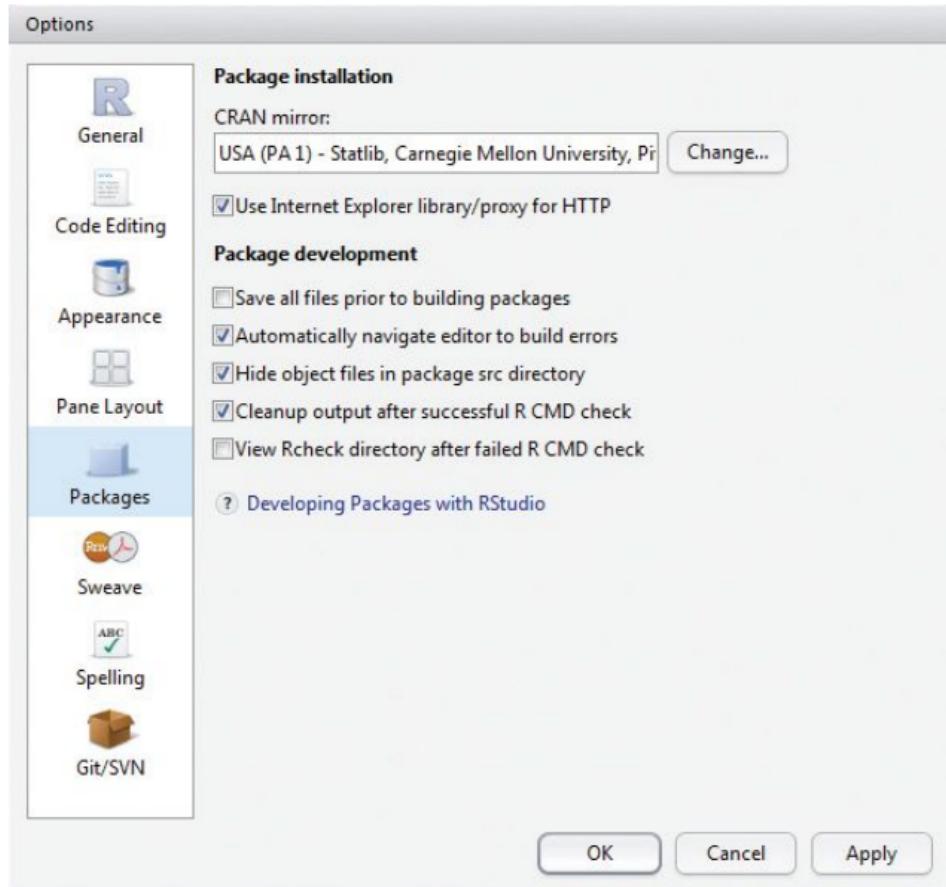
## Options



**Figure 2.15** These options control the placement of the various panes in RStudio.

The Packages options, shown in [Figure 2.16](#), set options regarding packages, although the most important is the CRAN mirror. While this is changeable from the console, this is the default

setting. It is best to pick the mirror that is geographically the closest.



**Figure 2.16** Options related to packages.  
The most important is the CRAN mirror selection.

Sweave, [Figure 2.17](#), may be a bit misnamed, as this is where to choose between using Sweave or knitr. Both are used for the generation of PDF documents with knitr also enabling the creation of HTML documents. knitr, detailed in [Chapter 23](#), is by far the better option, although it must be installed first, which is explained in [Section 3.1](#). This is also where the PDF viewer is selected.

## Options

The screenshot shows the RStudio Options dialog box. On the left is a vertical toolbar with icons for General, Code Editing, Appearance, Pane Layout, Packages, Sweave (which is highlighted with a blue background), Spelling, and Git/SVN. The main area has the following sections:

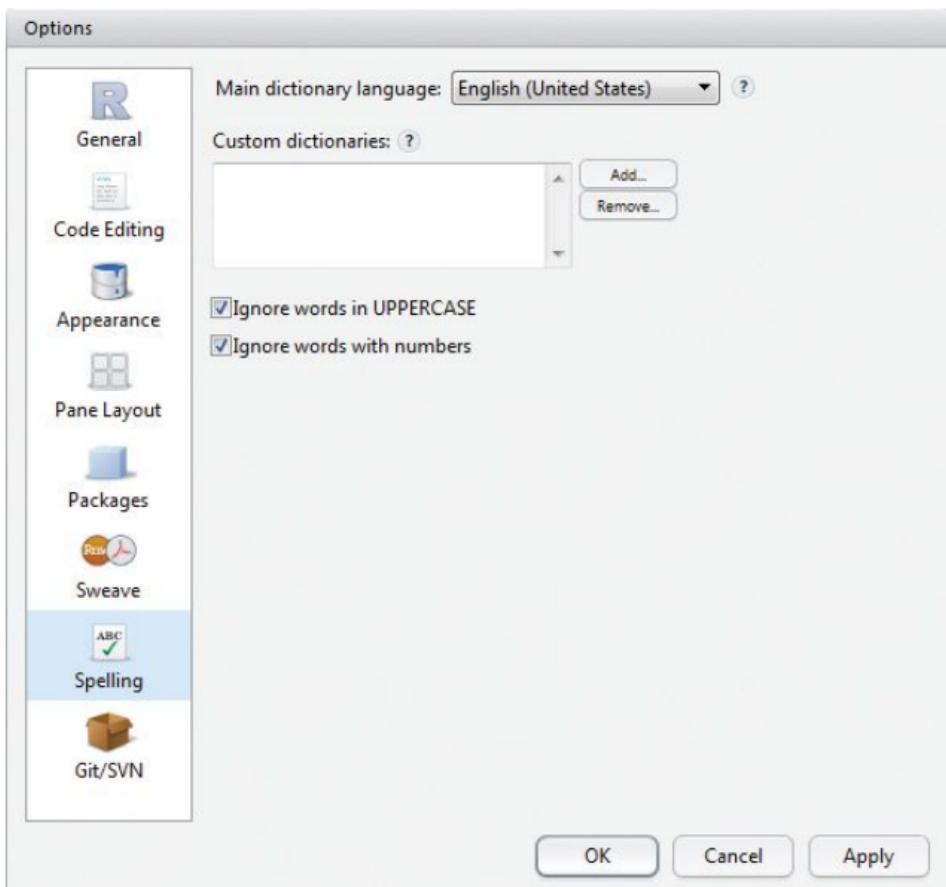
- Program defaults (when not in a project)**
  - Weave Rnw files using: `knitr` (dropdown menu with a question mark icon)
  - Typeset LaTeX into PDF using: `pdfLaTeX` (dropdown menu with a question mark icon)
  - NOTE: The Rnw weave and LaTeX compilation options are also set on a per-project (and optionally per-file) basis. Click the help icons above for more details.*
- LaTeX editing and compilation**
  - Clean auxiliary output after compile
  - Enable shell escape commands
  - Insert numbered sections and subsections
- PDF preview**
  - Preview PDF after compile using: `Sumatra (Recommended)` (dropdown menu with a question mark icon)
  - Always enable Rnw concordance (required for synctex)

At the bottom right are three buttons: `OK`, `Cancel`, and `Apply`.

**Figure 2.17** This is where to choose whether to use Sweave or knitr and select the PDF viewer.

RStudio contains a spelling checker for writing LATEX and Markdown documents (using knitr, preferably), which is controlled from the

Spelling options, [Figure 2.18](#). Not much needs to be set here.



**Figure 2.18** These are the options for the spelling check dictionary, which allows language selection and the custom dictionaries.

The last option, Git/SVN, [Figure 2.19](#), indicates where the executables for Git and SVN exist. This needs to be set only once but is necessary for version control.

## Options

The screenshot shows the 'Options' dialog box in RStudio. On the left is a sidebar with icons and labels for General, Code Editing, Appearance, Pane Layout, Packages, Sweave, Spelling, and Git/SVN. The 'Git/SVN' option is selected and highlighted with a blue background. The main area contains configuration options for version control:

- Enable version control interface for RStudio projects:** A checked checkbox.
- Git executable:** A text input field containing "C:/Program Files (x86)/Git/bin/git.exe" with a "Browse..." button to its right.
- Use Git Bash as shell for Git projects:** A checked checkbox.
- SVN executable:** A text input field containing "(Not Found)" with a "Browse..." button to its right.
- SSH RSA Key:** A text input field containing "C:/Users/Jared/.ssh/id\_rsa". To its right is a link "View public key". Below it is a link "Create RSA Key...".
- Using Version Control with RStudio:** A link with a question mark icon.

At the bottom are three buttons: "OK", "Cancel", and "Apply".

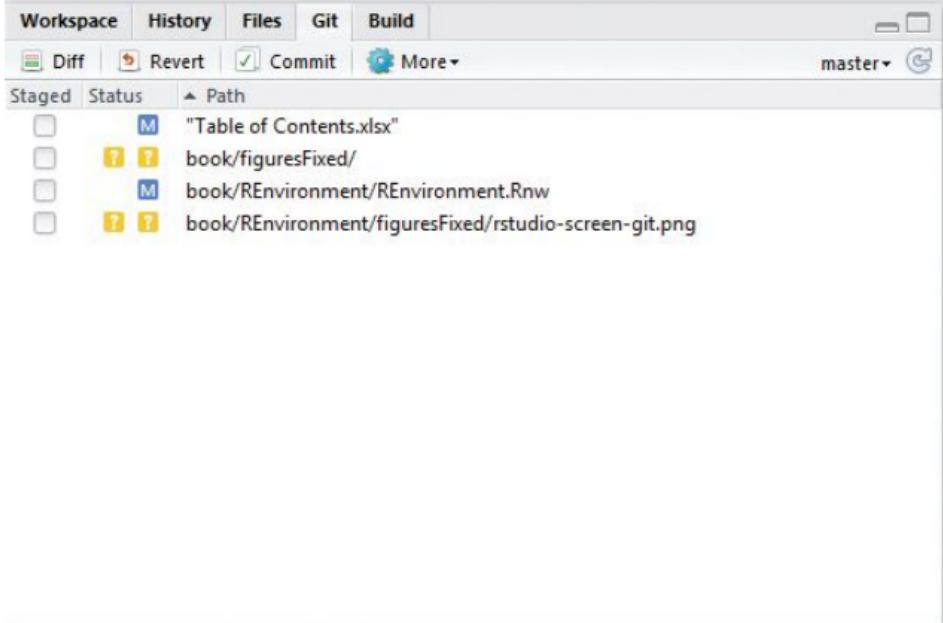
**Figure 2.19** This is where to set the location of Git and SVN executables so they can be used by RStudio.

## 2.2.3. Git Integration

Using version control is a great idea for many reasons. First and foremost it provides snapshots of code at different points in time and can easily revert to those snapshots. Ancillary benefits include having a backup of the code and the ability to easily transfer the code between computers with little effort.

While SVN used to be the gold standard in version control it has since been superseded by Git, so that will be our focus. After associating a project with a Git repository<sup>4</sup> RStudio has a pane for Git like the one shown in [Figure 2.20](#).

4. A Git account should be set up with either GitHub (<https://github.com/>) or Bitbucket (<https://bitbucket.org/>) beforehand.



**Figure 2.20** The Git pane shows the Git status of files under version control. A blue square with a white M indicates a file has been changed and needs to be committed. A yellow square with a white question mark indicates a new file that is not being tracked by Git.

The main functionality is committing changes, pushing them to the server and pulling changes made by other users. Clicking the Commit button brings up a dialog, [Figure 2.21](#), which displays

files that have been modified, or new files. Clicking on one of these files displays the changes; deletions are colored pink and additions are colored green. There is also a space to write a message describing the commit.

RStudio: Review Changes

Changes History master Stage Revert Ignore

Staged Status Path

Table of Contents.xlsx  
book/figuresFixed/  
book/REnvironment/REnvironment.Rnw  
book/REnvironment/figuresFixed/rstudio-screen-git.png

Commit message  
Minor changes made to a few paragraphs.

Show Staged Unstaged Context Line Stage All Discard All

64 64  
65 65 \subsection{RStudio Projects}  
66 66 \label{subsec:Projects}

67 A primary feature of \rstanio{} is projects. A project is a collection of files--and possibly data, results and graphs--that are all related to each other. Each package even has its own working directory. This is a great way to keep organized.

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68 68  
69 69 The simplest way to start a new project is to click Project \$>\$ Create Project.  
70 70  
71 71 \begin{center}  
72 72 \includegraphics[width=\linewidth]{figuresFixed/rstudio-project-menu}

@@ -94,11 +94,11 @@ Choosing to use version control\general{version control} (we prefer Git\general{

Stage chunk Discard chunk

94 94  
95 95 \begin{center}  
96 96 \includegraphics[width=\linewidth]{figuresFixed/rstudio-create-project-version-control}  
97 97 \end{center}  
98 98

99 Selecting Git\general{Git} asks for a repository URL, such as  
\url{git@github.com:jaredlander/coefplot.git} which will then fill in the project directory name.  
As with creating a new directory this will ask where to put this directory.

99 Selecting Git\general{Git} asks for a repository URL, such as  
\url{git@github.com:jaredlander/coefplot.git} which will then fill in the project directory name.  
As with creating a new directory this will ask where to put this directory.

100 100  
101 101 \begin{center}  
102 102 \includegraphics[width=\linewidth]{figuresFixed/rstudio-create-project-git}  
103 103 \end{center}

**Figure 2.21** This displays files and the changes made to the files, with green being additions and pink being deletions. The upper right contains a space for writing commit messages.

Clicking Commit will stage the changes and clicking Push will send them to the server.

## 2.3. Revolution Analytics RPE

Revolution Analytics provides an IDE based on Visual Studio called the R Productivity Environment (RPE). The greatest benefit of the RPE is the visual debugger. If this feature is not needed,<sup>5</sup> we recommend using Revolution with RStudio as the front-end, which can be set in the General options detailed in [Section 2.2.2](#).

- [5.](#) The latest version of RStudio now also offers a visual debugger.

## 2.4. Conclusion

R's usability has greatly improved over the past few years, mainly thanks to Revolution Analytics' RPE and RStudio. Using an IDE can greatly improve proficiency, and change working with R from merely tolerable to actually enjoyable.<sup>6</sup> RStudio's code completion, text editor, Git integration and projects are indispensable for a good programming work flow.

- [6.](#) One of our students relayed that he preferred Matlab to R until he used RStudio.

# Chapter 3. R Packages

Perhaps the biggest reason for R's phenomenally ascendant popularity is its collection of user-contributed packages. As of mid-September 2013, there were 4,845 packages available on CRAN<sup>1</sup>, written by an estimated 2,000 different people. Odds are good that if a statistical technique exists, it has been written in R and contributed to CRAN. Not only are there an incredibly large number of packages, many are written by the authorities in the field such as Andrew Gelman, Trevor Hastie, Dirk Eddelbuettel and Hadley Wickham.

1. <http://cran.r-project.org/web/packages/>

A package is essentially a library of prewritten code designed to accomplish some task or a collection of tasks. The survival package is used for survival analysis, ggplot2 is used for plotting and sp is for dealing with spatial data.

It is important to remember that not all packages are of the same quality. Some are built to be

very robust and are well-maintained, while others are built with good intentions but can fail with unforeseen errors and others still are just plain poor. Even with the best packages, it is important to remember that most were written by statisticians for statisticians, so they may differ from what a computer engineer would expect.

This book will not attempt to provide an exhaustive list of good packages to use because that is constantly changing. However, there are some packages that are so pervasive that they will be used in this book as if they were part of base R. Some of these are `ggplot2`, `reshape2` and `plyr` by Hadley Wickham; `glmnet` by Trevor Hastie, Robert Tibshirani and Jerome Friedman; `Rcpp` by Dirk Eddelbuettel; and `knitr` by Yihui Xie. We have written a package on CRAN, `coefplot`, with more to follow.

### 3.1. Installing Packages

As with many tasks in R, there are multiple ways to install packages. The simplest is to install them using the GUI provided by RStudio and shown in [Figure 3.1](#). Access the Packages pane shown in this figure either by clicking its tab or by pressing Ctrl+7 on the keyboard.

Plots Packages Help

Install Packages Check for Updates

<input checked="" type="checkbox"/>	<a href="#">coefplot</a>	Plots Coefficients from Fitted Models	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">colorspace</a>	Color Space Manipulation	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">compiler</a>	The R Compiler Package	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">data.table</a>	Extension of data.frame for fast indexing, fast ordered joins, fast assignment, fast grouping and list columns.	<input type="button" value="X"/>
<input checked="" type="checkbox"/>	<a href="#">datasets</a>	The R Datasets Package	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">Defaults</a>	Create Global Function Defaults	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">devtools</a>	Tools to make developing R code easier	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">dichromat</a>	Color schemes for dichromats	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">digest</a>	Create cryptographic hash digests of R objects	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">epsi</a>	Edge Preserving Smoothing for Images	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">evaluate</a>	Parsing and evaluation tools that provide more details than the default.	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">fAssets</a>	Rmetrics - Assets Selection and Modelling	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">fBasics</a>	Rmetrics - Markets and Basic Statistics	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">fCopulae</a>	Rmetrics - Dependence Structures with Copulas	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">fields</a>	Tools for spatial data	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">foreach</a>	Foreach looping construct for R	<input type="button" value="X"/>
<input type="checkbox"/>	<a href="#">foreign</a>	Read Data Stored by Minitab, S, SAS, SPSS, Stata, Systat, dBase ...	<input type="button" value="X"/>

**Figure 3.1** RStudio's Packages pane.

In the upper-left corner, click the Install Packages button to bring up the dialog in [Figure 3.2](#).

## Install Packages

Install from:

? Configuring Repositories

Repository (CRAN, CRANextra)

Packages (separate multiple with space or comma):

coefplot

Install to Library:

C:/Users/Jared/Documents/R/win-library/2.15 [Default]

Install dependencies

Install

Cancel

**Figure 3.2** RStudio's package installation dialog.

From here simply type the name of a package (RStudio has a nice autocomplete feature for this) and click Install. Multiple packages can be specified, separated by commas. This downloads and installs the desired package, which is then available for use. Selecting the Install dependencies checkbox will automatically download and install all packages that the desired package requires.

to work. For example, our `coefplot` package depends on `ggplot2`, `plyr`, `useful`, `stringr` and `reshape2`, and each of those may have further dependencies.

An alternative is to type a very simple command into the console:

[Click here to view code image](#)

```
> install.packages("coefplot")
```

This will accomplish the same thing as working in the GUI.

There has been a movement recently to install packages directly from GitHub or BitBucket repositories, especially to get the development versions of packages. This can be accomplished using `devtools`.

[Click here to view code image](#)

```
> require(devtools)  
> install_github(repo = "coefplot", username = "jaredlander")
```

If the package being installed from a repository contains source code for a compiled language—generally C++ or FORTRAN—then the proper compilers must be installed. More information is in [Section 24.6](#).

Sometimes there is a need to install a package from a local file, either a zip of a prebuilt package or a tar.gz of package code. This can be done using the installation dialog mentioned before but switching the Install from: option to Package Archive File as shown in [Figure 3.3](#). Then browse to the file and install. Note that this will not install dependencies, and if they are not present the installation will fail. Be sure to install dependencies first.

## Install Packages

Install from:

Package Archive File (.zip)



Package archive:

Browse...

Install to Library:

C:/Users/Jared/Documents/R/win-library/2.15 [Default]



Install dependencies

Install

Cancel

**Figure 3.3** RStudio's package installation dialog to install from an archive file.

Similarly to before, this can be accomplished using `install.packages`.

[Click here to view code image](#)

```
> install.packages("coefplot_1.1.7.zip")
```

### 3.1.1. Uninstalling Packages

In the rare instance when a package needs to be uninstalled, it is easiest to click the white X inside a grey circle on the right of the package description in RStudio's Packages pane shown in [Figure 3.1](#). Alternatively, this can be done with `remove.packages` where the first argument is a character vector naming the packages to be removed.

## 3.2. Loading Packages

Now that packages are installed they are almost ready to use and just need to be loaded first. There are two commands that can be used, either library or require. They both accomplish the same thing—loading the package—but require will return TRUE if it succeeds and FALSE with a warning if it cannot find the package. This returned value is useful when loading a package from within a function, a practice considered acceptable to some, improper to others. In general usage there is not much of a difference, so it comes down to personal preference. The argument to either function is the name of the desired package, with or without quotes. So loading the coefplot package would look like:

[Click here to view code image](#)

```
> require(coefplot)
```

*Loading required package: coefplot*

*Loading required package: ggplot2*

It prints out the dependent packages that get loaded as well. This can be suppressed by setting the argument quietly to TRUE.

[Click here to view code image](#)

```
> require(coefplot, quietly = TRUE)
```

A package only needs to be loaded when starting a new R session. Once loaded, it remains available until either R is restarted or the package is unloaded, as described in [Section 3.2.1](#).

An alternative to loading a package through code is to select the checkbox next to the package name in RStudio's Packages pane, seen on the left of [Figure 3.1](#). This will load the package by running the code just shown.

### 3.2.1. Unloading Packages

Sometimes a package needs to be unloaded. This is simple enough either by clearing the checkbox in RStudio's Packages pane or by using the detach function. The function takes the package name preceded by package: all in quotes.

[Click here to view code image](#)

```
> detach("package:coefplot")
```

It is not uncommon for functions in different packages to have the same name. For example, `coefplot` is in both `arm` (by Andrew Gelman) and `coefplot`.<sup>2</sup> If both packages are loaded, the function in the package loaded last will be invoked when calling that function. A way around this is to precede the function with the name of the package, separated by two colons (::).

2. This particular instance is because we built `coefplot` as an improvement on the one available in `arm`. There are other instances where the names have nothing in common.

[Click here to view code image](#)

```
> arm::coefplot(object)
> coefplot::coefplot(object)
```

Not only does this call the appropriate function, it also allows the function to be called without even loading the package beforehand.

## 3.3. Building a Package

Building a package is one of the more rewarding parts of working with R, especially sharing that package with the community through CRAN. [Chapter 24](#) discusses this process in detail.

## 3.4. Conclusion

Packages make up the backbone of the R community and experience. They are often considered what makes working with R so desirable. This is how the community makes its work, and so many of the statistical techniques, available to the world. With such a large number of packages, finding the right one can be overwhelming. CRAN Task Views (<http://cran.r-project.org/web/views/>) offers a curated listing of packages for different needs. However, the best way to find a new package might just be to ask the community. [Appendix A](#) gives some resources for doing just that.

# Chapter 4. Basics of R

R is a powerful tool for all manner of calculations, data manipulation and scientific computations. Before getting to the complex operations possible in R we must start with the basics. Like most languages R has its share of mathematical capability, variables, functions and data types.

## 4.1. Basic Math

Being a statistical programming language, R can certainly be used to do basic math and that is where we will start.

We begin with the “Hello, World!” of basic math:  $1 + 1$ . In the console there is a right angle bracket ( $>$ ) where code should be entered. Simply test R by running

```
> 1 + 1  
[1] 2
```

If this returns 2, then everything is great; if not, then something is very, very wrong. Assuming it worked, let's look at some slightly more complicated expressions:

```
> 1 + 2 + 3  
[1] 6  
> 3 * 7 * 2  
[1] 42  
> 4/2  
[1] 2  
> 4/3  
[1] 1.333
```

These follow the basic order of operations: Parenthesis, Exponents, Multiplication, Division, Addition and Subtraction (PEMDAS). This means operations inside parentheses take priority over other operations. Next on the priority list is exponentiation. After that multiplication and division are performed, followed by addition and subtraction.

This is why the first two lines in the following code have the same result while the third is different.

```
> 4 * 6 + 5  
[1] 29  
> (4 * 6) + 5  
[1] 29  
> 4 * (6 + 5)  
[1] 44
```

So far we have put white space in between each operator such as `*` and `/`. This is not necessary but is encouraged as good coding practice.

## 4.2. Variables

Variables are an integral part of any programming language and R offers a great deal of flexibility. Unlike statically typed languages such as C++, R does not require variable types to be declared. A variable can take on any available data type as described in [Section 4.3](#). It can also hold any R object such as a function, the result of an analysis or a plot. A single variable can at one point hold a number, then later hold a character and then later a number again.

#### 4.2.1. Variable Assignment

There are a number of ways to assign a value to a variable, and again, this does not depend on the type of value being assigned.

The valid assignment operators are `<-` and `=` with the first being preferred.

For example, let's save 2 to the variable `x` and 5 to the variable `y`.

```
> x <- 2  
> x  
[1] 2  
> y = 5  
> y  
[1] 5
```

The arrow operator can also point in the other direction.

```
> z <- 3  
> z  
[1] 3
```

The assignment operation can be used successively to assign a value to multiple variables simultaneously.

```
> a <- b <- 7  
> a  
[1] 7  
> b  
[1] 7
```

A more laborious, though sometimes necessary, way to assign variables is to use the `assign` function.

```
> assign("j", 4)  
> j  
[1] 4
```

Variable names can contain any combination of alphanumeric characters along with periods (.) and underscores (\_). However, they cannot *start* with a number or an underscore.

The most common form of assignment in the R community is the left arrow (<-), which may seem awkward to use at first but eventually becomes second nature. It even seems to make

sense, as the variable is sort of pointing to its value. There is also a particularly nice benefit for people coming from languages like SQL, where a single equal sign (=) tests for equality.

It is generally considered best practice to use actual names, usually nouns, for variables instead of single letters. This provides more information to the person reading the code. This is seen throughout this book.

## 4.2.2. Removing Variables

For various reasons a variable may need to be removed. This is easily done using remove or its shortcut rm.

[Click here to view code image](#)

```
> j  
[1] 4  
> rm(j)  
> # now it is gone  
> j  
Error: object 'j' not found
```

This frees up memory so that R can store more objects, although it does not necessarily free up memory for the operating system. To guarantee that, use `gc`, which performs garbage collection, releasing unused memory to the operating system. R automatically does garbage collection periodically, so this function is not essential.

Variable names are case sensitive, which can trip up people coming from a language like SQL or Visual Basic.

[Click here to view code image](#)

```
> theVariable <- 17
```

```
> theVariable
```

```
[1] 17
```

```
> THEVARIABLE
```

```
Error: object 'THEVARIABLE' not found
```

## 4.3. Data Types

There are numerous data types in R that store various kinds of data. The four main types of data most likely to be used are numeric, character (string), Date/POSIXct (time-based) and logical (TRUE/FALSE).

The type of data contained in a variable is checked with the `class` function.

```
> class(x)  
[1] "numeric"
```

### 4.3.1. Numeric Data

As expected, R excels at running numbers, so numeric data is the most common type in R. The most commonly used numeric data is numeric. This is similar to a float or double in other languages. It handles integers and decimals, both positive and negative, and, of course, zero. A numeric value stored in a variable is automatically assumed to be numeric. Testing whether a variable is numeric is done with the function `is.numeric`.

```
> is.numeric(x)  
[1] TRUE
```

Another important, if less frequently used, type is integer. As the name implies this is for whole numbers only, no decimals. To set an integer to a variable it is necessary to append the value with an L. As with checking for a numeric, the `is.integer` function is used.

```
> i <- 5L  
> i
```

```
[1] 5  
> is.integer(i)  
[1] TRUE
```

Do note that, even though i is an integer, it will also pass a numeric check.

```
> is.numeric(i)  
[1] TRUE
```

R nicely promotes integers to numeric when needed. This is obvious when multiplying an integer by a numeric, but importantly it works when dividing an integer by another integer, resulting in a decimal number.

```
> class(4L)  
[1] "integer"  
> class(2.8)  
[1] "numeric"  
> 4L * 2.8  
[1] 11.2  
> class(4L * 2.8)  
[1] "numeric"  
>  
> class(5L)  
[1] "integer"  
> class(2L)
```

```
[1] "integer"  
> 5L/2L  
[1] 2.5  
> class(5L/2L)  
[1] "numeric"
```

### 4.3.2. Character Data

Even though it is not explicitly mathematical, the character (string) data type is very common in statistical analysis and must be handled with care. R has two primary ways of handling character data: character and factor. While they may seem similar on the surface, they are treated quite differently.

```
> x <- "data"  
> x  
[1] "data"  
> y <- factor("data")  
> y  
[1] data  
Levels: data
```

Notice that x contains the word “data” encapsulated in quotes, while y has the word “data” without quotes and a second line of information

about the levels of y. That is explained further in [Section 4.4.2](#) about vectors.

Characters are case sensitive, so “Data” is different from “data” or “DATA.”

To find the length of a character (or numeric) use the nchar function.

```
> nchar(x)
[1] 4
> nchar("hello")
[1] 5
> nchar(3)
[1] 1
> nchar(452)
[1] 3
```

This will not work for factor data.

[Click here to view code image](#)

```
> nchar(y)
Error: 'nchar()' requires a character vector
```

### 4.3.3. Dates

Dealing with dates and times can be difficult in any language, and to further complicate matters R has numerous different types of dates. The most useful are Date and POSIXct. Date stores just a date while POSIXct stores a date and time. Both objects are actually represented as the number of days (Date) or seconds (POSIXct) since January 1, 1970.

[Click here to view code image](#)

```
> date1 <- as.Date("2012-06-28")
> date1
[1] "2012-06-28"
> class(date1)
[1] "Date"
> as.numeric(date1)
[1] 15519
>
> date2 <- as.POSIXct("2012-06-28 17:42")
> date2
[1] "2012-06-28 17:42:00 EDT"
> class(date2)
[1] "POSIXct" "POSIXt"
> as.numeric(date2)
[1] 1340919720
```

Easier manipulation of date and time objects can be accomplished using the lubridate and chron packages.

Using functions such as `as.numeric` or `as.Date` does not merely change the formatting of an object but actually changes the underlying type.

[Click here to view code image](#)

```
> class(date1)
[1] "Date"
> class(as.numeric(date1))
[1] "numeric"
```

#### 4.3.4. Logical

logicals are a way of representing data that can be either TRUE or FALSE. Numerically, TRUE is the same as 1 and FALSE is the same as 0. So `TRUE * 5` equals 5 while `FALSE * 5` equals 0.

```
> TRUE * 5
[1] 5
> FALSE * 5
[1] 0
```

Similar to other types, logicals have their own test, using the `is.logical` function.

```
> k <- TRUE  
> class(k)  
[1] "logical"  
> is.logical(k)  
[1] TRUE
```

R provides T and F as shortcuts for TRUE and FALSE, respectively, but it is best practice not to use them, as they are simply variables storing the values TRUE and FALSE and can be overwritten, which can cause a great deal of frustration as seen in the following example.

```
> TRUE  
[1] TRUE  
> T  
[1] TRUE  
> class(T)  
[1] "logical"  
> T <- 7  
> T  
[1] 7  
> class(T)  
[1] "numeric"
```

logicals can result from comparing two numbers, or characters.

[Click here to view code image](#)

```
> # does 2 equal 3?  
> 2 == 3  
[1] FALSE  
> # does 2 not equal three?  
> 2 != 3  
[1] TRUE  
> # is two less than three?  
> 2 < 3  
[1] TRUE  
> # is two less than or equal to three?  
> 2 <= 3  
[1] TRUE  
> # is two greater than three?  
> 2 > 3  
[1] FALSE  
> # is two greater than or equal to three?  
> 2 >= 3  
[1] FALSE  
> # is 'data' equal to 'stats'?  
> "data" == "stats"  
[1] FALSE  
> # is 'data' less than 'stats'?  
> "data" < "stats"  
[1] TRUE
```

## 4.4. Vectors

A vector is a collection of elements, all of the same type. For instance, `c(1, 3, 2, 1, 5)` is a vector consisting of the numbers 1, 3, 2, 1, 5, in that order. Similarly, `c("R", "Excel", "SAS", "Excel")` is a vector of the character elements “R,” “Excel,” “SAS” and “Excel.” A vector cannot be of mixed type.

vectors play a crucial, and helpful, role in R. More than being simple containers, vectors in R are special in that R is a vectorized language. That means operations are applied to each element of the vector automatically, without the need to loop through the vector. This is a powerful concept that may seem foreign to people coming from other languages, but it is one of the greatest things about R.

vectors do not have a dimension, meaning there is no such thing as a column vector or row vector. These vectors are not like the mathematic-

al vector where there is a difference between row and column orientation.<sup>1</sup>

1. Column or row vectors can be represented as one-dimensional matrices, which are discussed in [Section 5.3](#).

The most common way to create a vector is with `c`. The “`c`” stands for combine because multiple elements are being combined into a vector.

[Click here to view code image](#)

```
> x <- c(1, 2, 3, 4, 5, 6, 7, 8, 9, 10)
> x
[1] 1 2 3 4 5 6 7 8 9 10
```

#### 4.4.1. Vector Operations

Now that we have a vector of the first ten numbers, we might want to multiply each element by 3. In R this is a simple operation using just the multiplication operator (`*`).

[Click here to view code image](#)

```
> x * 3
[1] 3 6 9 12 15 18 21 24 27 30
```

No loops are necessary. Addition, subtraction and division are just as easy. This also works for any number of operations.

[Click here to view code image](#)

```
> x + 2  
[1] 3 4 5 6 7 8 9 10 11 12  
> x - 3  
[1] -2 -1 0 1 2 3 4 5 6 7  
> x/4  
[1] 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50  
> x^2  
[1] 1 4 9 16 25 36 49 64 81 100  
> sqrt(x)  
[1] 1.000 1.414 1.732 2.000 2.236 2.449 2.646 2.828 3.000  
3.162
```

Earlier we created a vector of the first ten numbers using the `c` function, which creates a vector. A shortcut is the `:` operator, which generates a sequence of consecutive numbers, in either direction.

[Click here to view code image](#)

```
> 1:10  
[1] 1 2 3 4 5 6 7 8 9 10  
> 10:1
```

```
[1] 10 9 8 7 6 5 4 3 2 1  
> -2:3  
[1] -2 -1 0 1 2 3  
> 5:-7  
[1] 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7
```

Vector operations can be extended even further. Let's say we have two vectors of equal length. Each of the corresponding elements can be operated on together.

[Click here to view code image](#)

```
> # create two vectors of equal length  
> x <- 1:10  
> y <- -5:4  
> # add them  
> x + y  
[1] -4 -2 0 2 4 6 8 10 12 14  
> # subtract them  
> x - y  
[1] 6 6 6 6 6 6 6 6 6 6  
> # multiply them  
> x * y  
[1] -5 -8 -9 -8 -5 0 7 16 27 40  
> # divide them--notice division by 0 results in Inf  
> x/y  
[1] -0.2 -0.5 -1.0 -2.0 -5.0 Inf 7.0 4.0 3.0 2.5  
> # raise one to the power of the other  
> x^y
```

```
[1] 1.000e+00 6.250e-02 3.704e-02 6.250e-02 2.000e-01  
1.000e+00  
[7] 7.000e+00 6.400e+01 7.290e+02 1.000e+04  
> # check the length of each  
> length(x)  
[1] 10  
> length(y)  
[1] 10  
> # the length of them added together should be the same  
> length(x + y)  
[1] 10
```

In the preceding code block, notice the hash # symbol. This is used for comments. Anything following the hash, on the same line, will be commented out and not run.

Things get a little more complicated when operating on two vectors of unequal length. The shorter vector gets recycled, that is, its elements are repeated, in order, until they have been matched up with every element of the longer vector. If the longer one is not a multiple of the shorter one, a warning is given.

[Click here to view code image](#)

```
> x + c(1, 2)
```

```
[1] 2 4 4 6 6 8 8 10 10 12  
> x + c(1, 2, 3)
```

Warning: longer object length is not a multiple of shorter object length

```
[1] 2 4 6 5 7 9 8 10 12 11
```

Comparisons also work on vectors. Here the result is a vector of the same length containing TRUE or FALSE for each element.

[Click here to view code image](#)

```
> x <= 5
```

```
[1] TRUE TRUE TRUE TRUE TRUE FALSE FALSE  
FALSE FALSE FALSE
```

```
> x > y
```

```
[1] TRUE TRUE TRUE TRUE TRUE TRUE TRUE  
TRUE TRUE TRUE
```

```
> x < y
```

```
[1] FALSE FALSE FALSE FALSE FALSE FALSE FALSE  
FALSE FALSE FALSE
```

To test whether all the resulting elements are TRUE, use the all function. Similarly, the any function checks whether any element is TRUE.

```
> x <- 10:1  
> y <- -4:5
```

```
> any(x < y)
```

```
[1] TRUE
```

```
> all(x < y)
```

```
[1] FALSE
```

The nchar function also acts on each element of a vector.

[Click here to view code image](#)

```
> q <- c("Hockey", "Football", "Baseball", "Curling",  
"Rugby",  
+     "Lacrosse", "Basketball", "Tennis", "Cricket", "Soc-  
cer")  
> nchar(q)  
[1] 6 8 8 7 5 8 10 6 7 6  
> nchar(y)  
[1] 2 2 2 2 1 1 1 1 1 1
```

Accessing individual elements of a vector is done using square brackets ([ ]). The first element of x is retrieved by typing x[1], the first two elements by x[1:2] and nonconsecutive elements by x[c(1, 4)].

```
> x[1]
```

```
[1] 10
```

```
> x[1:2]
```

```
[1] 10 9
```

```
> x[c(1, 4)]  
[1] 10 7
```

This works for all types of vectors whether they are numeric, logical, character and so forth.

It is possible to give names to a vector either during creation or after the fact.

[Click here to view code image](#)

```
> # provide a name for each element of an array using a  
name-value pair  
> c(One = "a", Two = "y", Last = "r")  
One Two Last  
"a" "y" "r"  
>  
> # create a vector  
> w <- 1:3  
> # name the elements  
> names(w) <- c("a", "b", "c")  
> w  
a b c  
1 2 3
```

## 4.4.2. Factor Vectors

factors are an important concept in R, especially when building models. Let's create a simple vector of text data that has a few repeats. We will start with the vector q we created earlier and add some elements to it.

[Click here to view code image](#)

```
> q2 <- c(q, "Hockey", "Lacrosse", "Hockey", "Water  
Polo",  
+      "Hockey", "Lacrosse")
```

Converting this to a factor is easy with `as.factor`.

[Click here to view code image](#)

```
> q2Factor <- as.factor(q2)  
> q2Factor  
[1] Hockey   Football  Baseball  Curl-  
ing   Rugby    Lacrosse  
[7] Basketball Tennis   Cricket   Soc-  
cer   Hockey   Lacrosse  
[13] Hockey   Water Polo Hockey  Lacrosse  
11 Levels: Baseball Basketball Cricket Curling Foot-  
ball ... Water Polo
```

Notice that after printing out every element of q2Factor, R also prints the levels of q2Factor. The levels of a factor are the unique values of that factor variable. Technically, R is giving each unique value of a factor a unique integer tying it back to the character representation. This can be seen with as.numeric.

[Click here to view code image](#)

```
> as.numeric(q2Factor)
[1] 6 5 1 4 8 7 2 10 3 9 6 7 6 11 6 7
```

In ordinary factors the order of the levels does not matter and one level is no different from another. Sometimes, however, it is important to understand the order of a factor, such as when coding education levels. Setting the ordered argument to TRUE creates an ordered factor with the order given in the levels argument.

[Click here to view code image](#)

```
> factor(x=c("High School", "College", "Masters", "Doctorate"),
+         levels=c("High School", "College", "Masters", "Doctorate"),
```

+ ordered=TRUE)

```
[1] High School College Masters Doctorate  
Levels: High School < College < Masters < Doctorate
```

factors can drastically reduce the size of the variable because they are storing only the unique values, but they can cause headaches if not used properly. This will be discussed further throughout the book.

## 4.5. Calling Functions

Earlier we briefly used a few basic functions like nchar, length and as.Date to illustrate some concepts. Functions are very important and helpful in any language because they make code easily repeatable. Almost every step taken in R involves using functions, so it is best to learn the proper way to call them. R function calling is filled with a good deal of nuance, so we are going to focus on the gist of what is needed to know. Of course, throughout the book there will be many examples of calling functions.

Let's start with the simple mean function, which computes the average of a set of numbers. In its simplest form it takes a vector as an argument.

```
> mean(x)  
[1] 5.5
```

More complicated functions have multiple arguments that can be either specified by the order they are entered or by using their name with an equal sign. We will see further use of this throughout the book.

R provides an easy way for users to build their own functions, which we will cover in more detail in [Chapter 8](#).

## 4.6. Function Documentation

Any function provided in R has accompanying documentation, of varying quality of course. The easiest way to access that documentation is to place a question mark in front of the function name, like this: ?mean.

To get help on binary operators like +, \* or == surround them with back ticks (`).

```
> ?`+`  
> ?`*`  
> ?`==`
```

There are occasions when we have only a sense of the function we want to use. In that case we can look up the function by using part of the name with apropos.

[Click here to view code image](#)

```
> apropos("mea")  
[1] ".cache/mean-  
simple_ce29515dafe58a90a771568646d73aae"  
[2] ".colMeans"  
[3] ".rowMeans"  
[4] "colMeans"  
[5] "influence.measures"  
[6] "kmeans"  
[7] "mean"  
[8] "mean.Date"  
[9] "mean.default"  
[10] "mean.difftime"  
[11] "mean.POSIXct"  
[12] "mean.POSIXlt"  
[13] "mean_cl_boot"
```

```
[14] "mean_cl_normal"  
[15] "mean_sdl"  
[16] "mean_se"  
[17] "rowMeans"  
[18] "weighted.mean"
```

## 4.7. Missing Data

Missing data plays a critical role in both statistics and computing, and R has two types of missing data, NA and NULL. While they are similar, they behave differently and that difference needs attention.

### 4.7.1. NA

Often we will have data that has missing values for any number of reasons. Statistical programs use varying techniques to represent missing data such as a dash, a period or even the number 99. R uses NA. NA will often be seen as just another element of a vector. `is.na` tests each element of a vector for missingness.

[Click here to view code image](#)

```
> z <- c(1, 2, NA, 8, 3, NA, 3)
```

```
> z  
[1] 1 2 NA 8 3 NA 3  
> is.na(z)  
[1] FALSE FALSE TRUE FALSE FALSE TRUE FALSE
```

NA is entered simply by typing the letters “N” and “A” as if they were normal text. This works for any kind of vector.

[Click here to view code image](#)

```
> zChar <- c("Hockey", NA, "Lacrosse")  
> zChar  
[1] "Hockey" NA      "Lacrosse"  
> is.na(zChar)  
[1] FALSE TRUE FALSE
```

Handling missing data is an important part of statistical analysis. There are many techniques depending on field and preference. One popular technique is multiple imputation, which is discussed in detail in Chapter 25 of Andrew Gelman and Jennifer Hill’s book *Data Analysis Using Regression and Multilevel/Hierarchical Models*, and is implemented in the mi, mice and Amelia packages.

## 4.7.2. NULL

NULL is the absence of anything. It is not exactly missingness, it is nothingness. Functions can sometimes return NULL and their arguments can be NULL. An important difference between NA and NULL is that NULL is atomical and cannot exist within a vector. If used inside a vector it simply disappears.

```
> z <- c(1, NULL, 3)
> z
[1] 1 3
```

Even though it was entered into the vector z, it did not get stored in z. In fact, z is only two elements long.

The test for a NULL value is `is.null`.

```
> d <- NULL
> is.null(d)
[1] TRUE
> is.null(7)
[1] FALSE
```

Since NULL cannot be a part of a vector, `is.null` is appropriately not vectorized.

## 4.8. Conclusion

Data come in many types, and R is well equipped to handle them. In addition to basic calculations, R can handle numeric, character and time-based data. One of the nicer parts of working with R, although one that requires a different way of thinking about programming, is vectorization. This allows operating on multiple elements in a vector simultaneously, which leads to faster and more mathematical code.

# Chapter 5. Advanced Data Structures

Sometimes data requires more complex storage than simple vectors and thankfully R provides a host of data structures. The most common are the data.frame, matrix and list followed by the array. Of these, the data.frame will be most familiar to anyone who has used a spreadsheet, the matrix to people familiar with matrix math and the list to programmers.

## 5.1. data.frames

Perhaps one of the most useful features of R is the data.frame. It is one of the most often cited reasons for R's ease of use.

On the surface a data.frame is just like an Excel spreadsheet in that it has columns and rows. In statistical terms, each column is a variable and each row is an observation.

In terms of how R organizes data.frames, each column is actually a vector, each of which has the same length. That is very important because it lets each column hold a different type of data (see [Section 4.3](#)). This also implies that within a column each element must be of the same type, just like with vectors.

There are numerous ways to construct a data.frame, the simplest being to use the data.frame function. Let's create a basic data.frame using some of the vectors we have already introduced, namely x, y and q.

[Click here to view code image](#)

```
> x <- 10:1
> y <- -4:5
> q <- c("Hockey", "Football", "Baseball", "Curling",
  "Rugby",
  +     "Lacrosse", "Basketball", "Tennis", "Cricket", "Soc-
cer")
> theDF <- data.frame(x, y, q)
> theDF
   x   y      q
1 10  -4  Hockey
2   9  -3 Football
```

```
3 8 -2 Baseball
4 7 -1 Curling
5 6 0 Rugby
6 5 1 Lacrosse
7 4 2 Basketball
8 3 3 Tennis
9 2 4 Cricket
10 1 5 Soccer
```

This creates a 10x3 data.frame consisting of those three vectors. Notice the names of theDF are simply the variables. We could have assigned names during the creation process, which is generally a good idea.

[Click here to view code image](#)

```
> theDF <- data.frame(First = x, Second = y, Sport = q)
> theDF
```

	First	Second	Sport
1	10	-4	Hockey
2	9	-3	Football
3	8	-2	Baseball
4	7	-1	Curling
5	6	0	Rugby
6	5	1	Lacrosse
7	4	2	Basketball
8	3	3	Tennis
9	2	4	Cricket

data.frames are complex objects with many attributes. The most frequently checked attributes are the number of rows and columns. Of course there are functions to do this for us: nrow and ncol. And in case both are wanted at the same time there is the dim function.

```
> nrow(theDF)
[1] 10
> ncol(theDF)
[1] 3
> dim(theDF)
[1] 10 3
```

Checking the column names of a data.frame is as simple as using the names function. This returns a character vector listing the columns. Since it is a vector we can access individual elements of it just like any other vector.

[Click here to view code image](#)

```
> names(theDF)
[1] "First" "Second" "Sport"
> names(theDF)[3]
```

```
[1] "Sport"
```

We can also check and assign the row names of a data.frame.

[Click here to view code image](#)

```
> rownames(theDF)
[1] "1" "2" "3" "4" "5" "6" "7" "8" "9" "10"
> rownames(theDF) <- c("One", "Two", "Three", "Four",
  "Five", "Six",
  +                 "Seven", "Eight", "Nine", "Ten")
> rownames(theDF)
[1] "One"  "Two"  "Three"
"Four"  "Five"  "Six"  "Seven" "Eight"
[9] "Nine" "Ten"
> # set them back to the generic index
> rownames(theDF) <- NULL
> rownames(theDF)
[1] "1" "2" "3" "4" "5" "6" "7" "8" "9" "10"
```

Usually a data.frame has far too many rows to print them all to the screen, so thankfully the head function prints out only the first few rows.

[Click here to view code image](#)

```
> head(theDF)
First Second Sport
1    10     -4 Hockey
```

```
2 9 -3 Football  
3 8 -2 Baseball  
4 7 -1 Curling  
5 6 0 Rugby  
6 5 1 Lacrosse
```

```
> head(theDF, n = 7)
```

	First	Second	Sport
1	10	-4	Hockey
2	9	-3	Football
3	8	-2	Baseball
4	7	-1	Curling
5	6	0	Rugby
6	5	1	Lacrosse
7	4	2	Basketball

```
> tail(theDF)
```

	First	Second	Sport
5	6	0	Rugby
6	5	1	Lacrosse
7	4	2	Basketball
8	3	3	Tennis
9	2	4	Cricket
10	1	5	Soccer

As we can with other variables, we can check the class of a data.frame using the class function.

```
> class(theDF)  
[1] "data.frame"
```

Since each column of the data.frame is an individual vector, it can be accessed individually and each has its own class. Like many other aspects of R, there are multiple ways to access an individual column. There is the \$ operator and also the square brackets. Running theDF\$Sport will give the third column in theDF. That allows us to specify one particular column by name.

[Click here to view code image](#)

```
> theDF$Sport  
[1] Hockey  Football Baseball Curl-  
ing   Rugby   Lacrosse  
[7] Basketball Tennis Cricket Soccer  
10 Levels: Baseball Basketball Cricket Curling Football ...  
Tennis
```

Similar to vectors, data.frames allow us to access individual elements by their position using square brackets, but instead of having one position two are specified. The first is the row number and the second is the column number. So to get the third row from the second column we use theDF[3, 2].

```
> theDF[3, 2]  
[1] -2
```

To specify more than one row or column use a vector of indices.

[Click here to view code image](#)

```
> # row 3, columns 2 through 3  
> theDF[3, 2:3]  
  Second  Sport  
3    -2 Baseball  
>  
> # rows 3 and 5, column 2  
> # since only one column was selected it was returned as a  
vector  
> # hence the column names will not be printed  
> theDF[c(3, 5), 2]  
[1] -2 0  
>  
> # rows 3 and 5, columns 2 through 3  
> theDF[c(3, 5), 2:3]  
  Second  Sport  
3    -2 Baseball  
5    0   Rugby
```

To access an entire row, specify that row while not specifying any column. Likewise, to access

an entire column, specify that column while not specifying any row.

[Click here to view code image](#)

```
> # all of column 3
> # since it is only one column a vector is returned
> theDF[, 3]
[1] Hockey   Football  Baseball  Curl-
ing   Rugby    Lacrosse
[7] Basketball Tennis   Cricket   Soccer
10 Levels: Baseball Basketball Cricket Curling Football ...
Tennis
>
> # all of columns 2 through 3
> theDF[, 2:3]
  Second   Sport
  1 -4   Hockey
  2 -3   Football
  3 -2   Baseball
  4 -1   Curling
  5  0   Rugby
  6  1   Lacrosse
  7  2 Basketball
  8  3   Tennis
  9  4   Cricket
 10 5   Soccer
>
> # all of row 2
> theDF[2, ]
```

```
First Second Sport
2   9   -3 Football
>
> # all of rows 2 through 4
> theDF[2:4, ]
First Second Sport
2   9   -3 Football
3   8   -2 Baseball
4   7   -1 Curling
```

To access multiple columns by name, make the column argument a character vector of the names.

[Click here to view code image](#)

```
> theDF[, c("First", "Sport")]
First   Sport
1   10   Hockey
2   9   Football
3   8   Baseball
4   7   Curling
5   6   Rugby
6   5   Lacrosse
7   4   Basketball
8   3   Tennis
9   2   Cricket
10  1   Soccer
```

Yet another way to access a specific column is to use its column name (or its number) either as second argument to the square brackets or as the only argument to either single or double square brackets.

[Click here to view code image](#)

```
> # just the "Sport" column
> # since it is one column it returns as a (factor) vector
> theDF[, "Sport"]
[1] Hockey  Football Baseball Curl-
ing  Rugby  Lacrosse
[7] Basketball Tennis Cricket Soccer
10 Levels: Baseball Basketball Cricket Curling Football ...
Tennis
> class(theDF[, "Sport"])
[1] "factor"
>
> # just the "Sport" column
> # this returns a one column data.frame
> theDF["Sport"]
      Sport
1   Hockey
2   Football
3  Baseball
4   Curling
5   Rugby
6 Lacrosse
```

```
7 Basketball
8 Tennis
9 Cricket
10 Soccer
> class(theDF[\"Sport"])
[1] "data.frame"
>
> # just the "Sport" column
> # this also returns a (factor) vector
> theDF[["Sport"]]
[1] Hockey  Football Baseball Curl-
ing   Rugby   Lacrosse
[7] Basketball Tennis  Cricket Soccer
10 Levels: Baseball Basketball Cricket Curling Football ...
Tennis
> class(theDF[["Sport"]])
[1] "factor"
```

All of these methods have differing outputs. Some return a vector, some return a single-column data.frame. To ensure a single-column data.frame while using single-square brackets, there is a third argument: drop=FALSE. This also works when specifying a single column by number.

[Click here to view code image](#)

```
> theDF[, "Sport", drop = FALSE]
```

```
Sport
1 Hockey
2 Football
3 Baseball
4 Curling
5 Rugby
6 Lacrosse
7 Basketball
8 Tennis
9 Cricket
10 Soccer
```

```
> class(theDF[, "Sport", drop = FALSE])
[1] "data.frame"
```

```
>
```

```
> theDF[, 3, drop = FALSE]
```

```
Sport
1 Hockey
2 Football
3 Baseball
4 Curling
5 Rugby
6 Lacrosse
7 Basketball
8 Tennis
9 Cricket
10 Soccer
```

```
> class(theDF[, 3, drop = FALSE])
[1] "data.frame"
```

In [Section 4.4.2](#) we see that factors are stored specially. To see how they would be represented in data.frame form, use model.matrix to create a set of indicator (or dummy) variables. That is one column for each level of a factor, with a 1 if a row contains that level or a 0 otherwise.

[Click here to view code image](#)

```
> newFactor <- factor(c("Pennsylvania", "New York",
  "New Jersey", "New York",
  + "Tennessee", "Massachusetts", "Pennsylvania", "New
  York"))

> model.matrix(~newFactor - 1)
   newFactorMassachusetts newFactorNew Jersey newFact-
orNew York
 1                  0                  0                  0
 2                  0                  0                  1
 3                  0                  1                  0
 4                  0                  0                  1
 5                  0                  0                  0
 6                  1                  0                  0
 7                  0                  0                  0
 8                  0                  0                  1

   newFactorPennsylvania newFactorTennessee
 1                  1                  0
 2                  0                  0
 3                  0                  0
```

```
4          0          0
5          0          1
6          0          0
7          1          0
8          0          0
attr("assign")
[1] 1 1 1 1 1
attr("contrasts")
attr("contrasts")$newFactor
[1] "contr.treatment"
```

We learn more about formulas (the argument to `model.matrix`) in [Sections 11.2](#) and [12.3.2](#) and [Chapters 15](#) and [16](#).

## 5.2. Lists

Often a container is needed to hold arbitrary objects of either the same type or varying types. R accomplishes this through lists. They store any number of items of any type. A list can contain all numerics or characters or a mix of the two or `data.frames` or, recursively, other lists.

Lists are created with the `list` function where each argument to the function becomes an element of the list.

## [Click here to view code image](#)

```
> # creates a three element list
> list(1, 2, 3)
[[1]]
[1] 1
[[2]]
[1] 2
[[3]]
[1] 3
>
> # creates a single element list where the only element is a
vector
> # that has three elements
> list(c(1, 2, 3))
[[1]]
[1] 1 2 3
>
> # creates a two element list
> # the first element is a three element vector
> # the second element is a five element vector
> (list3 <- list(c(1, 2, 3), 3:7))
[[1]]
[1] 1 2 3
[[2]]
[1] 3 4 5 6 7
>
> # two element list
> # first element is a data.frame
> # second element is a 10 element vector
```

```
> list(theDF, 1:10)
[[1]]
  First Second    Sport
1    10     -4  Hockey
2     9     -3 Football
3     8     -2 Baseball
4     7     -1  Curling
5     6      0   Rugby
6     5      1 Lacrosse
7     4      2 Basketball
8     3      3   Tennis
9     2      4 Cricket
10    1      5 Soccer
[[2]]
[1] 1 2 3 4 5 6 7 8 9 10
>
> # three element list
> # first is a data.frame
> # second is a vector
> # third is list3, which holds two vectors
> list5 <- list(theDF, 1:10, list3)
> list5
[[1]]
  First Second    Sport
1    10     -4  Hockey
2     9     -3 Football
3     8     -2 Baseball
4     7     -1  Curling
5     6      0   Rugby
6     5      1 Lacrosse
```

```
7   4   2 Basketball
8   3   3   Tennis
9   2   4   Cricket
10  1   5   Soccer
[[2]]
[1] 1 2 3 4 5 6 7 8 9 10
[[3]]
[[3]][[1]]
[1] 1 2 3
[[3]][[2]]
[1] 3 4 5 6 7
```

Notice in the previous block of code (where list3 was created) that enclosing an expression in parentheses displays the results after execution.

Like data.frames, lists can have names. Each element has a unique name that can be either viewed or assigned using names.

[Click here to view code image](#)

```
> names(list5)
NULL
> names(list5) <- c("data.frame", "vector", "list")
> names(list5)
[1] "data.frame" "vector"    "list"
> list5
$data.frame
First Second    Sport
```

```
1 10 -4 Hockey
2 9 -3 Football
3 8 -2 Baseball
4 7 -1 Curling
5 6 0 Rugby
6 5 1 Lacrosse
7 4 2 Basketball
8 3 3 Tennis
9 2 4 Cricket
10 1 5 Soccer
$vector
[1] 1 2 3 4 5 6 7 8 9 10
$list
$list[[1]]
[1] 1 2 3
$list[[2]]
[1] 3 4 5 6 7
```

Names can also be assigned to list elements during creation using name-value pairs.

[Click here to view code image](#)

```
> list6 <- list(TheDataFrame = theDF, TheVector = 1:10,
  TheList = list3)
> names(list6)
[1] "TheDataFrame" "TheVector"      "TheList"
> list6
$TheDataFrame
First Second      Sport
```

```
1 10 -4 Hockey
2 9 -3 Football
3 8 -2 Baseball
4 7 -1 Curling
5 6 0 Rugby
6 5 1 Lacrosse
7 4 2 Basketball
8 3 3 Tennis
9 2 4 Cricket
10 1 5 Soccer
```

\$TheVector

```
[1] 1 2 3 4 5 6 7 8 9 10
```

\$TheList

```
$TheList[[1]]
```

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

```
$TheList[[2]]
```

```
[1] 3 4 5 6 7
```

Creating an empty list of a certain size is, perhaps confusingly, done with vector.

[Click here to view code image](#)

```
> (emptyList <- vector(mode = "list", length = 4))
[[1]]
NULL
[[2]]
NULL
[[3]]
NULL
```

```
[[4]]
```

```
NULL
```

To access an individual element of a list, use double square brackets, specifying either the element number or name. Note that this allows access to only one element at a time.

[Click here to view code image](#)

```
> list5[[1]]
```

	First	Second	Sport
1	10	-4	Hockey
2	9	-3	Football
3	8	-2	Baseball
4	7	-1	Curling
5	6	0	Rugby
6	5	1	Lacrosse
7	4	2	Basketball
8	3	3	Tennis
9	2	4	Cricket
10	1	5	Soccer

```
> list5[["data.frame"]]
```

	First	Second	Sport
1	10	-4	Hockey
2	9	-3	Football
3	8	-2	Baseball
4	7	-1	Curling
5	6	0	Rugby
6	5	1	Lacrosse

7	4	2	Basketball
8	3	3	Tennis
9	2	4	Cricket
10	1	5	Soccer

Once an element is accessed it can be treated as if that actual element is being used, allowing nested indexing of elements.

[Click here to view code image](#)

```
> list5[[1]]$Sport
[1] Hockey  Football Baseball Curl-
ing Rugby  Lacrosse
[7] Basketball Tennis Cricket Soccer
10 Levels: Baseball Basketball Cricket Curling Football ...
Tennis
> list5[[1]][, "Second"]
[1] -4 -3 -2 -1  0  1  2  3  4  5
> list5[[1]][, "Second", drop = FALSE]
Second
 1   -4
 2   -3
 3   -2
 4   -1
 5    0
 6    1
 7    2
 8    3
 9    4
```

It is possible to append elements to a list simply by using an index (either numeric or named) that does not exist.

[Click here to view code image](#)

```
> # see how long it currently is
> length(list5)
[1] 3
>
> # add a fourth element, unnamed
> list5[[4]] <- 2
> length(list5)
[1] 4
>
> # add a fifth element, named
> list5[["NewElement"]] <- 3:6
> length(list5)
[1] 5
>
> names(list5)
[1] "data.frame" "vector"    "list"      ""         "NewElement"
> list5
$data.frame
  First Second   Sport
1    10     -4  Hockey
2     9     -3 Football
```

```
3   8   -2  Baseball
4   7   -1  Curling
5   6   0   Rugby
6   5   1   Lacrosse
7   4   2   Basketball
8   3   3   Tennis
9   2   4   Cricket
10  1   5   Soccer
$vector
[1] 1 2 3 4 5 6 7 8 9 10
$list
$list[[1]]
[1] 1 2 3
$list[[2]]
[1] 3 4 5 6 7
[[4]]
[1] 2
$NewElement
[1] 3 4 5 6
```

Occasionally appending to a list—or vector or data.frame for that matter—is fine, but doing so repeatedly is computationally expensive. So it is best to create a list as long as its final desired size and then fill it in using the appropriate indices.

## 5.3. Matrices

A very common mathematical structure that is essential to statistics is a matrix. This is similar to a `data.frame` in that it is rectangular with rows and columns except that every single element, regardless of column, must be the same type, most commonly all numerics. They also act similarly to vectors with element-by-element addition, multiplication, subtraction, division and equality. The `nrow`, `ncol` and `dim` functions work just like they do for `data.frames`.

[Click here to view code image](#)

```
> # create a 5x2 matrix
> A <- matrix(1:10, nrow = 5)
> # create another 5x2 matrix
> B <- matrix(21:30, nrow = 5)
> # create another 5x2 matrix
> C <- matrix(21:40, nrow = 2)
> A
      [,1] [,2]
[1,]    1    6
[2,]    2    7
[3,]    3    8
[4,]    4    9
```

```
[5,] 5 10
> B
 [,1] [,2]
[1,] 21 26
[2,] 22 27
[3,] 23 28
[4,] 24 29
[5,] 25 30
> C
 [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
[1,] 21 23 25 27 29 31 33 35 37 39
[2,] 22 24 26 28 30 32 34 36 38 40
> nrow(A)
[1] 5
> ncol(A)
[1] 2
> dim(A)
[1] 5 2
> # add them
> A + B
 [,1] [,2]
[1,] 22 32
[2,] 24 34
[3,] 26 36
[4,] 28 38
[5,] 30 40
> # multiply them
> A * B
 [,1] [,2]
[1,] 21 156
```

```
[2,] 44 189  
[3,] 69 224  
[4,] 96 261  
[5,] 125 300  
> # see if the elements are equal  
> A == B  
[1] [2]  
[1,] FALSE FALSE  
[2,] FALSE FALSE  
[3,] FALSE FALSE  
[4,] FALSE FALSE  
[5,] FALSE FALSE
```

Matrix multiplication is a commonly used operation in mathematics, requiring the number of columns of the left-hand matrix to be the same as the number of rows of the right-hand matrix. Both A and B are  $5 \times 2$  so we will transpose B so it can be used on the right-hand side.

[Click here to view code image](#)

```
> A %*% t(B)  
[1] [2] [3] [4] [5]  
[1,] 177 184 191 198 205  
[2,] 224 233 242 251 260  
[3,] 271 282 293 304 315  
[4,] 318 331 344 357 370  
[5,] 365 380 395 410 425
```

Another similarity with `data.frames` is that matrices can also have row and column names.

[Click here to view code image](#)

```
> colnames(A)
NULL
> rownames(A)
NULL
> colnames(A) <- c("Left", "Right")
> rownames(A) <- c("1st", "2nd", "3rd", "4th", "5th")
>
> colnames(B)
NULL
> rownames(B)
NULL
> colnames(B) <- c("First", "Second")
> rownames(B) <- c("One", "Two", "Three", "Four",
  "Five")
>
> colnames(C)
NULL
> rownames(C)
NULL
> colnames(C) <- LETTERS[1:10]
> rownames(C) <- c("Top", "Bottom")
```

There are two special vectors, letters and LETTERS, that contain the lower-case and upper-case letters, respectively.

Notice the effect when transposing a matrix and multiplying matrices. Transposing naturally flips the row and column names. Matrix multiplication keeps the row names from the left matrix and the column names from the right matrix.

[Click here to view code image](#)

```
> t(A)
```

```
    1st 2nd 3rd 4th 5th
```

```
Left 1 2 3 4 5
```

```
Right 6 7 8 9 10
```

```
> A %*% C
```

```
    A B C D E F G H I J
```

```
1st 153 167 181 195 209 223 237 251 265 279
```

```
2nd 196 214 232 250 268 286 304 322 340 358
```

```
3rd 239 261 283 305 327 349 371 393 415 437
```

```
4th 282 308 334 360 386 412 438 464 490 516
```

```
5th 325 355 385 415 445 475 505 535 565 595
```

## 5.4. Arrays

An array is essentially a multidimensional vector. It must all be of the same type and individual elements are accessed in a similar fashion using square brackets. The first element is the row index, the second is the column index and the remaining elements are for outer dimensions.

[Click here to view code image](#)

```
> theArray <- array(1:12, dim = c(2, 3, 2))
> theArray
, , 1
[1,] [,1] [,2] [,3]
[1,] 1 3 5
[2,] 2 4 6
, , 2
[1,] [,1] [,2] [,3]
[1,] 7 9 11
[2,] 8 10 12
> theArray[1, , ]
[1,] [,1] [,2]
[1,] 1 7
[2,] 3 9
[3,] 5 11
> theArray[1, , 1]
[1] 1 3 5
> theArray[, , 1]
```

```
[,1] [,2] [,3]  
[1,] 1 3 5  
[2,] 2 4 6
```

The main difference between an array and a matrix is that matrices are restricted to two dimensions while arrays can have an arbitrary number.

## 5.5. Conclusion

Data come in many types and structures, which can pose a problem for some analysis environments but R handles them with aplomb. The most common data structure is the one-dimensional vector, which forms the basis of everything in R. The most powerful structure is the `data.frame`—something special in R that most other languages do not have—which handles mixed data types in a spreadsheet-like format. Lists are useful for storing collections of items like a hash in Perl.

# Chapter 6. Reading Data into R

Now that we have seen some of R's basic functionality, it is time to load in data. As with everything in R, there are numerous ways to get data; the most common is probably reading comma separated values (CSV) files. Of course there are many other options that we will cover as well.

## 6.1. Reading CSVs

The best way to read data from a CSV file is to use `read.table`. It might be tempting to use `read.csv` but that is more trouble than it is worth, and all it does is call `read.table` with some arguments preset. The result of using `read.table` is a `data.frame`.

The first argument to `read.table` is the full path of the file to be loaded. The file can be sitting on disk or even on the Web. For the purposes of this book we will read from the Web.

Any CSV will work but we have posted an incredibly simple CSV at [ht-  
tp://www.jaredlander.com/data/Tomato%20First.csv](http://www.jaredlander.com/data/Tomato%20First.csv). Let's read that into R using read.table.

[Click here to view code image](#)

```
> theUrl <- "http://www.jaredlander.com/data/Tomato%20First.csv"  
> tomato <- read.table (file = theUrl, header = TRUE, sep = ",")
```

This can now be seen using head.

[Click here to view code image](#)

```
> head(tomato)  
Round Tomato Price Source Sweet Acid Col-  
or Texture  
1 1 Simpson SM 3.99 Whole Foods 2.8 2.8 3.7 3.  
2 1 Tuttoro (blue) 2.99 Pion-  
eer 3.3 2.8 3.4 3.0  
3 1 Tuttoro (green) 0.99 Pion-  
eer 2.8 2.6 3.3 2.8  
4 1 La Fede SM DOP 3.99 Shop Rite 2.6 2.8 3.0 2.  
5 2 Cento SM DOP 5.49 D Agostino 3.3 3.1 2.9 2.  
6 2 Cento Organ-  
ic 4.99 D Agostino 3.2 2.9 2.9 3.1
```

	Overall	Avg.of.Totals	Total.of.Avg
1	3.4	16.1	16.1
2	2.9	15.3	15.3
3	2.9	14.3	14.3
4	2.8	13.4	13.4
5	3.1	14.4	15.2
6	2.9	15.5	15.1

As mentioned before, the first argument is the file name in quotes (or as a character variable). Notice how we explicitly used the argument names file, header and sep. As discussed in [Section 4.5](#), function arguments can be specified without the name of the argument (positionally indicated) but specifying the arguments is good practice. The second argument, header, indicates that the first row of data holds the column names. The third argument gives the delimiter separating data cells. Changing this to other values such as “\t” (tab delimited) or “;” (semicolon delimited) allows it to read other types of files.

One often unknown argument that is helpful to use is stringsAsFactors. Setting this to FALSE (the default is TRUE) prevents character columns

from being converted to factor columns. This both saves computation time—this can be dramatic if it is a large dataset with many character columns with many unique values—and keeps the columns as character data, which are easier to work with.

Although we do not mention this argument in [Section 5.1](#), `stringsAsFactors` can be used in `data.frame`. Re-creating that first bit of code results in an easier-to-use “Sport” column.

[Click here to view code image](#)

```
> x <- 10:1
> y <- -4:5
> q <- c("Hockey", "Football", "Baseball", "Curling",
  "Rugby",
  +      "Lacrosse", "Basketball", "Tennis", "Cricket", "Soc-
  cer")
> theDF <- data.frame(First=x, Second=y, Sport=q, string-
  sAsFactors=FALSE)
> theDF$Sport
[1] "Hockey"    "Football"   "Baseball"   "Curl-
  ing"       "Rugby"
[6] "Lacrosse"   "Basketball"  "Tennis"     "Crick-
  et"        "Soccer"
```

There are numerous other arguments to `read.table`, the most useful being `quote` and `colClasses`, specifying the character used for enclosing cells and the data type for each column, respectively.

Sometimes CSVs (or tab delimited files) are poorly built, where the cell separator has been used inside a cell. In this case `read.csv2` (or `read.delim2`) should be used instead of `read.table`.

## 6.2. Excel Data

While Excel may be the world's most popular data analysis tool, it is unfortunately difficult to read Excel data into R. The simplest method would be to use Excel (or another spreadsheet program) to convert the Excel file to a CSV file. That might sound like a cop-out but it is the easiest method to use. The R community abounds with hacks to get data from Excel into R, such as using the Clipboard to copy and paste, but those are inelegant at best and can fail with large amounts of data.

A number of packages exist to tackle this problem such as gdata, XLConnect, xlsReadWrite, and others but they all have some erroneous requirement such as Java, Perl or 32-bit R, which is neither preferable nor so common anymore. The RODBC package has a function, odbcConnectExcel2007, that reads Excel files but requires a DSN<sup>1</sup> connection, which is not a feasible everyday strategy.

1. A DSN is a data source connection used to describe communication to a data source, often a database.

We understand that Excel 2007 files are essentially XML files. This would mean that they could theoretically be parsed using the XML package, but we have not seen this done as of yet.

## 6.3. Reading from Databases

Databases arguably store the vast majority of the world's data. Most of these, whether they be Microsoft SQL Server, DB2, MySQL or Microsoft Access, provide an ODBC connection. Accordingly, R makes use of ODBC through the aptly named RODBC package (which comes with base R). Like any other package, it must be loaded before use.

```
> require(RODBC)
```

The first step to reading from a database is to create a DSN. This differs by operating system but should result in a string name for that connection. This is used in `odbcConnect` to create a connection for R to use. Optional, but common, arguments are `uid` and `pwd` for the database username and password, respectively.

[Click here to view code image](#)

```
> db <- odbcConnect("QV Training")
```

At this point we are ready to run a query on that database using `sqlQuery`. This can be any valid SQL query of arbitrary complexity. `sqlQuery` returns a `data.frame` just like any other. Fortunately, `sqlQuery` has the `stringsAsFactors` argument first seen in [Section 6.1](#). Again, setting this to `TRUE` is usually a good idea, as it will save processing time.

[Click here to view code image](#)

```
> # simple SELECT * query from one table
> ordersTable <- sqlQuery(db, "SELECT * FROM Orders",
  stringsAsFactors=FALSE)
> # simple SELECT * query from one table
> detailsTable <- sqlQuery(db, "SELECT * FROM [Order
  Details]",
  stringsAsFactors=FALSE)
> # do a join between the two tables
> longQuery <- "SELECT * FROM Orders, [Order Details]
  WHERE Orders.OrderID = [Order Details].OrderID"
> detailsJoin <- sqlQuery(db, longQuery, stringsAsFactor-
  s=FALSE)
```

We can easily check the results of these queries by viewing the resulting `data.frames`.

[Click here to view code image](#)

> **head**(ordersTable)

OrderID OrderDate CustomerID EmployeeID ShipperID  
Freight

1	10248	2008-06-29	4	2	2	43.48
2	10249	2007-06-29	79	7	2	29.20
3	10250	2008-07-03	34	2	2	79.17
4	10251	2007-12-02	1	7	2	43.41
5	10252	2008-04-04	76	5	1	23.20
6	10253	2008-07-05	34	3	2	66.54

> **head**(detailsTable)

OrderID LineNo ProductID Quantity UnitPrice Discount

1	10402	2	63	65	18.94	0.00
2	10403	1	48	70	31.83	0.15
3	10403	2	16	21	10.15	0.15
4	10404	1	42	40	13.37	0.05
5	10404	2	49	30	19.82	0.05
6	10404	3	26	30	33.93	0.05

> **head**(detailsJoin)

OrderID OrderDate CustomerID EmployeeID ShipperID  
Freight

1	10402	2006-04-28	20	4	1	46.63
2	10403	2006-09-28	20	4	1	26.43
3	10403	2006-09-28	20	4	1	26.43
4	10404	2006-04-19	49	6	1	72.73
5	10404	2006-04-19	49	6	1	72.73
6	10404	2006-04-19	49	6	1	72.73

OrderID.1 LineNo ProductID Quantity UnitPrice Discount

1	10402	2	63	65	18.94	0.00
---	-------	---	----	----	-------	------

2	10403	1	48	70	31.83	0.15
3	10403	2	16	21	10.15	0.15
4	10404	1	42	40	13.37	0.05
5	10404	2	49	30	19.82	0.05
6	10404	3	26	30	33.93	0.05

While it is not necessary, it is good practice to close the ODBC connection using `odbcClose`, although it will close automatically when either R closes or we open another connection using `odbcConnect`. Only one connection may be open at a time.

## 6.4. Data from Other Statistical Tools

In an ideal world another tool besides R would never be needed, but in reality data are sometimes locked in a proprietary format such as those from SAS, SPSS or Octave. The `foreign` package provides a number of functions similar to `read.table` to read in data from other tools.

A partial list of functions to read data from commonly used statistical tools is in [Table 6.1](#). The arguments for these functions are generally similar to `read.table`. These functions usually re-

turn the data as a `data.frame` but do not always succeed.

---

Function	Format
<code>read.spss</code>	SPSS
<code>read.dta</code>	Stata
<code>read.ssd</code>	SAS
<code>read.octave</code>	Octave
<code>read.mtp</code>	Minitab
<code>read.systat</code>	Systat

---

**Table 6.1 Functions for Reading Data from Some Commonly Used Statistical Tools**

While `read.ssd` can read SAS data, it requires a valid SAS license. This can be sidestepped by using Revolution R from Revolution Analytics with their special `RxSasData` function in their `RevoScaleR` package.

## 6.5. R Binary Files

When working with other R programmers, a good way to pass around data—or any R objects like variables and functions—is to use RData files. These are binary files that represent R objects of any kind. They can store a single object or multiple objects and can be passed among Windows, Mac and Linux without a problem.

First, let's create an RData file, remove the object that created it, and then read it back into R.

[Click here to view code image](#)

```
> # save the tomato data.frame to disk  
> save(tomato, file = "data/tomato.rdata")  
> # remove tomato from memory  
> rm(tomato)  
> # check if it still exists  
> head(tomato)
```

**Error: object 'tomato' not found**

```
> # read it from the rdata file  
> load("data/tomato.rdata")  
> # check if it exists now  
> head(tomato)
```

Round	Tomato Price	Source	Sweet	Acid	Color
Texture					

1	1	Simpson SM	3.99	Whole Foods	2.8	2.8	3.7	3.4
2	1	Tuttorosso (blue)	2.99	Pioneer	3.3	2.8	3.4	3.0
3	1	Tuttorosso (green)	0.99	Pioneer	2.8	2.6	3.3	2.8
4	1	La Fede SM DOP	3.99	Shop Rite	2.6	2.8	3.0	2.3
5	2	Cento SM DOP	5.49	D Agostino	3.3	3.1	2.9	2.8
6	2	Cento Organic	4.99	D Agostino	3.2	2.9	2.9	3.1
		Overall Avg.of.Totals		Total.of.Avg				
1	3.4	16.1	16.1					
2	2.9	15.3	15.3					
3	2.9	14.3	14.3					
4	2.8	13.4	13.4					
5	3.1	14.4	15.2					
6	2.9	15.5	15.1					

Now let's create a few objects to store in a single RData file, remove them and then load them again.

[Click here to view code image](#)

```
> # create some objects
> n <- 20
> r <- 1:10
> w <- data.frame(n, r)
```

```
> # check them out
> n
[1] 20
> r
[1] 1 2 3 4 5 6 7 8 9 10
> w
  n  r
1 20 1
2 20 2
3 20 3
4 20 4
5 20 5
6 20 6
7 20 7
8 20 8
9 20 9
10 20 10
> # save them
> save(n, r, w, file = "data/multiple.rdata")
> # delete them
> rm(n, r, w)
> # are they gone?
> n
Error: object 'n' not found
> r
Error: object 'r' not found
> w
Error: object 'w' not found
> # load them back
> load("data/multiple.rdata")
```

```
> # check them out again  
> n  
[1] 20  
> r  
[1] 1 2 3 4 5 6 7 8 9 10  
> w  
    n   r  
1 20 1  
2 20 2  
3 20 3  
4 20 4  
5 20 5  
6 20 6  
7 20 7  
8 20 8  
9 20 9  
10 20 10
```

## 6.6. Data Included with R

R and some packages come with data included, so we can easily have data to use. Accessing these data is simple as long as we know what to look for. `ggplot2`, for instance, comes with a data-set about diamonds. It can be loaded using the `data` function.

[Click here to view code image](#)

```
> require(ggplot2)
> data(diamonds)
> head(diamonds)
```

	carat	cut	color	clarity	depth	table	price	x	y	z
1	0.23	Ideal	E	SI2	61.5	55	326	3.95	3.98	2.43
2	0.21	Premium	E	SI1	59.8	61	326	3.89	3.84	2.31
3	0.23	Good	E	VS1	56.9	65	327	4.05	4.07	2.31
4	0.29	Premium	I	VS2	62.4	58	334	4.20	4.23	2.63
5	0.31	Good	J	SI2	63.3	58	335	4.34	4.35	2.75
6	0.24	Very Good	J	VVS2	62.8	57	336	3.94	3.96	2.48

To find a list of available data, simply type `data()` into the console.

## 6.7. Extract Data from Web Sites

These days a lot of data are displayed on Web pages. If we are lucky, it is stored neatly in an HTML table. If we are not so lucky, we might need to parse the text of the page.

## 6.7.1. Simple HTML Tables

If the data are stored neatly in an HTML table we can use `readHTMLTable` in the `XML` package to easily extract it. On my site there is a post about a Super Bowl pool I was asked to analyze at <http://www.jaredlander.com/2012/02/another-kind-of-super-bowl-pool>. In that post there is a table with three columns that we wish to extract. It is fairly simple to do with the following code.

[Click here to view code image](#)

```
> require(XML)
> theURL <- "http://www.jaredlander.com/2012/02/
  another-kind-of-
  +   super-bowl-pool/"
> bowlPool <- readHTMLTable(theURL, which = 1,
  header = FALSE,
  +   stringsAsFactors = FALSE)
> bowlPool
      V1     V2     V3
  1 Participant 1 Giant A Patriot Q
  2 Participant 2 Giant B Patriot R
  3 Participant 3 Giant C Patriot S
  4 Participant 4 Giant D Patriot T
  5 Participant 5 Giant E Patriot U
  6 Participant 6 Giant F Patriot V
```

```
7 Participant 7 Giant G Patriot W  
8 Participant 8 Giant H Patriot X  
9 Participant 9 Giant I Patriot Y  
10 Participant 10 Giant J Patriot Z
```

Here the first argument was the URL but it could have also been a file on disk. The which argument allows us to choose which table to read if there are multiple tables. For this example, there was only one table but it could have easily been the second or third or fourth. We set header to FALSE to indicate that no header was in the table. Last, we used stringsAsFactors=FALSE so that the character columns would not be converted to factors.

## 6.7.2. Scraping Web Data

If the data are not so neatly stored, it is possible to scrape them off the page, although this is a very involved process. It requires good pattern matching and regular expressions, which are covered in Section 13.14. The idea is to figure out what common pattern surrounds different pieces of data, and this requires at least a basic knowledge of HTML.

## 6.8. Conclusion

Reading data is the first step to any analysis; without the data there is nothing to do. The most common way to read data into R is from a CSV using `read.table`. RODBC provides an excellent method for reading from any database with a DSN. Reading from data trapped in HTML tables is made easy using the XML package. R also has a special binary file format, RData, for the quick storage, loading and transfer of R objects.

# Chapter 7. Statistical Graphics

One of the hardest parts of an analysis is producing quality supporting graphics. Conversely, a good graph is one of the best ways to present findings. Fortunately, R provides excellent graphing capabilities, both in the base installation and with add-on packages such as lattice and ggplot2. We will briefly present some simple graphs using base graphics and then show their counterparts in ggplot2. This will be supplemented throughout the book where supporting graphics—with code—will be made using ggplot2 and occasionally base graphics.

Graphics are used in statistics primarily for two reasons: exploratory data analysis (EDA) and presenting results. Both are incredibly important but must be targeted to different audiences.

## 7.1. Base Graphics

When graphing for the first time with R, most people use base graphics and then move on to ggplot2 when their needs become more complex. While base graphs can be beautiful creations, we recommend spending the most time learning about ggplot2 in [Section 7.2](#). This section is here for completeness and because base graphics are just needed, especially for modifying the plots generated by other functions.

Before we can go any further we need some data. Most of the datasets built into R are tiny, even by standards from ten years ago. A good dataset for example graphs is, ironically, included with ggplot2. In order to access it, ggplot2 must first be installed and loaded. Then the diamonds data can be loaded and inspected.

[Click here to view code image](#)

```
> require(ggplot2)
> data(diamonds)
> head(diamonds)
  carat    cut color clarity depth table price     x     y     z
```

1	0.23	Ideal	E	SI2	61.5	55	326	3.95	3.98	2.43
2	0.21	Premi-								
um	E	SI1	59.8	61	326	3.89	3.84	2.31		
3	0.23	Good	E	VS1	56.9	65	327	4.05	4.07	2.31
4	0.29	Premi-								
um	I	VS2	62.4	58	334	4.20	4.23	2.63		
5	0.31	Good	J	SI2	63.3	58	335	4.34	4.35	2.75
6	0.24	Very Good	J	VVS2	62.8	57	336	3.94	3.96	2.48

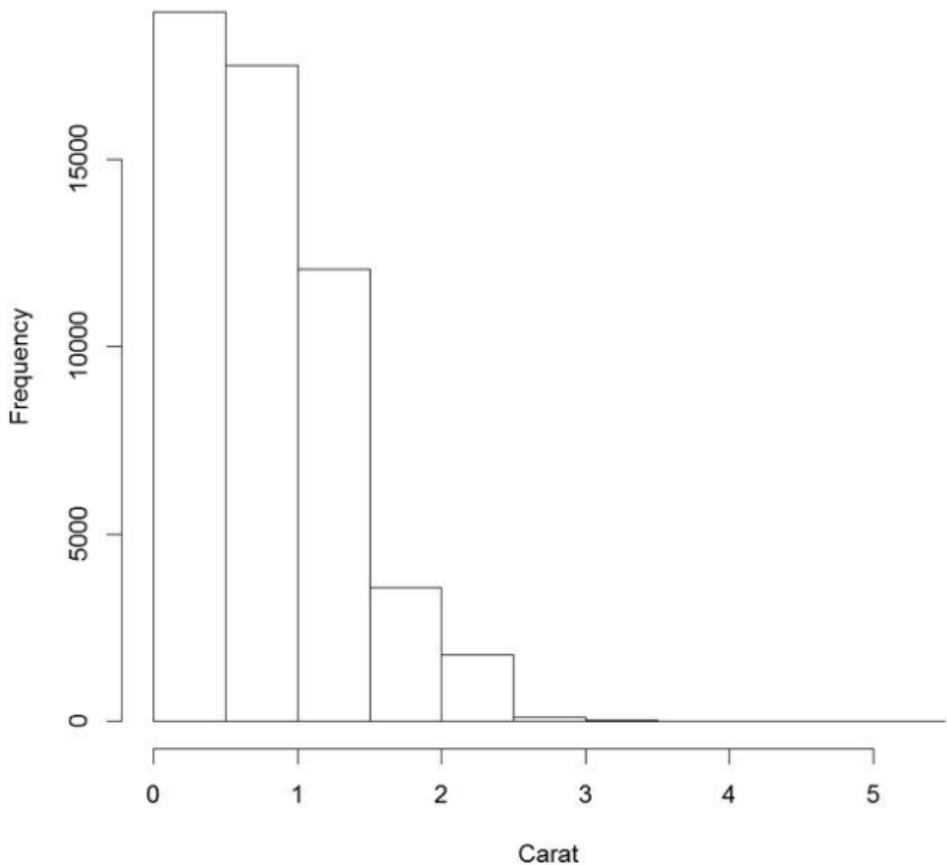
### 7.1.1. Base Histograms

The most common graph of data in a single variable is a histogram. This shows the distribution of values for that variable. Creating a histogram is very simple and illustrated in [Figure 7.1](#) for the carat column in diamonds.

[Click here to view code image](#)

```
> hist(diamonds$carat, main = "Carat Histogram", xlab =  
"Carat")
```

### Carat Histogram



**Figure 7.1** Histogram of diamond carats.

This shows the distribution of the carat size. Notice that the title was set using the main argument and the *x*-axis label with the *xlab* argument. More complicated histograms are easier to create

with ggplot2. These extra capabilities are presented in [Section 7.2.1](#).

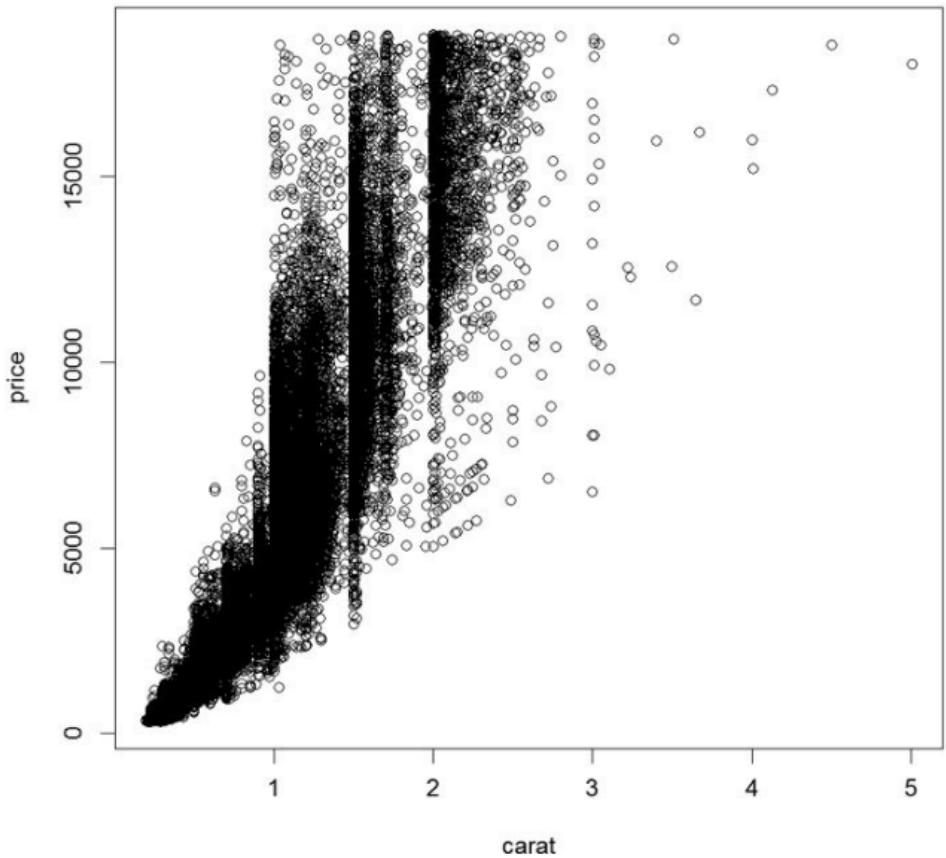
Histograms break the data into buckets and the heights of the bars represent the number of observations that fall into each bucket. This can be sensitive to the number and size of buckets, so making a good histogram can require some experimentation.

### 7.1.2. Base Scatterplot

It is frequently good to see two variables in comparison with each other; this is where the scatterplot is used. Every point represents an observation in two variables where the  $x$ -axis represents one variable and the  $y$ -axis another. We will plot the price of diamonds against the carat using formula notation (see [Figure 7.2](#)).

[Click here to view code image](#)

```
> plot(price ~ carat, data = diamonds)
```



**Figure 7.2** Scatterplot of diamond price versus carat.

The  $\sim$  separating price and carat indicates that we are viewing price against carat where price is the  $y$  value and carat is the  $x$  value. Formulas are explained in more detail in [Chapters 15](#) and [16](#).

It is also possible to build a scatterplot by simply specifying the  $x$  and  $y$  variables without the formula interface. This allows plotting of variables that are not necessarily in a data.frame.

[Click here to view code image](#)

```
> plot(diamonds$carat, diamonds$price)
```

Scatterplots are one of the most frequently used statistical graphs and will be detailed further using ggplot2 in [Section 7.2.2](#).

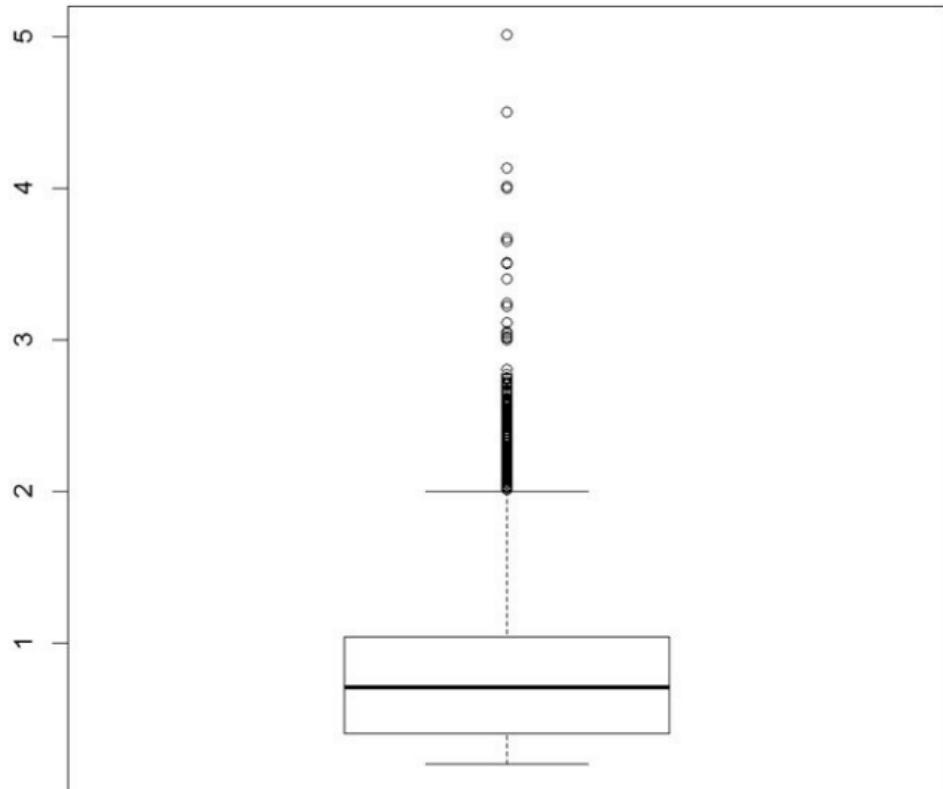
### 7.1.3. Boxplots

Although boxplots are often among the first graphs taught to statistics students, they are a matter of great debate in the statistics community. Andrew Gelman from Columbia University has been very vocal in his displeasure with boxplots.<sup>1</sup> However, other people such as Hadley Wickham<sup>2</sup> and John Tukey are strong proponents of the boxplot. Given their ubiquity (deserved or not) it is important to learn them. Thankfully, R has the boxplot function (see [Figure 7.3](#)).

1. [http://andrewgelman.com/2009/02/boxplot\\_challen/](http://andrewgelman.com/2009/02/boxplot_challen/) and  
[http://andrewgelman.com/2009/10/better\\_than\\_a\\_b/](http://andrewgelman.com/2009/10/better_than_a_b/)
2. <http://vita.had.co.nz/papers/boxplots.pdf>

[Click here to view code image](#)

> **boxplot**(diamonds\$carat)



**Figure 7.3** Boxplot of diamond carat.

The idea behind the boxplot is that the thick middle line represents the median and the box is bounded by the first and third quartiles. That is, the middle 50% of data (the Interquartile Range or IQR) is held in the box. The lines extend out to  $1.5 \times \text{IQR}$  in both directions. Outlier points are then plotted beyond that. It is important to note that while 50% of the data are very visible in the box, that means 50% of the data are not really displayed. That is a lot of information to not see.

As with other graphs previously discussed, more details will be provided using ggplot2 in [Section 7.2.3](#).

Many objects, such as linear models and contingency tables, have built-in plot functions, which we will see later in the book.

## 7.2. ggplot2

While R's base graphics are extremely powerful and flexible and can be customized to a great extent, using them can be labor intensive. Two packages—ggplot2 and lattice—were built to make graphing easier. Over the past few years ggplot2 has far exceeded lattice in popularity and features. We re-create all the previous graphs in [Section 7.1](#) and expand the examples with more advanced features. Neither this chapter nor this book is an exhaustive review of ggplot2. But throughout this book, where there is a plot the accompanying code (mostly with ggplot2, although some use base graphics) is included.

Initially, the ggplot2 syntax is harder to grasp, but the effort is more than worthwhile. It is much easier to delineate data by color, shape, or size and add legends with ggplot2. Graphs are quicker to build. Graphs that could take 30 lines of code with base graphics are possible with just one line in ggplot2.

The basic structure for ggplot2 starts with the `ggplot` function,<sup>3</sup> which at its most basic should take the data as its first argument. It can take more arguments, or fewer, but we will stick with that for now. After initializing the object, we add layers using the `+` symbol. To start, we will just discuss geometric layers such as points, lines and histograms. They are included using functions like `geom point`, `geom line` and `geom histogram`. These functions take multiple arguments, the most important being which variable in the data gets mapped to which axis or other aesthetic using `aes`. Furthermore, each layer can have different aesthetic mappings and even different data.

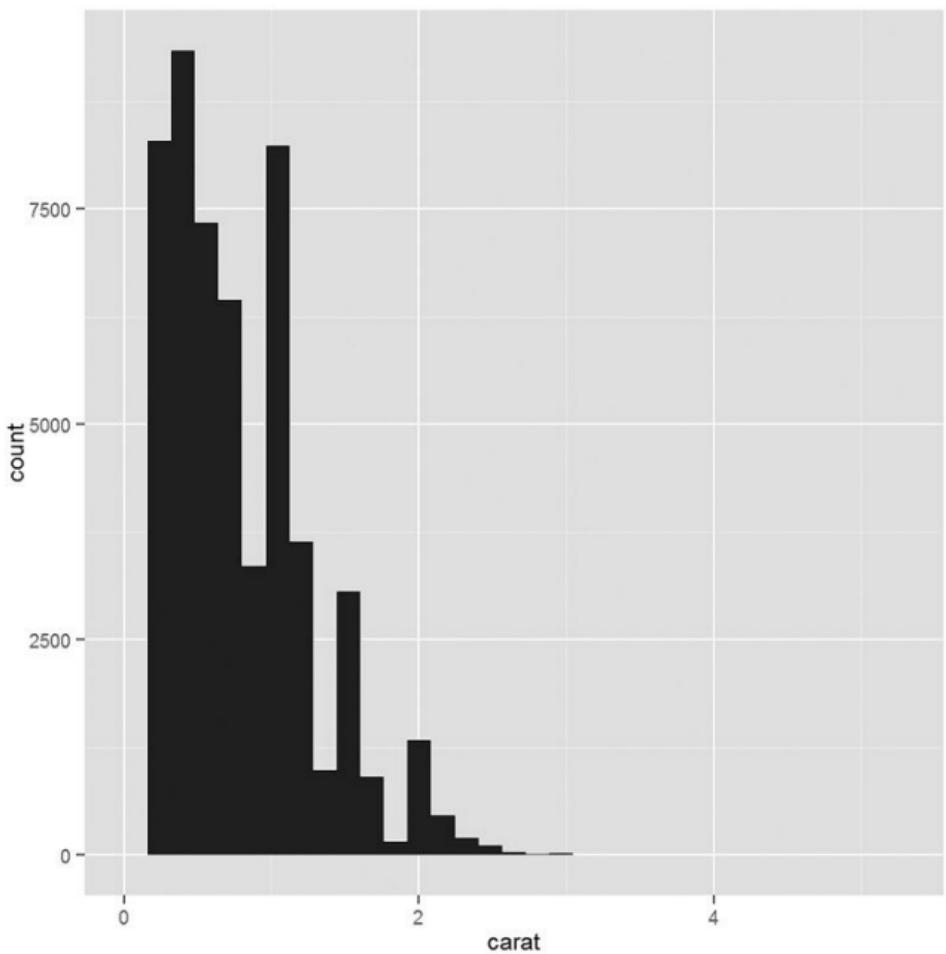
3. The package was previously called `ggplot` but early on Hadley made massive changes, so he upgraded the name to `ggplot2`.

## 7.2.1. ggplot2 Histograms and Densities

Returning to the histogram seen in [Figure 7.1](#), we plot the distribution of diamond carats using ggplot2. This is built using ggplot and geom histogram. Because histograms are one-dimensional displays of data, we need to specify only one aesthetic mapping, the *x*-axis. [Figure 7.4](#) shows the plot.

[Click here to view code image](#)

```
> ggplot(data = diamonds) + geom_histogram(aes(x = carat))
```



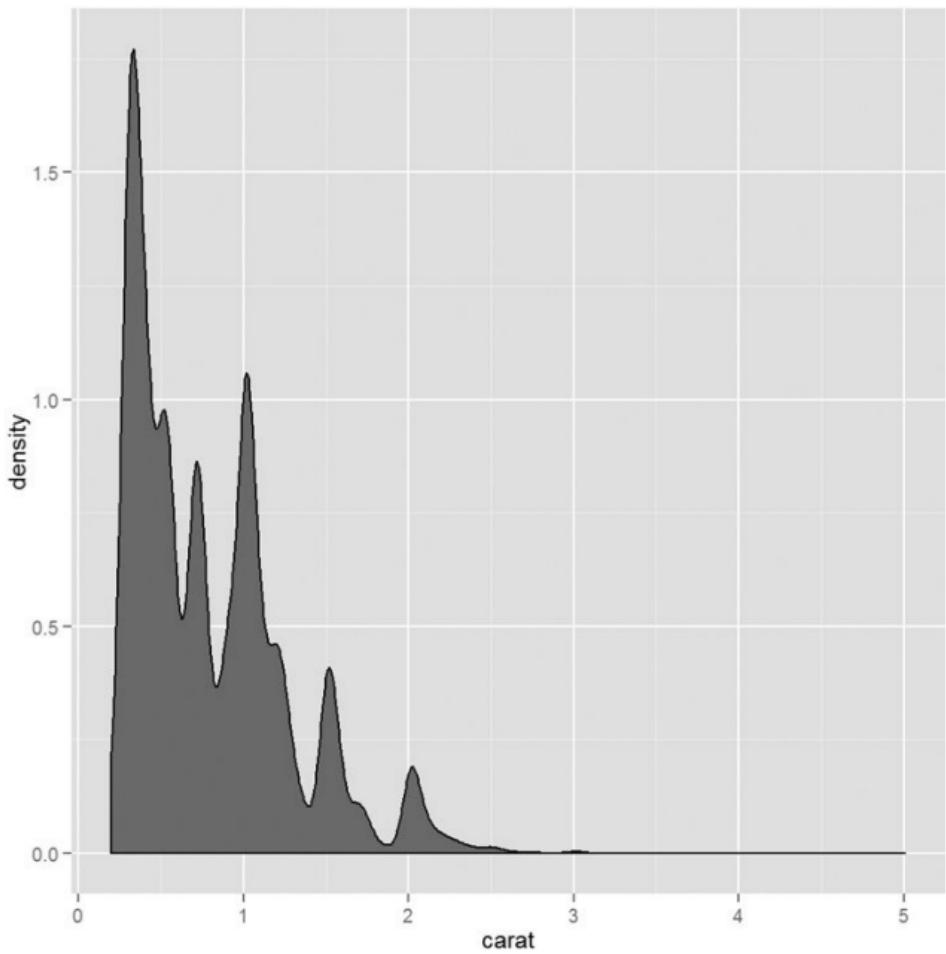
**Figure 7.4** Histogram of diamond carats using ggplot2.

A similar display is the density plot, which is done by changing geom histogram to geom density. We also specify the color to fill in the

graph using the fill argument. This differs from the color argument that we will see later. Also notice that the fill argument was entered outside the aes function. This is because we want the whole graph to be that color. We will see how it can be used inside aes later. This results in the graph shown in [Figure 7.5](#)

[Click here to view code image](#)

```
> ggplot(data = diamonds) + geom_density(aes(x = carat),  
  fill = "grey50")
```



**Figure 7.5** Density plot of diamond carats using ggplot2.

Whereas histograms display counts of data in buckets, density plots show the probability of observations falling within a sliding window along

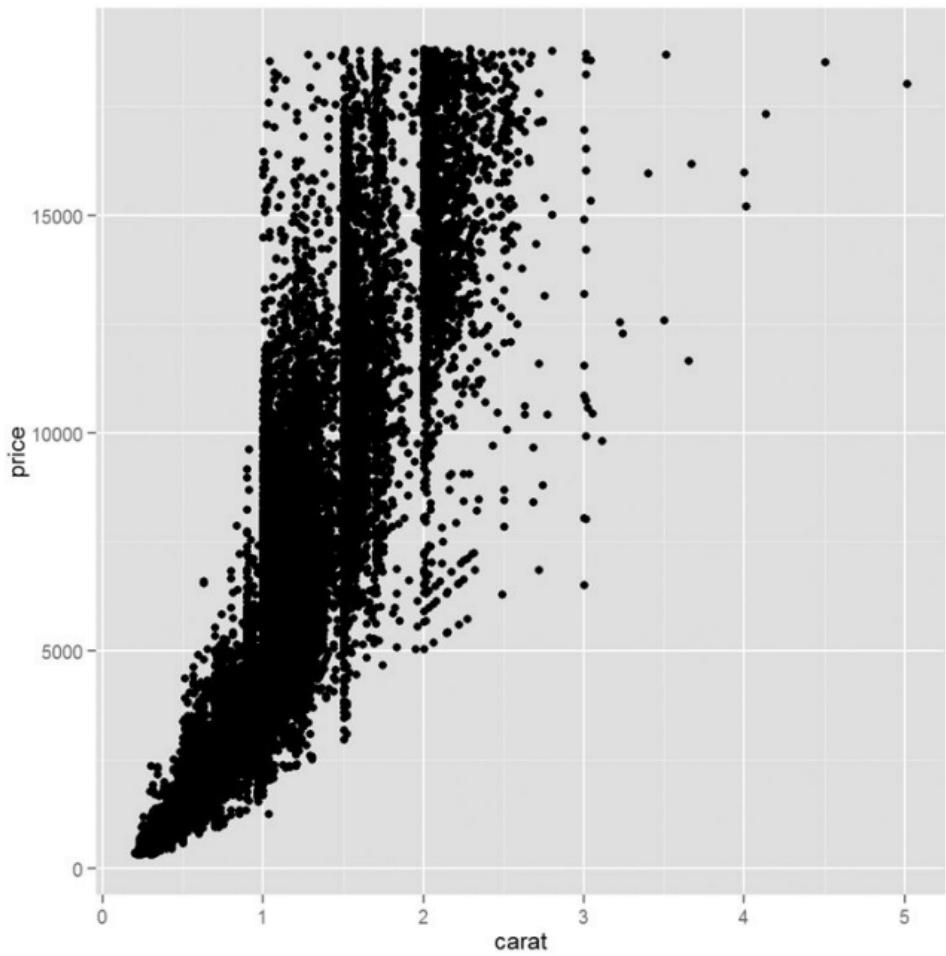
the variable of interest. The difference between the two is subtle but important. Histograms are more of a discrete measurement while density plots are more of a continuous measurement.

## 7.2.2. **ggplot2** Scatterplots

Here we not only show the ggplot2 way of making scatterplots but also show off some of the power of ggplot2. We start by re-creating the simple scatterplot in [Figure 7.2](#). Like before, we use ggplot to initialize the object, but this time we include aes inside the ggplot call instead of using it in the geom. The ggplot2 version is shown in [Figure 7.6](#).

[Click here to view code image](#)

```
> ggplot(diamonds, aes(x = carat, y = price)) +  
  geom_point()
```



**Figure 7.6** Simple ggplot2 scatterplot.

In the next few examples we will be using `ggplot(diamonds, aes(x=carat, y=price))` repeatedly, which ordinarily would require a lot of redundant typing. Fortunately we can save ggplot objects to

variables and add layers later. We will save it to g. Notice that nothing is plotted.

[Click here to view code image](#)

```
> # save basics of ggplot object to a variable  
> g <- ggplot(diamonds, aes(x = carat, y = price))
```

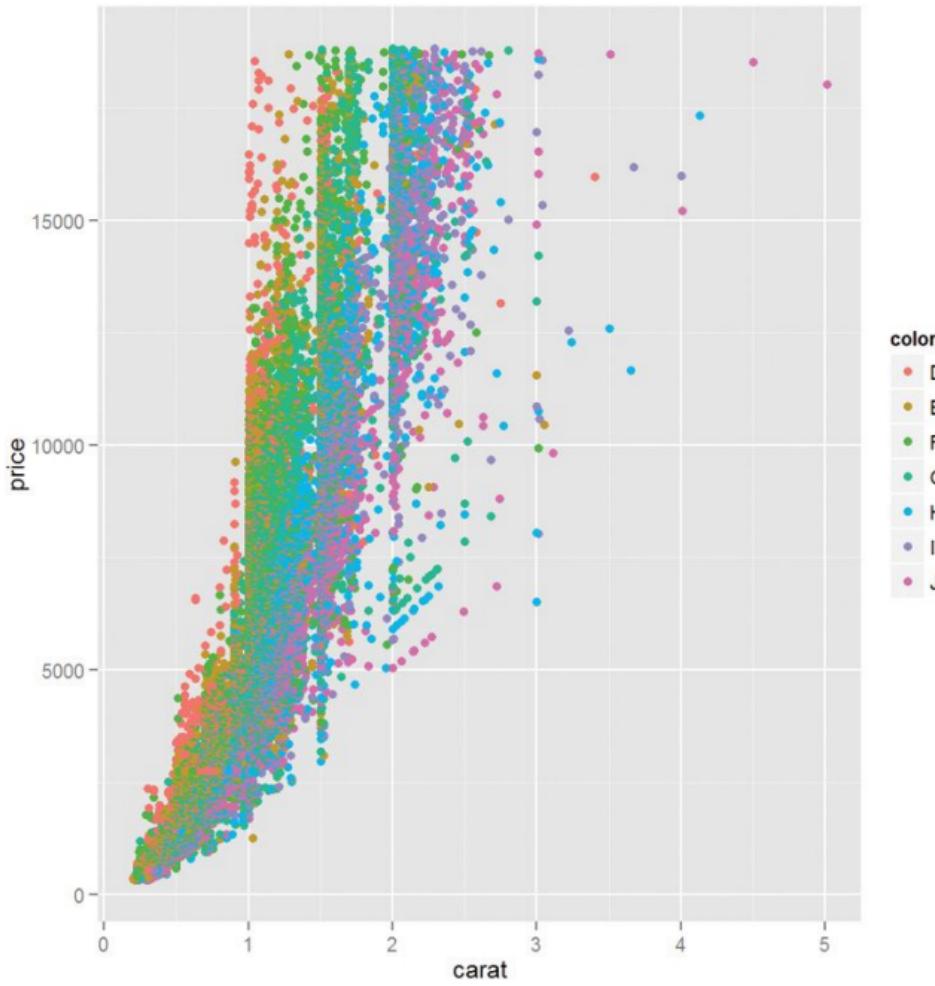
Going forward we can add any layer to g. Running g + geom point() would re-create the graph shown in [Figure 7.6](#).

The diamonds data have many interesting variables we can examine. Let's first look at color, which we will map to the color<sup>4</sup> aesthetic in [Figure 7.7](#).

<sup>4</sup>. ggplot will accept both the American (color) and British (colour) spellings.

[Click here to view code image](#)

```
> g + geom_point(aes(color = color))
```



**Figure 7.7** Scatterplot of diamonds data mapping diamond color to the color aesthetic.

Notice that we set `color=color` inside `aes`. This is because the designated color will be determin-

ed by the data. Also see that a legend was automatically generated. Recent versions of ggplot2 have added flexibility with the legend, which we will discuss later.

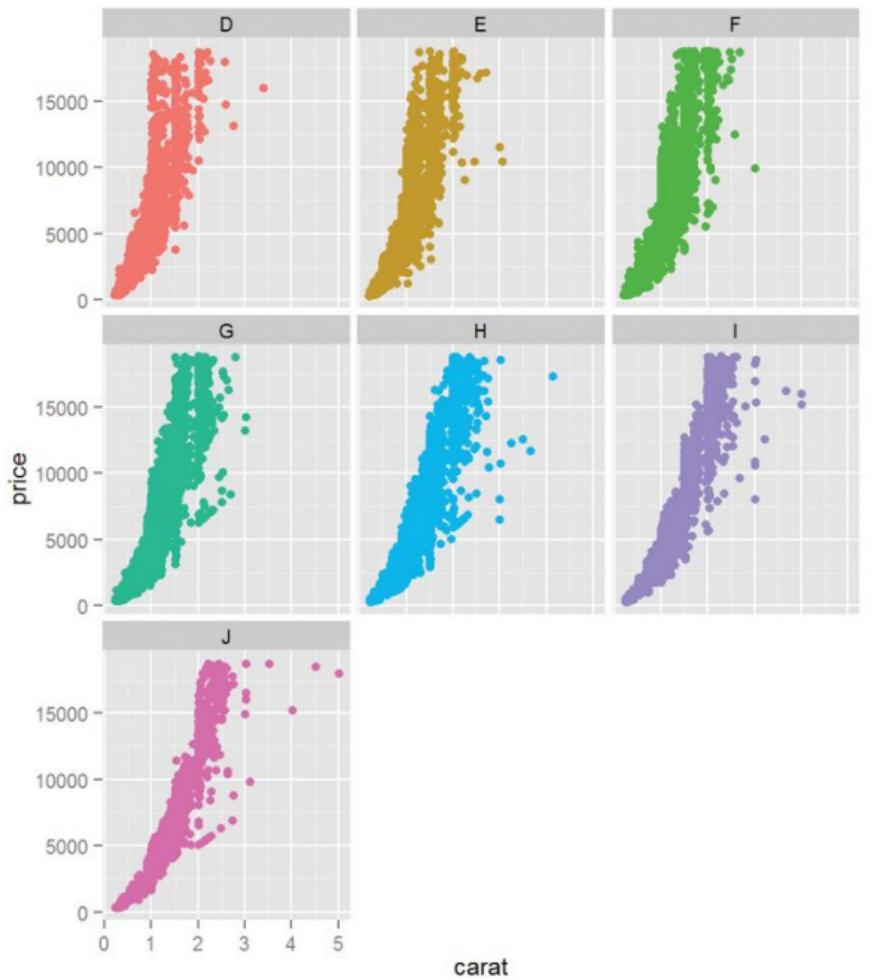
ggplot2 also has the ability to make faceted plots, or small multiples as Edward Tufte would say. This is done using facet wrap or facet grid. facet wrap takes the levels of one variable, cuts up the underlying data according to them, makes a separate pane for each set, and arranges them to fit in the plot, as seen in [Figure 7.8](#). Here the row and column placement have no real meaning. facet grid acts similarly but assigns all levels of a variable to either a row or column as shown in [Figure 7.9](#). In this case the upper left pane displays a scatterplot where the data are only for diamonds with Fair cut and I1 clarity. The pane to the right is a scatterplot where the data are only for diamonds with Fair cut and SI2 clarity. The pane in the second row, first column is a scatterplot where the data are only for diamonds with Good cut and I1 clarity. After understanding how

to read one pane in this plot we can easily understand all the panes and make quick comparisons.

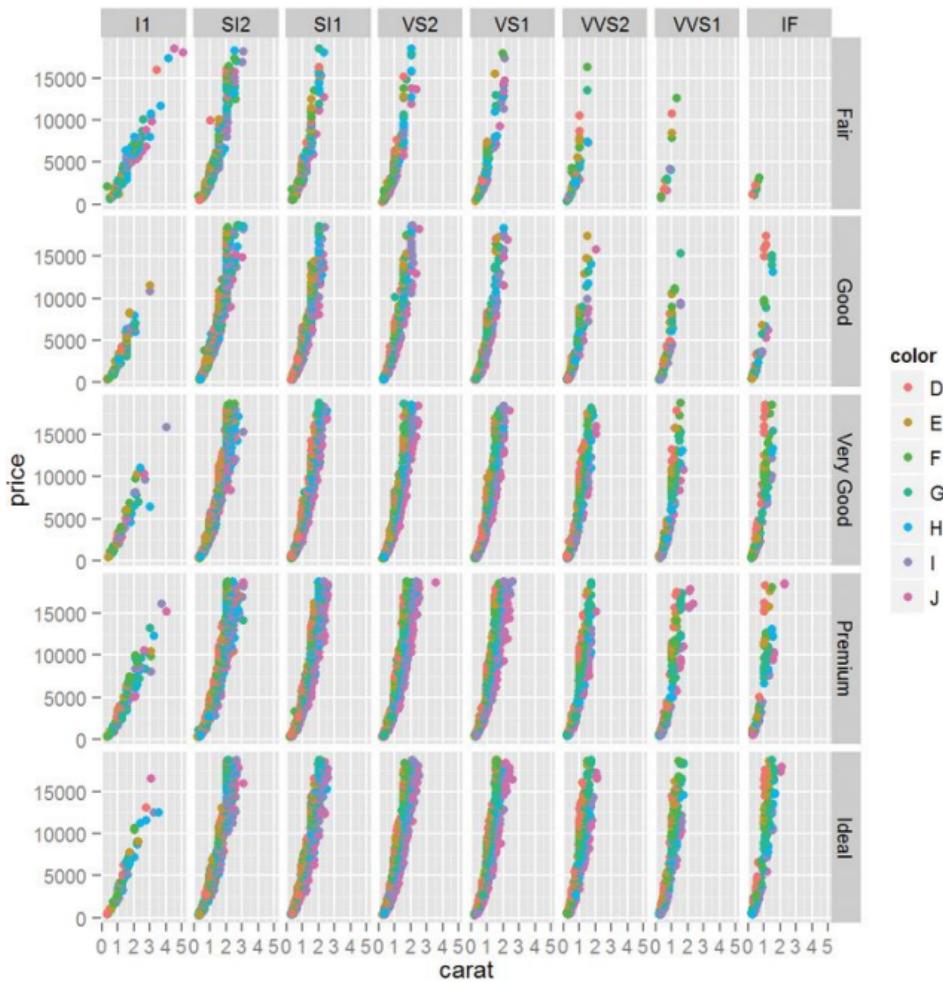
[Click here to view code image](#)

```
> g + geom_point(aes(color = color)) + facet_wrap(~color)
```

```
> g + geom_point(aes(color = color)) + facet_grid(cut ~ clarity)
```



**Figure 7.8** Scatterplot faceted by color.

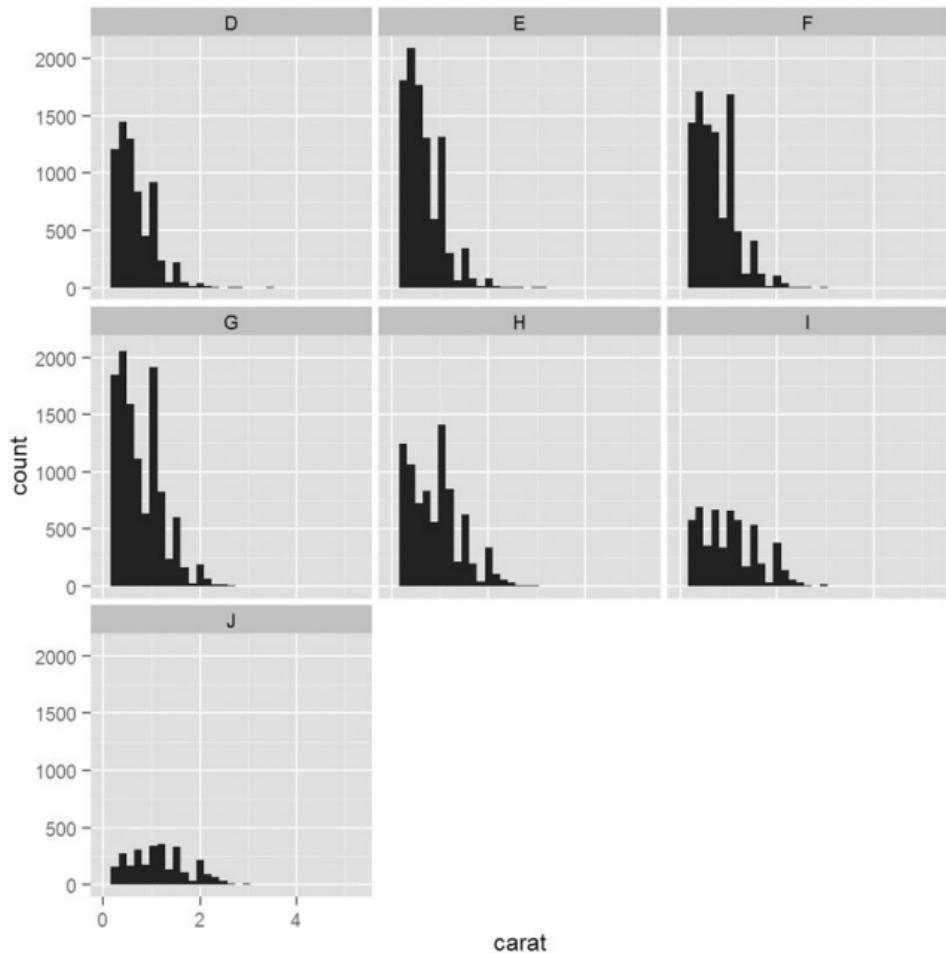


**Figure 7.9** Scatterplot faceted by cut and clarity. Notice that cut is aligned vertically while clarity is aligned horizontally.

Faceting also works with histograms or any other geom as shown in [Figure 7.10](#).

[Click here to view code image](#)

```
> ggplot(diamonds, aes(x = carat)) + geom_histogram() +  
  facet_wrap(~color)
```



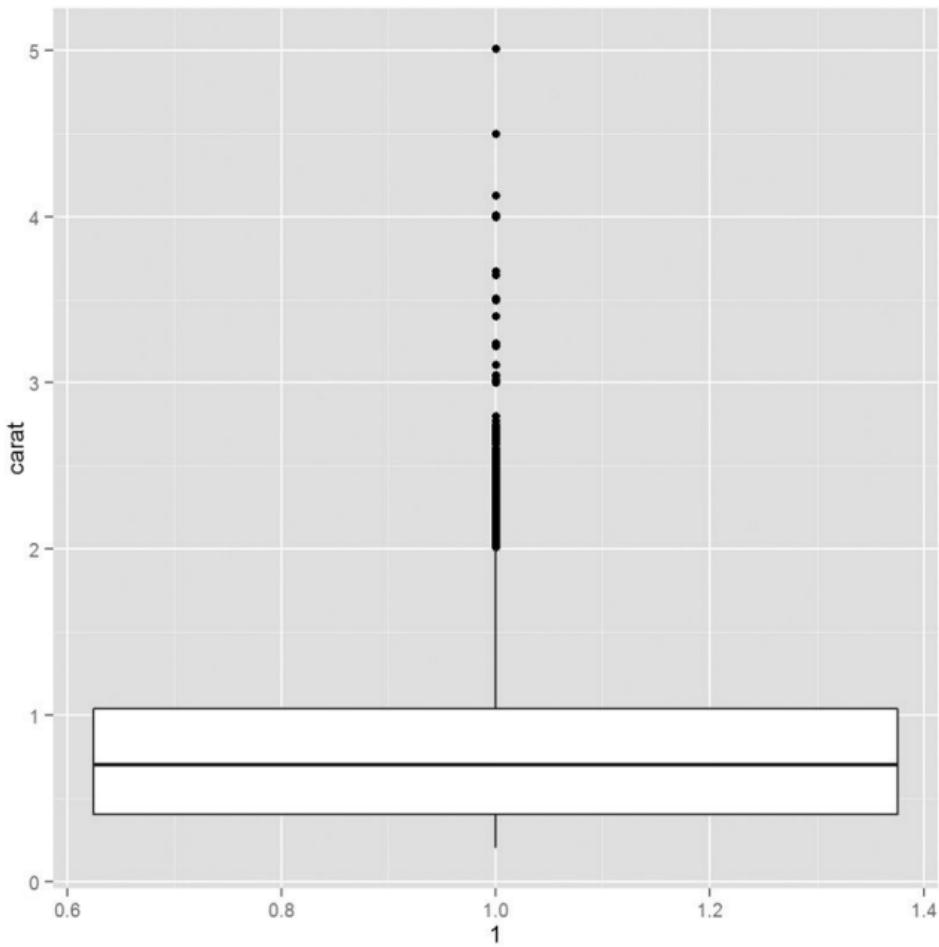
**Figure 7.10** Histogram faceted by color.

## 7.2.3. ggplot2 Boxplots and Violins Plots

Being a complete graphics package, ggplot2 offers a boxplot geom through geom\_boxplot. Even though it is one-dimensional, using a *y* aesthetic, there needs to be some *x* aesthetic, so we will use 1. The result is shown in [Figure 7.11](#).

[Click here to view code image](#)

```
> ggplot(diamonds, aes(y = carat, x = 1)) +  
  geom_boxplot()
```

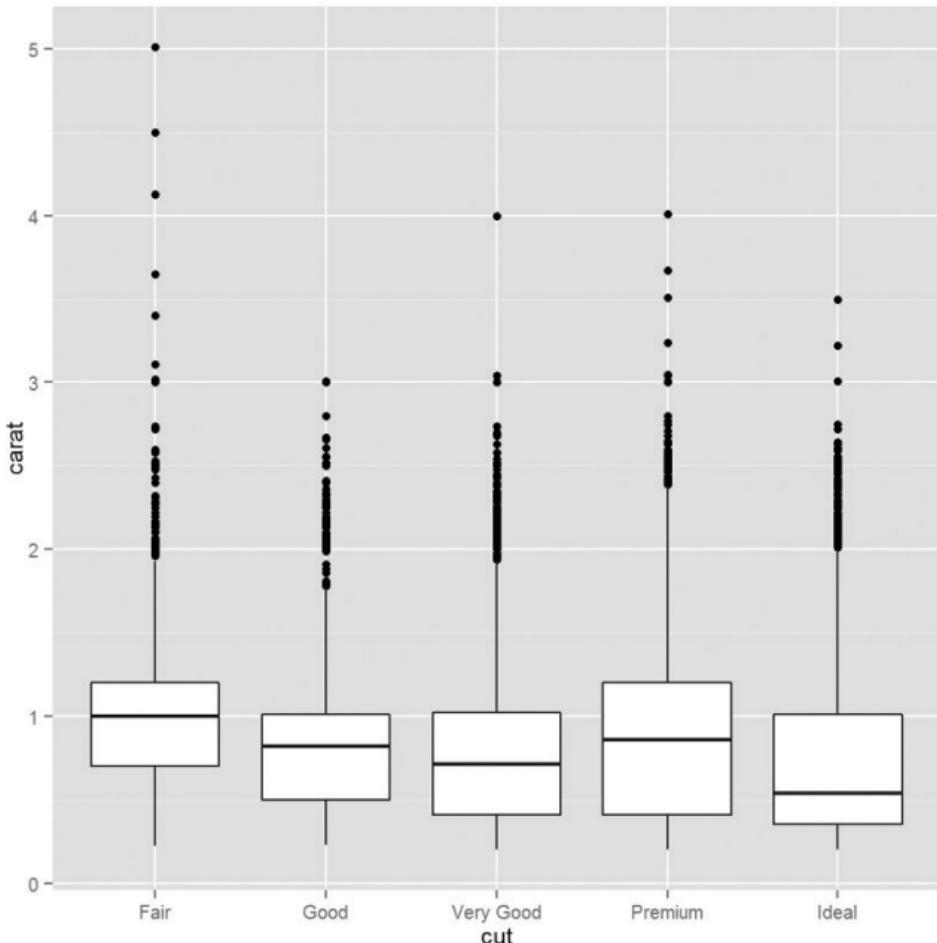


**Figure 7.11** Boxplot of diamond carats using ggplot2.

This is neatly extended to drawing multiple boxplots, one for each level of a variable, as seen in [Figure 7.12](#).

[Click here to view code image](#)

```
> ggplot(diamonds, aes(y = carat, x = cut)) +  
  geom_boxplot()
```

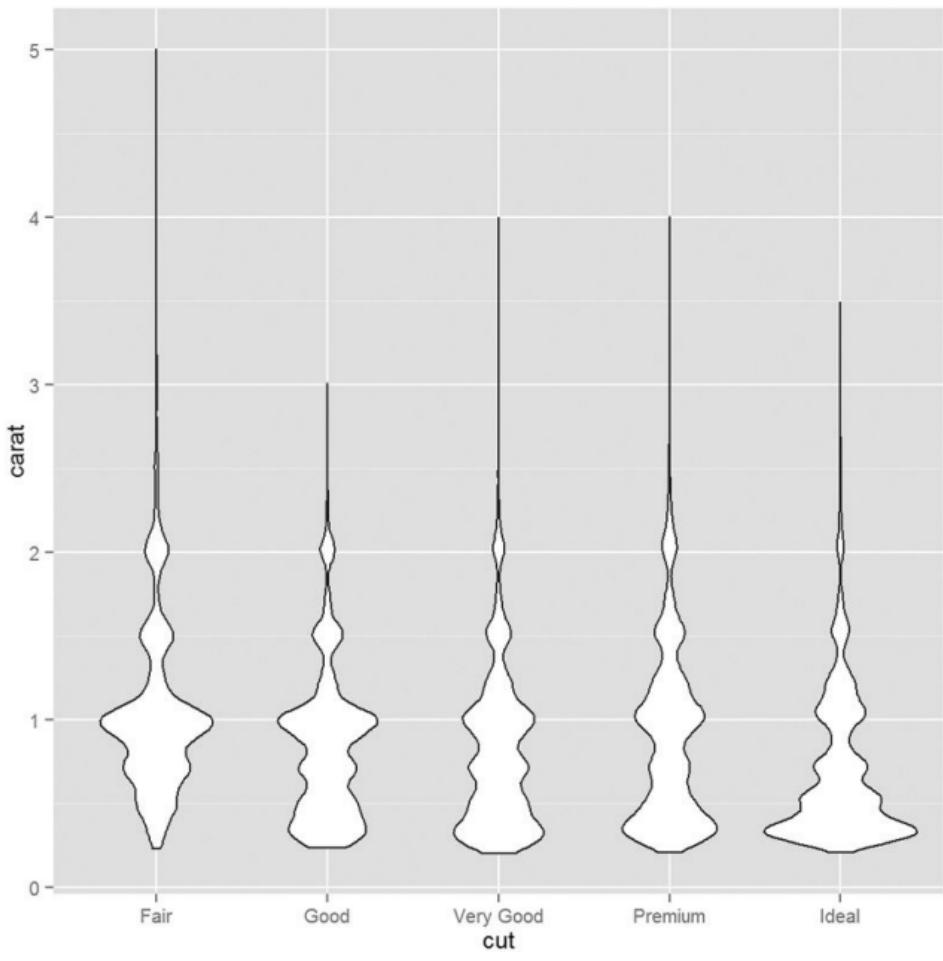


**Figure 7.12** Boxplot of diamond carats by cut using ggplot2.

Getting fancy, we can swap out the boxplot for violin plots using geom violin as shown in [Figure 7.13](#).

[Click here to view code image](#)

```
> ggplot(diamonds, aes(y = carat, x = cut)) +  
  geom_violin()
```



**Figure 7.13** Violin plot of diamond carats by cut using ggplot2.

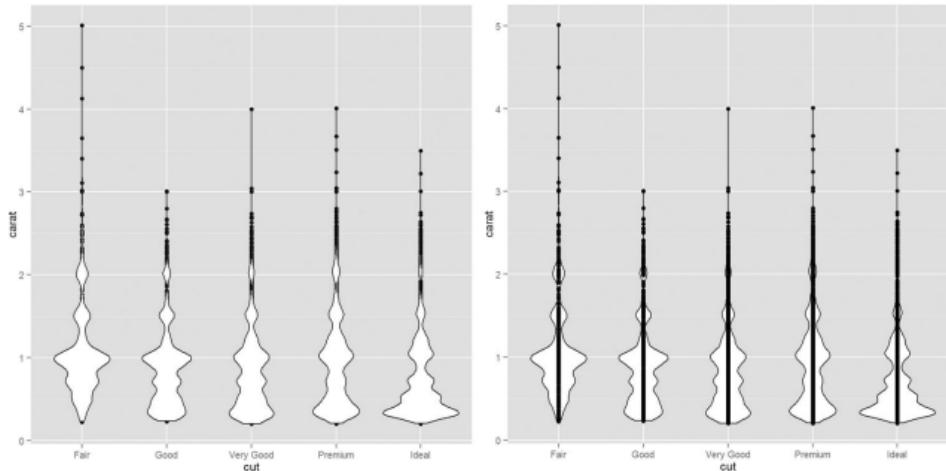
Violin plots are similar to boxplots except that the boxes are curved, giving a sense of the dens-

ity of the data. This provides more information than the straight sides of ordinary boxplots.

We can use multiple layers (geoms) on the same plot, as seen in [Figure 7.14](#). Notice that the order of the layers matters. In the graph on the left, the points are underneath the violins, while in the graph on the right, the points are on top of the violins.

[Click here to view code image](#)

```
> ggplot(diamonds, aes(y = carat, x = cut)) + geom_point()  
+ geom_violin()  
> ggplot(diamonds, aes(y = carat, x = cut)) +  
geom_violin() + geom_point()
```



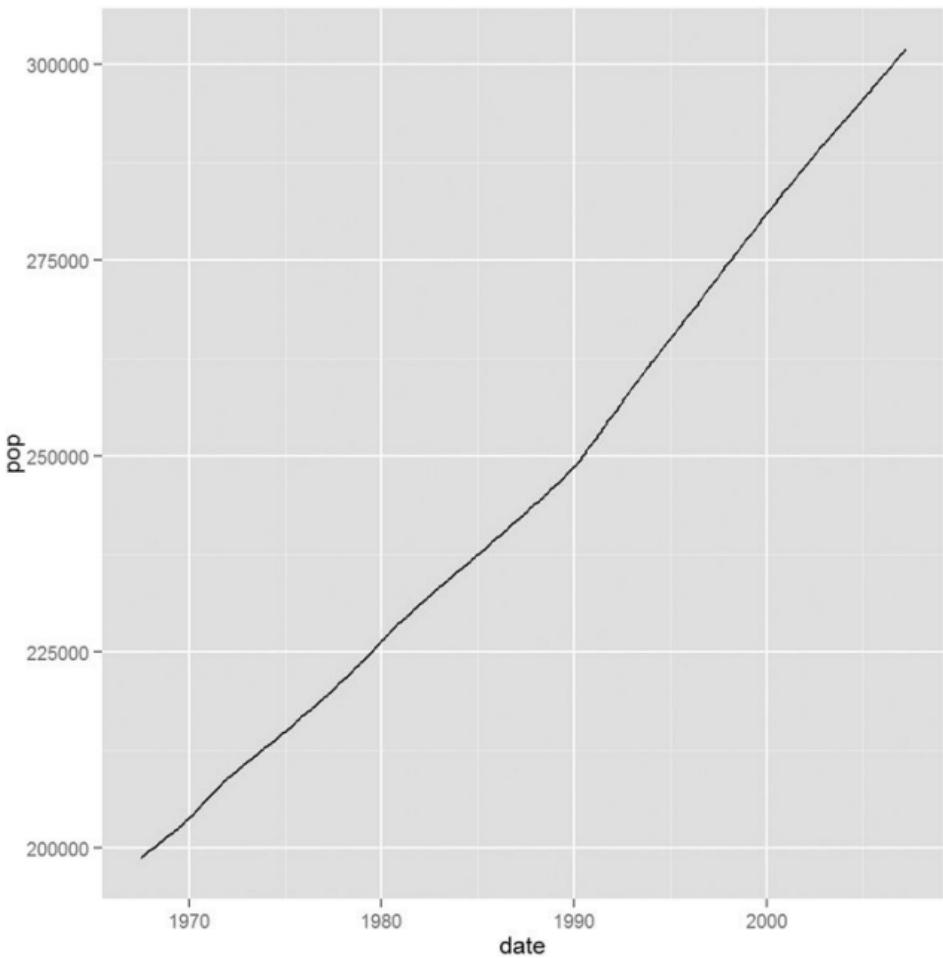
**Figure 7.14** Violin plots with points. The graph on the left was built by adding the `points geom` and then the `violin geom`, while the plot on the right was built in the opposite order. The order in which the geoms are added determines the positioning of the layers.

## 7.2.4. ggplot2 Line Graphs

Line charts are often used when one variable has a certain continuity, but that is not always necessary because there is often a good reason to use a line with categorical data. [Figure 7.15](#) shows an example of a line plot using the economics data from ggplot2. ggplot2 intelligently handles dates and plots them on a logical scale.

[Click here to view code image](#)

```
> ggplot(economics, aes(x = date, y = pop)) + geom_line()
```



**Figure 7.15** Line plot using ggplot2.

While this worked just fine, it is sometimes necessary to use `aes(group=1)` with `geom line`. Yes, it is hacky, but it gets the job done, just like when plotting a single boxplot as in [Section 7.2.3](#).

It is a quirk of ggplot2 that sometimes lines cannot be plotted without a group aesthetic.

A common task for line plots is displaying a metric over the course of a year for many years. To prepare the economics data we will use Wickham's lubridate package, which has convenient functions for manipulating dates. We need to create two new variables, year and month. To simplify things we will subset the data to include only years starting with 2000.

[Click here to view code image](#)

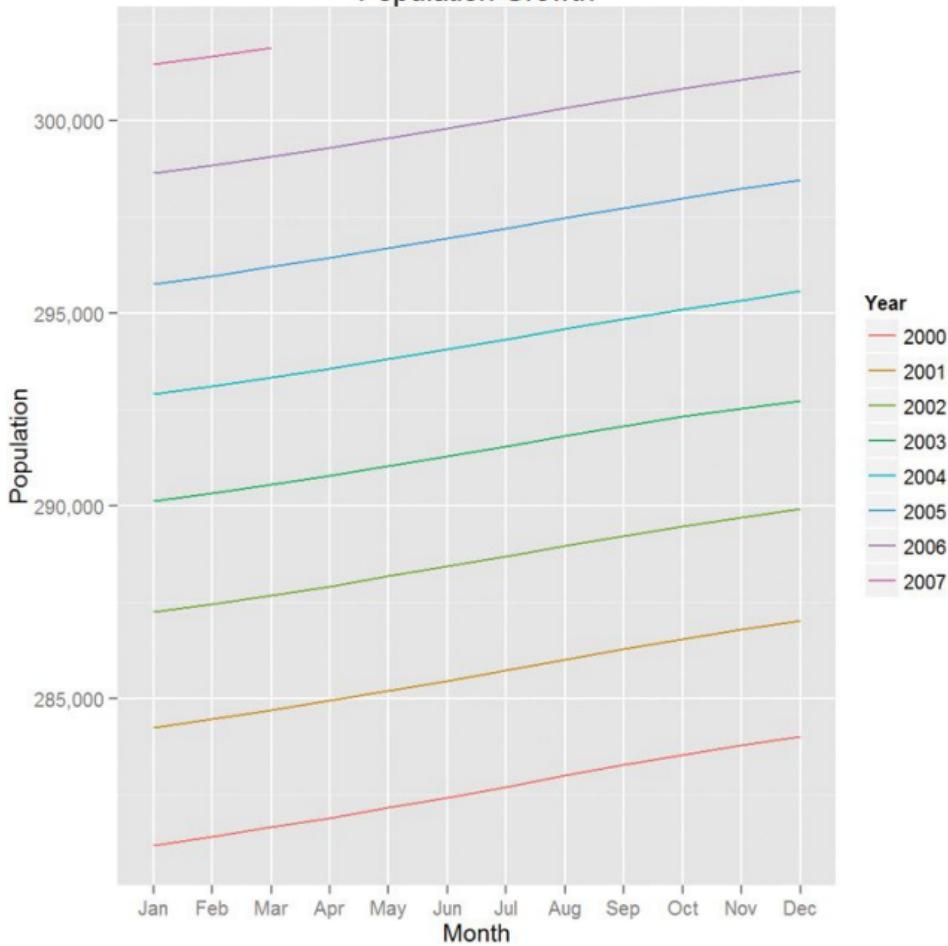
```
> # load the lubridate package
> require(lubridate)
>
> ## create year and month variables
> economics$year <- year(economics$date)
> # the label argument to month means that the result
should be the
> # names of the month instead of the number
> economics$month <- month(economics$date, la-
bel=TRUE)
>
> # subset the data
> # the which function returns the indices of observations
where the
```

```
> # tested condition was TRUE  
> econ2000 <- economics[which(economics$year >= 2000), ]  
>  
> # load the scales package for better axis formatting  
> require(scales)  
>  
> # build the foundation of the plot  
> g <- ggplot(econ2000, aes(x=month, y=pop))  
> # add lines color coded and grouped by year  
> # the group aesthetic breaks the data into separate groups  
> g <- g + geom_line(aes(color=factor(year), group=year))  
> # name the legend "Year"  
> g <- g + scale_color_discrete(name="Year")  
> # format the y axis  
> g <- g + scale_y_continuous(labels=comma)  
> # add a title and axis labels  
> g <- g + labs(title="Population Growth", x="Month", y="Population")  
> # plot the graph  
> g
```

Figure 7.16 contains many new concepts. The first part, `ggplot(econ2000, aes(x=month, y=-pop)) + geom_line(aes(color=factor(year), group=year))`, is code we have seen before; it creates the line graph with a separate line and color for each year. Notice that we converted year

to a factor so that it would get a discrete color scale. That scale was named by using scale\_color\_discrete(name="Year"). The *y*-axis was formatted to have commas using scale\_y\_continuous(labels=comma). Last, the title, *x*-label and *y*-label were set with labs(title="Population Growth", x="Month", y="Population"). All of these pieces put together built a professional-looking, publication-quality graph.

### Population Growth



**Figure 7.16** Line plot with a separate line for each year.

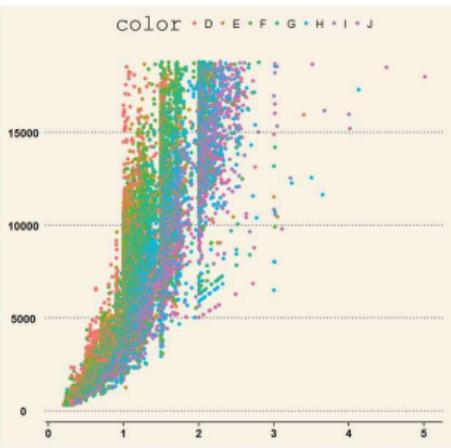
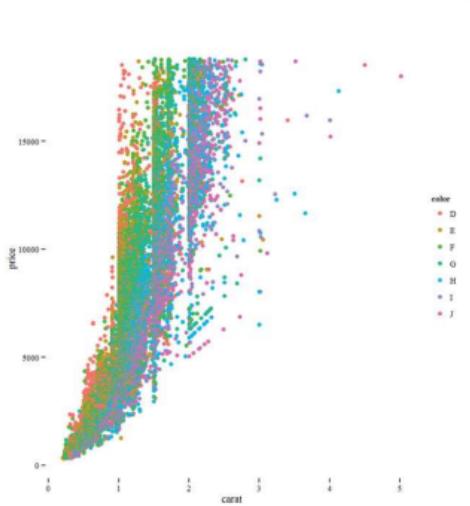
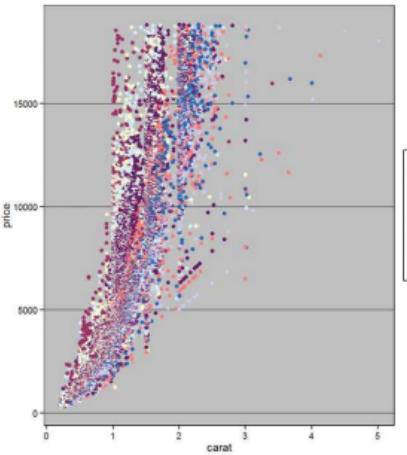
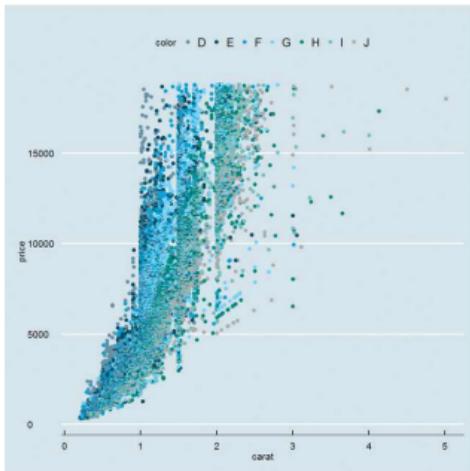
Also note the use of which to subset the data. This is similar to a where clause in SQL.

## 7.2.5. Themes

A great part of ggplot2 is the ability to use themes to easily change the way plots look. While building a theme from scratch can be daunting, Jeffrey Arnold from the University of Rochester has put together ggthemes, a package of themes to re-create commonly used styles of graphs. Just a few styles—The Economist, Excel, Edward Tufte and The Wall Street Journal—are exhibited in [Figure 7.17](#).

[Click here to view code image](#)

```
> require(ggthemes)
> # build a plot and store it in g2
> g2 <- ggplot(diamonds, aes(x=carat, y=price)) +
+   geom_point(aes(color=color))
>
> # apply a few themes
> g2 + theme_economist() + scale_colour_economist()
> g2 + theme_excel() + scale_colour_excel()
> g2 + theme_tufte()
> g2 + theme_wsj()
```



**Figure 7.17** Various themes from the ggthemes package. Starting from top left and going clockwise: The Economist, Excel (for those with bosses who demand Excel output), Edward Tufte and The Wall Street Journal.

## 7.3. Conclusion

We have seen both basic graphs and ggplot graphs that are both nicer and easier to create. We have covered histograms, scatterplots, box-plots, line plots and density graphs. We have also looked at using colors and small multiples for distinguishing data. There are many other features in ggplot2 such as jittering, stacking, dodging and alpha, which we will demonstrate in context throughout the book.

# Chapter 8. Writing R functions

If we find ourselves running the same code repeatedly, it is probably a good idea to turn it into a function. In programming it is best to reduce redundancy whenever possible. There are several reasons for doing so, including maintainability and ease of reuse. R has a convenient way to make functions but it is very different from other languages, so some expectation adjustment might be necessary.

## 8.1. Hello, World!

This would not be a serious book about a programming language if we did not include a “Hello, World!” example, so we will start with that. Let’s build a function that simply prints “Hello, World!” to the console.

[Click here to view code image](#)

```
> say.hello <- function()
+ {
```

```
+   print("Hello, World!")  
+ }
```

First, note that in R the period (.) is just another character and has no special meaning,<sup>1</sup> unlike in other languages. This allows us to call this function say.hello.

1. One exception is that objects with names starting with a period are accessible but invisible, so they will not be found by ls.

Next, we see that functions are assigned to objects just like any other variable, using the <- operator. This is the strangest part of writing functions for people coming from other languages.

Following function are a set of parentheses that can either be empty—not have any arguments—or contain any number of arguments. We will cover those in [Section 8.2](#).

The body of the function is enclosed in curly braces ({ and }). This is not necessary if the function contains only one line, but that is rare. Notice the indenting for the commands inside the function. While not required, it is good practice to

properly indent code to ensure readability. It is here in the body that we put the lines of code we want the function to perform. A semicolon (;) can be used to indicate the end of the line but is not necessary, and its use is actually frowned upon.

Calling `say.hello()` prints as desired.

## 8.2. Function Arguments

More often than not we want to pass arguments to our function. These are easily added inside the parentheses of the function declaration. We will use an argument to print “Hello Jared.”

Before we do that, however, we need to briefly learn about the `sprintf` function. Its first argument is a string with special input characters and subsequent arguments that will be substituted into the special input characters.

[Click here to view code image](#)

```
> # one substitution
> sprintf("Hello %s", "Jared")
[1] "Hello Jared"
> # two substitutions
```

```
> sprintf("Hello %s, today is %s", "Jared", "Sunday")
[1] "Hello Jared, today is Sunday"
```

We now use sprintf to build a string to print based on a function's arguments.

[Click here to view code image](#)

```
> hello.person <- function(name)
+ {
+   print(sprintf("Hello %s", name))
+ }
> hello.person("Jared")
[1] "Hello Jared"
> hello.person("Bob")
[1] "Hello Bob"
> hello.person("Sarah")
[1] "Hello Sarah"
```

The argument name can be used as a variable inside the function (it does not exist outside the function), and can be used like any other variable and as an argument to further function calls.

We can add a second argument to be printed as well. When calling functions with more than one argument, there are two ways to specify which

argument goes with which value, either positionally or by name.

[Click here to view code image](#)

```
> hello.person <- function(first, last)
+ {
+   print(sprintf("Hello %s %s", first, last))
+ }
> # by position
> hello.person("Jared", "Lander")
[1] "Hello Jared Lander"
> # by name
> hello.person(first = "Jared", last = "Lander")
[1] "Hello Jared Lander"
> # the other order
> hello.person(last = "Lander", first = "Jared")
[1] "Hello Jared Lander"
> # just specify one name
> hello.person("Jared", last = "Lander")
[1] "Hello Jared Lander"
> # specify the other
> hello.person(first = "Jared", "Lander")
[1] "Hello Jared Lander"
> # specify the second argument first then provide the first
  argument
> # with no name
> hello.person(last = "Lander", "Jared")
[1] "Hello Jared Lander"
```

Being able to specify the arguments by name adds a lot of flexibility to calling functions. Even partial argument names can be supplied but this should be done with care.

[Click here to view code image](#)

```
> hello.person(fir = "Jared", l = "Lander")
[1] "Hello Jared Lander"
```

### 8.2.1. Default Arguments

When using multiple arguments it is sometimes desirable to not have to enter a value for each. In other languages functions can be overloaded by defining the function multiple times, each with a differing number of arguments. R instead provides the ability to specify default arguments. These can be NULL, characters, numbers or any valid R object.

Let's rewrite hello.person to provide "Doe" as the default last name.

[Click here to view code image](#)

```
> hello.person <- function(first, last = "Doe")
+ {
```

```
+   print(sprintf("Hello %s %s", first, last))
+ }
>
> # call without specifying last
> hello.person("Jared")
[1] "Hello Jared Doe"
> # call with a different last
> hello.person("Jared", "Lander")
[1] "Hello Jared Lander"
```

## 8.2.2. Extra Arguments

R offers a special operator that allows functions to take an arbitrary number of arguments that do not need to be specified in the function definition. This is the dot-dot-dot argument (...). This should be used very carefully, although it can allow great flexibility. For now we will just see how it can absorb extra arguments; later we will find a use for it when passing arguments between functions.

[Click here to view code image](#)

```
> # call hello.person with an extra argument
> hello.person("Jared", extra = "Goodbye")
Error: unused argument (extra = "Goodbye")
> # call it with two valid arguments and a third
> hello.person("Jared", "Lander", "Goodbye")
```

## Error: unused argument ("Goodbye")

```
>  
> # now build hello.person with ... so that it absorbs extra  
arguments  
> hello.person <- function(first, last = "Doe", ...)  
+ {  
+   print(sprintf("Hello %s %s", first, last))  
+ }  
> # call hello.person with an extra argument  
> hello.person("Jared", extra = "Goodbye")  
[1] "Hello Jared Doe"  
> # call it with two valid arguments and a third  
> hello.person("Jared", "Lander", "Goodbye")  
[1] "Hello Jared Lander"
```

## 8.3. Return Values

Functions are generally used for computing some value, so they need a mechanism to supply that value back to the caller. This is called returning and is done quite easily. There are two ways to accomplish this with R. The value of the last line of code in a function is automatically returned, although this can be bad practice. The return command more explicitly specifies that a value should be returned and the function should be exited.

To illustrate, we will build a function that doubles its only argument and returns that value.

[Click here to view code image](#)

```
> # first build it without an explicit return
> double.num <- function(x)
+ {
+   x * 2
+ }
>
> double.num(5)
[1] 10
>
> # now build it with an explicit return
> double.num <- function(x)
+ {
+   return(x * 2)
+ }
>
> double.num(5)
[1] 10
>
> # build it again, this time with another argument after the
  explicit
> # return
> double.num <- function(x)
+ {
+   return(x * 2)
+ }
```

```
+ # below here is not executed because the function  
already exited  
+ print("Hello!")  
+ return(17)  
+ }  
>  
> double.num(5)  
[1] 10
```

## 8.4. do.call

A particularly underused trick is the `do.call` function. This allows us to specify the name of a function either as a character or as an object, and provide arguments as a list.

[Click here to view code image](#)

```
> do.call("hello.person", args = list(first = "Jared", last =  
"Lander"))  
[1] "Hello Jared Lander"  
> do.call(hello.person, args = list(first = "Jared", last =  
"Lander"))  
[1] "Hello Jared Lander"
```

This is particularly useful when building a function that allows the user to specify an action.

In the following example the user supplies a vector and a function to be run.

[Click here to view code image](#)

```
> run.this <- function(x, func = mean)
+ {
+   do.call(func, args = list(x))
+ }
>
> # finds the mean by default
> run.this(1:10)
[1] 5.5
> # specify to calculate the mean
> run.this(1:10, mean)
[1] 5.5
> # calculate the sum
> run.this(1:10, sum)
[1] 55
> # calculate the standard deviation
> run.this(1:10, sd)
[1] 3.028
```

## 8.5. Conclusion

Functions allow us to create reusable code that avoids repetition and allows easy modification. Important points to remember are function arguments, default values and returned values. Later in this book we will see functions that get far more complicated than the ones we have seen so far.

# Chapter 9. Control Statements

Control statements allow us to control the flow of our programming and cause different things to happen depending on the values of tests. Tests result in a logical, TRUE, or FALSE, which is used in if-like statements. The main control statements are if, else, ifelse and switch.

## 9.1. if and else

The most common test is the if command. It essentially says: If something is TRUE, then perform some action; otherwise, do not perform that action. The thing we are testing goes inside parentheses following the if command. The most basic checks are equal to (==), less than (<), less than or equal to (<=), greater than (>), greater than or equal to (>=) and not equal (!=).

If these tests pass they result in TRUE, and if they fail they result in FALSE. As noted in [Sec-](#)

[tion 4.3.4](#), TRUE is numerically equivalent to 1 and FALSE is equivalent to 0.

```
> as.numeric(TRUE)  
[1] 1  
> as.numeric(FALSE)  
[1] 0
```

These tests do not need to be used inside if statements. The following are some simple examples.

```
> 1 == 1 # TRUE  
[1] TRUE  
> 1 < 1 # FALSE  
[1] FALSE  
> 1 <= 1 # TRUE  
[1] TRUE  
> 1 > 1 # FALSE  
[1] FALSE  
> 1 >= 1 # TRUE  
[1] TRUE  
> 1 != 1 # FALSE  
[1] FALSE
```

We can now show that using this test inside an if statement controls actions that follow.

## [Click here to view code image](#)

```
> # set up a variable to hold 1
> toCheck <- 1
>
> # if toCheck is equal to 1, print hello
> if (toCheck == 1)
+ {
+   print("hello")
+ }
[1] "hello"
>
> # now if toCheck is equal to 0, print hello
> if (toCheck == 0)
+ {
+   print("hello")
+ }
> # notice nothing was printed
```

Notice that if statements are similar to functions in that all statements (there can be one or multiple) go inside curly braces.

Life is not always so simple that we want an action only if some relationship is TRUE. We often want a different action if that relationship is FALSE. In the following example we put an if

statement followed by an else statement inside a function, so that it can be used repeatedly.

[Click here to view code image](#)

```
> # first create the function
> check.bool <- function(x)
+ {
+   if (x == 1)
+   {
+     # if the input is equal to 1, print hello
+     print("hello")
+   } else
+   {
+     # otherwise print goodbye
+     print("goodbye")
+   }
+ }
```

Notice that else is on the same line as its preceding closing curly brace ()). This is important, as the code will fail otherwise.

Now let's use that function and see if it works.

```
> check.bool(1)
[1] "hello"
> check.bool(0)
[1] "goodbye"
> check.bool("k")
```

```
[1] "goodbye"  
> check.bool(TRUE)  
[1] "hello"
```

Anything other than 1 caused the function to print “goodbye.” That is exactly what we wanted. Passing TRUE printed “hello” because TRUE is numerically the same as 1.

Perhaps we want to successively test a few cases. That is where we can use else if. We first test a single statement, then make another test, and then perhaps fall over to catch all. We will modify `check.bool` to test for one condition and then another.

[Click here to view code image](#)

```
> check.bool <- function(x)  
+ {  
+   if (x == 1)  
+     {  
+       # if the input is equal to 1, print hello  
+       print("hello")  
+     } else if (x == 0)  
+     {  
+       # if the input is equal to 0, print goodbye  
+       print("goodbye")  
+     }  
+   }  
+ }  
+ }
```

```
+ } else
+ {
+   # otherwise print confused
+   print("confused")
+ }
+
>
> check.bool(1)
[1] "hello"
> check.bool(0)
[1] "goodbye"
> check.bool(2)
[1] "confused"
> check.bool("k")
[1] "confused"
```

## 9.2. switch

If we have multiple cases to check, writing else if repeatedly can be cumbersome and inefficient. This is where switch is most useful. The first argument is the value we are testing. Subsequent arguments are a particular value and what should be the result. The last argument, if not given a value, is the default result.

To illustrate, we build a function that takes in a value and returns a corresponding result.

## [Click here to view code image](#)

```
> use.switch <- function(x)
+ {
+   switch(x,
+     "a"="first",
+     "b"="second",
+     "z"="last",
+     "c"="third",
+     "other")
+ }
>
> use.switch("a")
[1] "first"
> use.switch("b")
[1] "second"
> use.switch("c")
[1] "third"
> use.switch("d")
[1] "other"
> use.switch("e")
[1] "other"
> use.switch("z")
[1] "last"
```

If the first argument is numeric, it is matched positionally to the following arguments, regardless of the names of the subsequent arguments. If

the numeric argument is greater than the number of subsequent arguments, NULL is returned.

[Click here to view code image](#)

```
> use.switch(1)
[1] "first"
> use.switch(2)
[1] "second"
> use.switch(3)
[1] "last"
> use.switch(4)
[1] "third"
> use.switch(5)
[1] "other"
> use.switch(6) # nothing is returned
> is.null(use.switch(6))
[1] TRUE
```

Here we introduced a new function, `is.null`, which, as the name implies, tests if an object is `NULL`.

## 9.3. ifelse

While `if` is like the `if` statement in traditional languages, `ifelse` is more like the `if` function in Excel. The first argument is the condition to be tested (much like in a traditional `if` statement), the second argument is the return value if the test is `TRUE` and the third argument is the return value if the test is `FALSE`. The beauty here—unlike with the traditional `if`—is that this works with vectorized arguments. As is often the case in R, using vectorization avoids for loops and speeds up our code. The nuances of `ifelse` can be tricky, so we show numerous examples.

We start with a very simple example, testing if 1 is equal to 1, and printing “Yes” if that is `TRUE` and “No” if it is `FALSE`.

[Click here to view code image](#)

```
> # see if 1 == 1
> ifelse(1 == 1, "Yes", "No")
[1] "Yes"
> # see if 1 == 0
> ifelse(1 == 0, "Yes", "No")
```

```
[1] "No"
```

This clearly gives us the results we want. `ifelse` uses all the regular equality tests seen in [Section 9.1](#) and any other logical test. It is worth noting, however, that if testing just a single element (a vector of length 1 or a simple `is.na`) it is more efficient to use `if` than `ifelse`. This can result in a nontrivial speedup of our code.

Next we will illustrate a vectorized first argument.

[Click here to view code image](#)

```
> toTest <- c(1, 1, 0, 1, 0, 1)
> ifelse(toTest == 1, "Yes", "No")
[1] "Yes" "Yes" "No" "Yes" "No" "Yes"
```

This returned “Yes” for each element of `toTest` that equaled 1 and “No” for each element of `toTest` that did not equal 1.

The `TRUE` and `FALSE` arguments can even refer to the testing element.

## [Click here to view code image](#)

```
> ifelse(toTest == 1, toTest * 3, toTest)
[1] 3 3 0 3 0 3
> # the FALSE argument is repeated as needed
> ifelse(toTest == 1, toTest * 3, "Zero")
[1] "3"  "3"  "Zero" "3"  "Zero" "3"
```

Now let's say that toTest has NA elements. In that case the corresponding result from ifelse is NA.

## [Click here to view code image](#)

```
> toTest[2] <- NA
> ifelse(toTest == 1, "Yes", "No")
[1] "Yes" NA  "No" "Yes" "No" "Yes"
```

This would be the same if the TRUE and FALSE arguments are vectors.

## [Click here to view code image](#)

```
> ifelse(toTest == 1, toTest * 3, toTest)
[1] 3 NA 0 3 0 3
> ifelse(toTest == 1, toTest * 3, "Zero")
[1] "3"  NA  "Zero" "3"  "Zero" "3"
```

## 9.4. Compound Tests

The statement being tested with if, ifelse and switch can be any argument that results in a logical TRUE or FALSE. This can be an equality check or even the result of is.numeric or is.na. Sometimes we want to test more than one relationship at a time. This is done using logical and and or operators. These are & and && for and and | and || for or. The differences are subtle but can impact our code's speed.

The double form (&& or ||) is best used in if and the single form (& or |) is necessary for ifelse. The double form compares only one element from each side, while the single form compares each element of each side.

[Click here to view code image](#)

```
> a <- c(1, 1, 0, 1)
> b <- c(2, 1, 0, 1)
>
> # this checks each element of a and each element of b
> ifelse(a == 1 & b == 1, "Yes", "No")
[1] "No" "Yes" "No" "Yes"
>
```

```
> # this only checks the first element of a and the first ele-  
  ment of b,  
> # returning only one result  
> ifelse(a == 1 && b == 1, "Yes", "No")  
[1] "No"
```

Another difference between the double and single forms is how they are processed. When using the single form, both sides of the operator are always checked. With the double form, sometimes only the left side needs to be checked. For instance, if testing  $1 == 0 \&\& 2 == 2$ , the left side fails, so there is no reason to check the right side. Similarly, when testing  $3 == 3 || 0 == 0$ , the left side passes, so there is no need to check the right side. This can be particularly helpful when the right side would throw an error if the left side had failed.

There can be more than just two conditions tested. Many conditions can be strung together using multiple and or or operators. The different clauses can be grouped by parentheses just like mathematical operations. Without parentheses, the order of operations is similar to PEMDAS,

seen in [Section 4.1](#), where and is equivalent to multiplication and or is equivalent to addition, so and takes precedence over or.

## 9.5. Conclusion

Controlling the flow of our program, both at the command line and in functions, plays an important role when processing and analyzing our data. if statements, along with else, are the most common—and efficient—for testing single element objects, although ifelse is far more common in R programming because of its vectorized nature. switch statements are often forgotten but can come in very handy. The and (& and &&) and or (| and ||) operators allow us to combine multiple tests into one.

# Chapter 10. Loops, the Un-R Way to Iterate

When starting to use R, most people use loops whenever they need to iterate over elements of a vector, list or data.frame. While it is natural to do this in other languages, with R we generally want to use vectorization. That said, sometimes loops are unavoidable, so R offers both for and while loops.

## 10.1. for Loops

The most commonly used loop is the for loop. It iterates over an index—provided as a vector—and performs some operations. For a first simple example, we print out the first ten numbers.

The loop is declared using for, which takes one English-seeming argument in three parts. The third part is any vector of values of any kind, most commonly numeric or character. The first part is the

variable that is iteratively assigned the values in the vector from the third part. The middle part is simply the word in indicating that the variable (the first part) is in the vector (the third part).

```
> for (i in 1:10)
+ {
+   print(i)
+ }
[1] 1
[1] 2
[1] 3
[1] 4
[1] 5
[1] 6
[1] 7
[1] 8
[1] 9
[1] 10
```

Here we generated a vector holding the numbers 1 through 10, and then printed each. Notice that this could have been performed simply by using the built-in vectorization of the print function.

[Click here to view code image](#)

```
> print(1:10)
```

```
[1] 1 2 3 4 5 6 7 8 9 10
```

Sure, it does not look exactly the same, but that is just cosmetic.

The vector in for loops does not have to be sequential; it can be any vector.

[Click here to view code image](#)

```
> # build a vector holding fruit names
> fruit <- c("apple", "banana", "pomegranate")
> # make a variable to hold their lengths, with all NA to start
> fruitLength <- rep(NA, length(fruit))
> # show it, all NAs
> fruitLength
[1] NA NA NA
> # give it names
> names(fruitLength) <- fruit
> # show it again, still NAs
> fruitLength
    apple    banana pomegranate
        NA        NA        NA
> # loop through the fruit assigning their lengths to the result vector
> for (a in fruit)
+ {
+   fruitLength[a] <- nchar(a)
+ }
```

```
> # show the lengths  
> fruitLength  
apple    banana pomegranate  
      5        6       11
```

Again, R's built-in vectorization could have made all of this much easier.

[Click here to view code image](#)

```
> # simply call nchar  
> fruitLength2 <- nchar(fruit)  
> # give it names  
> names(fruitLength2) <- fruit  
> # show it  
> fruitLength2  
apple    banana pomegranate  
      5        6       11
```

This, as expected, provides identical results, as seen next.

[Click here to view code image](#)

```
> identical(fruitLength, fruitLength2)  
[1] TRUE
```

## 10.2. while Loops

Although used far less frequently in R than the for loop, the while loop is just as simple to implement. It simply runs the code inside the braces repeatedly as long as the tested condition proves true. In the following example, we print the value of x and iterate it until it reaches 5. This is a highly trivial example but shows the functionality nonetheless.

```
> x <- 1
> while (x <= 5)
+ {
+   print(x)
+   x <- x + 1
+ }
[1] 1
[1] 2
[1] 3
[1] 4
[1] 5
```

## 10.3. Controlling Loops

Sometimes we have to skip to the next iteration of the loop or completely break out of it. This is accomplished with next and break. We use a for loop to demonstrate.

```
> for (i in 1:10)
+ {
+   if (i == 3)
+   {
+     next
+   }
+   print(i)
+ }
[1] 1
[1] 2
[1] 4
[1] 5
[1] 6
[1] 7
[1] 8
[1] 9
[1] 10
```

Notice that the number 3 did not get printed.

```
> for (i in 1:10)
+ {
```

```
+ if (i == 4)
+ {
+   break
+ }
+ print(i)
+
[1] 1
[1] 2
[1] 3
```

Here, even though we told R to iterate over the first ten integers, it stopped after 3 because we broke the loop at 4.

## 10.4. Conclusion

The two primary loops are for, which iterates over a fixed sequence of elements, and while, which continues a loop as long as some condition holds true. As stated earlier, if a solution can be done without loops, via vectorization or matrix algebra, then avoid the loop. It is particularly important to avoid nested loops. Loops inside other loops are extremely slow in R.

# Chapter 11. Group Manipulation

A general rule of thumb for data analysis is that manipulating the data (or “data munging,” a term coined by Simple founder Josh Reich) consumes about 80% of the effort. This often requires repeated operations on different sections of the data, something Hadley Wickham coined “split-apply-combine.” That is, we split the data into discrete sections based on some metric, apply a transformation of some kind to each section, and then combine all the sections together. This is somewhat like the MapReduce<sup>1</sup> paradigm of Hadoop.<sup>2</sup> There are many different ways to iterate over data in R, and we will look at some of the more convenient functions.

1. MapReduce is where data are split into discrete sets, computed on, and then recombined in some fashion.
2. Hadoop is a framework for distributing data and computations across a grid of computers.

## 11.1. Apply Family

Built into R is the apply function and all of its relatives such as tapply, lapply and mapply. Each has its quirks and necessities and is best used in different situations.

### 11.1.1. apply

apply is the first member of this family that users usually learn, and it is also the most restrictive. It must be used on a matrix, meaning all of the elements must be of the same type whether they are character, numeric or logical. If used on some other object, such as a data.frame, it will be converted to a matrix first.

The first argument to apply is the object we are working with. The second argument is the margin to apply the function over, with 1 meaning to operate over the rows and 2 meaning to operate over the columns. The third argument is the function we want to apply. Any following arguments will be passed on to that function. apply will iterate over each row (or column) of the mat-

rix treating them as individual inputs to the first argument of the specified function.

To illustrate its use we start with a trivial example, summing the rows or columns of a matrix.

[Click here to view code image](#)

```
> # build the matrix  
> theMatrix <- matrix(1:9, nrow = 3)  
> # sum the rows  
> apply(theMatrix, 1, sum)  
[1] 12 15 18  
> # sum the columns  
> apply(theMatrix, 2, sum)  
[1] 6 15 24
```

Notice that this could alternatively be accomplished using the built-in rowSums and colSums functions, yielding the same results.

```
> rowSums(theMatrix)  
[1] 12 15 18  
> colSums(theMatrix)  
[1] 6 15 24
```

For a moment, let's set an element of theMatrix to NA to see how we handle missing data us-

ing the na.rm argument and the use of additional arguments.

[Click here to view code image](#)

```
> theMatrix[2, 1] <- NA
> apply(theMatrix, 1, sum)
[1] 12 NA 18
> apply(theMatrix, 1, sum, na.rm = TRUE)
[1] 12 13 18
> rowSums(theMatrix)
[1] 12 NA 18
> rowSums(theMatrix, na.rm = TRUE)
[1] 12 13 18
```

### 11.1.2. lapply and sapply

lapply works by applying a function to each element of a list and returning the results as a list.

[Click here to view code image](#)

```
> theList <- list(A = matrix(1:9, 3), B = 1:5, C = matrix(1:4, 2), D = 2)
> lapply(theList, sum)
$A
[1] 45
$B
[1] 15
$C
```

```
[1] 10  
$D  
[1] 2
```

Dealing with lists can be cumbersome, so to return the result of lapply as a vector instead, use sapply. It is exactly the same as lapply in every other way.

```
> sapply(theList, sum)  
A B C D  
45 15 10 2
```

Because a vector is technically a form of a list, lapply and sapply can also take a vector as their input.

[Click here to view code image](#)

```
> theNames <- c("Jared", "Deb", "Paul")  
> lapply(theNames, nchar)  
[[1]]  
[1] 5  
[[2]]  
[1] 3  
[[3]]  
[1] 4
```

### 11.1.3. mapply

Perhaps the most-overlooked-when-so-useful member of the apply family is mapply, which applies a function to each element of multiple lists. Often when confronted with this scenario, people will resort to using a loop, which is certainly not necessary.

[Click here to view code image](#)

```
> ## build two lists
> firstList <- list(A = matrix(1:16, 4), B = matrix(1:16, 2),
+ C = 1:5)
> secondList <- list(A = matrix(1:16, 4), B = matrix(1:16,
+ 8), C = 15:1)
> # test element-by-element if they are identical
> mapply(identical, firstList, secondList)
      A     B     C
TRUE FALSE FALSE
> ## build a simple function that adds the number of rows
(or length) of
> ## each corresponding element
> simpleFunc <- function(x, y)
+ {
+   NROW(x) + NROW(y)
+ }
> # apply the function to the two lists
> mapply(simpleFunc, firstList, secondList)
```

A	B	C
8	10	20

## 11.1.4. Other apply Functions

There are many other members of the apply family that either do not get used much or have been superseded by functions in the plyr package. (Some would argue that lapply and sapply have been superseded, but they do have their advantages over their corresponding plyr functions.)

These include

- tapply
- rapply
- eapply
- vapply
- by

## 11.2. aggregate

People experienced with SQL generally want to run an aggregation and group by as their first R task. The way to do this is to use the aptly named aggregate function. There are a number of different ways to call aggregate, so we will look at perhaps its most convenient method, using a formula.

We will see formulas used to great extent with linear models in [Chapter 16](#) and they play a useful role in R. formulas consist of a left side and a right side separated by a tilde ( $\sim$ ). The left side represents a variable that we want to make a calculation on and the right side represents one or more variables that we want to group the calculation by.<sup>3</sup>

3. As we show in [Chapter 16](#), the right side can be numeric, although for the aggregate function we will just use categorical variables.

To demonstrate aggregate we once again turn to the diamonds data in ggplot2.

[Click here to view code image](#)

```
> require(ggplot2)
> data(diamonds)
> head(diamonds)
```

	carat	cut	color	clarity	depth	table	price	x	y	z
1	0.23	Ideal	E	SI2	61.5	55	326	3.95	3.98	2.43
2	0.21	Premium	E	SI1	59.8	61	326	3.89	3.84	2.31
3	0.23	Good	E	VS1	56.9	65	327	4.05	4.07	2.31
4	0.29	Premium	I	VS2	62.4	58	334	4.20	4.23	2.63
5	0.31	Good	J	SI2	63.3	58	335	4.34	4.35	2.75
6	0.24	Very Good	J	VVS2	62.8	57	336	3.94	3.96	2.48

We calculate the average price for each type of cut: Fair, Good, Very Good, Premium and Ideal. The first argument to aggregate is the formula specifying that price should be broken up (or group by in SQL terms) by cut. The second argument is the data to use, in this case diamonds. The third argument is the function to apply to each subset of the data; for us this will be the mean.

[Click here to view code image](#)

```
> aggregate(price ~ cut, diamonds, mean)
```

	cut	price
1	Fair	4358.758
2	Good	3928.864
3	Very Good	3981.760
4	Premium	4584.258
5	Ideal	3457.542

For the first argument we specified that price should be aggregated by cut. Notice that we only specified the column name and did not have to identify the data because that is given in the second argument. After the third argument specifying the function, additional named arguments to that function can be passed, such as aggregate(price ~ cut, diamonds, mean, na.rm=TRUE).

To group the data by more than one variable, add the additional variable to the right side of the formula separating it with a plus sign (+).

[Click here to view code image](#)

```
> aggregate(price ~ cut + color, diamonds, mean)
   cut color  price
1  Fair    D 4291.061
2  Good    D 3405.382
3 Very Good D 3470.467
```

4	Premium	D	3631.293
5	Ideal	D	2629.095
6	Fair	E	3682.312
7	Good	E	3423.644
8	Very Good	E	3214.652
9	Premium	E	3538.914
10	Ideal	E	2597.550
11	Fair	F	3827.003
12	Good	F	3495.750
13	Very Good	F	3778.820
14	Premium	F	4324.890
15	Ideal	F	3374.939
16	Fair	G	4239.255
17	Good	G	4123.482
18	Very Good	G	3872.754
19	Premium	G	4500.742
20	Ideal	G	3720.706
21	Fair	H	5135.683
22	Good	H	4276.255
23	Very Good	H	4535.390
24	Premium	H	5216.707
25	Ideal	H	3889.335
26	Fair	I	4685.446
27	Good	I	5078.533
28	Very Good	I	5255.880
29	Premium	I	5946.181
30	Ideal	I	4451.970
31	Fair	J	4975.655
32	Good	J	4574.173
33	Very Good	J	5103.513

34 Premium J 6294.592  
35 Ideal J 4918.186

To aggregate two variables (for now we still just group by cut), they must be combined using cbind on the left side of the formula.

[Click here to view code image](#)

```
> aggregate(cbind(price, carat) ~ cut, diamonds, mean)
   cut price carat
1 Fair 4358.758 1.0461366
2 Good 3928.864 0.8491847
3 Very Good 3981.760 0.8063814
4 Premium 4584.258 0.8919549
5 Ideal 3457.542 0.7028370
```

This finds the mean of both price and carat for each value of cut. It is important to note that only one function can be supplied, and hence applied, to the variables. To apply more than one function it is easier to use the plyr package, which is explained in [Section 11.3](#).

Of course, multiple variables can be supplied to both the left and right sides at the same time.

[Click here to view code image](#)

```
> aggregate(cbind(price, carat) ~ cut + color, diamonds,
mean)
```

	cut	color	price	carat
1	Fair	D	4291.061	0.9201227
2	Good	D	3405.382	0.7445166
3	Very Good	D	3470.467	0.6964243
4	Premium	D	3631.293	0.7215471
5	Ideal	D	2629.095	0.5657657
6	Fair	E	3682.312	0.8566071
7	Good	E	3423.644	0.7451340
8	Very Good	E	3214.652	0.6763167
9	Premium	E	3538.914	0.7177450
10	Ideal	E	2597.550	0.5784012
11	Fair	F	3827.003	0.9047115
12	Good	F	3495.750	0.7759296
13	Very Good	F	3778.820	0.7409612
14	Premium	F	4324.890	0.8270356
15	Ideal	F	3374.939	0.6558285
16	Fair	G	4239.255	1.0238217
17	Good	G	4123.482	0.8508955
18	Very Good	G	3872.754	0.7667986
19	Premium	G	4500.742	0.8414877
20	Ideal	G	3720.706	0.7007146
21	Fair	H	5135.683	1.2191749
22	Good	H	4276.255	0.9147293
23	Very Good	H	4535.390	0.9159485
24	Premium	H	5216.707	1.0164492
25	Ideal	H	3889.335	0.7995249

26 Fair I 4685.446 1.1980571  
27 Good I 5078.533 1.0572222  
28 Very Good I 5255.880 1.0469518  
29 Premium I 5946.181 1.1449370  
30 Ideal I 4451.970 0.9130291  
31 Fair J 4975.655 1.3411765  
32 Good J 4574.173 1.0995440  
33 Very Good J 5103.513 1.1332153  
34 Premium J 6294.592 1.2930941  
35 Ideal J 4918.186 1.0635937

## 11.3. plyr

One of the best things to ever happen to R was the development of the `plyr`<sup>4</sup> package by Hadley Wickham. It epitomizes the “split-apply-combine” method of data manipulation. The core of `plyr` consists of functions such as `ddply`, `llply` and `ldply`. All of the manipulation functions consist of five letters, with the last three always being `ply`. The first letter indicates the type of input and the second letter indicates the type of output. For instance, `ddply` takes in a `data.frame` and outputs a `data.frame`, `llply` takes in a list and outputs a list and `ldply` takes in a list and outputs a `data.frame`. A full enumeration is listed in [Table 11.1](#).

<sup>4</sup> A play on the word *plier* because it is one of the most versatile and essential tools.

Function	Input Type	Output Type
ddply	data.frame	data.frame
llply	list	list
aaply	array/vector/matrix	array/vector/matrix
dlply	data.frame	list
daply	data.frame	array/vector/matrix
d_ply	data.frame	none (used for side effects)
ldply	list	data.frame
laply	list	array/vector/matrix
l_ply	list	none (used for side effects)
adply	array/vector/matrix	data.frame
alply	array/vector/matrix	list
a_ply	array/vector/matrix	none (used for side effects)

**Table 11.1** plyr Functions and their Corresponding Inputs and Outputs

### 11.3.1. ddply

`ddply` takes a `data.frame`, splits it according to some variable(s), performs a desired action on it and returns a `data.frame`. To learn about `ddply` we look at the baseball data that come with `plyr`.

**Click here to view code image**

```
> require(plyr)  
> head(baseball)
```

A common statistic in baseball is On Base Percentage (OBP), which is calculated as

$$OBP = \frac{H + BB + HBP}{AB + BB + HBP + SF} \quad (11.1)$$

where

H = Hits

BB = Bases on Balls (Walks)

HBP = Times Hit by Pitch

AB = At Bats

SF = Sacrifice Flies

Before 1954 sacrifice flies were counted as part of sacrifice hits, which includes bunts, so for players before 1954 sacrifice flies should be assumed to be 0. That will be the first change we make to the data. There are many instances of HBP (hit by pitch) that are NA, so we set those to 0 as well. We also exclude players with less than 50 at bats in a season.

[Click here to view code image](#)

```
> # subsetting with [ is faster than using ifelse
> baseball$sf[baseball$year < 1954] <- 0
> # check that it worked
> any(is.na(baseball$sf))
[1] FALSE
> # set NA hbp's to 0
> baseball$hbp[is.na(baseball$hbp)] <- 0
> # check that it worked
> any(is.na(baseball$hbp))
[1] FALSE
> # only keep players with at least 50 at bats in a season
> baseball <- baseball[baseball$ab >= 50, ]
```

Calculating the OBP for a given player in a given year is easy enough with just vector operations.

[Click here to view code image](#)

```
> # calculate OBP
> baseball$OBP <- with(baseball, (h + bb + hbp)/(ab + bb
+ hbp + sf))
> tail(baseball)
   id year stint team lg g ab r h X2b X3b hr rbi sb
89499 claytro01 2007 1 TOR AL 69 189
23 48 14 0 1 12 2
89502 cirilje01 2007 1 MIN AL 50 153
18 40 9 2 2 21 2
89521 bondsba01 2007 1 SFN NL 126 340 75 94 14 0
28 66 5
89523 biggicr01 2007 1 HOU NL 141 517 68
130 31 3 10 50 4
89530 ausmubr01 2007 1 HOU NL 117 349
38 82 16 3 3 25 6
89533 aloumo01 2007 1 NYN NL 87 328 51
112 19 1 13 49 3
   cs bb so ibb hbp sh sf gidp      OBP
89499 1 14 50 0 1 3 3 8 0.3043478
89502 0 15 13 0 1 3 2 9 0.3274854
89521 0 132 54 43 3 0 2 13 0.4800839
89523 3 23 112 0 3 7 5 5 0.2846715
89530 1 37 74 3 6 4 1 11 0.3180662
89533 0 27 30 5 2 0 3 13 0.3916667
```

Here we used a new function, with. This allows us to specify the columns of a data.frame without having to specify the data.frame name each time.

To calculate the OBP for a player's entire career we cannot just average his individual season OBPs; we need to calculate and sum the numerator, and then divide by the sum of the denominator. This requires the use of ddply.

First we make a function to do that calculation, then we use ddply to run that calculation for each player.

[Click here to view code image](#)

```
> # this function assumes that the column names for the  
data are as  
> # below  
> obp <- function(data)  
+ {  
+   c(OBP = with(data, sum(h + bb + hbp)/sum(ab + bb +  
hbp + sf)))  
+ }  
>  
> # use ddply to calculate career OBP for each player
```

```
> careerOBP <- ddply(baseball, .variables = "id", .fun =  
  obp)  
> # sort the results by OBP  
> careerOBP <- careerOBP[order(careerOBP$OBP, de-  
  creasing = TRUE), ]  
> # see the results  
> head(careerOBP, 10)  
    id      OBP  
1089 willite01 0.4816861  
875  ruthba01 0.4742209  
658 mcgrajo01 0.4657478  
356 gehrilo01 0.4477848  
85  bondsba01 0.4444622  
476 hornsro01 0.4339068  
184 cobbty01 0.4329655  
327 foxxji01 0.4290509  
953 speaktr01 0.4283386  
191 collied01 0.4251246
```

This nicely returns the top ten players by career on base percentage. Notice that Billy Hamilton and Bill Joyce are absent from our results because they are mysteriously missing from the baseball data.

### 11.3.2. llply

In [Section 11.1.2](#) we use lapply to sum each element of a list.

[Click here to view code image](#)

```
> theList <- list(A = matrix(1:9, 3), B = 1:5, C = matrix(1:4, 2), D = 2)
> lapply(theList, sum)
$A
[1] 45
$B
[1] 15
$C
[1] 10
$D
[1] 2
```

This can be done with llply, yielding identical results.

[Click here to view code image](#)

```
> llply(theList, sum)
$A
[1] 45
$B
[1] 15
$C
```

```
[1] 10  
$D  
[1] 2  
> identical(lapply(theList, sum), llply(theList, sum))  
[1] TRUE
```

To get the result as a vector, laply can be used similarly to sapply.

```
> sapply(theList, sum)  
A B C D  
45 15 10 2  
> laply(theList, sum)  
[1] 45 15 10 2
```

Notice, however, that while the results are the same, laply did not include names for the vector. These little nuances can be maddening but help dictate when to use which function.

### 11.3.3. plyr Helper Functions

plyr has a great deal of useful helper functions such as each, which lets us supply multiple functions to a function like aggregate.

[Click here to view code image](#)

```
> aggregate(price ~ cut, diamonds, each(mean, median))
   cut price.mean price.median
1  Fair  4358.758  3282.000
2  Good  3928.864  3050.500
3 Very Good  3981.760  2648.000
4 Premium  4584.258  3185.000
5 Ideal   3457.542  1810.000
```

Another great function is `idata.frame`, which creates a reference to a `data.frame` so that subsetting is much faster and more memory efficient. To illustrate this, we do a simple operation on the baseball data with the regular `data.frame` and an `idata.frame`.

[Click here to view code image](#)

```
> system.time(dplyr::dlply(baseball, "id", nrow))
  user  system elapsed
  0.29    0.00   0.33
> iBaseball <- idata.frame(baseball)
> system.time(dplyr::dlply(iBaseball, "id", nrow))
  user  system elapsed
  0.42    0.00   0.47
```

While saving less than a second in run time might seem trivial the savings can really add up with more complex operations, bigger data, more groups to split by and repeated operation.

#### 11.3.4. Speed versus Convenience

A criticism often leveled at plyr is that it can run slowly. The typical response to this is that using plyr is a question of speed versus convenience. Most of the functionality in plyr can be accomplished using base functions or other packages, but few of those offer the ease of use of plyr. That said, in recent years Hadley Wickham has taken great steps to speed up plyr, including optimized R code, C++ code and parallelization.

## 11.4. data.table

For speed junkies there is a package called `data.table` that extends and enhances the functionality of `data.frames`. The syntax is a little different from regular `data.frames`, so it will take getting used to, which is probably the primary reason it has not seen near-universal adoption.

The secret to the speed is that `data.tables` have an index like databases. This allows faster value accessing, group by operations and joins.

Creating `data.tables` is just like creating `data.frames`, and the two are very similar.

[Click here to view code image](#)

```
> require(data.table)
> # create a regular data.frame
> theDF <- data.frame(A=1:10,
+                      B=letters[1:10],
+                      C=LETTERS[11:20],
+                      D=rep(c("One", "Two", "Three"),
length.out=10))
> # create a data.table
> theDT <- data.table(A=1:10,
+                      B=letters[1:10],
```

```
+           C=LETTERS[11:20],  
+           D=rep(c("One", "Two", "Three"),  
length.out=10))  
> # print them and compare  
> theDF  
  A B C   D  
1 1 a K One  
2 2 b L Two  
3 3 c M Three  
4 4 d N One  
5 5 e O Two  
6 6 f P Three  
7 7 g Q One  
8 8 h R Two  
9 9 i S Three  
10 10 j T One  
> theDT  
  A B C   D  
1: 1 a K One  
2: 2 b L Two  
3: 3 c M Three  
4: 4 d N One  
5: 5 e O Two  
6: 6 f P Three  
7: 7 g Q One  
8: 8 h R Two  
9: 9 i S Three  
10: 10 j T One  
> # notice by default data.frame turns character data into  
  factors
```

```
> # while data.table does not  
> class(theDF$B)  
[1] "factor"  
> class(theDT$B)  
[1] "character"
```

The data are identical—except that data.frame turned B into a factor while data.table did not—and only the way it was printed looks different.

It is also possible to create a data.table out of an existing data.frame.

[Click here to view code image](#)

```
> diamondsDT <- data.table(diamonds)  
> diamondsDT  
   carat      cut color clarity depth table price     x     y     z  
1: 0.23    Ideal     E     SI2  61.5   55  326 3.95 3.98 2.43  
2: 0.21 Premi-  
um     E     SI1  59.8   61  326 3.89 3.84 2.31  
3: 0.23    Good     E     VS1  56.9   65  327 4.05 4.07 2.31  
4: 0.29 Premi-  
um     I     VS2  62.4   58  334 4.20 4.23 2.63  
5: 0.31    Good     J     SI2  63.3   58  335 4.34 4.35 2.75  
---  
53936: 0.72    Ideal     D     SI1  60.8   57  2757 5.75 5.76 3.50  
53937: 0.72    Good     D     SI1  63.1   55  2757 5.69 5.75 3.60  
53938: 0.70 Very Good     D     SI1  62.8   60  2757 5.66 5.68 3.50
```

53939:	0.86	Premi-								
um	H	SI2	61.0	58	2757	6.15	6.12	3.74		
53940:	0.75	Ideal	D	SI2	62.2	55	2757	5.83	5.87	3.64

Notice that printing the diamonds data would try to print out all the data but data.table intelligently just prints the first five and last five rows.

Accessing rows can be done similarly to accessing rows in a data.frame.

```
> theDT[1:2, ]
  A B C  D
1: 1 a K One
2: 2 b L Two
> theDT[theDT$A >= 7, ]
  A B C  D
1: 7 g Q  One
2: 8 h R  Two
3: 9 i S Three
4: 10 j T One
```

While the second line in the preceding code is valid syntax, it is not necessarily efficient syntax. That line creates a vector of length nrow(theDT)=10 consisting of TRUE or FALSE entries, which is a vector scan. After we create a key for the data.table we can use different syntax

to pick rows through a binary search, which will be much faster and is covered in [Section 11.4.1](#).

Accessing individual columns must be done a little differently than accessing columns in `data.frames`. In [Section 5.1](#) we show that multiple columns in a `data.frame` should be specified as a character vector. With `data.tables` the columns should be specified as a list of the actual names, not as characters.

[Click here to view code image](#)

```
> theDT[, list(A, C)]  
    A C  
 1: 1 K  
 2: 2 L  
 3: 3 M  
 4: 4 N  
 5: 5 O  
 6: 6 P  
 7: 7 Q  
 8: 8 R  
 9: 9 S  
10: 10 T  
> # just one column  
> theDT[, B]  
[1] "a" "b" "c" "d" "e" "f" "g" "h" "i" "j"
```

```
> # one column while maintaining data.table structure  
> theDT[, list(B)]  
B  
1: a  
2: b  
3: c  
4: d  
5: e  
6: f  
7: g  
8: h  
9: i  
10: j
```

If we must specify the column names as characters (perhaps because they were passed as arguments to a function), the with argument should be set to FALSE.

[Click here to view code image](#)

```
> theDT[, "B", with = FALSE]  
B  
1: a  
2: b  
3: c  
4: d  
5: e  
6: f  
7: g
```

```
8: h  
9: i  
10: j  
> theDT[, c("A", "C"), with = FALSE]  
   A C  
1: 1 K  
2: 2 L  
3: 3 M  
4: 4 N  
5: 5 O  
6: 6 P  
7: 7 Q  
8: 8 R  
9: 9 S  
10: 10 T
```

This time we used a vector to hold the column names instead of a list. These nuances are important to proper functions of data.tables but can lead to a great deal of frustration.

### 11.4.1. Keys

Now that we have a few data.tables in memory, we might be interested in seeing some information about them.

## [Click here to view code image](#)

```
> # show tables
> tables()
      NAME      NROW MB
[1,] diamondsDT 53,940 4
[2,] theDT       10 1
      COLS                  KEY
[1,] carat,cut,color,clarity,depth,table,price,x,y,z
[2,] A,B,C,D
Total: 5MB
```

This shows, for each data.table in memory, the name, the number of rows, the size in megabytes, the column names and the key. We have not assigned keys for any of the tables so that column is blank. The key is used to index the data.table and will provide the extra speed.

We start by adding a key to theDT. We will use the D column to index the data.table. This is done using setkey, which takes the name of the data.table as its first argument and the name of the desired column (without quotes, as is consistent with column selection) as the second argument.

[Click here to view code image](#)

```
> # set the key  
> setkey(theDT, D)  
> # show the data.table again  
> theDT  
    A B C    D  
1: 1 a K  One  
2: 4 d N  One  
3: 7 g Q  One  
4: 10 j T One  
5: 3 c M Three  
6: 6 f P Three  
7: 9 i S Three  
8: 2 b L Two  
9: 5 e O Two  
10: 8 h R Two
```

The data have been reordered according to column D, which is sorted alphabetically.  
We can confirm the key was set with key.

```
> key(theDT)  
[1] "D"
```

Or tables.

[Click here to view code image](#)

```
> tables()
  NAME      NROW MB
[1,] diamondsDT 53,940 4
[2,] theDT      10 1
      COLS                      KEY
[1,] carat,cut,color,clarity,depth,table,price,x,y,z
[2,] A,B,C,D                  D
Total: 5MB
```

This adds some new functionality to selecting rows from data.tables. In addition to selecting rows by the row number or by some expression that evaluates to TRUE or FALSE, a value of the key column can be specified.

```
> theDT["One", ]
  D A B C
1: One 1 a K
2: One 4 d N
3: One 7 g Q
4: One 10 j T
> theDT[c("One", "Two"), ]
  D A B C
1: One 1 a K
2: One 4 d N
3: One 7 g Q
4: One 10 j T
```

- 5: Two 2 b L
- 6: Two 5 e O
- 7: Two 8 h R

More than one column can be set as the key.

[Click here to view code image](#)

```
> # set the key  
> setkey(diamondsDT, cut, color)
```

To access rows according to both keys, there is a special function named J. It takes multiple arguments, each of which is a vector of values to select.

[Click here to view code image](#)

```
> # access some rows  
> diamondsDT[J("Ideal", "E"), ]  
  cut color carat clarity depth table price x y z  
1: Ideal E 0.23 SI2 61.5 55 326 3.95 3.98 2.43  
2: Ideal E 0.26 VVS2 62.9 58 554 4.02 4.06 2.54  
3: Ideal E 0.70 SI1 62.5 57 2757 5.70 5.72 3.57  
4: Ideal E 0.59 VVS2 62.0 55 2761 5.38 5.43  
3.35  
5: Ideal E 0.74 SI2 62.2 56 2761 5.80 5.84 3.62  
---  
3899: Ideal E 0.70 SI1 61.7 55 2745 5.71 5.74 3.53
```

```

3900: Ideal    E 0.51   VVS1 61.9   54 2745 5.17 5.11
3.18
3901: Ideal    E 0.56   VVS1 62.1   56 2750 5.28 5.29
3.28
3902: Ideal    E 0.77   SI2 62.1   56 2753 5.84 5.86 3.63
3903: Ideal    E 0.71   SI1 61.9   56 2756 5.71 5.73 3.54
> diamondsDT[J("Ideal", c("E", "D")), ]
      cut color carat clarity depth table price x y z
1: Ideal    E 0.23   SI2 61.5   55 326 3.95 3.98 2.43
2: Ideal    E 0.26   VVS2 62.9   58 554 4.02 4.06 2.54
3: Ideal    E 0.70   SI1 62.5   57 2757 5.70 5.72 3.57
4: Ideal    E 0.59   VVS2 62.0   55 2761 5.38 5.43
3.35
5: Ideal    E 0.74   SI2 62.2   56 2761 5.80 5.84 3.62
---
6733: Ideal    D 0.51   VVS2 61.7   56 2742 5.16 5.14
3.18
6734: Ideal    D 0.51   VVS2 61.3   57 2742 5.17 5.14
3.16
6735: Ideal    D 0.81   SI1 61.5   57 2748 6.00 6.03
3.70
6736: Ideal    D 0.72   SI1 60.8   57 2757 5.75 5.76
3.50
6737: Ideal    D 0.75   SI2 62.2   55 2757 5.83 5.87
3.64

```

## 11.4.2. `data.table` Aggregation

The primary benefit of indexing is faster aggregation. While aggregate and the various d\*ply functions will work because `data.tables` are just enhanced `data.frames`, they will be slower than using the built-in aggregation functionality of `data.table`.

In [Section 11.2](#) we calculate the mean price of diamonds for each type of cut.

[Click here to view code image](#)

```
> aggregate(price ~ cut, diamonds, mean)
   cut  price
1 Fair 4358.758
2 Good 3928.864
3 Very Good 3981.760
4 Premium 4584.258
5 Ideal 3457.542
```

To get the same result using `data.table`, we do this:

[Click here to view code image](#)

```
> diamondsDT[, mean(price), by = cut]
```

```
cut      V1
1: Fair 4358.758
2: Good 3928.864
3: Very Good 3981.760
4: Premium 4584.258
5: Ideal 3457.542
```

The only difference between this and the previous result is that the columns have different names. To specify the name of the resulting column, pass the aggregation function as a named list.

[Click here to view code image](#)

```
> diamondsDT[, list(price = mean(price)), by = cut]
      cut      price
1: Fair 4358.758
2: Good 3928.864
3: Very Good 3981.760
4: Premium 4584.258
5: Ideal 3457.542
```

To aggregate on multiple columns, specify them as a list().

[Click here to view code image](#)

```
> diamondsDT[, mean(price), by = list(cut, color)]
```

	cut	color	V1
1:	Fair	D	4291.061
2:	Fair	E	3682.312
3:	Fair	F	3827.003
4:	Fair	G	4239.255
5:	Fair	H	5135.683
6:	Fair	I	4685.446
7:	Fair	J	4975.655
8:	Good	D	3405.382
9:	Good	E	3423.644
10:	Good	F	3495.750
11:	Good	G	4123.482
12:	Good	H	4276.255
13:	Good	I	5078.533
14:	Good	J	4574.173
15:	Very Good	D	3470.467
16:	Very Good	E	3214.652
17:	Very Good	F	3778.820
18:	Very Good	G	3872.754
19:	Very Good	H	4535.390
20:	Very Good	I	5255.880
21:	Very Good	J	5103.513
22:	Premium	D	3631.293
23:	Premium	E	3538.914
24:	Premium	F	4324.890
25:	Premium	G	4500.742
26:	Premium	H	5216.707
27:	Premium	I	5946.181
28:	Premium	J	6294.592
29:	Ideal	D	2629.095

```
30: Ideal E 2597.550
31: Ideal F 3374.939
32: Ideal G 3720.706
33: Ideal H 3889.335
34: Ideal I 4451.970
35: Ideal J 4918.186
cut color V1
```

To aggregate multiple arguments, pass them as a list. Unlike with aggregate, a different metric can be measured for each column.

[Click here to view code image](#)

```
> diamondsDT[, list(price = mean(price), carat =
mean(carat)), by = cut]
    cut price carat
1: Ideal 3457.542 0.7028370
2: Premium 4584.258 0.8919549
3: Good 3928.864 0.8491847
4: Very Good 3981.760 0.8063814
5: Fair 4358.758 1.0461366
> diamondsDT[, list(price = mean(price), carat =
mean(carat),
+   caratSum = sum(carat)), by = cut]
    cut price carat caratSum
1: Ideal 3457.542 0.7028370 15146.84
2: Premium 4584.258 0.8919549 12300.95
3: Good 3928.864 0.8491847 4166.10
4: Very Good 3981.760 0.8063814 9742.70
```

5: Fair 4358.758 1.0461366 1684.28

Finally, both multiple metrics can be calculated and multiple grouping variables can be specified at the same time.

[Click here to view code image](#)

```
> diamondsDT[, list(price = mean(price), carat =  
mean(carat)),  
+   by = list(cut, color)]  
    cut color  price  carat  
1: Ideal   E 2597.550 0.5784012  
2: Premium E 3538.914 0.7177450  
3: Good    E 3423.644 0.7451340  
4: Premium I 5946.181 1.1449370  
5: Good    J 4574.173 1.0995440  
6: Very Good J 5103.513 1.1332153  
7: Very Good I 5255.880 1.0469518  
8: Very Good H 4535.390 0.9159485  
9: Fair     E 3682.312 0.8566071  
10: Ideal   J 4918.186 1.0635937  
11: Premium F 4324.890 0.8270356  
12: Ideal   I 4451.970 0.9130291  
13: Good    I 5078.533 1.0572222  
14: Very Good E 3214.652 0.6763167  
15: Very Good G 3872.754 0.7667986  
16: Very Good D 3470.467 0.6964243  
17: Very Good F 3778.820 0.7409612  
18: Good    F 3495.750 0.7759296
```

19: Good H 4276.255 0.9147293  
20: Good D 3405.382 0.7445166  
21: Ideal G 3720.706 0.7007146  
22: Premium D 3631.293 0.7215471  
23: Premium J 6294.592 1.2930941  
24: Ideal D 2629.095 0.5657657  
25: Premium G 4500.742 0.8414877  
26: Premium H 5216.707 1.0164492  
27: Fair F 3827.003 0.9047115  
28: Ideal F 3374.939 0.6558285  
29: Ideal H 3889.335 0.7995249  
30: Fair H 5135.683 1.2191749  
31: Good G 4123.482 0.8508955  
32: Fair G 4239.255 1.0238217  
33: Fair J 4975.655 1.3411765  
34: Fair I 4685.446 1.1980571  
35: Fair D 4291.061 0.9201227

cut color price carat

## 11.5. Conclusion

Aggregating data is a very important step in the analysis process. Sometimes it is the end goal, and other times it is in preparation for applying more advanced methods. No matter the reason for aggregation, there are plenty of functions to make it possible. These include aggregate, apply and lapply in base; ddply, llply and the rest in plyr; and the group by functionality in data.table.

# Chapter 12. Data Reshaping

As noted in [Chapter 11](#), manipulating the data takes a great deal of effort before serious analysis can begin. In this chapter we will consider when the data needs to be rearranged from column oriented to row oriented (or the opposite) and when the data are in multiple, separate sets and need to be combined into one.

There are base functions to accomplish these tasks but we will focus on those in plyr, reshape2 and data.table.

## 12.1. cbind and rbind

The simplest case is when we have two datasets with either identical columns (both the number of and names) or the same number of rows. In this case, either rbind or cbind work great.

As a first trivial example, we create two simple data.frames by combining a few vectors with cbind, and then stack them using rbind.

[Click here to view code image](#)

```
> # make two vectors and combine them as columns in a  
data.frame  
> sport <- c("Hockey", "Baseball", "Football")  
> league <- c("NHL", "MLB", "NFL")  
> trophy <- c("Stanley Cup", "Commissioner's Trophy",  
+           "Vince Lombardi Trophy")  
> trophies1 <- cbind(sport, league, trophy)  
> # make another data.frame using data.frame()  
> trophies2 <- data.frame(sport=c("Basketball", "Golf"),  
+                         league=c("NBA", "PGA"),  
+                         trophy=c("Larry O'Brien Championship  
Trophy",  
+                               "Wanamaker Trophy"),  
+                         stringsAsFactors=FALSE)  
> # combine them into one data.frame with rbind  
> trophies <- rbind(trophies1, trophies2)
```

Both cbind and rbind can take multiple arguments to combine an arbitrary number of objects. Note that it is possible to assign new column names to vectors in cbind.

## [Click here to view code image](#)

> **cbind**(Sport = sport, Association = league, Prize = trophy)

Sport	Association	Prize
[1,] "Hockey"	"NHL"	"Stanley Cup"
[2,] "Baseball"	"MLB"	"Commissioner's Trophy"
[3,] "Football"	"NFL"	"Vince Lombardi Trophy"

## 12.2. Joins

Data do not always come so nicely aligned for combining using cbind, so they need to be joined together using a common key. This concept should be familiar to SQL users. Joins in R are not as flexible as SQL joins, but are still an essential operation in the data analysis process.

The three most commonly used functions for joins are merge in base R, join in plyr and the merging functionality in data.table. Each has pros and cons with some pros outweighing their respective cons.

To illustrate these functions I have prepared data originally made available as part of the USAID Open Government initiative.<sup>1</sup> The data

have been chopped into eight separate files so that they can be joined together. They are all available in a zip file at [http://jaredlander.com/data/US\\_Foreign\\_Aid.zip](http://jaredlander.com/data/US_Foreign_Aid.zip). These should be downloaded and unzipped to a folder on our computer. This can be done a number of ways (including using a mouse!) but we show how to download and unzip using R.

1. More information about the data is available at <http://gbk.eads.usaidallnet.gov/>.

[Click here to view code image](#)

```
> download.file(url="http://jaredlander.com/data/  
US_Foreign_Aid.zip",  
+                 destfile="data/ForeignAid.zip")  
> unzip("data/ForeignAid.zip", exdir="data")
```

To load all of these files programmatically, we use a for loop as seen in [Section 10.1](#). We get a list of the files using dir, and then loop through that list assigning each dataset to a name specified using assign.

[Click here to view code image](#)

```
> require(stringr)
```

```
> # first get a list of the files  
> theFiles <- dir("data/", pattern=".\\*.csv")  
> ## loop through those files  
> for(a in theFiles)  
+ {  
+   # build a good name to assign to the data  
+   nameToUse <- str_sub(string=a, start=12, end=18)  
+   # read in the csv using read.table  
+   # file.path is a convenient way to specify a folder and  
file name  
+   temp <- read.table(file=file.path("data", a),  
+                      header=TRUE, sep=",", stringsAsFactor-  
s=FALSE)  
+   # assign them into the workspace  
+   assign(x=nameToUse, value=temp)  
+ }
```

## 12.2.1. merge

R comes with a built-in function, called `merge`, to merge two `data.frames`.

[Click here to view code image](#)

```
> Aid90s00s <- merge(x=Aid_90s, y=Aid_00s,  
+                     by.x=c("Country.Name", "Program.Name"),  
+                     by.y=c("Country.Name", "Program.Name"))  
> head(Aid90s00s)  
  Country.Name          Program.Name  
1 Afghanistan          Child Survival and Health
```

2	Afghanistan ity Assistance	Department of Defense Secur-					
3	Afghanistan	Development Assistance					
4	Afghanistan Economic Support Fund/Security Sup- port Assistance						
5	Afghanistan	Food For Education					
6	Afghanistan al	Global Health and Child Surviv-					
	FY1990	FY1991	FY1992	FY1993	FY1994	FY1995	FY19
1	NA	NA	NA	NA	NA	NA	N
2	NA	NA	NA	NA	NA	NA	N
3	NA	NA	NA	NA	NA	NA	N
4	NA	NA	NA	14178135	2769948	NA	NA
5	NA	NA	NA	NA	NA	NA	N
6	NA	NA	NA	NA	NA	NA	N
	FY1999	FY2000	FY2001	FY2002	FY2003	FY200	
1	NA	NA	NA	2586555	56501189	40215304	3
2	NA	NA	NA	2964313	NA	45635526	151
3	NA	NA	4110478	8762080	54538965	180539337	
4	NA	NA	61144	31827014	341306822	102552203	
5	NA	NA	NA	NA	3957312	2610006	325
6	NA	NA	NA	NA	NA	NA	NA
	FY2006	FY2007	FY2008	FY2009			
1	40856382	72527069	28397435	NA			
2	230501318	214505892	495539084	552524990			
3	212648440	173134034	150529862	3675202			
4	1357750249	1266653993	1400237791	1418688520			
5	386891	NA	NA	NA			
6	NA	NA	63064912	1764252			

The by.x specifies the key column(s) in the left data.frame and by.y does the same for the right data.frame. The ability to specify different column names for each data.frame is the most useful feature of merge. The biggest drawback, however, is that merge can be much slower than the alternatives.

## 12.2.2. plyr join

Returning to Hadley Wickham's plyr package, we see it includes a join function, which works similarly to merge but is much faster. The biggest drawback, though, is that the key column(s) in each table must have the same name. We use the same data used previously to illustrate.

[Click here to view code image](#)

```
> require(plyr)
> Aid90s00sJoin <- join(x = Aid_90s, y = Aid_00s, by =
  c("Country.Name",
  + "Program.Name"))
> head(Aid90s00sJoin)
  Country.Name          Program.Name
  1 Afghanistan        Child Survival and Health
```

2	Afghanistan Assistance	Department of Defense Security						
3	Afghanistan	Development Assistance						
4	Afghanistan Economic Support Fund/Security Support Assistance							
5	Afghanistan	Food For Education						
6	Afghanistan	Global Health and Child Survival						
	FY1990	FY1991	FY1992	FY1993	FY1994	FY1995		
	FY1996	FY1997	FY1998					
1	NA	NA	NA	NA	NA	NA	NA	NA
2	NA	NA	NA	NA	NA	NA	NA	NA
3	NA	NA	NA	NA	NA	NA	NA	NA
4	NA	NA	NA	14178135				
	2769948	NA	NA	NA	NA			
5	NA	NA	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA	NA	NA
	FY1999							
	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005		
1	NA	NA	NA	2586555	56501189	40215304	39817	
2	NA	NA	NA	2964313	NA	45635526	15133490	
3	NA	NA						
4110478	8762080	54538965	180539337	193598227				
4	NA	NA	61144	31827014	341306822	1025522037		
1157530168								
5	NA	NA	NA	NA	3957312	2610006	3254408	
6	NA	NA	NA	NA	NA	NA	NA	
	FY2006	FY2007	FY2008	FY2009				
1	40856382	72527069	28397435	NA				
2	230501318	214505892	495539084	552524990				
3	212648440	173134034	150529862	3675202				

```
4 1357750249 1266653993 1400237791 1418688520
5 386891      NA      NA      NA
6      NA      NA  63064912  1764252
```

join has an argument for specifying a left, right, inner or full (outer) join.

We have eight data.frames containing foreign assistance data that we would like to combine into one data.frame without hand coding each join. The best way to do this is to put all the data.frames into a list, and then successively join them together using Reduce.

[Click here to view code image](#)

```
> # first figure out the names of the data.frames
> frameNames <- str_sub(string = theFiles, start = 12, end
= 18)
> # build an empty list
> frameList <- vector("list", length(frameNames))
> names(frameList) <- frameNames
> # add each data.frame into the list
> for (a in frameNames)
+ {
+   frameList[[a]] <- eval(parse(text = a))
+ }
```

A lot happened in that section of code, so let's go over it carefully. First we reconstructed the names of the data.frames using str sub from Hadley Wickham's stringr package, which is shown in more detail in [Chapter 13](#). Then we built an empty list with as many elements as there are data.frames, in this case eight, using vector and assigning its mode to "list." We then set appropriate names to the list.

Now that the list is built and named, we loop through it, assigning to each element the appropriate data.frame. The problem is that we have the names of the data.frames as characters but the <- operator requires a variable, not a character. So we parse and evaluate the character, which realizes the actual variable. Inspecting, we see that the list does indeed contain the appropriate data.frames.

[Click here to view code image](#)

```
> head(frameList[[1]])
```

Country.Name	Program.Name
--------------	--------------

1 Afghanistan	Child Survival and Health
---------------	---------------------------

2	Afghanistan ity Assistance	Department of Defense Secur-					
3	Afghanistan	Development Assistance					
4	Afghanistan Economic Support Fund/Security Sup- port Assistance	Economic Support Fund/Security Sup- port Assistance					
5	Afghanistan	Food For Education					
6	Afghanistan	Global Health and Child Survival					
FY2000	FY2001	FY2002	FY2003	FY2004	FY2005		
1	NA	NA	2586555	56501189	40215304	39817970	4
2	NA	NA	2964313	NA	45635526	45635526	230
3	NA	4110478	8762080	54538965	180539337	193598227	
4	NA	61144	31827014	341306822	1025522037	115753016	
5	NA	NA	NA	3957312	2610006	3254408	386
6	NA	NA	NA	NA	NA	NA	
		FY2007	FY2008	FY2009			
1	72527069	28397435	NA				
2	214505892	495539084	552524990				
3	173134034	150529862	3675202				
4	1266653993	1400237791	1418688520				
5	NA	NA	NA				
6	NA	63064912	1764252				
> <b>head(frameList[["Aid_00s"]])</b>							
Country.Name				Program.Name			
1	Afghanistan			Child Survival and Health			
2	Afghanistan ity Assistance			Department of Defense Secur-			
3	Afghanistan			Development Assistance			
4	Afghanistan Economic Support Fund/Security Sup- port Assistance			Economic Support Fund/Security Sup- port Assistance			
5	Afghanistan			Food For Education			

6 Afghanistan		Global Health and Child Survival						
FY2000	FY2001	FY2002	FY2003	FY2004	FY2005			
1	NA	NA	2586555	56501189	40215304	39817970	4	
2	NA	NA	2964313	NA	45635526	151334908	230	
3	NA	4110478	8762080	54538965	180539337	193598227		
4	NA	61144	31827014	341306822	1025522037	115753016		
5	NA	NA	NA	3957312	2610006	3254408	386	
6	NA	NA	NA	NA	NA	NA	NA	
	FY2007	FY2008	FY2009					
1	72527069	28397435	NA					
2	214505892	495539084	552524990					
3	173134034	150529862	3675202					
4	1266653993	1400237791	1418688520					
5	NA	NA	NA					
6	NA	63064912	1764252					

> **head(frameList[[5]])**

	Country.Name	Program.Name						
1	Afghanistan	Child Survival and Health						
2	Afghanistan	Department of Defense Security Assistance						
3	Afghanistan	Development Assistance						
4	Afghanistan	Economic Support Fund/Security Support Assistance						
5	Afghanistan	Food For Education						
6	Afghanistan	Global Health and Child Survival						
	FY1960	FY1961	FY1962	FY1963	FY1964	FY1965	FY1966	
1	NA	NA	NA	NA	NA	NA	NA	
2	NA	NA	NA	NA	NA	NA	NA	
3	NA	NA	NA	NA	NA	NA	NA	
4	NA	NA	181177853	NA	NA	NA	NA	

5	NA									
6	NA									

FY1969

1	NA
2	NA
3	NA
4	NA
5	NA
6	NA

> **head**(frameList[["Aid\_60s"]])

	Country.Name	Program.Name
1	Afghanistan	Child Survival and Health
2	Afghanistan ity Assistance	Department of Defense Secur-
3	Afghanistan	Development Assistance
4	Afghanistan Economic Support Fund/Security Sup- port Assistance	
5	Afghanistan	Food For Education
6	Afghanistan	Global Health and Child Survival

FY1960 FY1961 FY1962 FY1963 FY1964 FY1965 FY1966

1	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	NA	NA	181177853	NA	NA	NA	NA	NA	NA
5	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA	NA	NA	NA

FY1969

1	NA
2	NA
3	NA

4 NA  
5 NA  
6 NA

Having all the data.frames in a list allows us to iterate through the list, joining all the elements together (or applying any function to the elements iteratively). Rather than using a loop, we use the Reduce function to speed up the operation.

[Click here to view code image](#)

```
> allAid <- Reduce(function(...)  
+ {  
+   join(..., by = c("Country.Name", "Program.Name"))  
+ }, frameList)  
> dim(allAid)  
[1] 2453 67  
> require(useful)  
> corner(allAid, c = 15)
```

Country.Name	Program.Name
1 Afghanistan	Child Survival and Health
2 Afghanistan Assistance	Department of Defense Security
3 Afghanistan	Development Assistance
4 Afghanistan Economic Support Fund/Security Support Assistance	
5 Afghanistan	Food For Education
FY2000 FY2001 FY2002	FY2003 FY2004 FY2005

1	NA	NA	2586555	56501189	40215304	39817970	4
2	NA	NA	2964313	NA	45635526	151334908	230
3	NA						
4110478	8762080	54538965	180539337	193598227	212648		
4	NA	61144	31827014	341306822	1025522037		
1157530168	1357750249						
5	NA	NA	NA	3957312	2610006	3254408	386
	FY2007	FY2008	FY2009	FY2010	FY1946		
FY1947							
1	72527069	28397435	NA	NA	NA	NA	
2	214505892	495539084	552524990	316514796	NA	NA	N
3	173134034	150529862	3675202	NA	NA	NA	
4	1266653993	1400237791	1418688520				
279748831	NA	NA					
5	NA	NA	NA	NA	NA	NA	
> <b>bottomleft</b> (allAid, c = 15)							
Country.Name	Pro-						
gram.Name	FY2000	FY2001	FY2002				
2449	Zimbabwe	Other State Assist-					
ance	1341952	322842	NA				
2450	Zimbabwe	Other USAID Assistance	3033599				
8464897	6624408						
2451	Zimbabwe	Peace Corps	2140530				
1150732	407834						
2452	Zimbabwe	Title I	NA	NA	NA		
2453	Zimbabwe	Title II	NA	NA			
31019776							
	FY2003	FY2004	FY2005	FY2006	FY2007	FY200	
2449	NA	318655	44553	883546	1164632	2455592	

```
2450 11580999 12805688 10091759
4567577 10627613 11466426 41940500
2451 NA NA NA NA NA NA NA NA
2452 NA NA NA NA NA NA NA NA
2453 NA NA NA 277468 100053600
180000717 174572685
    FY2010 FY1946 FY1947
2449 1605765 NA NA
2450 30011970 NA NA
2451 NA NA NA
2452 NA NA NA
2453 79545100 NA NA
```

Reduce can be a difficult function to grasp, so we illustrate it with a simple example. Let's say we have a vector of the first ten integers, `1:10`, and want to sum them (forget for a moment that `sum(1:10)` will work perfectly). We can call `Reduce(sum, 1:10)`, which will first add 1 and 2. It will then add 3 to that result, then 4 to that result, and so on, resulting in 55.

Likewise, we passed a list to a function that joins its inputs, which in this case was simply . . . , meaning that anything could be passed. Using . . . is an advanced trick of R programming that can be difficult to get right. Reduce passed the

first two data.frames in the list, which were then joined. That result was then joined to the next data.frame and so on until they were all joined together.

### 12.2.3. data.table merge

Like many other operations in data.table, joining data requires a different syntax, and possibly a different way of thinking. To start, we convert two of our foreign aid datasets' data.frames into data.tables.

[Click here to view code image](#)

```
> require(data.table)
> dt90 <- data.table(Aid_90s, key = c("Country.Name",
  "Program.Name"))
> dt00 <- data.table(Aid_00s, key = c("Country.Name",
  "Program.Name"))
```

Then, doing the join is a simple operation. Note that the join requires specifying the keys for the data.tables, which we did during their creation.

```
> dt0090 <- dt90[dt00]
```

In this case dt90 is the left side, dt00 is the right side and a left join was performed.

## 12.3. reshape2

The next most common munging need is either melting data (going from column orientation to row orientation) or casting data (going from row orientation to column orientation). As with most other procedures in R, there are multiple functions available to accomplish these tasks but we will focus on Hadley Wickham's reshape2 package. (We talk about Wickham a lot because his products have become so fundamental to the R developer's toolbox.)

### 12.3.1. melt

Looking at the Aid\_00s data.frame, we see that each year is stored in its own column. That is, the dollar amount for a given country and program is found in a different column for each year. This is called a cross table, which, while nice for human consumption, is not ideal for graphing with ggplot2 or for some analysis algorithms.

[Click here to view code image](#)

```
> head(Aid_00s)
  Country.Name           Program.Name
  1 Afghanistan          Child Survival and Health
  2 Afghanistan          Department of Defense Security
  Assistance
  3 Afghanistan          Development Assistance
  4 Afghanistan          Economic Support Fund/Security Support
  Assistance
  5 Afghanistan          Food For Education
  6 Afghanistan          Global Health and Child Survival
  FY2000   FY2001   FY2002   FY2003   FY2004   FY2005
  1   NA     NA  2586555  56501189  40215304  39817970  4
  2   NA     NA  2964313      NA  45635526  151334908 230
  3   NA
  4110478  8762080  54538965  180539337 193598227 212648
  4   NA  61144 31827014 341306822 1025522037
  1157530168 1357750249
```

5	NA	NA	NA	3957312	2610006	3254408	386
6	NA	NA	NA	NA	NA	NA	NA
	FY2007	FY2008	FY2009				
1	72527069	28397435		NA			
2	214505892	495539084	552524990				
3	173134034	150529862	3675202				
4	1266653993	1400237791	1418688520				
5	NA	NA	NA				
6	NA	63064912	1764252				

We want it set up so that each row represents a single country-program-year entry with the dollar amount stored in one column. To achieve this we melt the data using melt from reshape2.

[Click here to view code image](#)

```
> require(reshape2)
> melt00 <- melt(Aid_00s, id.vars=c("Country.Name",
  "Program.Name"),
+                   variable.name="Year", value.name="Dollars")
> tail(melt00, 10)
  Country.Name
24521 Zimbabwe
24522 Zimbabwe
24523 Zimbabwe
24524 Zimbabwe
24525 Zimbabwe
24526 Zimbabwe
24527 Zimbabwe
```

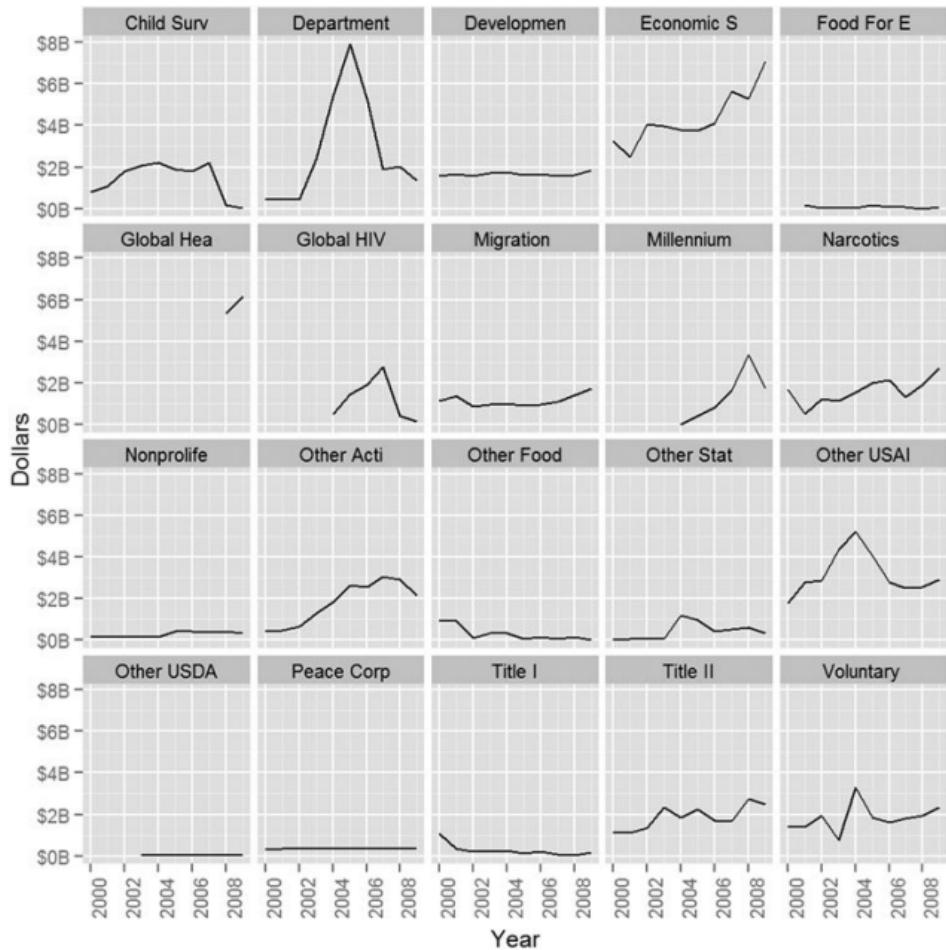
24528	Zimbabwe	
24529	Zimbabwe	
24530	Zimbabwe	
		Program.Name Year
24521	Migration and Refugee Assistance	
FY2009		
24522	Narcotics Control	FY2009
24523	Nonproliferation, Anti-Terrorism, Demining and Related	FY2009
24524	Other Active Grant Programs	
FY2009		
24525	Other Food Aid Programs	
FY2009		
24526	Other State Assistance	FY2009
24527	Other USAID Assistance	
FY2009		
24528	Peace Corps	FY2009
24529	Title I	FY2009
24530	Title II	FY2009
	Dollars	
24521	3627384	
24522	NA	
24523	NA	
24524	7951032	
24525	NA	
24526	2193057	
24527	41940500	
24528	NA	
24529	NA	
24530	174572685	

The id.vars argument specifies which columns uniquely identify a row. After some manipulation of the Year column and aggregating, this is now prime for plotting, as shown in [Figure 12.1](#). The plot uses faceting allowing us to quickly see and understand the funding for each program over time.

[Click here to view code image](#)

```
> require(scales)
> # strip the "FY" out of the year column and convert it to numeric
> melt00$Year <- as.numeric(str_sub(melt00$Year, start=3, 6))
> # aggregate the data so we have yearly numbers by program
> meltAgg <- aggregate(Dollars ~ Program.Name + Year,
  data=melt00,
  + sum, na.rm=TRUE)
> # just keep the first 10 characters of program name
> # then it will fit in the plot
> meltAgg$Program.Name <- str_sub(meltAgg$Program.Name, start=1,
  + end=10)
>
> ggplot(meltAgg, aes(x=Year, y=Dollars)) +
  + geom_line(aes(group=Program.Name)) +
```

```
+  facet_wrap(~ Program.Name) +
+  scale_x_continuous(breaks=seq(from=2000, to=2009,
by=2)) +
+  theme(axis.text.x=element_text(angle=90, vjust=1,
hjust=0)) +
+  scale_y_continuous(labels=multiple_format(extra=-
dollar,
+
                           multiple="B"))
```



**Figure 12.1** Plot of foreign assistance by year for each of the programs.

## 12.3.2. dcast

Now that we have the foreign aid data melted, we cast it back into the wide format for illustration purposes. The function for this is dcast, and it has trickier arguments than melt. The first is the data to be used, in our case melt00. The second argument is a formula where the left side specifies the columns that should remain columns and the right side specifies the columns that should become row names. The third argument is the column (as a character) that holds the values to be populated into the new columns representing the unique values of the right side of the formula argument.

[Click here to view code image](#)

```
> cast00 <- dcast(melt00, Country.Name + Program.Name  
~ Year,  
+ value.var = "Dollars")  
> head(cast00)  
Country.Name          Program.Name  
2000                  NA  
1 Afghanistan          Child Survival and  
Health NA
```

2 Afghanistan Assistance	NA	Department of Defense Security			
3 Afghanistan Assistance	NA	Development Assistance			
4 Afghanistan Economic Support Fund/Security Support Assistance	NA				
5 Afghanistan Education NA		Food For Education			
6 Afghanistan Al NA		Global Health and Child Survival			
	2001 2002 2003 2004 2005 2006				
1 NA 2586555	56501189	40215304	39817970	408563	
2 NA 2964313	NA	45635526	151334908	23050131	
3					
4110478	8762080	54538965	180539337	193598227	212648
4 61144	31827014	341306822	1025522037	1157530168	
1357750249					
5 NA NA 3957312	2610006	3254408	386891		
6 NA NA NA NA NA NA					
2007 2008 2009					
1 72527069	28397435	NA			
2 214505892	495539084	552524990			
3 173134034	150529862	3675202			
4 1266653993	1400237791	1418688520			
5 NA NA NA					
6 NA 63064912	1764252				

## 12.4. Conclusion

Getting the data just right to analyze can be a time-consuming part of our work flow, although it is often inescapable. In this chapter we examined combining multiple datasets into one and changing the orientation from column based (wide) to row based (long). We used `plyr`, `reshape2` and `data.table` along with base functions to accomplish this. This chapter combined with [Chapter 11](#) covers most of the basics of data munging with an eye to both convenience and speed.

# Chapter 13. Manipulating Strings

Strings (character data) often need to be constructed or deconstructed to identify observations, pre-process text, combine information or satisfy any number of other needs. R offers functions for building strings, like `paste` and `sprintf`. It also provides a number of functions for using regular expressions and examining text data, although for those purposes it is better to use Hadley Wickham's `stringr` package.

## 13.1. `paste`

The first function new R users reach for when putting together strings is `paste`. This function takes a series of strings, or expressions that evaluate to strings, and puts them together into one string. We start by putting together three simple strings.

## [Click here to view code image](#)

```
> paste("Hello", "Jared", "and others")
[1] "Hello Jared and others"
```

Notice that spaces were put between the strings. This is because paste has a third argument, sep, that determines what to put in between entries. This can be any valid text, including empty text ("").

## [Click here to view code image](#)

```
> paste("Hello", "Jared", "and others", sep = "/")
[1] "Hello/Jared/and others"
```

Like many functions in R, paste is vectorized. This means each element can be a vector of data to be put together.

## [Click here to view code image](#)

```
> paste(c("Hello", "Hey", "Howdy"), c("Jared", "Bob",
  "David"))
[1] "Hello Jared" "Hey Bob"   "Howdy David"
```

In this case each vector had the same number of entries so they paired one-to-one. When the

vectors do not have the same length they are recycled.

[Click here to view code image](#)

```
> paste("Hello", c("Jared", "Bob", "David"))
[1] "Hello Jared" "Hello Bob"  "Hello David"
> paste("Hello", c("Jared", "Bob", "David"), c("Goodbye",
  "Seeya"))
[1] "Hello Jared Goodbye" "Hello Bob Seeya" "Hello
  David Goodbye"
```

paste also has the ability to collapse a vector of text into one vector containing all the elements with any arbitrary separator, using the collapse argument.

[Click here to view code image](#)

```
> vectorOfText <- c("Hello", "Everyone", "out there", ".")
> paste(vectorOfText, collapse = " ")
[1] "Hello Everyone out there ."
> paste(vectorOfText, collapse = "***")
[1] "Hello*Everyone*out there*."
```

## 13.2. sprintf

While paste is convenient for putting together short bits of text, it can become unwieldy when piecing together long pieces of text, such as when inserting a number of variables into a long piece of text. For instance, we might have a lengthy sentence that has a few spots that require the insertion of special variables. An example is “Hello Jared, your party of eight will be seated in 25 minutes” where “Jared,” “eight” and “25” could be replaced with other information.

Reforming this with paste can make reading the line in code difficult.

To start, we make some variables to hold the information.

```
> person <- "Jared"  
> partySize <- "eight"  
> waitTime <- 25
```

Now we build the paste expression.

[Click here to view code image](#)

```
> paste("Hello ", person, ", your party of ", partySize,  
+       " will be seated in ", waitTime, " minutes.", sep="")  
[1] "Hello Jared, your party of eight will be seated in 25  
minutes."
```

Making even a small change to this sentence would require putting the commas in just the right places.

A good alternative is the sprintf function. With this function we build one long string with special markers indicating where to insert values.

[Click here to view code image](#)

```
> sprintf("Hello %s, your party of %s will be seated in %s  
minutes",  
+       person, partySize, waitTime)  
[1] "Hello Jared, your party of eight will be seated in 25  
minutes"
```

Here, each %s was replaced with its corresponding variable. While the long sentence is easier to read in code, we must maintain the order of %s's and variables.

sprintf is also vectorized. Note that the vector lengths must be multiples of each other.

[Click here to view code image](#)

```
> sprintf("Hello %s, your party of %s will be seated in %s  
minutes",  
+   c("Jared", "Bob"), c("eight", 16, "four", 10), waitTime)  
[1] "Hello Jared, your party of eight will be seated in 25  
minutes"  
[2] "Hello Bob, your party of 16 will be seated in 25  
minutes"  
[3] "Hello Jared, your party of four will be seated in 25  
minutes"  
[4] "Hello Bob, your party of 10 will be seated in 25  
minutes"
```

### 13.3. Extracting Text

Often text needs to be ripped apart to be made useful, and while R has a number of functions for doing so, the stringr package is much easier to use.

First we need some data, so we use the XML package to download a table of United States presidents from Wikipedia.

```
> require(XML)
```

Then we use `readHTMLTable` to parse the table.

**Click here to view code image**

```
> load("data/presidents.rdata")
> theURL <- "http://www.loc.gov/rr/print/list/
057_chron.html"
> presidents <- readHTMLTable(theURL, which=3,
as.data.frame=TRUE,
+
skip.rows=1, header=TRUE,
+
stringsAsFactors=FALSE)
```

Now we take a look at the data.

[Click here to view code image](#)

> <b>head</b> (presidents)		
	YEAR	PRESIDENT
1	1789-1797	George Washington
2	1797-1801	John Adams
3	1801-1805	Thomas Jefferson
4	1805-1809	Thomas Jefferson
5	1809-1812	James Madison
6	1812-1813	James Madison
	FIRST LADY VICE PRESIDENT	
1	Martha Washington	John Adams
2	Abigail Adams	Thomas Jefferson

3	Martha Wayles Skelton Jefferson	(no image)	Aaron Burr
4	Martha Wayles Skelton Jefferson	(no image)	George Clinton
5	Dolley Madison	George Clinton	
6	Dolley Madison	office vacant	

Examining it more closely, we see that the last few rows contain information we do not want, so we keep only the first 64 rows.

[Click here to view code image](#)

```
> tail(presidents$YEAR)
[1] "2001-2009"
[2] "2009-"
[3] "Presidents: Introduction (Rights/Ordering\n      Info.) | Adams\n- Cleveland | Clinton - Harding Harrison\n      - Jefferson | Johnson
- McKinley | Monroe\n      - Roosevelt | Taft - Truman |
Tyler\n      - WilsonList of names, Alphabetically"
[4] "First Ladies: Introduction\n(Rights/Ordering Info.) | Adams\n      - Coolidge | Eisenhower
- HooverJackson\n      - Pierce | \nPolk - Wilson | List\n      of names, Alphabetically"
[5] "Vice Presidents: Introduction (Rights/Ordering Info.) |
```

```
Adams - Coolidge | Curtis - Hobart Humphrey - Rocke-
feller | Roosevelt
- WilsonList of names, Alphabetically"
[6] "Top\n          of Page"
> presidents <- presidents[1:64, ]
```

To start, we create two new columns, one for the beginning of the term and one for the end of the term. To do this we need to split the Year column on the hyphen (-). The stringr package has the str split function that splits a string based on some value. It returns a list with an element for each element of the input vector. Each of these elements has as many elements as necessary for the split, in this case either two (a start and stop year) or one (when the president served less than one year).

[Click here to view code image](#)

```
> require(stringr)
> # split the string
> yearList <- str_split(string = presidents$YEAR, pattern =
"^-")
> head(yearList)
[[1]]
[1] "1789" "1797"
```

```
[[2]]  
[1] "1797" "1801"  
[[3]]  
[1] "1801" "1805"  
[[4]]  
[1] "1805" "1809"  
[[5]]  
[1] "1809" "1812"  
[[6]]  
[1] "1812" "1813"  
> # combine them into one matrix  
> yearMatrix <- data.frame(Reduce(rbind, yearList))  
> head(yearMatrix)  
   X1  X2  
1 1789 1797  
2 1797 1801  
3 1801 1805  
4 1805 1809  
5 1809 1812  
6 1812 1813  
> # give the columns good names  
> names(yearMatrix) <- c("Start", "Stop")  
> # bind the new columns onto the data.frame  
> presidents <- cbind(presidents, yearMatrix)  
> # convert the start and stop columns into numeric  
> presidents$Start <- as.numeric(as.character(president-  
s$Start))  
> presidents$Stop <- as.numeric(as.character(president-  
s$Stop))  
> # view the changes
```

> **head**(presidents)

YEAR PRESIDENT

1	1789-1797	George Washington
2	1797-1801	John Adams
3	1801-1805	Thomas Jefferson
4	1805-1809	Thomas Jefferson
5	1809-1812	James Madison
6	1812-1813	James Madison

FIRST LADY VICE

PRESIDENT

1	Martha Washington	John Adams
2	Abigail Adams	Thomas Jefferson
3	Martha Wayles Skelton Jefferson\n (no image)	Aaron Burr
4	Martha Wayles Skelton Jefferson\n (no image)	George Clinton
5	Dolley Madison	George Clinton
6	Dolley Madison	office vacant

Start Stop

1	1789	1797
2	1797	1801
3	1801	1805
4	1805	1809
5	1809	1812
6	1812	1813

> **tail**(presidents)

YEAR PRESIDENT

FIRST

LADY VICE PRESIDENT

59	1977-1981	Jimmy Carter	Rosalynn Carter	Walter F. Mondale
----	-----------	--------------	-----------------	-------------------

60	1981-1989	Ronald Reagan	Nancy
		Reagan	George Bush
61	1989-1993	George Bush	Barbara Bush
		Quayle	Dan
62	1993-2001	Bill Clinton	Hillary Rodham Clinton
		Albert Gore	
63	2001-2009	George W. Bush	Laura
		Bush	Richard Cheney
64	2009-	Barack Obama	Michelle Obama
		R. Biden	Joseph
		Start Stop	
59	1977 1981		
60	1981 1989		
61	1989 1993		
62	1993 2001		
63	2001 2009		
64	2009 NA		

In the preceding example there was a quirk of R that can be frustrating at first pass. In order to convert the factor presidents\$Start into a numeric, we first had to convert it into a character. That is because factors are simply labels on top of integers, as seen in [Section 4.4.2](#). So when applying as.numeric to a factor, it is converted to the underlying integers.

Just like in Excel, it is possible to select specified characters from text using str sub.

[Click here to view code image](#)

```
> # get the first 3 characters
> str sub(string = presidents$PRESIDENT, start = 1, end =
3)
[1] "Geo" "Joh" "Tho" "Tho" "Jam" "Jam" "Jam" "Jam"
"Jam" "Joh" "And"
[12] "And" "Mar" "Wil" "Joh" "Jam" "Zac" "Mil" "Fra"
"Fra" "Jam" "Abr"
[23] "Abr" "And" "Uly" "Uly" "Uly" "Rut" "Jam" "Che"
"Gro" "Gro" "Ben"
[34] "Gro" "Wil" "Wil" "Wil" "The" "The" "Wil" "Wil"
"Woo" "War" "Cal"
[45] "Cal" "Her" "Fra" "Fra" "Fra" "Har" "Har" "Dwi"
"Joh" "Lyn" "Lyn"
[56] "Ric" "Ric" "Ger" "Jim" "Ron" "Geo" "Bil" "Geo"
"Bar"
> # get the 4th through 8th characters
> str sub(string = presidents$PRESIDENT, start = 4, end =
8)
[1] "rge W" "n Ada" "mas J" "mas J" "es Ma" "es Ma" "es
Ma" "es Ma"
[9] "es Mo" "n Qui" "rew J" "rew J" "tin V" "liam " "n Tyl"
"es K."
[17] "hary " "lard " "nklin" "nklin" "es Bu" "aham " "aham
" "rew J"
```

[25] "sses " "sses " "sses " "herfo" "es A." "ster " "ver C"  
"ver C"  
[33] "jamin" "ver C" "liam " "liam " "liam " "odore"  
"odore" "liam "  
[41] "liam " "drow " "ren G" "vin C" "vin C" "bert " "nklin"  
"nklin"  
[49] "nklin" "ry S." "ry S." "ght D" "n F. " "don B" "don B"  
"hard "  
[57] "hard " "ald R" "my Ca" "ald R" "rge B" "l Cli" "rge  
W" "ack O"

This is good for finding a president whose term started in a year ending in 1, which means he got elected in a year ending in 0, a preponderance of which ones died in office.

[Click here to view code image](#)

```
> presidents[str sub(string = presidents$Start, start = 4,  
+ end = 4) == 1, c("YEAR", "PRESIDENT", "Start",  
"Stop")]
```

	YEAR	PRESIDENT	Start	Stop
3	1801-1805	Thomas Jefferson	1801	1805
14	1841	William Henry Harrison	1841	1841
15	1841-1845	John Tyler	1841	1845
22	1861-1865	Abraham Lincoln	1861	1865
29	1881	James A. Garfield	1881	1881
30	1881-1885	Chester A. Arthur	1881	1885
37	1901	William McKinley	1901	1901
38	1901-1905	Theodore Roosevelt	1901	1905

43	1921-1923	Warren G. Harding	1921	1923
48	1941-1945	Franklin D. Roosevelt	1941	1945
53	1961-1963	John F. Kennedy	1961	1963
60	1981-1989	Ronald Reagan	1981	1989
63	2001-2009	George W. Bush	2001	2009

## 13.4. Regular Expressions

Sifting through text often requires searching for patterns, and usually these patterns have to be general and flexible. This is where regular expressions are very useful. We will not make an exhaustive lesson of regular expressions but will illustrate how to use them within R.

Let's say we want to find any president with "John" in his name, either first or last. Since we do not know where in the name "John" would occur, we cannot simply use str sub. Instead we use str detect.

[Click here to view code image](#)

```
> # returns TRUE/FALSE if John was found in the name  
> johnPos <- str_detect(string = presidents$PRESIDENT,  
  pattern = "John")  
> presidents[johnPos, c("YEAR", "PRESIDENT", "Start",  
  "Stop")]
```

	YEAR	PRESIDENT	Start	Stop
2	1797-1801	John Adams	1797	1801
10	1825-1829	John Quincy Adams	1825	1829
15	1841-1845	John Tyler	1841	1845
24	1865-1869	Andrew Johnson	1865	1869
53	1961-1963	John F. Kennedy	1961	1963
54	1963-1965	Lyndon B. Johnson	1963	1965
55	1963-1969	Lyndon B. Johnson	1963	1969

This found John Adams, John Quincy Adams, John Tyler, Andrew Johnson, John F. Kennedy and Lyndon B. Johnson. Note that regular expressions are case sensitive, so to ignore case we have to put the pattern in `ignore.case`.

[Click here to view code image](#)

```
> badSearch <- str_detect(presidents$PRESIDENT, "john")
> goodSearch <- str_detect(presidents$PRESIDENT, ignore.case("John"))
> sum(badSearch)
[1] 0
> sum(goodSearch)
[1] 7
```

To show off some more interesting regular expressions we will make use of yet another table from Wikipedia, the list of United States wars.

Because we only care about one column, which has some encoding issues, we put an Rdata file of just that one column at [ht-tp://www.jaredlander.com/data/warTimes.rdata](http://www.jaredlander.com/data/warTimes.rdata).

We load that file using load and we then see a new object in our session named warTimes.

For some odd reason, loading rdata files from a URL is not as straightforward as reading in a CSV file from a URL. A connection must first be made using url, then that connection is loaded with load, and then the connection must be closed with close.

[Click here to view code image](#)

```
> con <- url("http://www.jaredlander.com/data/  
warTimes.rdata")  
> load(con)  
> close(con)
```

This vector holds the starting and stopping dates of the wars. Sometimes it has just years, sometimes it also includes months and possibly days. There are instances where it has only one year. Because of this, it is a good dataset to comb

through with various text functions. The first few entries follow.

[Click here to view code image](#)

```
> head(warTimes, 10)
[1] "September 1, 1774 ACAEA September 3, 1783"
[2] "September 1, 1774 ACAEA March 17, 1776"
[3] "1775ACAEA1783"
[4] "June 1775 ACAEA October 1776"
[5] "July 1776 ACAEA March 1777"
[6] "June 14, 1777 ACAEA October 17, 1777"
[7] "1777ACAEA1778"
[8] "1775ACAEA1782"
[9] "1776ACAEA1794"
[10] "1778ACAEA1782"
```

We want to create a new column that contains information for the start of the war. To get at this information we need to split the Time column. Thanks to Wikipedia's encoding, the separator is generally “ACAEA,” which was originally “Ã¢â€” and converted to these characters to make life easier. There are two instances where the “-” appears, once as a separator and once to make a hyphenated word. This is seen in the following code.

[Click here to view code image](#)

```
> warTimes[str_detect(string = warTimes, pattern = "-")]
[1] "6 June 1944 ACAEA mid-July 1944"
[2] "25 August-17 December 1944"
```

So when we are splitting our string, we need to search for either “ACAEA” or “-.” In str split the pattern argument can take a regular expression. In this case it will be “(ACAEA)|-,” which tells the engine to search for either “(ACAEA)” or (denoted by the vertical pipe) “-” in the string. To avoid the instance, seen before, where the hyphen is used in “mid-July” we set the argument n to 2 so it returns at most only two pieces for each element of the input vector. The parentheses are not matched but rather act to group the characters “ACAEA” in the search.<sup>1</sup> This grouping capability will prove important for advanced replacement of text, which will be demonstrated later in this section.

1. To match parentheses, they should be prefixed with a backslash (\).

## [Click here to view code image](#)

```
> theTimes <- str split(string = warTimes, pattern =  
  "(ACAEA)[-]", n = 2)  
> head(theTimes)  
[[1]]  
[1] "September 1, 1774" "September 3, 1783"  
[[2]]  
[1] "September 1, 1774" "March 17, 1776"  
[[3]]  
[1] "1775" "1783"  
[[4]]  
[1] "June 1775" "October 1776"  
[[5]]  
[1] "July 1776" "March 1777"  
[[6]]  
[1] "June 14, 1777" "October 17, 1777"
```

Seeing that this worked for the first few entries, we also check on the two instances where a hyphen was the separator.

## [Click here to view code image](#)

```
> which(str detect(string = warTimes, pattern = "-"))  
[1] 147 150  
> theTimes[[147]]  
[1] "6 June 1944" "mid-July 1944"  
> theTimes[[150]]  
[1] "25 August" "17 December 1944"
```

This looks correct, as the first entry shows “mid-July” still intact while the second entry shows the two dates split apart.

For our purposes we only care about the start date of the wars, so we need to build a function that extracts the first (in some cases only) element of each vector in the list.

[Click here to view code image](#)

```
> theStart <- sapply(theTimes, FUN = function(x) x[1])  
> head(theStart)  
[1] "September 1, 1774" "September 1, 1774" "1775"  
[4] "June 1775" "July 1776" "June 14, 1777"
```

The original text sometimes had spaces around the separators and sometimes did not, meaning that some of our text has trailing white spaces. The easiest way to get rid of them is with the str trim function.

[Click here to view code image](#)

```
> theStart <- str trim(theStart)  
> head(theStart)  
[1] "September 1, 1774" "September 1, 1774" "1775"  
[4] "June 1775" "July 1776" "June 14, 1777"
```

To extract the word “January” wherever it might occur, use str extract. In places where it is not found will be NA.

[Click here to view code image](#)

```
> # pull out 'January' anywhere it's found, otherwise return  
NA
```

```
> str extract(string = theStart, pattern = "January")
```

```
[1] NA    NA    NA    NA    NA    NA  
[7] NA    NA    NA    NA    NA    NA  
[13] "January" NA    NA    NA    NA    NA    NA  
[19] NA    NA    NA    NA    NA    NA  
[25] NA    NA    NA    NA    NA    NA  
[31] NA    NA    NA    NA    NA    NA  
[37] NA    NA    NA    NA    NA    NA  
[43] NA    NA    NA    NA    NA    NA  
[49] NA    NA    NA    NA    NA    NA  
[55] NA    NA    NA    NA    NA    NA  
[61] NA    NA    NA    NA    NA    NA  
[67] NA    NA    NA    NA    NA    NA  
[73] NA    NA    NA    NA    NA    NA  
[79] NA    NA    NA    NA    NA    NA  
[85] NA    NA    NA    NA    NA    NA  
[91] NA    NA    NA    NA    NA    NA  
[97] NA    NA    "January" NA    NA    NA  
[103] NA   NA    NA    NA    NA    NA  
[109] NA   NA    NA    NA    NA    NA  
[115] NA   NA    NA    NA    NA    NA  
[121] NA   NA    NA    NA    NA    NA
```

```
[127] NA     NA     NA     NA     "January" NA
[133] NA     NA     "January" NA     NA     NA
[139] NA     NA     NA     NA     NA     NA
[145] "January" "January" NA     NA     NA     NA
[151] NA     NA     NA     NA     NA     NA
[157] NA     NA     NA     NA     NA     NA
[163] NA     NA     NA     NA     NA     NA
[169] "January" NA     NA     NA     NA     NA
[175] NA     NA     NA     NA     NA     NA
[181] "January" NA     NA     NA     NA     "Janu-
ary"
[187] NA     NA
```

To find elements that contain “January” and return the entire entry—not just “January”—use str detect and subset theStart with the results.

[Click here to view code image](#)

```
> # just return elements where 'January' was detected
> theStart[str detect(string = theStart, pattern = "January")]
[1] "January"      "January 21"    "January 1942"
[4] "January"      "January 22, 1944" "22 January 1944"
[7] "January 4, 1989" "15 January 2002" "January 14,
2010"
```

To extract the year, we search for an occurrence of four numbers together. Because we do not know specific numbers, we have to use a

pattern. In a regular expression search, “[0-9]” searches for any number. We use “[0-9][0-9][0-9][0-9]” to search for four consecutive numbers.

[Click here to view code image](#)

```
> # get incidents of 4 numeric digits in a row
> head(str_extract(string = theStart,
  "[0-9][0-9][0-9][0-9]"), 20)
[1] "1774" "1774" "1775" "1775" "1776" "1777" "1777"
"1775" "1776"
[10] "1778" "1775" "1779" NA    "1785" "1798" "1801"
NA    "1812"
[19] "1812" "1813"
```

Writing “[0-9]” repeatedly is inefficient, especially when searching for many occurrences of a number. Putting “4” in curly braces after “[0-9]” causes the engine to search for any set of four numbers.

[Click here to view code image](#)

```
> # a smarter way to search for four numbers
> head(str_extract(string = theStart, "[0-9]{4}"), 20)
[1] "1774" "1774" "1775" "1775" "1776" "1777" "1777"
"1775" "1776"
```

```
[10] "1778" "1775" "1779" NA    "1785" "1798" "1801"  
NA    "1812"  
[19] "1812" "1813"
```

Even writing “[0-9]” can be inefficient, so there is a shortcut to denote any integer. In most other languages the shortcut is “\d” but in R there needs to be two backslashes (“\\d”).

[Click here to view code image](#)

```
> # "\\d" is a shortcut for "[0-9]"  
> head(str_extract(string = theStart, "\\d{4}"), 20)  
[1] "1774" "1774" "1775" "1775" "1776" "1777" "1777"  
"1775" "1776"  
[10] "1778" "1775" "1779" NA    "1785" "1798" "1801"  
NA    "1812"  
[19] "1812" "1813"
```

The curly braces offer even more functionality: for instance, searching for a number one to three times.

[Click here to view code image](#)

```
> # this looks for any digit that occurs either once, twice or  
thrice  
> str_extract(string = theStart, "\\d{1,3}")  
[1] "1"   "1"   "177" "177" "177" "14"  "177" "177" "177" "177"
```

```
[11] "177" "177" NA "178" "179" "180" NA "18" "181" "
[21] "181" "181" "181" "181" "181" "181" "181" "181" "
[31] "22" "181" "181" "5" "182" "182" "182" NA "6" "18"
[41] "23" "183" "19" "11" "25" "184" "184" "184" "184" "
[51] "185" "184" "28" "185" "13" "4" "185" "185" "185" "18"
[61] "185" "185" "6" "185" "6" "186" "12" "186" "186" "18"
[71] "186" "186" "17" "31" "186" "20" "186" "186" "186" "18"
[81] "186" "17" "1" "6" "12" "27" "187" "187" "187" "187"
[91] "187" "187" NA "30" "188" "189" "22" "189" "21" "18"
[101] "25" "189" "189" "189" "189" "189" "189" "2" "189" "
[111] "191" "21" "28" "191" "191" "191" "191" "191" "191" "
[121] "191" "191" "191" "7" "194" "194" NA NA "3" "7"
[131] "194" "194" NA "20" NA "1" "16" "194" "8" "19"
[141] "17" "9" "194" "3" "22" "22" "6" "6" "15" "25"
[151] "25" "16" "8" "6" "194" "195" "195" "195" "195" "19"
[161] "28" "25" "15" "24" "19" "198" "15" "198" "4" "20"
[171] "2" "199" "199" "199" "19" "20" "24" "7" "7" "7"
[181] "15" "7" "6" "20" "16" "14" "200" "19"
```

Regular expressions can search for text with anchors indicating the beginning of a line ("^") and the end of a line ("\$").

[Click here to view code image](#)

```
> # extract 4 digits at the beginning of the text
> head(str_extract(string = theStart, pattern = "\^\\d{4}"), 30)
[1] NA NA "1775" NA NA NA "1777"
"1775" "1776"
```

```
[10] "1778" "1775" "1779" NA    "1785" "1798"
"1801" NA    NA
[19] "1812" "1813" "1812" "1812" "1813" "1813" "1813"
"1814" "1813"
[28] "1814" "1813" "1815"
> # extract 4 digits at the end of the text
> head(str_extract(string = theStart, pattern = "\d{4}"), 30)
[1] "1774" "1774" "1775" "1775" "1776" "1777" "1777"
"1775" "1776"
[10] "1778" "1775" "1779" NA    "1785" "1798" "1801"
NA    "1812"
[19] "1812" "1813" "1812" "1812" "1813" "1813" "1813"
"1814" "1813"
[28] "1814" "1813" "1815"
> # extract 4 digits at the beginning AND the end of the
text
> head(str_extract(string = theStart, pattern = "^\d{4}$"), 30)
[1] NA    NA    "1775" NA    NA    NA    "1777"
"1775" "1776"
[10] "1778" "1775" "1779" NA    "1785" "1798" "1801"
NA    NA
[19] "1812" "1813" "1812" "1812" "1813" "1813" "1813"
"1814" "1813"
[28] "1814" "1813" "1815"
```

Replacing text selectively is another powerful feature of regular expressions. We start by simply replacing numbers with a fixed value.

[Click here to view code image](#)

```
> # replace the first digit seen with "x"
> head(str_replace(string=theStart, pattern="\d", replacement="x"), 30)
[1] "September x, 1774" "September x, 1774" "x775"
[4] "June x775"       "July x776"      "June x4, 1777"
[7] "x777"            "x775"          "x776"
[10] "x778"           "x775"          "x779"
[13] "January"         "x785"          "x798"
[16] "x801"            "August"        "June x8, 1812"
[19] "x812"            "x813"          "x812"
[22] "x812"           "x813"          "x813"
[25] "x813"           "x814"          "x813"
[28] "x814"           "x813"          "x815"
> # replace all digits seen with "x"
> # this means "7" -> "x" and "382" -> "xxx"
> head(str_replace_all(string=theStart, pattern="\d", replacement="x"),
+      30)
[1] "September x, xxxx" "September x, xxxx" "xxxx"
[4] "June xxxx"         "July xxxx"      "June xx, xxxx"
[7] "xxxx"              "xxxx"          "xxxx"
[10] "xxxx"              "xxxx"          "xxxx"
[13] "January"           "xxxx"          "xxxx"
[16] "xxxx"              "August"        "June xx, xxxx"
```

```
[19] "xxxx"      "xxxx"      "xxxx"
[22] "xxxx"      "xxxx"      "xxxx"
[25] "xxxx"      "xxxx"      "xxxx"
[28] "xxxx"      "xxxx"      "xxxx"
> # replace any strings of digits from 1 to 4 in length with
"X"
> # this means "7" -> "x" and "382" -> "x"
> head(str_replace_all(string=theStart, pattern="\d{1,4}",
+                      replacement="X"), 30)
[1] "September x, x" "September x, x" "x"
[4] "June x"        "July x"       "June x, x"
[7] "x"             "x"           "x"
[10] "x"            "x"           "x"
[13] "January"      "x"           "x"
[16] "x"            "August"      "June x, x"
[19] "x"            "x"           "x"
[22] "x"            "x"           "x"
[25] "x"            "x"           "x"
[28] "x"            "x"           "x"
```

Not only can regular expressions substitute fixed values into a string, they can also substitute part of the search pattern. To see this, we create a vector of some HTML commands.

[Click here to view code image](#)

```
> # create a vector of HTML commands
> commands <- c("<a href=index.html>The Link is
here</a>",
```

+ "This is bold text")

Now we would like to extract the text between the HTML tags. The pattern is a set of opening and closing angle brackets with something in between ("<.+?>"), some text (".+?") and another set of opening and closing brackets ("<.+?>"). The “.” indicates a search for anything, while the “+” means to search for it one or more times with the “?” meaning it is not a greedy search. Because we do not know what the text between the tags will be, and that is what we want to substitute back into the text, we group it inside parentheses and use a back reference to reinsert it using “\\1,” which indicates use of the first grouping. Subsequent groupings are referenced using subsequent numerals, up to nine. In other languages a “\$” is used instead of “\\.”

[Click here to view code image](#)

```
> # get the text between the HTML tags  
> # the content in (.+?) is substituted using 1  
> str_replace(string=commands, pattern="<.+?>(.+?)<.+>",  
+           replacement="\\"1")  
[1] "The Link is here" "This is bold text"
```

Since R has its own regular expression peculiarities, there is a handy help file that can be accessed with `?regex`.

## 13.5. Conclusion

R has many facilities for dealing with text, whether creating, extracting or manipulating it. For creating text, it is best to use `sprintf` and if necessary `paste`. For all other text needs, it is best to use Hadley Wickham's `stringr` package. This includes pulling out text specified by character position (`str_sub`), regular expressions (`str_detect`, `str_extract` and `str_replace`) and splitting strings (`str_split`).

# Chapter 14. Probability Distributions

Being a statistical programming language, R easily handles all the basic necessities of statistics, including drawing random numbers and calculating distribution values (the focus of this chapter), means, variances, maxima and minima, correlation and t-tests (the focus of [Chapter 15](#)).

Probability distributions lie at the heart of statistics, so naturally R provides numerous functions for making use of them. These include functions for generating random numbers and calculating the distribution and quantile.

## 14.1. Normal Distribution

Perhaps the most famous, and most used, statistical distribution is the normal distribution, sometimes referred to as the Gaussian distribution, which is defined as

$$f(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad (14.1)$$

where  $\mu$  is the mean and  $\sigma$  the standard deviation. This is the famous bell curve that describes so many phenomena in life. To draw random numbers from the normal distribution use the `rnorm` function, which, optionally, allows the specification of the mean and standard deviation.

[Click here to view code image](#)

```
> # 10 draws from the standard 0-1 normal distribution
> rnorm(n = 10)
[1] -2.1654005 0.7044448 0.1545891 1.3325220 -0.1965996
[7] 0.2055784 0.7698138 0.4276115 -0.6209493
> # 10 draws from the 100-20 distribution
> rnorm(n = 10, mean = 100, sd = 20)
[1] 99.50443 86.81502 73.57329 113.36646 70.55072
95.70594
[7] 67.10154 99.49917 111.02245 114.16694
```

The density (the probability of a particular value) for the normal distribution is calculated using `dnorm`.

[Click here to view code image](#)

```
> randNorm10 <- rnorm(10)
```

```
> randNorm10  
[1] -1.2376217 0.2989008 1.8963171 -1.1609135  
-0.9199759 0.4251059  
[7] -1.1112031 -0.3353926 -0.5533266 -0.5985041  
> dnorm(randNorm10)  
[1] 0.18548296 0.38151338 0.06607612 0.20335569  
0.26129210 0.36447547  
[7] 0.21517046 0.37712348 0.34231507 0.33352345  
> dnorm(c(-1, 0, 1))  
[1] 0.2419707 0.3989423 0.2419707
```

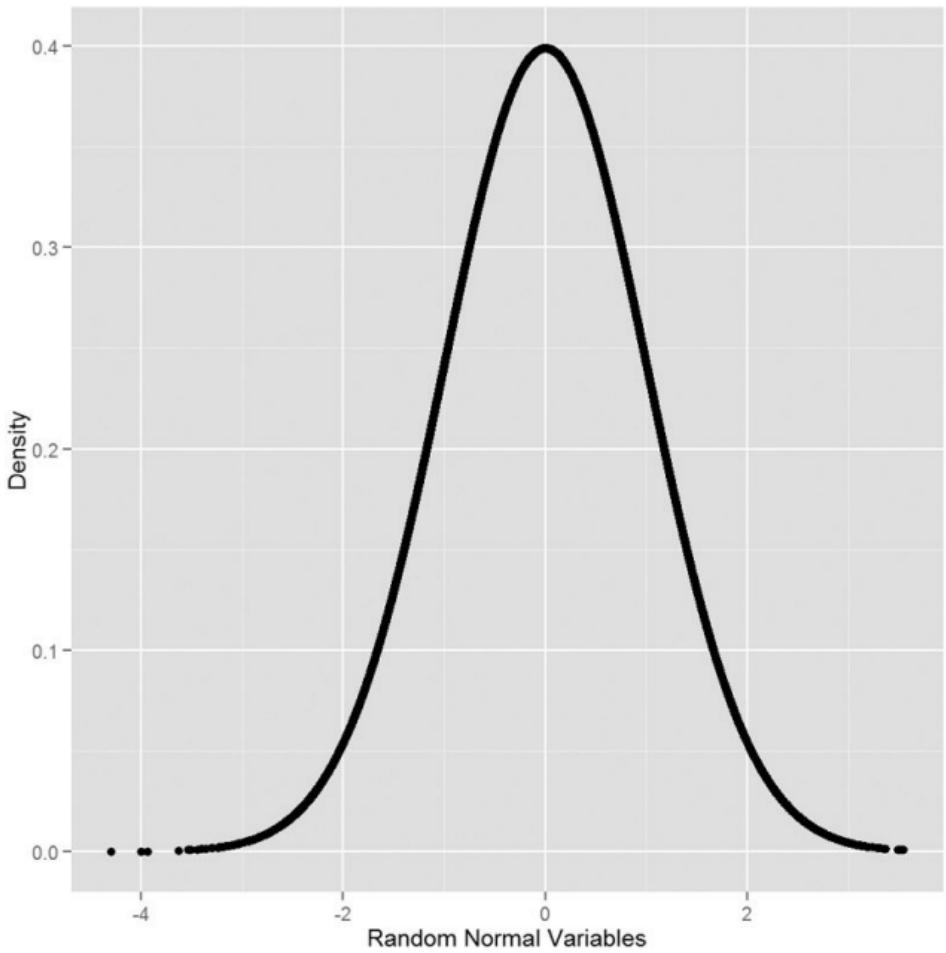
dnorm returns the probability of a specific number occurring. While it is technically mathematically impossible to find the exact probability of a number from a continuous distribution, this is an estimate of the probability. Like with rnorm, a mean and standard deviation can be specified for dnorm.

To see this visually we generate a number of normal random variables, calculate their distributions and then plot them. This should result in a nicely shaped bell curve, as seen in [Figure 14.1](#).

[Click here to view code image](#)

```
> # generate the normal variables  
> randNorm <- rnorm(30000)
```

```
> # calcualte their distributions
> randDensity <- dnorm(randNorm)
> # load ggplot2
> require(ggplot2)
> # plot them
> ggplot(data.frame(x = randNorm, y = randDensity)) +
  aes(x = x, y = y) +
  geom_point() + labs(x = "Random Normal Variables",
y = "Density")
```



**Figure 14.1** Plot of random normal variables and their densities, which results in a bell curve.

Similarly, `pnorm` calculates the distribution of the normal distribution; that is, the cumulative

probability that a given number, or smaller number, occurs. This is defined as

$$\Phi(a) = P\{X \leq a\} = \int_{-\infty}^a \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} dx \quad (14.2)$$

[Click here to view code image](#)

```
> pnorm(randNorm10)
[1] 0.1079282 0.6174921 0.9710409 0.1228385 0.1787927
0.6646203
[7] 0.1332405 0.3686645 0.2900199 0.2747518
```

[Click here to view code image](#)

```
> pnorm(c(-3, 0, 3))
[1] 0.001349898 0.500000000 0.998650102
> pnorm(-1)
[1] 0.1586553
```

By default this is left-tailed. To find the probability that the variable falls between two points, we must calculate the two probabilities and subtract them from each other.

```
> pnorm(1) - pnorm(0)
[1] 0.3413447
> pnorm(1) - pnorm(-1)
[1] 0.6826895
```

This probability is represented by the area under the curve and illustrated in [Figure 14.2](#), which is drawn by the following code.

[Click here to view code image](#)

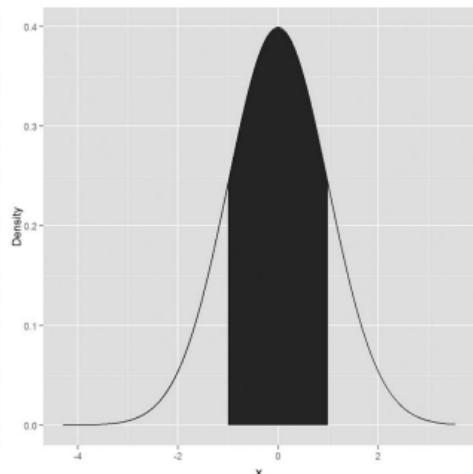
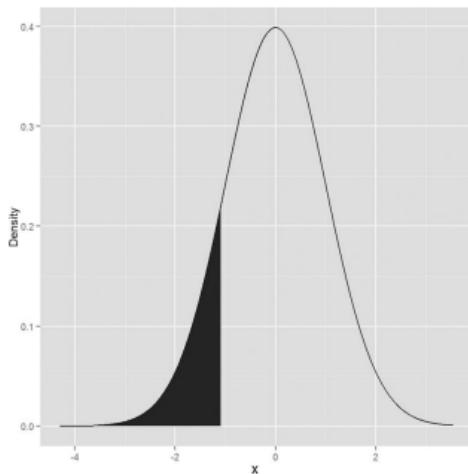
```
> # a few things happen with this first line of code  
> # the idea is to build a ggplot2 object that we can build  
upon later  
> # that is why it is saved to p  
> # we take randNorm and randDensity and put them into a  
data.frame  
> # we declare the x and y axes outside of any other func-  
tion  
> # this just gives more flexibility  
> # we add lines with geom_line()  
> # x- and y-axis labels with labs(x="x", y="Density")  
> p <- ggplot(data.frame(x=randNorm, y=randDensity)) +  
aes(x=x, y=y) +  
+   geom_line() + labs(x="x", y="Density")  
>  
> # plotting p will print a nice distribution  
> # to create a shaded area under the curve we first calcu-  
late that area  
> # generate a sequence of numbers going from the far left  
to -1  
> neg1Seq <- seq(from=min(randNorm), to=-1, by=.1)  
>  
> # build a data.frame of that sequence as x  
> # the distribution values for that sequence as y
```

```
> lessThanNeg1 <- data.frame(x=neg1Seq,  
y=dnorm(neg1Seq))  
>  
> head(lessThanNeg1)  
      x          y  
1 -3.873328 0.0002203542  
2 -3.773328 0.0003229731  
3 -3.673328 0.0004686713  
4 -3.573328 0.0006733293  
5 -3.473328 0.0009577314  
6 -3.373328 0.0013487051  
>  
> # combine this with endpoints at the far left and far right  
> # the height is 0  
> lessThanNeg1 <- rbind(c(min(randNorm), 0),  
+                           lessThanNeg1,  
+                           c(max(lessThanNeg1$x), 0))  
>  
> # use that shaded region as a polygon  
> p + geom_polygon(data=lessThanNeg1, aes(x=x, y=y))  
>  
> # create a similar sequence going from -1 to 1  
> neg1Pos1Seq <- seq(from=-1, to=1, by=.1)  
>  
> # build a data.frame of that sequence as x  
> # the distribution values for that sequence as y  
> neg1To1 <- data.frame(x=neg1Pos1Seq,  
y=dnorm(neg1Pos1Seq))  
>  
> head(neg1To1)
```

	x	y
1	-1.0	0.2419707
2	-0.9	0.2660852
3	-0.8	0.2896916
4	-0.7	0.3122539
5	-0.6	0.3332246
6	-0.5	0.3520653

>

```
> # combine this with endpoints at the far left and far right
> # the height is 0
> neg1To1 <- rbind(c(min(neg1To1$x), 0),
+                     neg1To1,
+                     c(max(neg1To1$x), 0))
>
> # use that shaded region as a polygon
> p + geom_polygon(data=neg1To1, aes(x=x, y=y))
```



**Figure 14.2** Area under a normal curve.

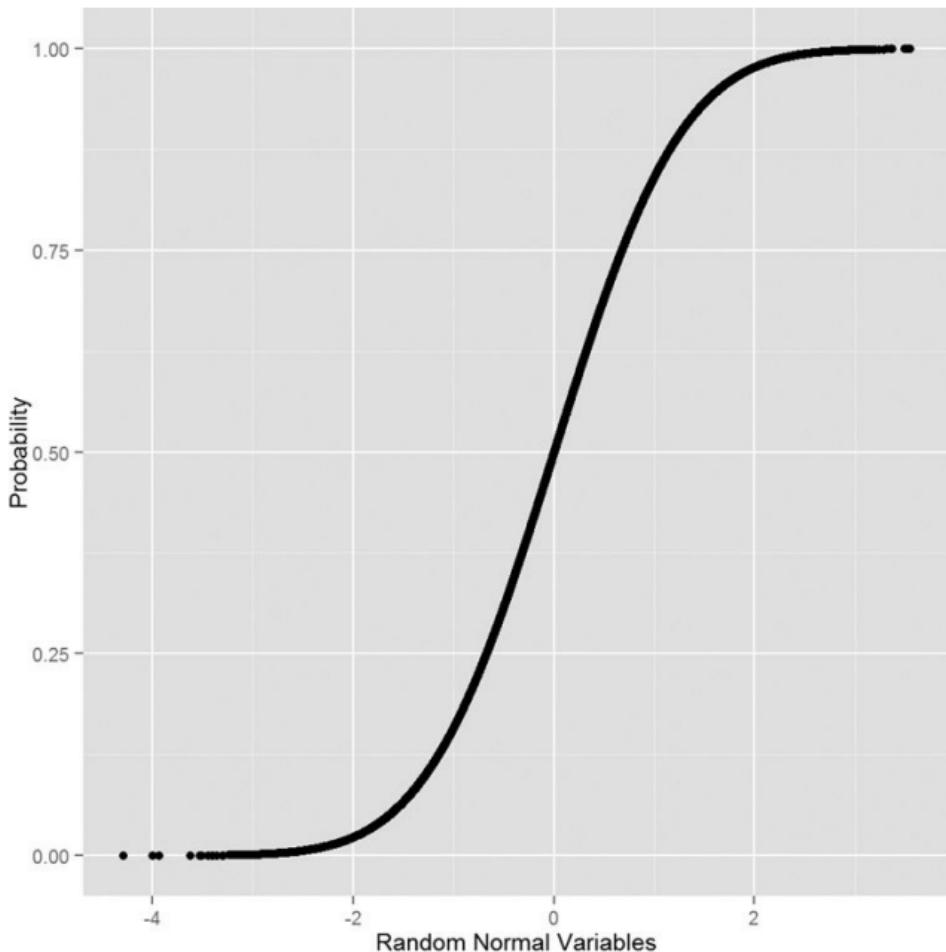
The plot on the left shows the area to the left of  $-1$ , while the plot on the right shows the area between  $-1$  and  $1$ .

The distribution has a non-decreasing shape, as shown in [Figure 14.3](#). The information displayed here is the same as in [Figure 14.2](#) but it is shown differently. Instead of the cumulative probability being shown as a shaded region it is displayed as a single point along the  $y$ -axis.

[Click here to view code image](#)

```
> randProb <- pnorm(randNorm)
```

```
> ggplot(data.frame(x=randNorm, y=randProb)) +  
  aes(x=x, y=y) +  
  geom_point() + labs(x="Random Normal Variables",  
  y="Probability")
```



**Figure 14.3** Normal distribution function.

The opposite of pnorm is qnorm. Given a cumulative probability it returns the quantile.

[Click here to view code image](#)

```
> randNorm10  
[1]  
-1.2376217 0.2989008 1.8963171 -1.1609135 -0.9199759  
0.4251059  
[7] -1.1112031 -0.3353926 -0.5533266 -0.5985041
```

[Click here to view code image](#)

```
> qnorm(pnorm(randNorm10))  
[1]  
-1.2376217 0.2989008 1.8963171 -1.1609135 -0.9199759 0  
[7] -1.1112031 -0.3353926 -0.5533266 -0.5985041  
> all.equal(randNorm10, qnorm(pnorm(randNorm10)))  
[1] TRUE
```

## 14.2. Binomial Distribution

Like the normal distribution, the binomial distribution is well represented in R. Its probability mass function is

$$p(x; n, p) = \binom{n}{x} p^x (1-p)^{n-x} \quad (14.3)$$

where

$$\binom{n}{x} = \frac{n!}{x!(n-x)!} \quad (14.4)$$

and  $n$  is the number of trials and  $p$  is the probability of success of a trial. The mean is  $np$  and the variance is  $np(1 - p)$ . When  $n = 1$  this reduces to the Bernoulli distribution.

Generating random numbers from the binomial distribution is not simply generating random numbers but rather generating the number of successes of independent trials. To simulate the number of successes out of ten trials with probability 0.4 of success, we run `rbinom` with  $n=1$  (only one run of the trials),  $size=10$  (trial size of 10), and  $prob=0.4$  (probability of success is 0.4).

[Click here to view code image](#)

```
> rbinom(n = 1, size = 10, prob = 0.4)
[1] 6
```

That is to say that ten trials were conducted, each with 0.4 probability of success, and the number generated is the number that succeeded.

As this is random, different numbers will be generated each time.

By setting n to anything greater than 1, R will generate the number of successes for each of the n sets of size trials.

[Click here to view code image](#)

```
> rbinom(n = 1, size = 10, prob = 0.4)
[1] 3
> rbinom(n = 5, size = 10, prob = 0.4)
[1] 5 3 6 5 4
> rbinom(n = 10, size = 10, prob = 0.4)
[1] 5 3 4 4 5 3 3 5 3 3
```

Setting size to 1 turns the numbers into a Bernoulli random variable, which can take on only the value 1 (success) or 0 (failure).

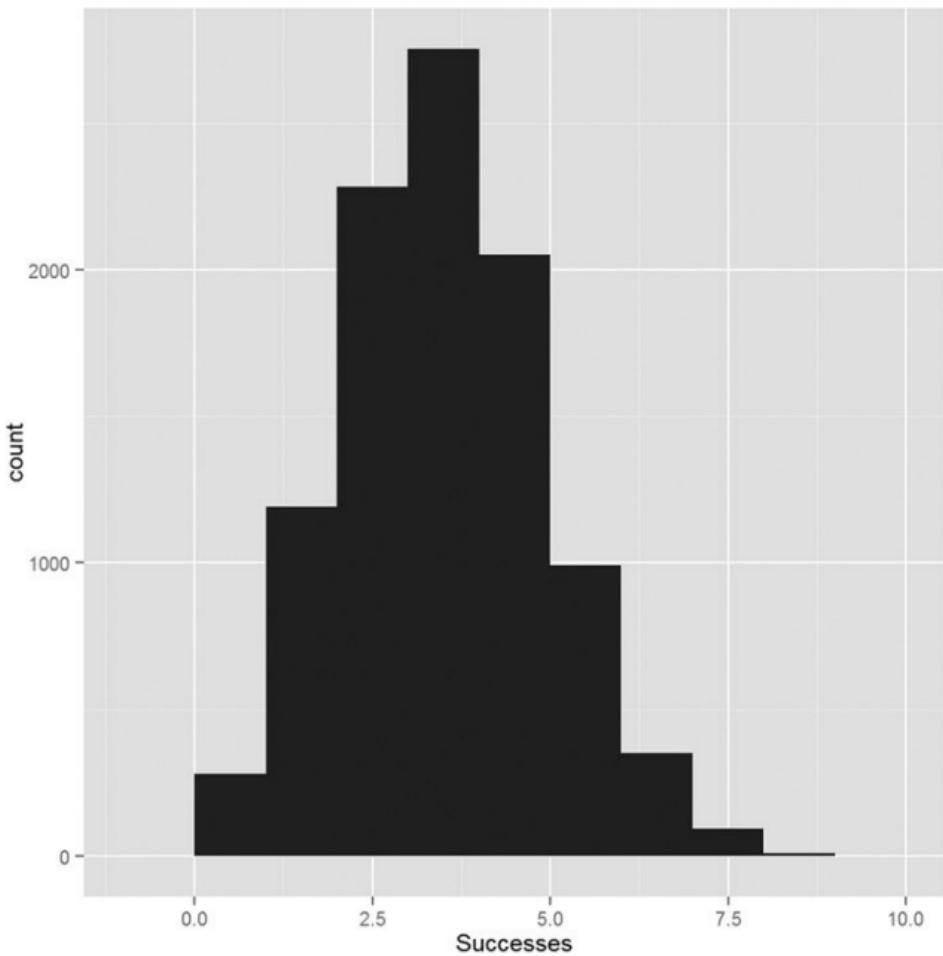
[Click here to view code image](#)

```
> rbinom(n = 1, size = 1, prob = 0.4)
[1] 1
> rbinom(n = 5, size = 1, prob = 0.4)
[1] 0 0 1 1 1
> rbinom(n = 10, size = 1, prob = 0.4)
[1] 0 0 0 1 0 1 0 0 1 0
```

To visualize the binomial distribution we randomly generate 10,000 experiments, each with 10 trials and 0.3 probability of success. This is seen in [Figure 14.4](#), which shows that the most common number of successes is 3, as expected.

[Click here to view code image](#)

```
> binomData <- data.frame(Successes = rbinom(n =  
10000, size = 10,  
+ prob = 0.3))  
> ggplot(binomData, aes(x = Successes)) +  
geom_histogram(binwidth = 1)
```



**Figure 14.4** Ten thousand runs of binomial experiments with ten trials each and probability of success of 0.3.

To see how the binomial distribution is well approximated by the normal distribution as the

number of trials grows large, we run similar experiments with differing numbers of trials and graph the results, as shown in [Figure 14.5](#), on page [181](#).

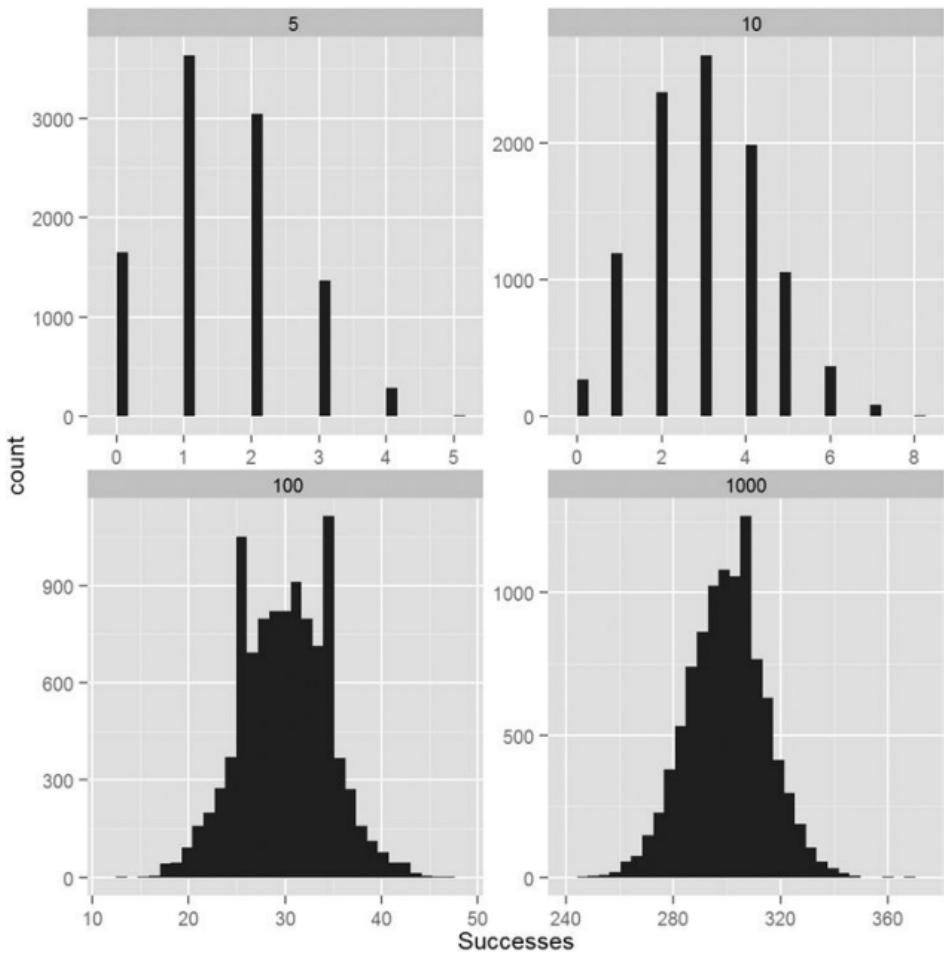
[Click here to view code image](#)

```
> # create a data.frame with Successes being the 10,000
random draws
> # Size equals 5 for all 10,000 rows

> binom5 <- data.frame(Successes=rbinom(n=10000,
size=5,
+      prob=.3), Size=5)
> dim(binom5)
[1] 10000   2
> head(binom5)
  Successes Size
1       1     5
2       1     5
3       2     5
4       2     5
5       3     5
6       0     5
>
> # similar to before, still 10,000 rows
> # numbers are drawn from a distribution with a different
size
> # Size now equals 10 for all 10,000 rows
```

```
> binom10 <- data.frame(Successes=rbinom(n=10000,  
size=10,  
+      prob=.3), Size=10)  
> dim(binom10)  
[1] 10000   2  
> head(binom10)  
 Successes Size  
1     1    10  
2     3    10  
3     3    10  
4     3    10  
5     0    10  
6     3    10  
>  
> binom100 <- data.frame(Successes=rbinom(n=10000,  
size=100,  
+      prob=.3), Size=100)  
>  
> binom1000 <- data.frame(Successes=rbinom(n=10000,  
size=1000,  
+      prob=.3), Size=1000)  
>  
> # combine them all into one data.frame  
> binomAll <- rbind(binom5, binom10, binom100,  
binom1000)  
> dim(binomAll)  
[1] 40000   2  
> head(binomAll, 10)  
 Successes Size  
1     1    5
```

```
2      1  5
3      2  5
4      2  5
5      3  5
6      0  5
7      1  5
8      1  5
9      1  5
10     1  5
> tail(binomAll, 10)
   Successes Size
39991    316 1000
39992    311 1000
39993    296 1000
39994    316 1000
39995    288 1000
39996    286 1000
39997    264 1000
39998    291 1000
39999    300 1000
40000    302 1000
>
> # build the plot
> # histograms only need an x aesthetic
> # it is faceted (broken up) based on the values of Size
> # these are 5, 10, 100, 1000
> ggplot(binomAll, aes(x=Successes)) +
  geom_histogram() +
  facet_wrap(~ Size, scales="free")
```



**Figure 14.5** Random binomial histograms faceted by trial size. Notice that while not perfect, as the number of trials increases the distribution appears more normal. Also note the differing scales in each pane.

The cumulative distribution function is

$$F(a; n, p) = P\{X \leq a\} = \sum_{i=0}^a \binom{n}{i} p^i (1-p)^{n-i} \quad (14.5)$$

where  $n$  and  $p$  are the number of trials and the probability of success, respectively, as before.

Similar to the normal distribution functions, `dbinom` and `pbinom` provide the density (probability of an exact value) and distribution (cumulative probability), respectively, for the binomial distribution.

[Click here to view code image](#)

```
> # probability of 3 successes out of 10
> dbinom(x = 3, size = 10, prob = 0.3)
[1] 0.2668279
> # probability of 3 or fewer successes out of 10
> pbinom(q = 3, size = 10, prob = 0.3)
[1] 0.6496107
> # both functions can be vectorized
> dbinom(x = 1:10, size = 10, prob = 0.3)
[1] 0.1210608210 0.2334744405 0.2668279320
0.2001209490 0.1029193452
[6] 0.0367569090 0.0090016920 0.0014467005
0.0001377810 0.0000059049
> pbinom(q = 1:10, size = 10, prob = 0.3)
```

```
[1] 0.1493083 0.3827828 0.6496107 0.8497317 0.9526510  
0.9894079  
[7] 0.9984096 0.9998563 0.9999941 1.0000000
```

Given a certain probability, `qbinom` returns the quantile, which for this distribution is the number of successes.

[Click here to view code image](#)

```
> qbinom(p = 0.3, size = 10, prob = 0.3)  
[1] 2  
> qbinom(p = c(0.3, 0.35, 0.4, 0.5, 0.6), size = 10, prob =  
0.3)  
[1] 2 2 3 3 3
```

## 14.3. Poisson Distribution

Another popular distribution is the Poisson distribution, which is for count data. Its probability mass function is

$$p(x; \lambda) = \frac{\lambda^x e^{-\lambda}}{x!} \quad (14.6)$$

and the cumulative distribution is

$$F(a; \lambda) = P\{X \leq a\} = \sum_{i=0}^a \frac{\lambda^i e^{-\lambda}}{i!} \quad (14.7)$$

where  $\lambda$  is both the mean and variance.

To generate random counts, the density, the distribution and quantiles use rpois, dpois, ppois and qpois, respectively.

As  $\lambda$  grows large the Poisson distribution begins to resemble the normal distribution. To see this we will simulate 10,000 draws from the Poisson distribution and plot their histograms to see the shape.

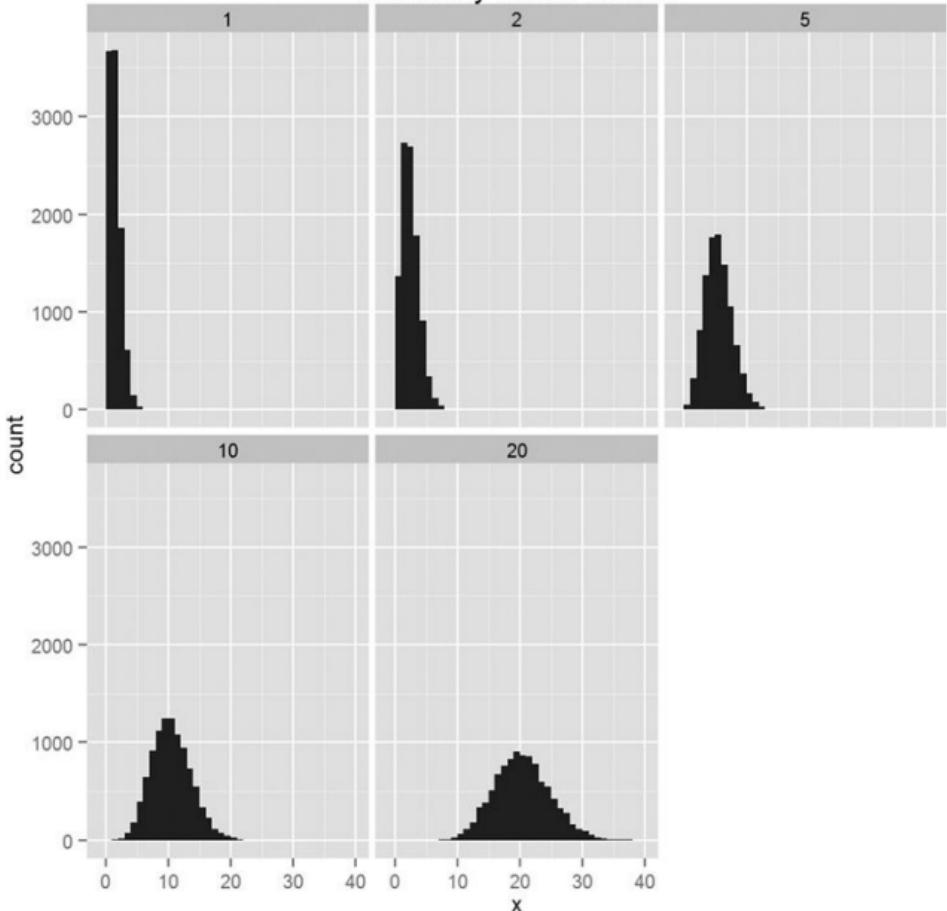
[Click here to view code image](#)

```
> # generate 10,000 random counts from 5 different Pois-  
son distributions  
> pois1 <- rpois(n=10000, lambda=1)  
> pois2 <- rpois(n=10000, lambda=2)  
> pois5 <- rpois(n=10000, lambda=5)  
> pois10 <- rpois(n=10000, lambda=10)  
> pois20 <- rpois(n=10000, lambda=20)  
> pois <- data.frame(Lambda.1=pois1, Lambda.2=pois2,  
+                         Lambda.5=pois5, Lambda.10=pois10,  
Lambda.20=pois20)  
> # load reshape2 package to melt the data to make it easier  
to plot  
> require(reshape2)  
> # melt the data into a long format
```

```
> pois <- melt(data=pois, variable.name="Lambda",
  value.name="x")
> # load the stringr package to help clean up the new
  column name
> require(stringr)
> # clean up the Lambda to just show the value for that
  lambda
> pois$Lambda <-
as.factor(as.numeric(str_extract(string=pois$Lambda,
+                                     pattern="\d+"))))
> head(pois)
  Lambda x
1     1 0
2     1 2
3     1 0
4     1 1
5     1 2
6     1 0
> tail(pois)
  Lambda x
49995   20 26
49996   20 14
49997   20 26
49998   20 22
49999   20 20
50000   20 23
```

Now we will plot a separate histogram for each value of  $\lambda$ , as shown in [Figure 14.6](#).

### Probability Mass Function



**Figure 14.6** Histograms for 10,000 draws from the Poisson distribution at varying levels of  $\lambda$ . Notice how the histograms become more like the normal distribution.

[Click here to view code image](#)

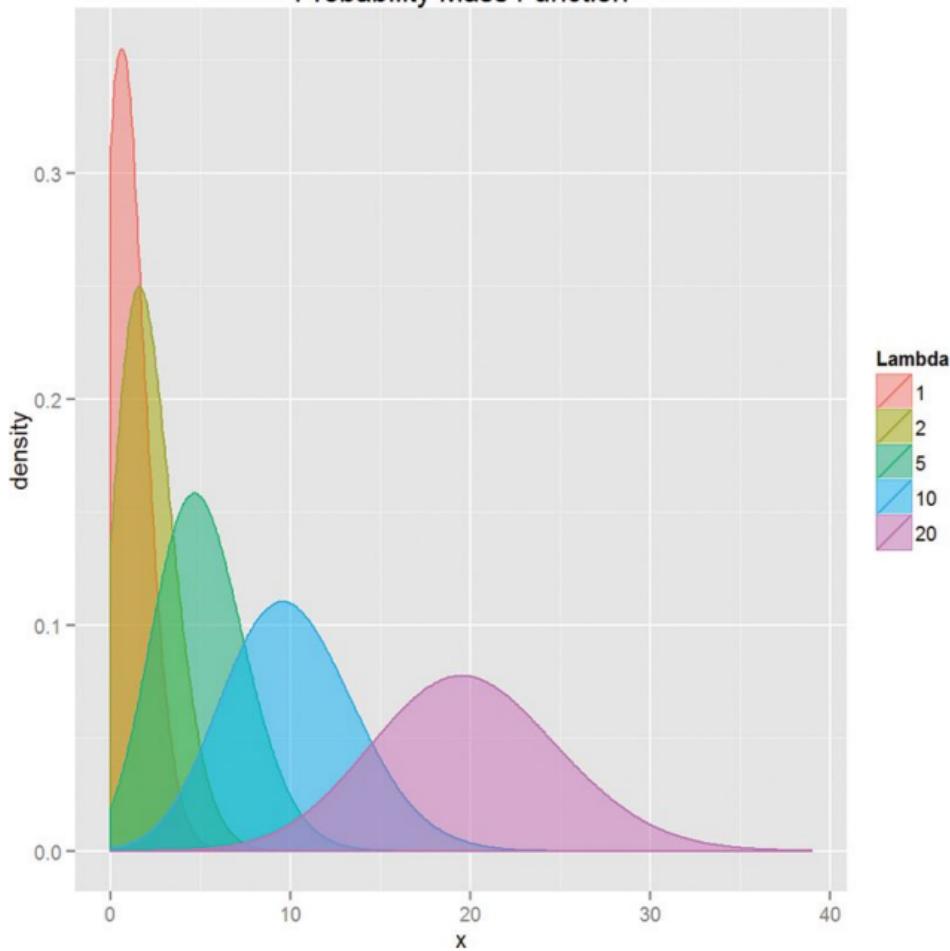
```
> require(ggplot2)
> ggplot(pois, aes(x=x)) + geom_histogram(binwidth=1)
+
+ facet_wrap(~ Lambda) + ggtitle("Probability Mass
Function")
```

Another, perhaps more compelling, way to visualize this convergence to normality is within overlaid density plots, as seen in [Figure 14.7](#).

[Click here to view code image](#)

```
> ggplot(pois, aes(x=x)) +
+   geom_density(aes(group=Lambda, color=Lambda,
fill=Lambda),
+   adjust=4, alpha=1/2) +
+   scale_color_discrete() + scale_fill_discrete() +
+   ggtitle("Probability Mass Function")
```

### Probability Mass Function



**Figure 14.7** Density plots for 10,000 draws from the Poisson distribution at varying levels of  $\lambda$ . Notice how the density plots become more like the normal distribution.

## 14.4. Other Distributions

R supports many distributions, some of which are very common, while others are quite obscure. They are listed in [Table 14.1](#); the mathematical formulas, means and variances are in [Table 14.2](#).

Distribution	Random Number	Density	Distribution	Quantile
Normal	rnorm	dnorm	pnorm	qnorm
Binomial	rbinom	dbinom	pbinom	qbinom
Poisson	rpois	dpois	ppois	qpois
t	rt	dt	pt	qt
F	rf	df	pf	qf
Chi-Squared	rchisq	dcchisq	pchisq	qchisq
Gamma	rgamma	dgamma	pgamma	qgamma
Geometric	rgeom	dgeom	pgeom	qgeom
Negative Binomial	rnbnom	dnbinom	pnbinom	qnbinom
Exponential	rexp	dexp	pexp	qexp
Weibull	rweibull	dweibull	pweibull	qweibull
Uniform (Continuous)	runif	dunif	punif	qunif
Beta	rbeta	dbeta	pbeta	qbeta
Cauchy	rcauchy	dcauchy	pcauchy	qcauchy
Multinomial	rmultinom	dmultinom	pmultinom	qmultinom
Hypergeometric	rhyper	dhyper	phyper	qhyper
Log-normal	rlnorm	dlnorm	plnorm	qlnorm
Logistic	rlogis	dlogis	plogis	qlogis

**Table 14.1 Statistical Distributions and their Functions**

Distribution	Formula	Mean	Variance
Normal	$f(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	$\mu$	$\sigma^2$
Binomial	$p(x; n, p) = \binom{n}{x} p^x (1-p)^{n-x}$	$np$	$np(1-p)$
Poisson	$p(i) = \binom{n}{i} p^i (1-p)^{n-i}$	$\lambda$	$\lambda$
t	$f(x; n) = \frac{\Gamma(\frac{n+1}{2})}{\sqrt{n\pi}\Gamma(\frac{n}{2})} \left(1 + \frac{x^2}{n}\right)^{-\frac{n+1}{2}}$	0	$\frac{n}{n-2}$
F	$f(x; \lambda_1, \lambda_2) = \frac{\sqrt{\frac{(\lambda_1 x)^{\lambda_1} \lambda_2^{\lambda_2}}{(\lambda_1 x + \lambda_2)^{\lambda_1 + \lambda_2}}}}{xB(\frac{\lambda_1}{2}, \frac{\lambda_2}{2})}$	$\frac{\lambda_2}{\lambda_2 - 2}$	$\frac{2\lambda_2^2(\lambda_1 + \lambda_2 - 2)}{\lambda_1(\lambda_2 - 2)^2(\lambda_2 - 4)}$
Chi-Squared	$f(x; n) = \frac{e^{-\frac{x}{2}} y^{(\frac{n}{2})-1}}{2^{\frac{n}{2}} \Gamma(\frac{n}{2})}$	$n$	$2n$
Gamma	$f(x; \lambda, s) = \frac{\lambda e^{-\lambda x} (\lambda x)^{s-1}}{\Gamma(s)}$	$\frac{s}{\lambda}$	$\frac{s}{\lambda^2}$
Geometric	$p(x; p) = p(1-p)^{x-1}$	$\frac{1}{\lambda}$	$\frac{1}{\lambda^2}$
Negative Binomial	$p(x; r, p) = \binom{x-1}{r-1} p^r (1-p)^{x-r}$	$\frac{r}{p}$	$\frac{r(1-p)}{p^2}$

Exponential	$f(x; \lambda) = \lambda e^{-\lambda x}$	$\frac{1}{\lambda}$	$\frac{1}{\lambda^2}$
Weibull	$f(x; \lambda, k) = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}$	$\lambda \Gamma(1 + \frac{1}{k})$	$\lambda^2 \Gamma(1 + \frac{2}{k}) - \mu^2$
Uniform	$f(x; a, b) = \frac{1}{b-a}$	$\frac{a+b}{2}$	$\frac{(b-a)^2}{12}$
Beta	$f(x; \alpha, \beta) = \frac{1}{B(\alpha, \beta)} x^{\alpha-1} (1-x)^{\beta-1}$	$\frac{\alpha}{\alpha+\beta}$	$\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$
Cauchy	$f(x; s, t) = \frac{s}{\pi(s^2 + (x-t)^2)}$	Undefined	Undefined
Multinomial	$p(x_1, \dots, x_k; n, p_1, \dots, p_k) = \frac{n!}{x_1! \cdots x_k!} p_1^{x_1} \cdots p_k^{x_k}$	$np_i$	$np_i(1-p_i)$
Hypergeometric	$p(x; N, n, m) = \frac{\binom{m}{x} \binom{N-m}{n-x}}{\binom{N}{n}}$	$\frac{nm}{N}$	$\frac{nm}{N} \left[ \frac{(n-1)(m-1)}{N-1} + 1 - \frac{nm}{N} \right]$
Log-normal	$f(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$	$e^{\mu + \frac{\sigma^2}{2}}$	$(e^{\sigma^2} - 1)e^{2\mu + \sigma^2}$
Logistic	$f(x; \mu, s) = \frac{e^{-\frac{x-\mu}{s}}}{s(1 + e^{-\frac{x-\mu}{s}})^2}$	$\mu$	$\frac{1}{3}s^2\pi^2$

**Table 14.2 Formulas, Means and Variances for Various Statistical Distributions (The  $B$  in the F distribution is the beta function,**

$$B(x, y) = \int_0^1 t^{x-1} (1-t)^{y-1} dt$$

## 14.5. Conclusion

R facilitates the use of many different probability distributions through the various random number, density, distribution and quantile functions outlined in [Table 14.1](#). We focused on three distributions—normal, Bernoulli and Poisson—in detail as they are the most commonly used. The formulas for every distribution available in the base packages of R, along with their means and variances, are listed in [Table 14.2](#).

# Chapter 15. Basic Statistics

Some of the most common tools used in statistics are means, variances, correlations and t-tests. These are all well represented in R with easy-to-use functions such as mean, var, cor and t.test.

## 15.1. Summary Statistics

The first thing many people think of in relation to statistics is the average, or mean, as it is properly called. We start by looking at some simple numbers and later in the chapter play with bigger data-sets. First we generate a random sampling of 100 numbers between 1 and 100.

[Click here to view code image](#)

```
> x <- sample(x = 1:100, size = 100, replace = TRUE)
> x
[1] 93 98 84 62 18 12 40 13 30 4 95 18 55 46 2 24
[17] 54 91 9 57 74 6 11 38 67 13 40 87 2 85 4 6
[33] 61 28 37 61 10 87 41 10 11 4 37 84 54 69 21 33
[49] 37 44 46 78 6 50 88 74 76 31 67 68 1 23 31 51
[65] 22 64 100 12 20 56 74 61 52 4 28 62 90 66 34 11
```

```
[81] 21 78 17 94 9 80 92 83 72 43 20 44 3 43 46 72  
[97] 32 61 16 12
```

sample uniformly draws size entries from x.  
Setting replace=TRUE means that the same number can be drawn multiple times.

Now that we have a vector of data we can calculate the mean.

```
> mean(x)  
[1] 44.51
```

This is the simple arithmetic mean.

$$E[X] = \frac{\sum_{i=1}^N x_i}{N} \quad (15.1)$$

Simple enough. Because this is statistics, we need to consider cases where some data are missing. To create this we take x and randomly set 20% of the elements to NA.

[Click here to view code image](#)

```
> # copy x  
> y <- x  
> # choose a random 20 elements, using sample, to set to  
NA
```

```
> y[sample(x = 1:100, size = 20, replace = FALSE)] <- NA  
> y  
[1] 93 98 84 62 18 12 40 NA 30 4 95 18 55 46 2 24  
[17] 54 91 NA 57 NA 6 11 38 67 NA 40 87 2 NA 4 6  
[33] 61 28 37 NA 10 NA 41 10 11 4 37 84 54 69 21 33  
[49] 37 44 46 78 6 50 88 74 76 NA 67 68 NA 23 31 51  
[65] 22 64 100 12 20 56 74 NA 52 4 NA 62 90 NA 34 11  
[81] 21 78 17 NA 9 80 NA 83 NA NA 20 44 NA NA 46 NA  
[97] 32 61 NA 12
```

Using mean on y will return NA. This is because, by default, if mean encounters even one element that is NA it will return NA. This is to avoid providing misleading information.

```
> mean(y)  
[1] NA
```

To have the NAs removed before calculating the mean, set na.rm to TRUE.

```
> mean(y, na.rm = TRUE)  
[1] 43.5875
```

To calculate the weighted mean of a set of numbers, the function weighted.mean takes a vector of numbers and a vector of weights. It also

has an optional argument, na.rm, to remove NAs before calculating; otherwise, a vector with NA values will return NA.

[Click here to view code image](#)

```
> grades <- c(95, 72, 87, 66)
> weights <- c(1/2, 1/4, 1/8, 1/8)
> mean(grades)
[1] 80
> weighted.mean(x = grades, w = weights)
[1] 84.625
```

The formula for weighted.mean is in [Equation 15.2](#), which is the same as the expected value of a random variable.

$$E[X] = \frac{\sum_{i=1}^N w_i x_i}{\sum_{i=1}^N w_i} = \sum_{i=1}^N p_i x_i \quad (15.2)$$

Another vitally important metric is the variance, which is calculated with var.

```
> var(x)
[1] 865.5049
```

This calculates variance as

$$Var(x) = \frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1} \quad (15.3)$$

which can be verified in R.

[Click here to view code image](#)

```
> var(x)
[1] 865.5049
> sum((x - mean(x))^2)/(length(x) - 1)
[1] 865.5049
```

Standard deviation is the square root of variance and is calculated with sd. Like mean and var, sd has the na.rm argument to remove NAs before computation; otherwise, any NAs will cause the answer to be NA.

```
> sqrt(var(x))
[1] 29.41947
> sd(x)
[1] 29.41947
> sd(y)
[1] NA
> sd(y, na.rm = TRUE)
[1] 28.89207
```

Other commonly used functions for summary statistics are min, max and median. Of course, all of these also have na.rm arguments.

```
> min(x)  
[1] 1  
> max(x)  
[1] 100  
> median(x)  
[1] 43  
> min(y)  
[1] NA  
> min(y, na.rm = TRUE)  
[1] 2
```

The median, as calculated before, is the middle of an ordered set of numbers. For instance, the median of 5, 2, 1, 8 and 6 is 5. In the case when there is an even amount of numbers, the median is the mean of the middle two numbers. For 5, 1, 7, 4, 3, 8, 6 and 2 the median is 4.5.

A helpful function that computes the mean, minimum, maximum and median is summary. There is no need to specify na.rm because if there

are NAs, they are automatically removed and their count is included in the results.

[Click here to view code image](#)

```
> summary(x)
```

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
1.00	17.75	43.00	44.51	68.25	100.00

```
> summary(y)
```

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
2.00	18.00	40.50	43.59	67.00	100.00	20

This summary also displayed the first and third quantiles. These can be computed using quantile.

[Click here to view code image](#)

```
> # calculate the 25th and 75th quantile
```

```
> quantile(x, probs = c(0.25, 0.75))
```

25% 75%

17.75 68.25

```
> # try the same on y
```

```
> quantile(y, probs = c(0.25, 0.75))
```

**Error: missing values and NaN's not allowed if 'na.rm' is FALSE**

```
> # this time use na.rm=TRUE
```

```
> quantile(y, probs = c(0.25, 0.75), na.rm = TRUE)
```

25% 75%

18 67

```
> # compute other quantiles  
> quantile(x, probs = c(0.1, 0.25, 0.5, 0.75, 0.99))  
10% 25% 50% 75% 99%  
6.00 17.75 43.00 68.25 98.02
```

Quantiles are numbers in a set where a certain percentage of the numbers are smaller than that quantile. For instance, of the numbers one through 200, the 75th quantile—the number that is larger than 75% of the numbers—is 150.25.

## 15.2. Correlation and Covariance

When dealing with more than one variable, we need to test their relationships with each other. Two simple, straightforward methods are correlation and covariance. To examine these concepts we look at the economics data from ggplot2.

[Click here to view code image](#)

```
> require(ggplot2)  
> head(economics)  
date pce pop psavert uempmed unem-  
ploy year month  
1 1967-06-30 507.8 198712 9.8 4.5 2944 1967 Jun  
2 1967-07-31 510.9 198911 9.8 4.7 2945 1967 Jul  
3 1967-08-31 516.7 199113 9.0 4.6 2958 1967 Aug
```

4	1967-09-30	513.3	199311	9.8	4.9	3143	1967	Sep
5	1967-10-31	518.5	199498	9.7	4.7	3066	1967	Oct
6	1967-11-30	526.2	199657	9.4	4.8	3018	1967	Nov

In the economics dataset, pce is personal consumption expenditures and psavert is the personal savings rate. We calculate their correlation using cor.

[Click here to view code image](#)

```
> cor(economics$pce, economics$psavert)
[1] -0.9271222
```

This very low correlation makes sense because spending and saving are opposites of each other. Correlation is defined as

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{(n - 1)s_x s_y} \quad (15.4)$$

where  $\bar{x}$  and  $\bar{y}$  are the means of  $x$  and  $y$ , and  $s_x$  and  $s_y$  are the standard deviations of  $x$  and  $y$ . It can range between -1 and 1, with higher positive numbers meaning a closer relationship between the two variables, lower negative numbers meaning an inverse relationship and num-

bers near zero meaning no relationship. This can be easily checked by computing [Equation 15.4](#).

[Click here to view code image](#)

```
> # use cor to calculate correlation
> cor(economics$pce, economics$psavert)
[1] 0.9271222
>
> ## calculate each part of correlation
> xPart <- economics$pce - mean(economics$pce)
> yPart <- economics$psavert - mean(economics$psavert)
> nMinusOne <- (nrow(economics) - 1)
> xSD <- sd(economics$pce)
> ySD <- sd(economics$psavert)
> # use correlation formula
> sum(xPart * yPart) / (nMinusOne * xSD * ySD)
[1] -0.9271222
```

To compare multiple variables at once, use cor on a matrix (only for numeric variables).

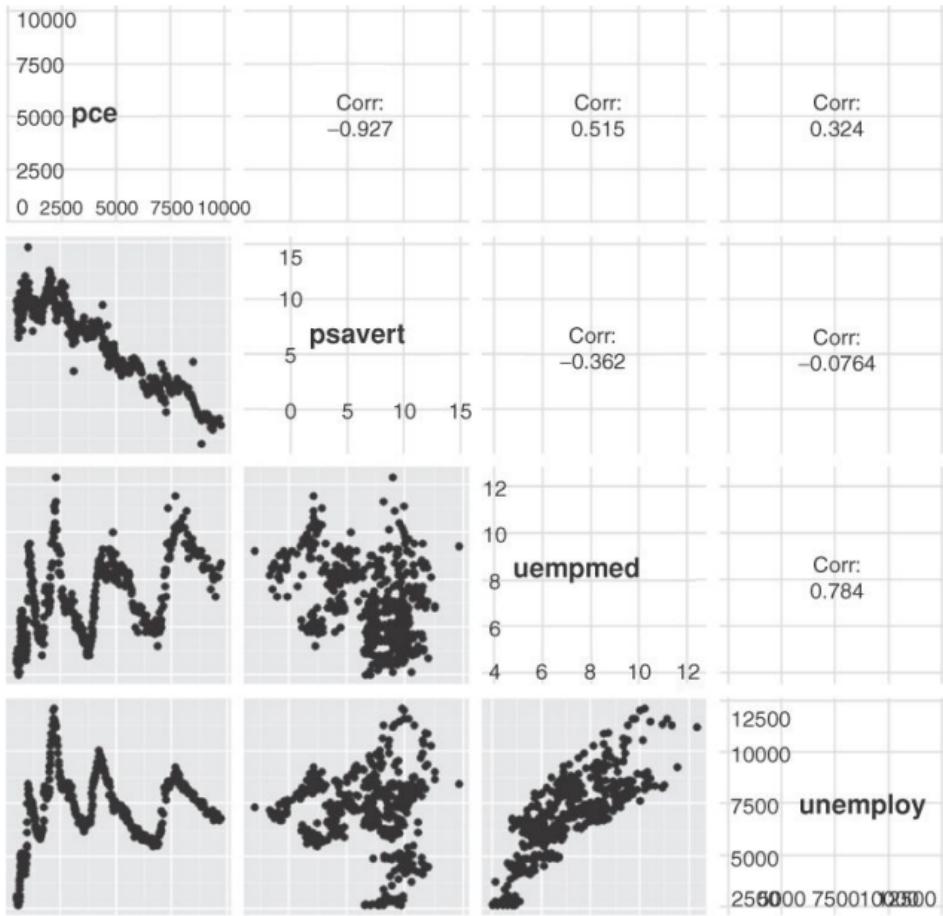
[Click here to view code image](#)

```
> cor(economics[, c(2, 4:6)])
      pce    psavert    uempmed    unemploy
pce    1.0000000 -0.9271221  0.5145862  0.32441514
psavert -0.9271222  1.0000000 -0.3615301 -0.07641651
uempmed  0.5145862 -0.36153012 1.0000000  0.78427918
unemploy 0.3244151 -0.07641651  0.7842792  1.00000000
```

Because this is just a table of numbers, it would be helpful to also visualize the information using a plot. For this we use the `ggpairs` function from the `GGally` package (a collection of helpful plots built on `ggplot2`) shown in [Figure 15.1](#). This shows a scatterplot of every variable in the data against every other variable. Loading `GGally` also loads the `reshape` package, which causes namespace issues with the newer `reshape2` package. So rather than load `GGally`, we call its function using the `::` operator, which allows access to functions within a package without loading it.

[Click here to view code image](#)

```
> GGally::ggpairs(economics[, c(2, 4:6)], params = list(labelSize = 8))
```



**Figure 15.1** Pairs plot of economics data showing the relationship between each pair of variables as a scatterplot with the correlations printed as numbers.

This is similar to a small multiples plot except that each pane has different  $x$ - and  $y$ -axes. While

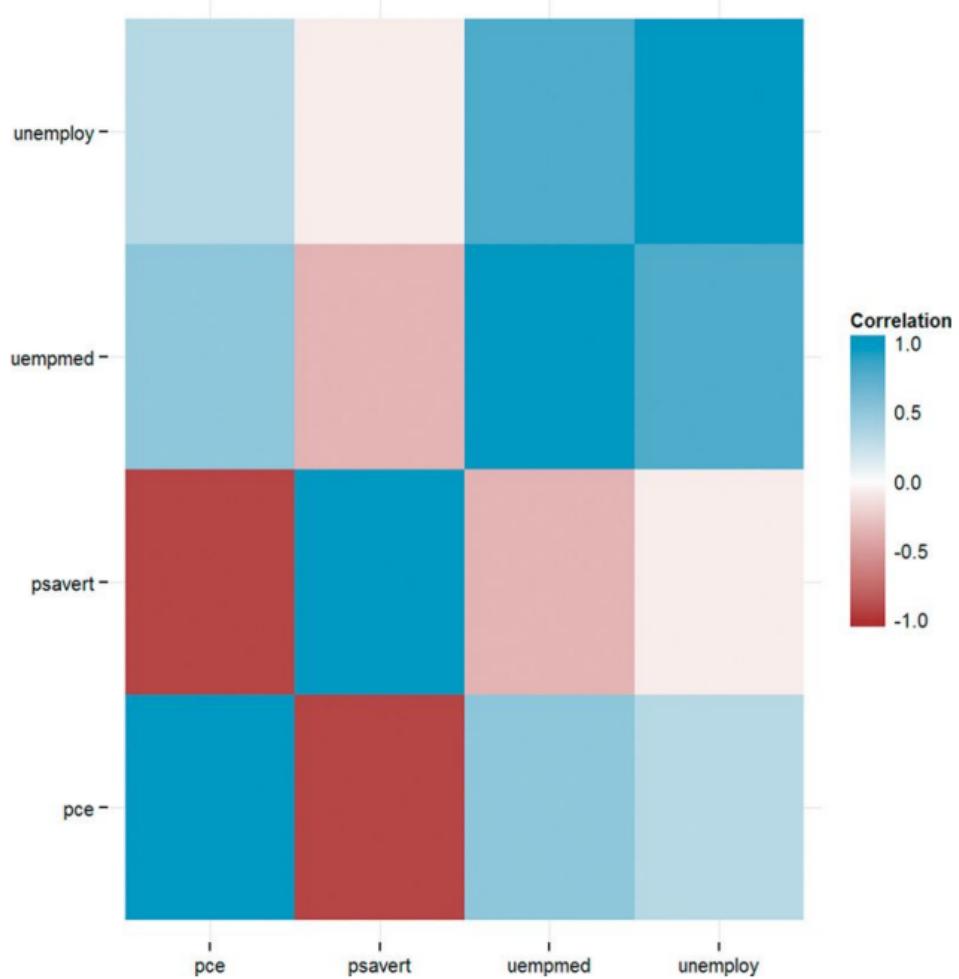
this shows the original data, it does not actually show the correlation. To show that we build a heatmap of the correlation numbers, as shown in [Figure 15.2](#). High positive correlation indicates a positive relationship between the variables, high negative correlation indicates a negative relationship between the variables and near zero correlation indicates no strong relationship.

[Click here to view code image](#)

```
> # load the reshape package for melting the data
> require(reshape2)
> # load the scales package for some extra plotting features
> require(scales)
> # build the correlation matrix
> econCor <- cor(economics[, c(2, 4:6)])
> # melt it into the long format
> econMelt <- melt(econCor, varnames=c("x", "y"),
+                     value.name="Correlation")
> # order it according to the correlation
> econMelt <- econMelt[order(econMelt$Correlation), ]
> # display the melted data
> econMelt
      x     y Correlation
2 psavert   pce -0.92712221
5   pce psavert -0.92712221
7 uempmed psavert -0.36153012
```

```
10 psavert uempmed -0.36153012
8 unemploy psavert -0.07641651
14 psavert unemploy -0.07641651
4 unemploy pce 0.32441514
13 pce unemploy 0.32441514
3 uempmed pce 0.51458618
9 pce uempmed 0.51458618
12 unemploy uempmed 0.78427918
15 uempmed unemploy 0.78427918
1 pce pce 1.00000000
6 psavert psavert 1.00000000
11 uempmed uempmed 1.00000000
16 unemploy unemploy 1.00000000
> ## plot it with ggplot
> # initialize the plot with x and y on the x and y axes
> ggplot(econMelt, aes(x=x, y=y)) +
+   # draw tiles filling the color based on Correlation
+   geom_tile(aes(fill=Correlation)) +
+   # make the fill (color) scale a three color gradient with
muted
+   # red for the low point, white for the middle and steel
blue
+   # for the high point
+   # the guide should be a colorbar with no ticks, whose
height is
+   # 10 lines
+   # limits indicates the scale should be filled from -1 to 1
+   scale_fill_gradient2(low=muted("red"), mid="white",
+                     high="steelblue",
```

```
+     guide=guide_colorbar(ticks=FALSE, bar-
height=10),
+     limits=c(-1, 1)) +
+   # use the minimal theme so there are no extras in the
plot
+   theme_minimal() +
+   # make the x and y labels blank
+   labs(x=NULL, y=NULL)
```



**Figure 15.2** Heatmap of the correlation of the economics data. The diagonal has elements with correlation 1 because every element is perfectly correlated with itself. Red indicates highly negative correlation, blue indicates highly positive correlation and white is no correlation.

Missing data is just as much a problem with cor as it is with mean and var, but it is dealt with differently because multiple columns are being considered simultaneously. Instead of specifying na.rm=TRUE to remove NA entries, one of "all.obs", "complete.obs", "pairwise.complete.obs", "everything" or "na.or.complete" is used. To illustrate this we first make a five-column matrix where only the fourth and fifth columns have no NA values; the other columns have one or two NAs.

[Click here to view code image](#)

```
> m <- c(9, 9, NA, 3, NA, 5, 8, 1, 10, 4)
> n <- c(2, NA, 1, 6, 6, 4, 1, 1, 6, 7)
> p <- c(8, 4, 3, 9, 10, NA, 3, NA, 9, 9)
```

```
> q <- c(10, 10, 7, 8, 4, 2, 8, 5, 5, 2)
> r <- c(1, 9, 7, 6, 5, 6, 2, 7, 9, 10)
> # combine them together
> theMat <- cbind(m, n, p, q, r)
```

The first option for use is "everything", which means that the entirety of all columns must be free of NAs, otherwise the result is NA. Running this should generate a matrix of all NAs except ones on the diagonal—because a vector is always perfectly correlated with itself—and between q and r. With the second option—"all.obs"—even a single NA in any column will cause an error.

[Click here to view code image](#)

```
> cor(theMat, use = "everything")
   m  n  p      q      r
m 1 NA NA      NA      NA
n NA 1 NA      NA      NA
p NA NA 1      NA      NA
q NA NA NA  1.0000000 -0.4242958
r NA NA NA -0.4242958  1.0000000
> cor(theMat, use = "all.obs")
Error: missing observations in cov/cor
```

The third and fourth options—"complete.obs" and "na.or.complete"—work similarly to each

other in that they keep only rows where every entry is not NA. That means our matrix will be reduced to rows 1, 4, 7, 9 and 10, and then have its correlation computed. The difference is that "complete.obs" will return an error if not a single complete row can be found, while "na.or.complete" will return NA in that case.

[Click here to view code image](#)

```
> cor(theMat, use = "complete.obs")
      m      n      p      q      r
m 1.0000000 -0.5228840 -0.2893527 0.2974398 -0.3459470
n -0.5228840 1.0000000 0.8090195 -0.7448453 0.9350718
p -0.2893527 0.8090195 1.0000000 -0.3613720 0.6221470
q  0.2974398 -0.7448453 -0.3613720 1.0000000 -0.9059384
r -0.3459470 0.9350718 0.6221470 -0.9059384 1.0000000
> cor(theMat, use = "na.or.complete")
      m      n      p      q      r
m 1.0000000 -0.5228840 -0.2893527 0.2974398 -0.3459470
n -0.5228840 1.0000000 0.8090195 -0.7448453 0.9350718
p -0.2893527 0.8090195 1.0000000 -0.3613720 0.6221470
q  0.2974398 -0.7448453 -0.3613720 1.0000000 -0.9059384
r -0.3459470 0.9350718 0.6221470 -0.9059384 1.0000000
> # calculate the correlation just on complete rows
> cor(theMat[c(1, 4, 7, 9, 10), ])
      m      n      p      q      r
m 1.0000000 -0.5228840 -0.2893527 0.2974398 -0.3459470
n -0.5228840 1.0000000 0.8090195 -0.7448453 0.9350718
```

```
p -0.2893527 0.8090195 1.0000000 -0.3613720 0.6221470
q 0.2974398 -0.7448453 -0.3613720 1.0000000 -0.9059384
r -0.3459470 0.9350718 0.6221470 -0.9059384 1.0000000
> # compare "complete.obs" and computing on select rows
> # should give the same result
> identical(cor(theMat, use = "complete.obs"),
+   cor(theMat[c(1, 4, 7, 9, 10), ]))
[1] TRUE
```

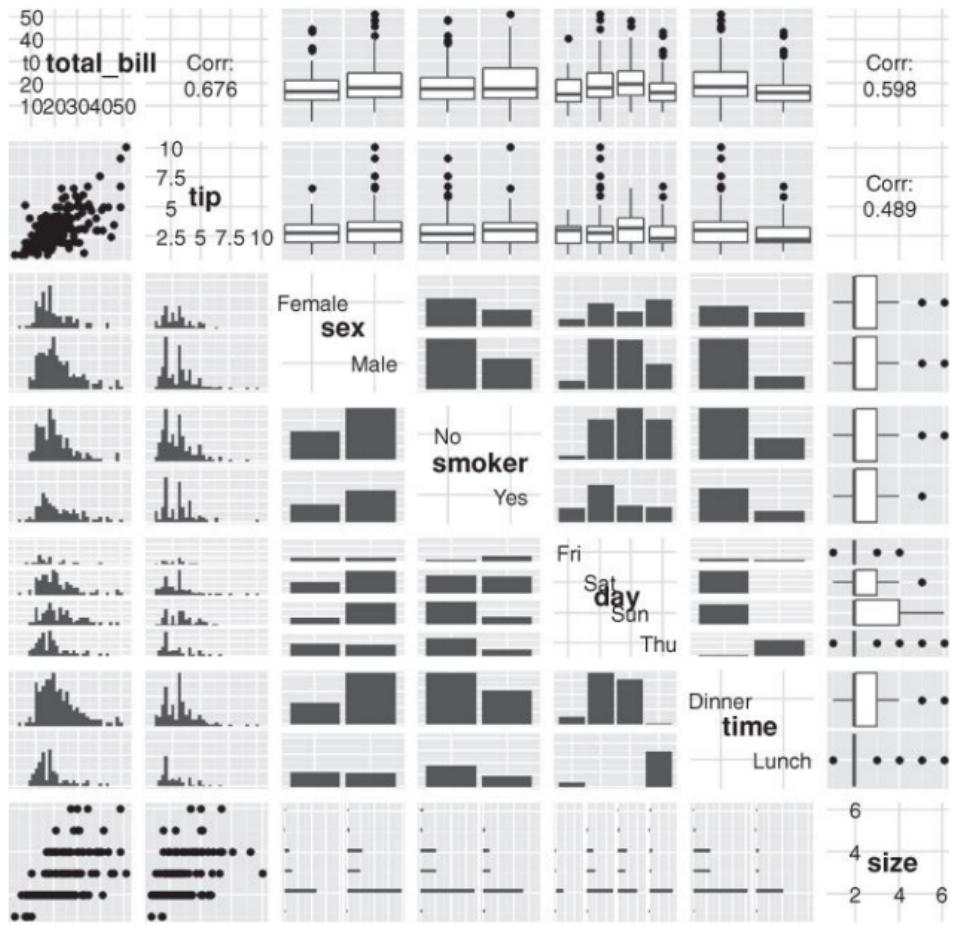
The final option is "pairwise.complete", which is much more inclusive. It compares two columns at a time and keeps rows—for those two columns—where neither entry is NA. This is essentially the same as computing the correlation between every combination of two columns with use set to "complete.obs".

[Click here to view code image](#)

```
> # the entire correlation matrix
> cor(theMat, use = "pairwise.complete.obs")
      m      n      p      q      r
m 1.0000000 -0.02511812 -0.3965859 0.4622943 -0.2001722
n -0.02511812 1.0000000 0.8717389 -0.5070416 0.5332259
p -0.39658588 0.87173889 1.0000000 -0.5197292 0.1312506
q 0.46229434 -0.50704163 -0.5197292 1.0000000 -0.4242958
r -0.20017222 0.53322585 0.1312506 -0.4242958 1.0000000
> # compare the entries for m vs n to this matrix
> cor(theMat[, c("m", "n")], use = "complete.obs")
```

```
m      n  
m 1.00000000 -0.02511812  
n -0.02511812  1.00000000  
> # compare the entries for m vs p to this matrix  
> cor(theMat[, c("m", "p")], use = "complete.obs")  
      m      p  
m 1.0000000 -0.3965859  
p -0.3965859  1.0000000
```

To see `ggpairs` in all its glory, look at tips data from the `reshape2` package in [Figure 15.3](#). This shows every pair of variables in relation to each other building either histograms, boxplots or scatterplots depending on the combination of continuous and discrete variables. While a data dump like this looks really nice, it is not always the most informative form of exploratory data analysis.



**Figure 15.3** ggpairs plot of tips data using both continuous and categorial variables.

[Click here to view code image](#)

```
> data(tips, package = "reshape2")
> head(tips)
  total_bill  tip  sex smoker day  time size
    16.99 1.01 Female No   Sun Dinner 2
    10.34 1.66 Female No   Sun Dinner 3
    21.01 3.50 Female No   Sun Dinner 3
    23.68 3.31 Female No   Sun Dinner 2
    24.02 3.61 Female No   Sun Dinner 4
```

```
1 16.99 1.01 Female No Sun Dinner 2
2 10.34 1.66 Male   No Sun Dinner 3
3 21.01 3.50 Male   No Sun Dinner 3
4 23.68 3.31 Male   No Sun Dinner 2
5 24.59 3.61 Female No Sun Dinner 4
6 25.29 4.71 Male   No Sun Dinner 4
> GGally::ggpairs(tips)
```

No discussion of correlation would be complete without the old refrain, “Correlation does not mean causation.” In other words, just because two variables are correlated does not mean they have an effect on each other. This is exemplified in xkcd<sup>1</sup> comic number 552. There is even an R package, RXKCD, for downloading individual comics. Running the following code should generate a pleasant surprise.

<sup>1</sup> xkcd is a Web comic by Randall Munroe, beloved by statisticians, physicists, mathematicians and the like. It can be found at <http://xkcd.com>.

```
> require(RXKCD)
> getXKCD(which = "552")
```

Similar to correlation is covariance, which is like a variance between variables; its formula is

in [Equation 15.5](#). Notice the similarity to correlation in [Equation 15.4](#) and variance in [Equation 15.3](#).

$$\text{cov}(X, Y) = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y}) \quad (15.5)$$

The cov function works similarly to the cor function, with the same arguments for dealing with missing data. In fact, ?cor and ?cov pull up the same help menu.

[Click here to view code image](#)

```
> cov(economics$pce, economics$psavert)
[1] -8412.231
> cov(economics[, c(2, 4:6)])
      pce    psavert   uempmed   unemploy
pce    6810308.380 -8412.230823 2202.786256 1573882.2016
psavert -8412.231  12.088756 -2.061893 -493.9304
uempmed  2202.786 -2.061893  2.690678 2391.6039
unem-
ploy 1573882.202 -493.930390 2391.603889 3456013.5176
> # check that cov and cor*sd*sd are the same
> identical(cov(economics$pce, economics$psavert),
+           cor(economics$pce, economics$psavert) *
+           sd(economics$pce) * sd(economics$psavert))
[1] TRUE
```

## 15.3. T-Tests

In traditional statistics classes, the t-test— invented by William Gosset while working at the Guinness brewery—is taught for conducting tests on the mean of data or for comparing two sets of data. To illustrate this we continue to use the tips data from [Section 15.2](#).

[Click here to view code image](#)

```
> head(tips)
  total_bill tip sex smoker day time size
1   16.99 1.01 Female  No Sun Dinner 2
2   10.34 1.66 Male   No Sun Dinner 3
3   21.01 3.50 Male   No Sun Dinner 3
4   23.68 3.31 Male   No Sun Dinner 2
5   24.59 3.61 Female No Sun Dinner 4
6   25.29 4.71 Male   No Sun Dinner 4
> # sex of the server
> unique(tips$sex)
[1] Female Male
Levels: Female Male
> # day of the week
> unique(tips$day)
[1] Sun Sat Thur Fri
Levels: Fri Sat Sun Thur
```

### 15.3.1. One-Sample T-Test

First we conduct a one-sample t-test on whether the average tip is equal to \$2.50. This test essentially calculates the mean of data and builds a confidence interval. If the value we are testing falls within that confidence interval then we can conclude that it is the true value for the mean of the data; otherwise, we conclude that it is not the true mean.

[Click here to view code image](#)

```
> t.test(tips$tip, alternative = "two.sided", mu = 2.5)
One Sample t-test
data: tips$tip
t = 5.6253, df = 243, p-value = 5.08e-08
alternative hypothesis: true mean is not equal to 2.5
95 percent confidence interval:
2.823799 3.172758
sample estimates:
mean of x
2.998279
```

The output very nicely displays the setup and results of the hypothesis test of whether the mean is equal to \$2.50. It prints the t-statistic, the de-

grees of freedom and p-value. It also provides the 95% confidence interval and mean for the variable of interest. The p-value indicates that the null hypothesis<sup>2</sup> should be rejected, and we conclude that the mean is not equal to \$2.50.

2. The null hypothesis is what is considered to be true, in this case that the mean is equal to \$2.50.

We encountered a few new concepts here. The t-statistic is the ratio where the numerator is the difference between the estimated mean and the hypothesized mean and the denominator is the standard error of the estimated mean. It is defined in Equation 15.6.

$$\text{t-statistic} = \frac{(\bar{x} - \mu_0)}{s_{\bar{x}}/\sqrt{n}} \quad (15.6)$$

Here,  $\bar{x}$  is the estimated mean,  $\mu_0$  is the hypothesized mean and  $\frac{s_{\bar{x}}}{\sqrt{n}}$  is the standard error of  $\bar{x}$ .<sup>3</sup>

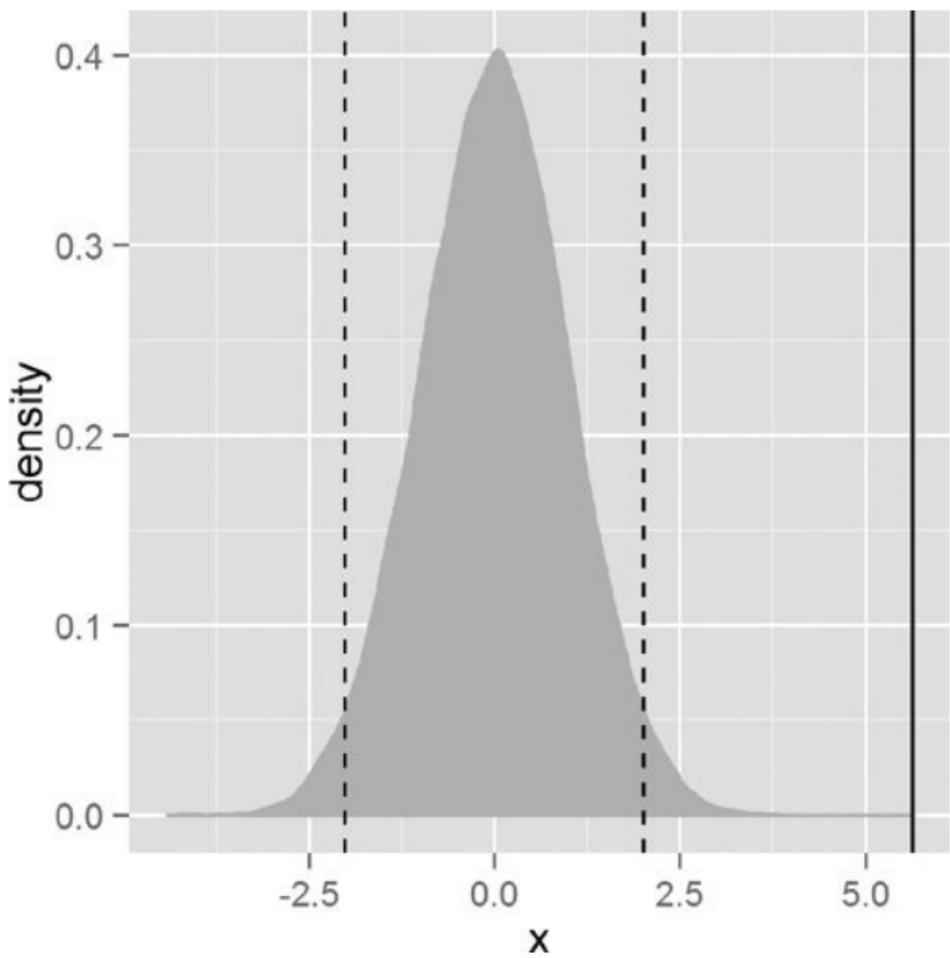
3.  $s_{\bar{x}}$  is the standard deviation of the data and  $n$  is the number of observations.

If the hypothesized mean is correct, then we expect the t-statistic to fall somewhere in the

middle—about two standard deviations from the mean—of the t distribution. In [Figure 15.4](#) we see that the thick black line, which represents the estimated mean, falls so far outside the distribution that we must conclude that the mean is not equal to \$2.50.

[Click here to view code image](#)

```
> ## build a t distribution
> randT <- rt(30000, df=NROW(tips)-1)
>
> # get t-statistic and other information
> tipTTest <- t.test(tips$tip, alternative="two.sided",
mu=2.50)
>
> # plot it
> ggplot(data.frame(x=randT)) +
+   geom_density(aes(x=x), fill="grey", color="grey") +
+   geom_vline(xintercept=tipTTest$statistic) +
+   geom_vline(xintercept=mean(randT) + c(-2,
2)*sd(randT), linetype=2)
```



**Figure 15.4** t distribution and t-statistic for tip data. The dashed lines are two standard deviations from the mean in either direction. The thick black line, the t-statistic, is so far outside the distribution that we must reject the null hypothesis and conclude that the true mean is not \$2.50.

The p-value is an often misunderstood concept. Despite all the misinterpretations, a p-value is the probability, if the null hypothesis were correct, of getting as extreme, or more extreme, a result. It is a measure of how extreme the statistic—in this case, the estimated mean—is. If the statistic is too extreme, we conclude that the null hypothesis should be rejected. The main problem with p-values, however, is determining what should be considered too extreme. Ronald A. Fisher, the father of modern statistics, decided we should consider a p-value that is smaller than either 0.10, 0.05 or 0.01 to be too extreme. While those p-values have been the standard for decades, they were arbitrarily chosen, leading some

modern data scientists to question their usefulness. In this example, the p-value is  $5.0799885 \times 10^{-8}$ ; this is smaller than 0.01 so we reject the null hypothesis.

Degrees of freedom is another difficult concept to grasp but is pervasive throughout statistics. It represents the effective number of observations. Generally, the degrees of freedom for some statistic or distribution is the number of observations minus the number of parameters being estimated. In the case of the t distribution, one parameter, the standard error, is being estimated. In this example, there are `nrow(tips)-1=243` degrees of freedom.

Next we conduct a one-sided t-test to see if the mean is greater than \$2.50.

[Click here to view code image](#)

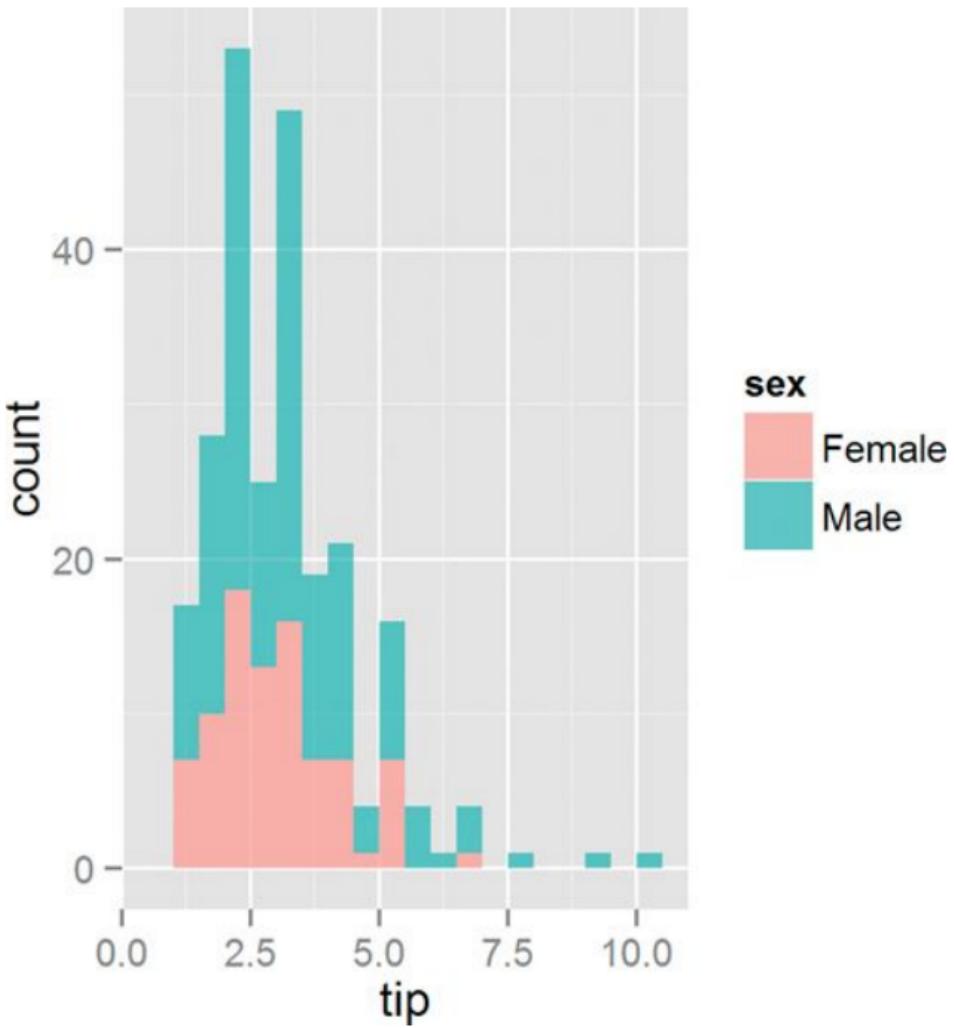
```
> t.test(tips$tip, alternative = "greater", mu = 2.5)
One Sample t-test
data: tips$tip
t = 5.6523, df = 243, p-value = 2.54e-08
alternative hypothesis: true mean is greater than 2.5
95 percent confidence interval:
```

```
2.852023 Inf  
sample estimates:  
mean of x  
2.998279
```

Once again, the p-value indicates that we should reject the null hypothesis and conclude that the mean is greater than \$2.50, which coincides nicely with the confidence interval.

### 15.3.2. Two-Sample T-Test

More often than not the t-test is used for comparing two samples. Continuing with the tips data, we compare how female and male servers are tipped. Before running the t-test, however, we first need to check the variance of each sample. A traditional t-test requires both groups to have the same variance, whereas the Welch two-sample t-test can handle groups with differing variances. We explore this both numerically and visually in [Figure 15.5](#).



**Figure 15.5** Histogram of tip amount by sex. Note that neither distribution appears to be normal.

## [Click here to view code image](#)

```
> # first just compute the variance for each group;  
> # using the the formula interface  
> # calculate the variance of tip for each level of sex  
  
> aggregate(tip ~ sex, data=tips, var)  
    sex      tip  
1 Female 1.3444282  
2 Male   2.217424  
  
> # now test for normality of tip distribution  
> shapiro.test(tips$tip)  
Shapiro-Wilk normality test  
data: tips$tip  
W = 0.8978, p-value = 8.2e-12  
> shapiro.test(tips$tip[tips$sex == "Female"])  
Shapiro-Wilk normality test  
data: tips$tip[tips$sex == "Female"]  
W = 0.9568, p-value = 0.005448  
> shapiro.test(tips$tip[tips$sex == "Male"])  
Shapiro-Wilk normality test  
data: tips$tip[tips$sex == "Male"]  
W = 0.8759, p-value = 3.708e-10  
> # all the tests fail so inspect visually  
> ggplot(tips, aes(x=tip, fill=sex)) +  
+   geom_histogram(binwidth=.5, alpha=1/2)
```

Since the data do not appear to be normally distributed, neither the standard F-test (via the var.test function) nor the Bartlett test (via the

`bartlett.test` function) will suffice. So we use the nonparametric Ansari-Bradley test to examine the equality of variances.

[Click here to view code image](#)

```
> ansari.test(tip ~ sex, tips)
Ansari-Bradley test
data: tip by sex
AB = 5582.5, p-value = 0.376
alternative hypothesis: true ratio of scales is not equal to 1
```

This test indicates that the variances are equal, meaning we can use the standard two-sample t-test.

[Click here to view code image](#)

```
> # setting var.equal=TRUE runs a standard two sample t-
test whereas
> # var.equal=FALSE (the default) would run the Welch
test
> t.test(tip ~ sex, data = tips, var.equal = TRUE)
Two Sample t-test
data: tip by sex
t = -1.3879, df = 242, p-value = 0.1665
alternative hypothesis: true difference in means is not equal
to 0
95 percent confidence interval:
```

-0.6197558 0.1074167

sample estimates:

mean in group Female mean in group Male

2.833448 3.089618

According to this test, the results were not significant, and we should conclude that female and male workers are tipped roughly equally. While all this statistical rigor is nice, a simple rule of thumb would be to see if the two means are within two standard deviations of each other.

[Click here to view code image](#)

```
> require(plyr)
> tipSummary <- ddply(tips, "sex", summarize,
+   tip.mean=mean(tip), tip.sd=sd(tip),
+   Lower=tip.mean -
2*tip.sd/sqrt(NROW(tip)),
+   Upper=tip.mean +
2*tip.sd/sqrt(NROW(tip)))
> tipSummary
   sex tip.mean tip.sd Lower Upper
1 Female 2.833448 1.159495 2.584827 3.082070
2 Male 3.089618 1.489102 2.851931 3.327304
```

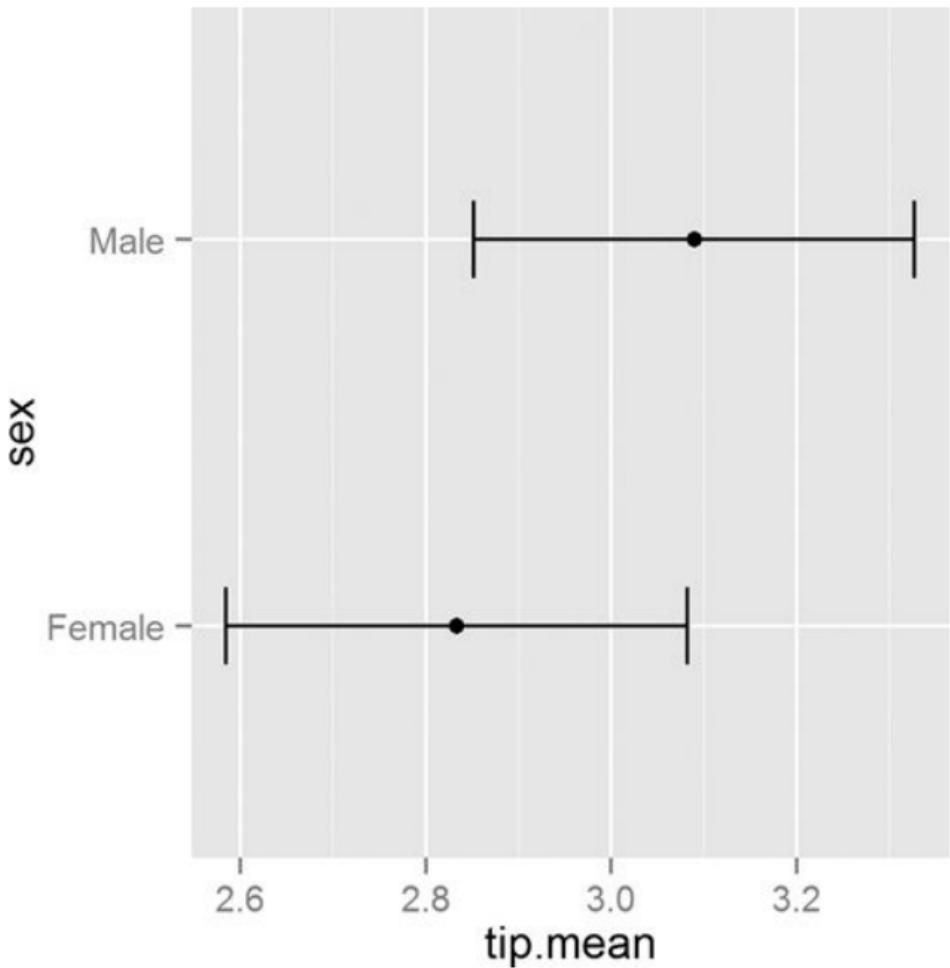
A lot happened in that code. First, ddply was used to split the data according to the levels of

sex. It then applied the summarize function to each subset of the data. This function applied the indicated functions to the data, creating a new data.frame.

As usual, we prefer visualizing the results rather than comparing numerical values. This requires reshaping the data a bit. The results, in [Figure 15.6](#), clearly show the confidence intervals overlapping, suggesting that the means for the two sexes are roughly equivalent.

[Click here to view code image](#)

```
> ggplot(tipSummary, aes(x=tip.mean, y=sex)) + geom  
  point() +  
  +   geom_errorbarh(aes(xmin=Lower, xmax=Upper),  
    height=.2)
```



**Figure 15.6** Plot showing the mean and two standard errors of tips broken down by the sex of the server.

### 15.3.3. Paired Two-Sample T-Test

For testing paired data (for example, measurements on twins, before and after treatment effects, father and son comparisons) a paired t-test should be used. This is simple enough to do by setting the paired argument in `t.test` to TRUE. To illustrate, we use data collected by Karl Pearson on the heights of fathers and sons that is located in the `UsingR` package. Heights are generally normally distributed, so we will forgo the tests of normality and equal variance.

[Click here to view code image](#)

```
> require(UsingR)
> head(father.son)
  fheight sheight
1 65.04851 59.77827
2 63.25094 63.21404
3 64.95532 63.34242
4 65.75250 62.79238
5 61.13723 64.28113
6 63.02254 64.24221
> t.test(father.son$fheight, father.son$sheight, paired =
TRUE)
Paired t-test
data: father.son$fheight and father.son$sheight
```

t = -11.7885, df = 1077, p-value < 2.2e-16

alternative hypothesis: true difference in means is not equal to 0

95 percent confidence interval:

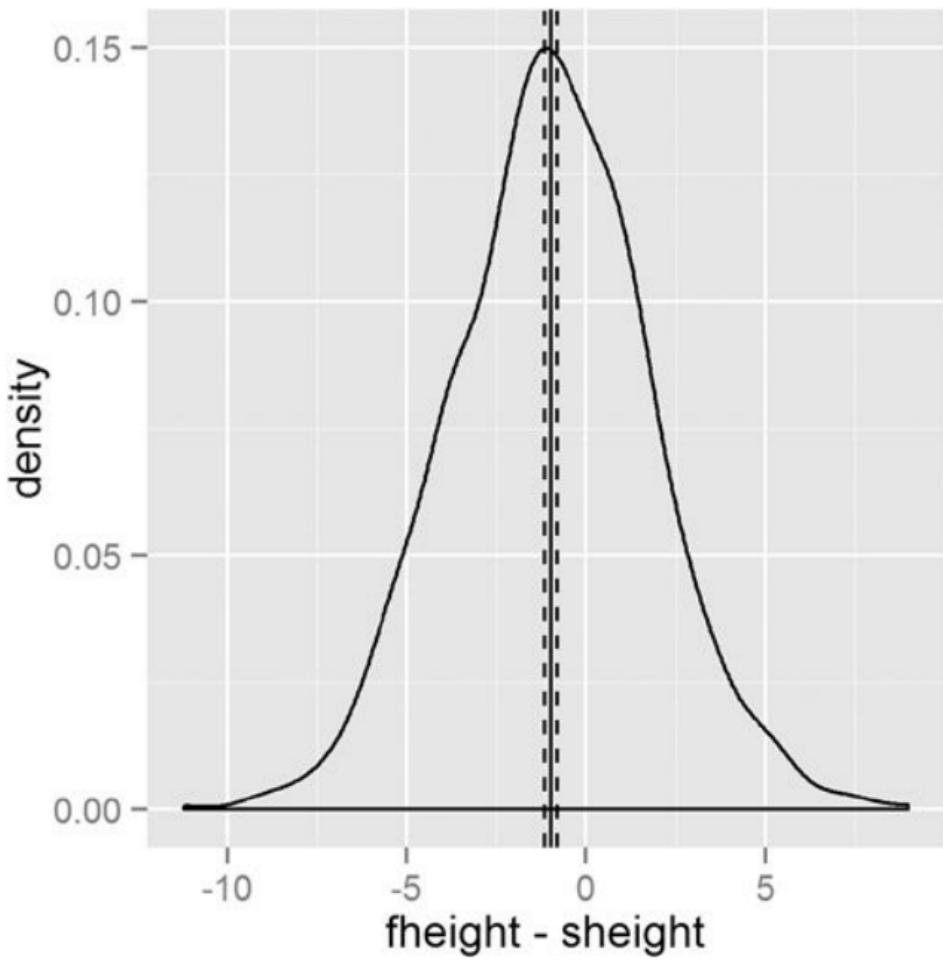
-1.1629160 -0.8310296

sample estimates:

mean of the differences

-0.9969728

This test shows that we should reject the null hypothesis and conclude that fathers and sons (at least for this dataset) have different heights. We visualize this data using a density plot of the differences, as shown in [Figure 15.7](#). In it we see a distribution with a mean not at zero and a confidence interval that barely excludes zero which agrees with the test.



**Figure 15.7** Density plot showing the difference of heights of fathers and sons.

[Click here to view code image](#)

```
> heightDiff <- father.son$fheight - father.son$sheight  
> ggplot(father.son, aes(x=fheight - sheight)) +
```

```
+ geom_density() +  
+ geom_vline(xintercept=mean(heightDiff)) +  
+ geom_vline(xintercept=mean(heightDiff) +  
+             2*c(-1, 1)*sd(heightDiff)/sqrt(nrow(fath-  
er.son)),  
+             linetype=2)
```

## 15.4. ANOVA

After comparing two groups, the natural next step is comparing multiple groups. Every year, far too many students in introductory statistics classes are forced to learn the ANOVA (analysis of variance) test and memorize its formula, which is

$$F = \frac{\sum_i n_i (\bar{Y}_i - \bar{Y})^2 / (K - 1)}{\sum_{ij} (Y_{ij} - \bar{Y}_i)^2 / (N - K)} \quad (15.7)$$

where  $n_i$  is the number of observations in group  $i$ ,  $\bar{Y}_i$  is the mean of group  $i$ ,  $\bar{Y}$  is the overall mean,  $Y_{ij}$  is observation  $j$  in group  $i$ ,  $N$  is the total number of observations and  $K$  is the number of groups.

Not only is this a laborious formula that often turns off a lot of students to statistics, it is also a

bit of an old-fashioned way of comparing groups. Even so, there is an R function—albeit rarely used—to conduct the ANOVA test. This also uses the formula interface where the left side is the variable of interest and the right side contains the variables that control grouping. To see this we compare tips by day of the week, which has levels Fri, Sat, Sun, Thur.

[Click here to view code image](#)

```
> tipAnova <- aov(tip ~ day - 1, tips)
```

In the formula the right side was day - 1. This might seem odd at first but will make more sense when comparing it to a call without -1.

[Click here to view code image](#)

```
> tipIntercept <- aov(tip ~ day, tips)
> tipAnova$coefficients
  dayFri  daySat  daySun  dayThur
2.734737 2.993103 3.255132 2.771452
> tipIntercept$coefficients
(Intercept)  daySat  daySun  dayThur
2.73473684 0.25836661 0.52039474 0.03671477
```

Here we see that just using `tip ~ day` includes only Saturday, Sunday and Thursday, along with an intercept, while `tip ~ day - 1` compares Friday, Saturday, Sunday and Thursday with no intercept. The importance of the intercept is made clear in [Chapter 16](#), but for now it suffices that having no intercept makes the analysis more straightforward.

The ANOVA tests whether any group is different from any other group but it does not specify which group is different. So printing a summary of the test just returns a single p-value.

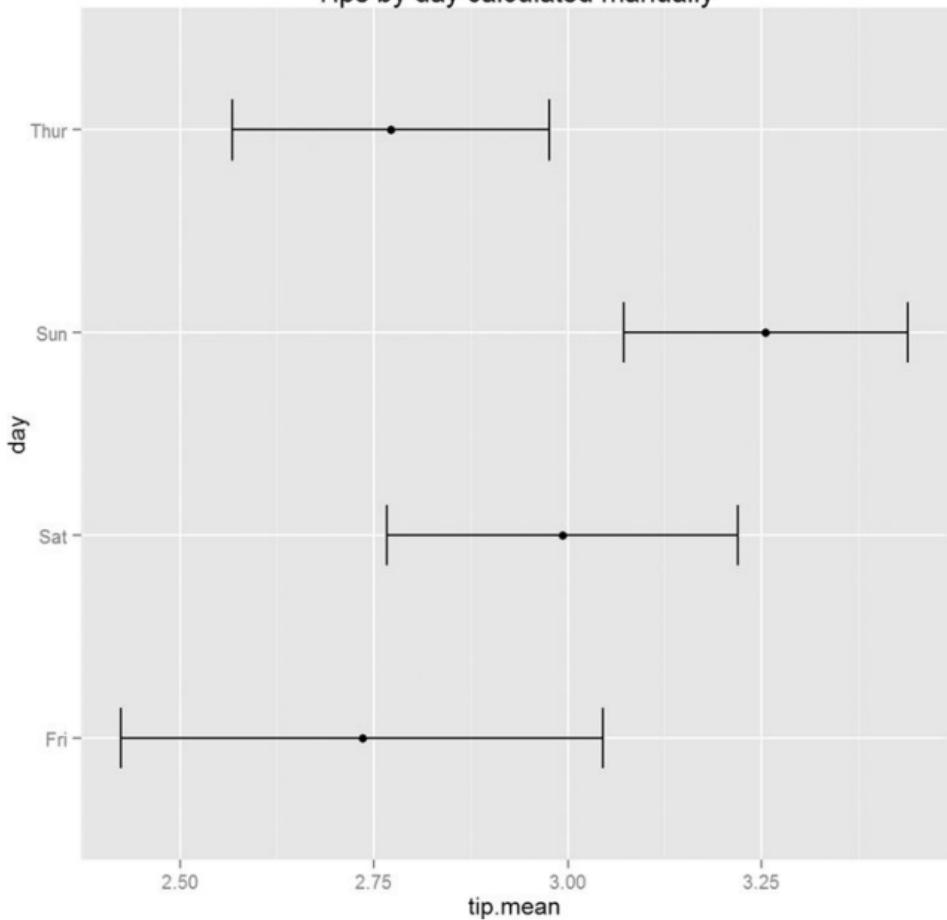
[Click here to view code image](#)

```
> summary(tipAnova)
   Df Sum Sq Mean Sq F value Pr(>F)
day      4 2203.0  550.8  290.1 <2e-16 ***
Residuals 240  455.7    1.9
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Since the test had a significant p-value, we would like to see which group differed from the others. The simplest way is to make a plot of

the group means and confidence intervals and see which overlap. [Figure 15.8](#) shows that tips on Sunday differ (just barely, at the 90% confidence level) from both Thursday and Friday.

Tips by day calculated manually



**Figure 15.8** Means and confidence intervals of tips by day. This shows that Sunday tips differ from Thursday and Friday tips.

[Click here to view code image](#)

```
> tipsByDay <- ddply(tips, "day", summarize,
```

```
+     tip.mean=mean(tip), tip.sd=sd(tip),
+     Length=NROW(tip),
+     tfrac=qt(p=.90, df=Length-1),
+     Lower=tip.mean - tfrac*tip.sd/sqrt(Length),
+     Upper=tip.mean + tfrac*tip.sd/sqrt(Length)
+   )
>
> ggplot(tipsByDay, aes(x=tip.mean, y=day)) + geom
point() +
+   geom_errorbar(aes(xmin=Lower, xmax=Upper),
height=.3)
```

The use of NROW instead of nrow is to guarantee computation. Where nrow works only on data.frames and matrices, NROW returns the length of objects that have only one dimension.

```
> nrow(tips)
[1] 244
> NROW(tips)
[1] 244
> nrow(tips$tip)
NULL
> NROW(tips$tip)
[1] 244
```

To confirm the results from the ANOVA, individual t-tests could be run on each pair of groups

just like in [Section 15.3.2](#). Traditional texts encourage adjusting the p-value to accommodate the multiple comparisons. However, some professors, including Andrew Gelman, suggest not worrying about adjustments for multiple comparisons.

An alternative to the ANOVA is to fit a linear regression with one categorical variable and no intercept. This is discussed in [Section 16.1.1](#).

## 15.5. Conclusion

Whether computing simple numerical summaries or conducting hypothesis tests, R has functions for all of them. Means, variances and standard deviations are computed with `mean`, `var` and `sd`, respectively. Correlation and covariance are computed with `cor` and `cov`. For t-tests `t.test` is used, while `aov` is for ANOVA.

# Chapter 16. Linear Models

The workhorse of statistical analysis is the linear model, particularly regression. Originally invented by Francis Galton to study the relationships between parents and children, which he described as regressing to the mean, it has become one of the most widely used modeling techniques and has spawned other models such as generalized linear models, regression trees, penalized regression and many others. In this chapter we focus on simple and multiple regression and some basic generalized linear models.

## 16.1. Simple Linear Regression

In its simplest form regression is used to determine the relationship between two variables. That is, given one variable, it tells us what we can expect from the other variable. This powerful tool, which is frequently taught and can accomplish a great deal of analysis with minimal effort, is called simple linear regression.

Before we go any further, we clarify some terminology. The outcome variable (what we are trying to predict) is called the response, and the input variable (what we are using to predict) is the predictor. Fields outside of statistics use other terms, such as measured variable, outcome variable and experimental variable for response, and covariate, feature and explanatory variable for predictor. Worst of all are the terms dependent (response) and independent (predictor) variables. These very names are misnomers. According to probability theory, if variable  $y$  is dependent on variable  $x$  then variable  $x$  *cannot* be independent

of variable  $y$ . So we stick with the terms response and predictor exclusively.

The general idea behind simple linear regression is using the predictor to come up with some average value of the response. The relationship is defined as

$$y = a + bx + \epsilon \quad (16.1)$$

where

$$b = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (16.2)$$

$$a = \bar{y} - b \quad (16.3)$$

and

$$\epsilon \sim \mathcal{N}(0, 1) \quad (16.4)$$

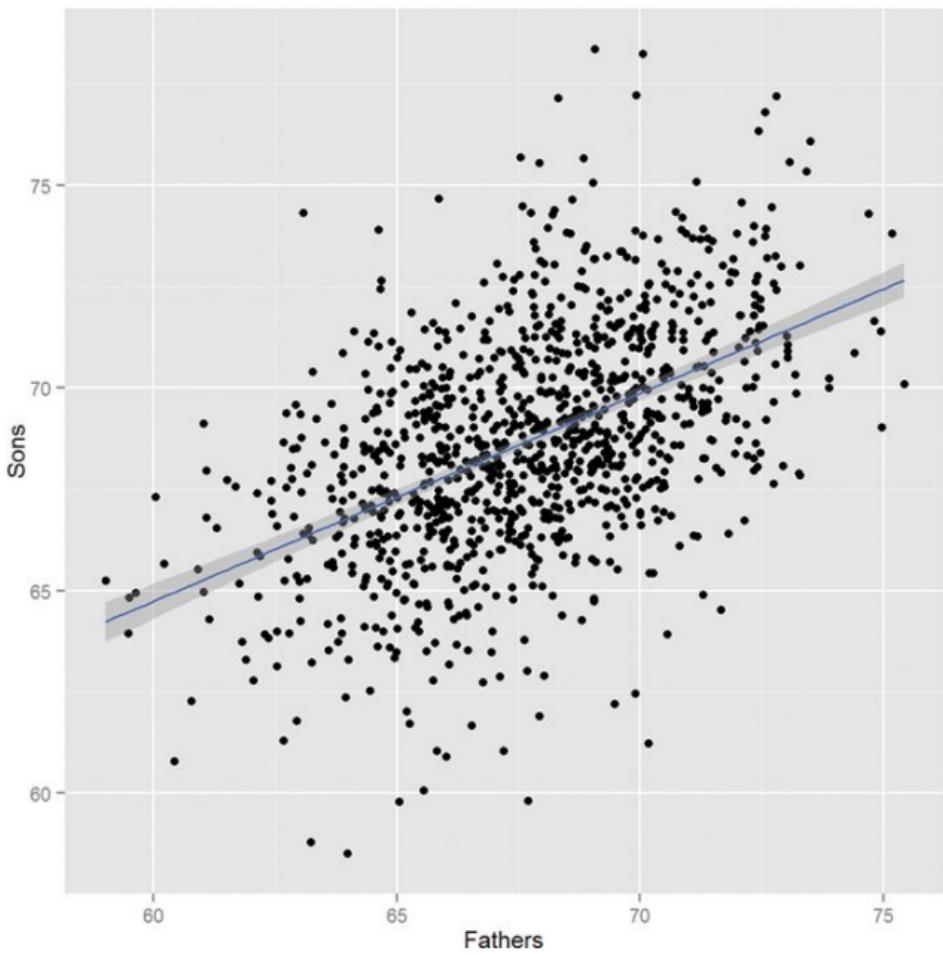
which is to say that there are normally distributed errors.

Equation 16.1 is essentially describing a straight line that goes through the data where  $a$  is the  $y$ -intercept and  $b$  is the slope. This is illustrated using fathers' and sons' height data, which are plotted in Figure 16.1. In this case we are us-

ing the fathers' heights as the predictor and the son's heights as the response. The blue line running through the points is the regression line and the grey band around it represents the uncertainty in the fit.

[Click here to view code image](#)

```
> require(UsingR)
> require(ggplot2)
> head(father.son)
  fheight   sheight
1 65.04851 59.77827
2 63.25094 63.21404
3 64.95532 63.34242
4 65.75250 62.79238
5 61.13723 64.28113
6 63.02254 64.24221
> ggplot(father.son, aes(x=fheight, y=sheight)) +
  geom_point() +
  +  geom_smooth(method="lm") + labs(x="Fathers",
y="Sons")
```



**Figure 16.1** Using fathers' heights to predict sons' heights using simple linear regression. The fathers' heights are the predictors and the sons' heights are the responses. The blue line running through the points is the regression line and the grey band around it represents the uncertainty in the fit.

While that code generated a nice graph showing the results of the regression (generated with `geom smooth(method="lm")`), it did not actually make those results available to us. To actually calculate a regression use the `lm` function.

[Click here to view code image](#)

```
> heightsLM <- lm(sheight ~ fheight, data = father.son)  
> heightsLM
```

Call:

```
lm(formula = sheight ~ fheight, data = father.son)
```

Coefficients:

(Intercept)	fheight
33.8866	0.5141

Here we once again see the formula notation that specifies to regress `sheight` (the response) on `fheight` (the predictor), using the `father.son` data, and adds the intercept term automatically. The results show coefficients for `(Intercept)` and `fheight` which is the slope for the `fheight`, predictor. The interpretation of this is that, for every extra inch of height in a father, we expect an extra half inch in height for his son. The intercept in this case does not make much sense because it represents the height of a son whose father had zero height, which obviously cannot exist in reality.

While the point estimates for the coefficients are nice, they are not very helpful without the standard errors, which give the sense of uncertainty about the estimate and are similar to standard deviations. To quickly see a full report on the model use `summary`.

[Click here to view code image](#)

> **summary**(heightsLM)

Call:

```
lm(formula = sheight ~ fheight, data = father.son)
```

Residuals:

Min	1Q	Median	3Q	Max
-8.8772	-1.5144	-0.0079	1.6285	8.9685

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	33.88660	1.83235	18.49	<2e-16 ***
fheight	0.51409	0.02705	19.01	<2e-16 ***

---

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

Residual standard error: 2.437 on 1076 degrees of freedom

Multiple R-squared: 0.2513, Adjusted R-squared: 0.2506

F-statistic: 361.2 on 1 and 1076 DF, p-value: <2.2e-16

This prints out a lot more information about the model, including the standard errors, t-test values and p-values for the coefficients, the degrees of freedom, residual summary statistics (seen in more detail in [Section 18.1](#)) and the results of an F-test. This is all diagnostic information to check the fit of the model, and is covered in more detail in [Section 16.2](#) about multiple regression.

## 16.1.1. ANOVA Alternative

An alternative to running an ANOVA test (discussed in [Section 15.4](#)) is to fit a regression with just one categorical variable and no intercept term. To see this we use the tips data in the reshape2 package on which we will fit a regression.

[Click here to view code image](#)

```
> data(tips, package = "reshape2")
> head(tips)
  total_bill tip sex smoker day time size
1    16.99 1.01 Female   No Sun Dinner 2
2    10.34 1.66 Male    No Sun Dinner 3
3    21.01 3.50 Male    No Sun Dinner 3
4    23.68 3.31 Male    No Sun Dinner 2
5    24.59 3.61 Female  No Sun Dinner 4
6    25.29 4.71 Male    No Sun Dinner 4

> tipsAnova <- aov(tip ~ day - 1, data = tips)
> # putting -1 in the formula indicates that the intercept
  should not
> # be included in the model; the categorical variable day is
> # automatically setup to have a coefficient for each level

> tipsLM <- lm(tip ~ day - 1, data = tips)
> summary(tipsAnova)

  Df Sum Sq Mean Sq F value Pr(>F)
day     4 2203.0 550.8 290.1 <2e-16 ***
Residuals 240 455.7  1.9
```

---

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

> **summary**(tipsLM)

Call:

lm(formula = tip ~ day - 1, data = tips)

Residuals:

	Min	1Q	Median	3Q	Max
	-2.2451	-0.9931	-0.2347	0.5382	7.0069

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
dayFri	2.7347	0.3161	8.651	7.46e-16 ***
daySat	2.9931	0.1477	20.261	< 2e-16 ***
daySun	3.2551	0.1581	20.594	< 2e-16 ***
dayThur	2.7715	0.1750	15.837	< 2e-16 ***

---

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

Residual standard error: 1.378 on 240 degrees of freedom

Multiple R-squared: 0.8286, Adjusted R-squared: 0.8257

F-statistic: 290.1 on 4 and 240 DF, p-value: <2.2e-16

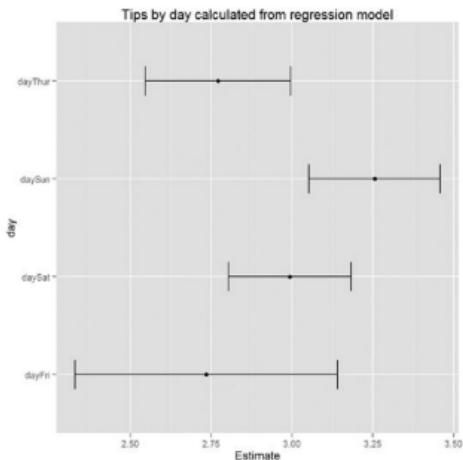
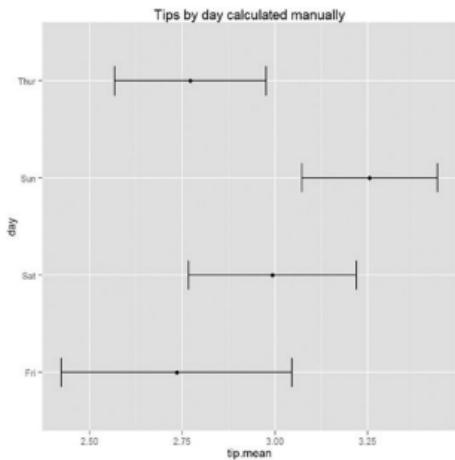
Notice that the F-value or F-statistic is the same for both, as are the degrees of freedom. This shows that the ANOVA and regression were derived along the same lines and can accomplish the same analysis. Visualizing the coefficients and standard errors should show the same results as computing them using the ANOVA formula. This

is seen in [Figure 16.2](#). The point estimates for the mean are identical and the confidence intervals are similar, the difference due to slightly different calculations.

[Click here to view code image](#)

```
> # first calculate the means and CI manually
> require(plyr)
> tipsByDay <- ddply(tips, "day", summarize,
+   tip.mean=mean(tip), tip.sd=sd(tip),
+   Length=NROW(tip),
+   tfrac=qt(p=.90, df=Length-1),
+   Lower=tip.mean - tfrac*tip.sd/sqrt(Length),
+   Upper=tip.mean + tfrac*tip.sd/sqrt(Length)
+ )
>
> # now extract them from the summary for tipsLM
> tipsInfo <- summary(tipsLM)
> tipsCoef <- as.data.frame(tipsInfo$coefficients[, 1:2])
> tipsCoef <- within(tipsCoef, {
+   Lower <- Estimate - qt(p=0.90, df=tipsInfo$df[2]) *
+     `Std. Error'
+   Upper <- Estimate + qt(p=0.90, df=tipsInfo$df[2]) *
+     `Std. Error'
+   day <- rownames(tipsCoef)
+ })
> # plot them both
> ggplot(tipsByDay, aes(x=tip.mean, y=day)) +
  geom_point() +
```

```
+ geom_errorbarh(aes(xmin=Lower, xmax=Upper),  
height=.3) +  
+ ggtitle("Tips by day calculated manually")  
>  
> ggplot(tipsCoef, aes(x=Estimate, y=day)) +  
geom_point() +  
+ geom_errorbarh(aes(xmin=Lower, xmax=Upper),  
height=.3) +  
+ ggtitle("Tips by day calculated from regression mod-  
el")
```



**Figure 16.2** Regression coefficients and confidence intervals as taken from a regression model and calculated manually. The point estimates for the mean are identical and the confidence intervals are very similar, the difference due to slightly different calculations. The *y*-axis labels are also different because when dealing with factors `lm` tacks on the name of the variable to the level value.

A new function and a new feature were used here. First, we introduced `within`, which is similar to `with` in that it lets us refer to columns in a `data.frame` by name but different in that we can

create new columns within that `data.frame`, hence the name. Second, one of the columns was named `Std. Error` with a space. In order to refer to a variable with spaces in its name, even as a column in a `data.frame`, we must enclose the name in back ticks.

## 16.2. Multiple Regression

The logical extension of simple linear regression is multiple regression, which allows for multiple predictors. The idea is still the same; we are still making predictions or inferences<sup>1</sup> on the response, but we now have more information in the form of multiple predictors. The math requires some matrix algebra but fortunately the `lm` is used with very little extra effort.

1. Prediction is the use of known predictors to predict an unknown response while inference is figuring out how predictors affect a response.

In this case the relationship between the response and the  $p$  predictors ( $p - 1$  predictors and the intercept) is modeled as

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \quad (16.5)$$

where  $\mathbf{Y}$  is the  $n \times 1$  response vector

$$\mathbf{Y} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \vdots \\ Y_n \end{bmatrix} \quad (16.6)$$

$\mathbf{X}$  is the  $n \times p$  matrix ( $n$  rows and  $p - 1$  predictors plus the intercept)

$$\mathbf{X} = \begin{bmatrix} 1 & X_{11} & X_{12} & \dots & X_{1,p-1} \\ 1 & X_{21} & X_{22} & \dots & X_{2,p-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X_{n1} & X_{n2} & \dots & X_{n,p-1} \end{bmatrix} \quad (16.7)$$

$\boldsymbol{\beta}$  is the  $p \times 1$  vector of coefficients (one for each predictor and intercept)

$$\boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_{p-1} \end{bmatrix} \quad (16.8)$$

and  $\epsilon$  is the  $n \times 1$  vector of normally distributed errors

$$\epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \vdots \\ \epsilon_n \end{bmatrix} \quad (16.9)$$

with

$$\epsilon_i \sim \mathcal{N}(0, 1) \quad (16.10)$$

which seems more complicated than simple regression but the algebra actually gets easier.

The solution for the coefficients is simply written as in [Equation 16.11](#).

$$\hat{\beta} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{Y} \quad (16.11)$$

To see this in action we use New York City condo evaluations for fiscal year 2011–2012, obtained through NYC Open Data. NYC Open Data is an initiative by New York City to make government more transparent and work better. It provides data on all manner of city services to

the public for analysis, scrutiny and app building (through <http://nycbigapps.com/>). It has been surprisingly popular, spawning hundreds of mobile apps and being copied in other cities such as Chicago and Washington, DC. Its Web site is at <https://data.cityofnewyork.us/>.

The original data were separated by borough with one file each for Manhattan,<sup>2</sup> Brooklyn,<sup>3</sup> Queens,<sup>4</sup> the Bronx<sup>5</sup> and Staten Island,<sup>6</sup> and contained extra information we will not be using. So we combined the five files into one, cleaned up the column names and posted it at <http://www.jaredlander.com/data/housing.csv>. To access the data, either download it from that URL and use `read.table` on the now local file, or read it directly from the URL.

2. <https://data.cityofnewyork.us/Finances/DOF-Condominium-Comparable-Rental-Income-Manhattan/dvzp-h4k9>
3. <https://data.cityofnewyork.us/Finances/DOF-Condominium-Comparable-Rental-Income-Brooklyn-/bss9-579f>

4. <https://data.cityofnewyork.us/Finances/DOF-Condominium-Comparable-Rental-Income-Queens-FY/jcih-dj9q>
5. <https://data.cityofnewyork.us/Property/DOF-Condominium-Comparable-Rental-Income-Bronx-FY-3qfc-4tta>
6. <https://data.cityofnewyork.us/Finances/DOF-Condominium-Comparable-Rental-Income-Staten-Is/tk-dy-59zg>

[Click here to view code image](#)

```
> housing <- read.table("http://www.jaredlander.com/data/  
housing.csv",  
+ sep = ",", header = TRUE,  
+ stringsAsFactors = FALSE)
```

A few reminders about what that code does: sep specifies that commas were used to separate columns; header means the first row contains the column names; and stringsAsFactors leaves character columns as they are and does not convert them to factors, which speeds up loading time and also makes them easier to work with. Looking at the data, we see that we have a lot of columns and some bad names, so we should rename those.

[Click here to view code image](#)

```
> names(housing) <- c("Neighborhood", "Class", "Units",
  "YearBuilt",
  +
  "SqFt", "Income", "IncomePerSqFt", "Ex-
  pense",
  +
  "ExpensePerSqFt", "NetIncome", "Value",
  +
  "ValuePerSqFt", "Boro")
```

```
> head(housing)
```

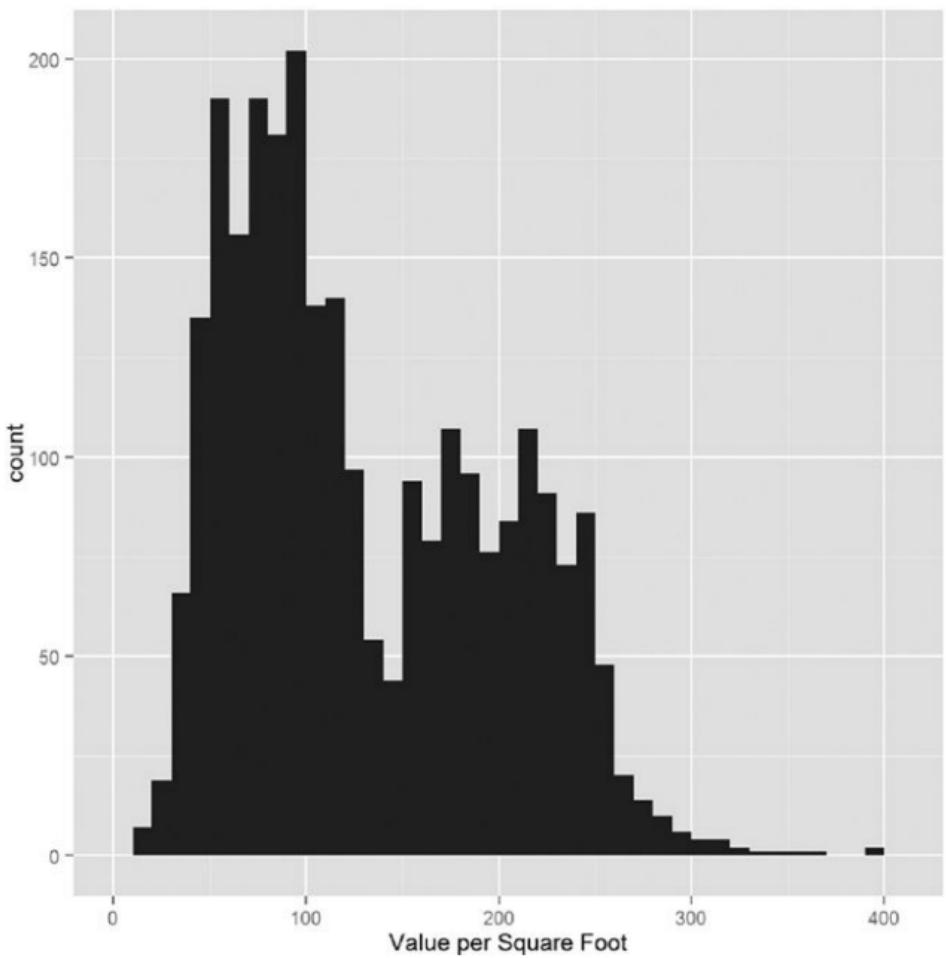
	Neighborhood	Class	Units	YearBuilt	SqFt	In- come
1	FINANCIAL					
	R9-CONDOMINIUM		42	1920	36500	1332615
2	FINANCIAL					
	R4-CONDOMINIUM		78	1985	126420	6633257
3	FINANCIAL RR-					
	CONDOMINIUM		500	NA	554174	17310000
4	FINANCIAL					
	R4-CONDOMINIUM		282	1930	249076	11776313
5	TRIBECA					
	R4-CONDOMINIUM		239	1985	219495	10004582
6	TRIBECA					
	R4-CONDOMINIUM		133	1986	139719	5127687
	IncomePerSqFt	Expense	ExpensePerSqFt	NetIn-		
	come	Value		come		
1	36.51	342005	9.37	990610	7300000	
2	52.47	1762295	13.94	4870962	30690000	
3	31.24	3543000	6.39	13767000	90970000	
4	47.28	2784670	11.18	8991643	67556006	
5	45.58	2783197	12.68	7221385	54320996	

6	36.70	1497788	10.72	3629899	26737996
	ValuePerSqFt	Boro			
1	200.00	Manhattan			
2	242.76	Manhattan			
3	164.15	Manhattan			
4	271.23	Manhattan			
5	247.48	Manhattan			
6	191.37	Manhattan			

For this data the response is the value per square foot and the predictors are everything else. However, we ignore the income and expense variables, as they are actually just estimates based on an arcane requirement that condos be compared to rentals for valuation purposes. The first step is to visualize the data in some exploratory data analysis. The natural place to start is with a histogram of ValuePerSqFt, which is shown in [Figure 16.3](#).

[Click here to view code image](#)

```
> ggplot(housing, aes(x=ValuePerSqFt)) +  
+   geom_histogram(binwidth=10) + labs(x="Value per  
Square Foot")
```



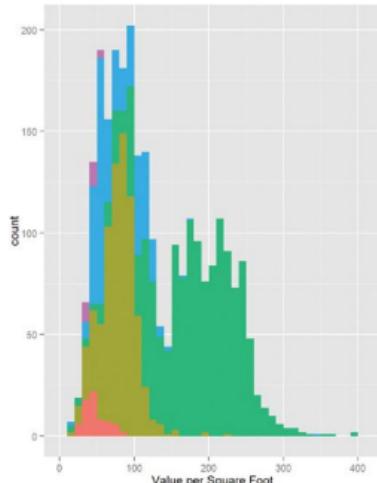
**Figure 16.3** Histogram of value per square foot for NYC condos. It appears to be bimodal.

The bimodal nature of the histogram means there is something left to be explored. Mapping

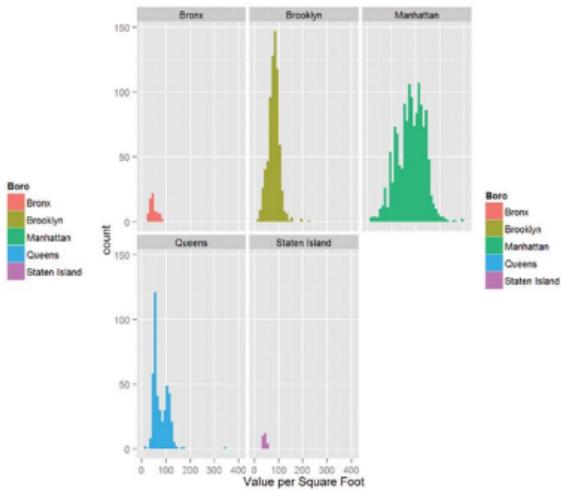
color to Boro in [Figure 16.4a](#) and faceting on Boro in [Figure 16.4b](#) reveal that Brooklyn and Queens make up one mode and Manhattan makes up the other, while there is not much data on the Bronx and Staten Island.

[Click here to view code image](#)

```
> ggplot(housing, aes(x=ValuePerSqFt, fill=Boro)) +  
+   geom_histogram(binwidth=10) + labs(x="Value per  
Square Foot")  
> ggplot(housing, aes(x=ValuePerSqFt, fill=Boro)) +  
+   geom_histogram(binwidth=10) + labs(x="Value per  
Square Foot") +  
+   facet_wrap(~Boro)
```



(a) Boros separated by color



(b) Boros separated by color and facet

**Figure 16.4** Histograms of value per square foot. These illustrate structure in the data revealing that Brooklyn and Queens make up one mode and Manhattan makes up the other, while there is not much data on the Bronx and Staten Island.

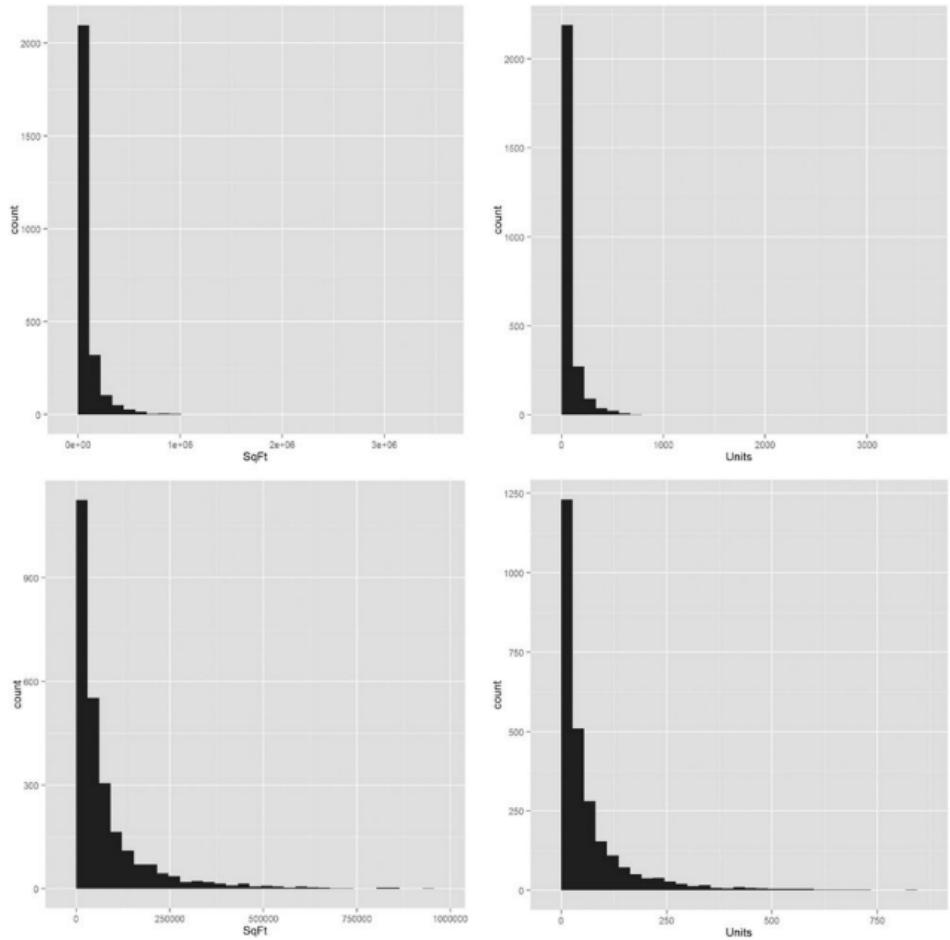
Next we should look at histograms for square footage and the number of units.

[Click here to view code image](#)

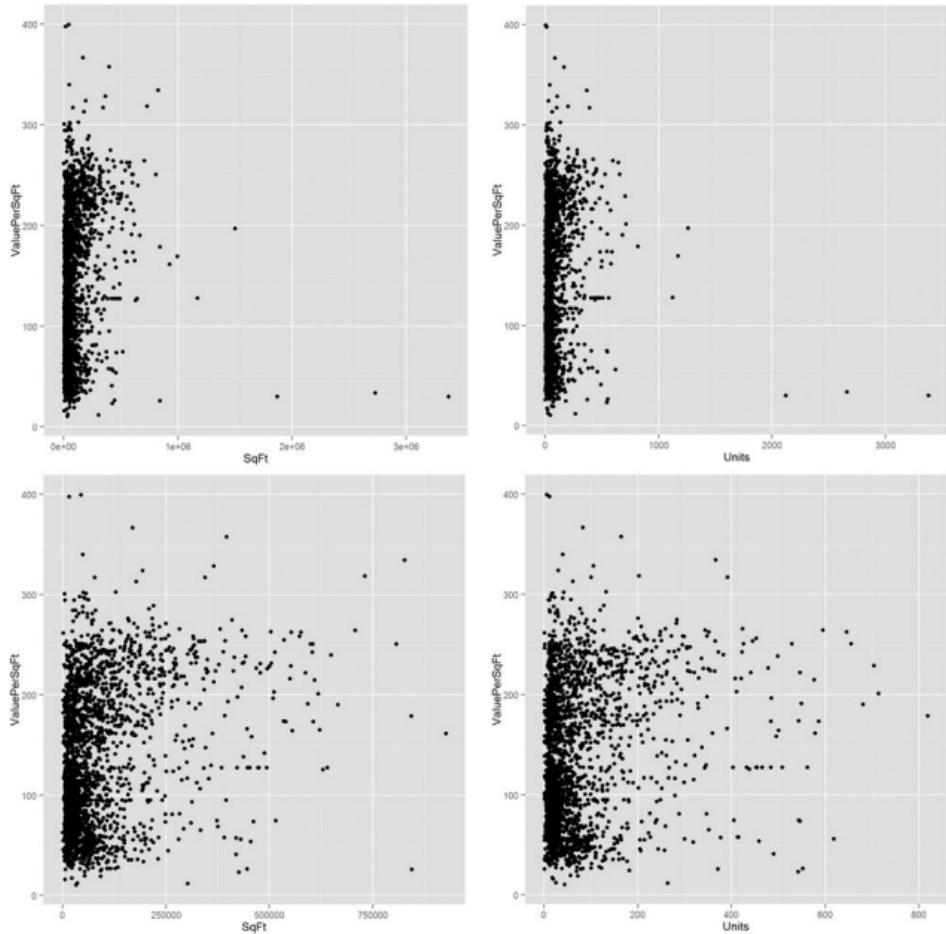
```
> ggplot(housing, aes(x=SqFt)) + geom_histogram()
> ggplot(housing, aes(x=Units)) + geom_histogram()
> ggplot(housing[housing$Units < 1000, ],
+         aes(x=SqFt)) + geom_histogram()
```

```
> ggplot(housing[housing$Units < 1000, ],  
+         aes(x=Units)) + geom_histogram()
```

[Figure 16.5](#) shows that there are quite a few buildings with an incredible number of units. Plotting scatterplots in [Figure 16.6](#) of the value per square foot versus both number of units and square footage, with and without those outlying buildings, gives us an idea whether we can remove them from the analysis.



**Figure 16.5** Histograms for total square feet and number of units. The distributions are highly right skewed in the top two graphs, so they were repeated after removing buildings with more than 1,000 units.



**Figure 16.6** Scatterplots of value per square foot versus square footage and value versus number of units, both with and without the buildings that have over 1,000 units.

## [Click here to view code image](#)

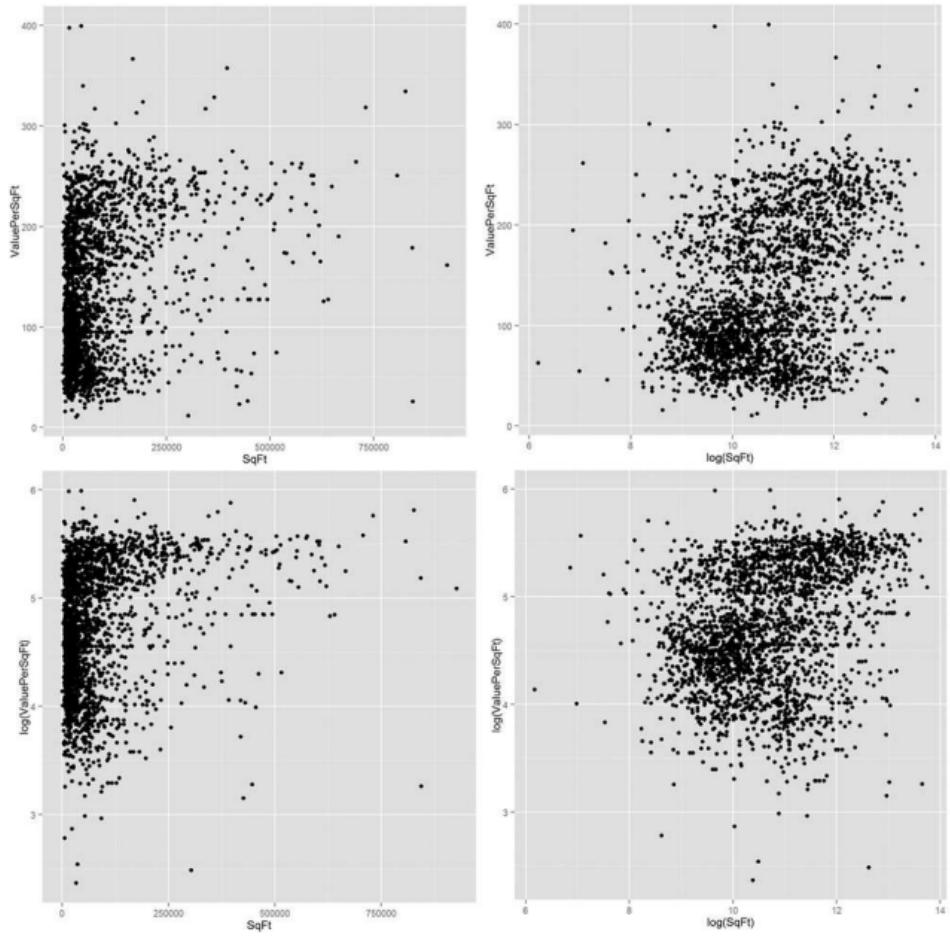
```
> ggplot(housing, aes(x = SqFt, y = ValuePerSqFt)) +  
  geom_point()  
> ggplot(housing, aes(x = Units, y = ValuePerSqFt)) +  
  geom_point()  
> ggplot(housing[housing$Units < 1000, ], aes(x = SqFt,  
+   y = ValuePerSqFt)) + geom_point()  
> ggplot(housing[housing$Units < 1000, ], aes(x = Units,  
+   y = ValuePerSqFt)) + geom_point()  
> # how many need to be removed?  
> sum(housing$Units >= 1000)  
[1] 6  
> # remove them  
> housing <- housing[housing$Units < 1000, ]
```

Even after we remove the outliers, it still seems like a log transformation of some data could be helpful. [Figures 16.7](#) and [16.8](#) show that taking the log of square footage and number of units might prove helpful. It also shows what happens when taking the log of value.

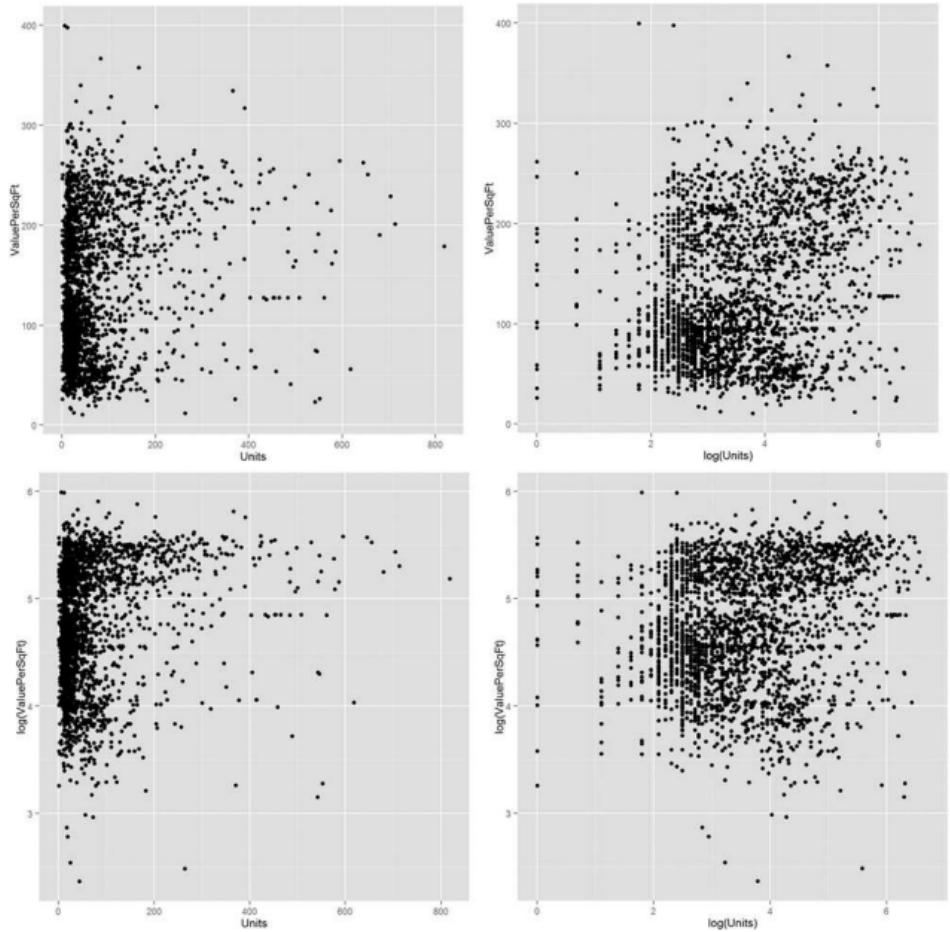
## [Click here to view code image](#)

```
> # plot ValuePerSqFt against SqFt  
> ggplot(housing, aes(x=SqFt, y=ValuePerSqFt)) +  
  geom_point()
```

```
> ggplot(housing, aes(x=log(SqFt), y=ValuePerSqFt)) +  
  geom_point()  
> ggplot(housing, aes(x=SqFt, y=log(ValuePerSqFt))) +  
  geom_point()  
> ggplot(housing, aes(x=log(SqFt), y=log(ValuePerSqFt)))  
+  
+  geom_point()
```



**Figure 16.7** Scatterplots of value versus square footage. The plots indicate that taking the log of SqFt might be useful in modeling.



**Figure 16.8** Scatterplots of value versus number of units. It is not yet certain whether taking logs will be useful in modeling.

[Click here to view code image](#)

> # plot ValuePerSqFt against Units

```
> ggplot(housing, aes(x=Units, y=ValuePerSqFt)) +  
  geom_point()  
> ggplot(housing, aes(x=log(Units), y=ValuePerSqFt)) +  
  geom_point()  
> ggplot(housing, aes(x=Units, y=log(ValuePerSqFt))) +  
  geom_point()  
> ggplot(housing, aes(x=log(Units), y=log(ValuePerSqFt)))  
+  
+  geom_point()
```

Now that we have viewed our data a few different ways, it is time to start modeling. We already saw from [Figure 16.4](#) that accounting for the different boroughs will be important and the various scatterplots indicated that Units and SqFt will be important as well.

Fitting the model uses the formula interface in lm. Now that there are multiple predictors, we separate them on the right side of the formula using plus signs (+).

[Click here to view code image](#)

```
> house1 <- lm(ValuePerSqFt ~ Units + SqFt + Boro, data  
= housing)  
> summary(house1)  
Call:
```

```
lm(formula = ValuePerSqFt ~ Units + SqFt + Boro, data =  
housing)
```

Residuals:

	Min	1Q	Median	3Q	Max
	-168.458	-22.680	1.493	26.290	261.761

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	4.430e+01	5.342e+00	8.293	<2e-16
***				
Units	-1.532e-01	2.421e-02	-6.330	2.88e-10 ***
SqFt	2.070e-04	2.129e-05	9.723	< 2e-16 ***
BoroBrook-				
lyn	3.258e+01	5.561e+00	5.858	5.28e-09 ***
BoroManhattan	1.274e+02	5.459e+00	23.343	< 2e-16 ***
BoroQueens	3.011e+01	5.711e+00	5.272	1.46e-07 ***
BoroStaten Island	-7.114e+00	1.001e+01	-0.711	0.477
---				

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

Residual standard error: 43.2 on 2613 degrees of freedom

Multiple R-squared: 0.6034, Adjusted R-squared: 0.6025

F-statistic: 662.6 on 6 and 2613 DF, p-value: < 2.2e-16

The first thing to notice is that in some versions of R there is a message warning us that Boro was converted to a factor. This is because Boro was stored as a character, and for modeling

purposes character data must be represented using indicator variables, which is how factors are treated inside modeling functions, as seen on page [60](#) in [Section 5.1](#).

The summary function prints out information about the model, including how the function was called, quantiles for the residuals, coefficient estimates, standard errors and p-values for each variable, and the degrees of freedom, p-value and F-statistic for the model. There is no coefficient for the Bronx because that is the baseline level of Boro, and all the other Boro coefficients are relative to that baseline.

The coefficients represent the effect of the predictors on the response and the standard errors are the uncertainty in the estimation of the coefficients. The t value (t-statistic) and p-value for the coefficients are numerical measures of statistical significance, though these should be viewed with caution as most modern data scientists do not like to look at the statistical significance of individual

coefficients but rather judge the model as a whole as covered in [Chapter 18](#).

The model p-value and F-statistic are measures of its goodness of fit. The degrees of freedom for a regression are calculated as the number of observations minus the number of coefficients. In this example, there are `nrow(housing)-length(coef(house1))=2613` degrees of freedom.

A quick way to grab the coefficients from a model is to either use the `coef` function or get them from the model using the `$` operator on the model object.

[Click here to view code image](#)

```
> house1$coefficients
  (Intercept)      Units      SqFt
  4.430325e+01 -1.532405e-01 2.069727e-04
  BoroBrooklyn    BoroManhattan   BoroQueens
  3.257554e+01  1.274259e+02  3.011000e+01
BoroStaten Island
  -7.113688e+00
> coef(house1)
  (Intercept)      Units      SqFt
  4.430325e+01 -1.532405e-01 2.069727e-04
  BoroBrooklyn    BoroManhattan   BoroQueens
```

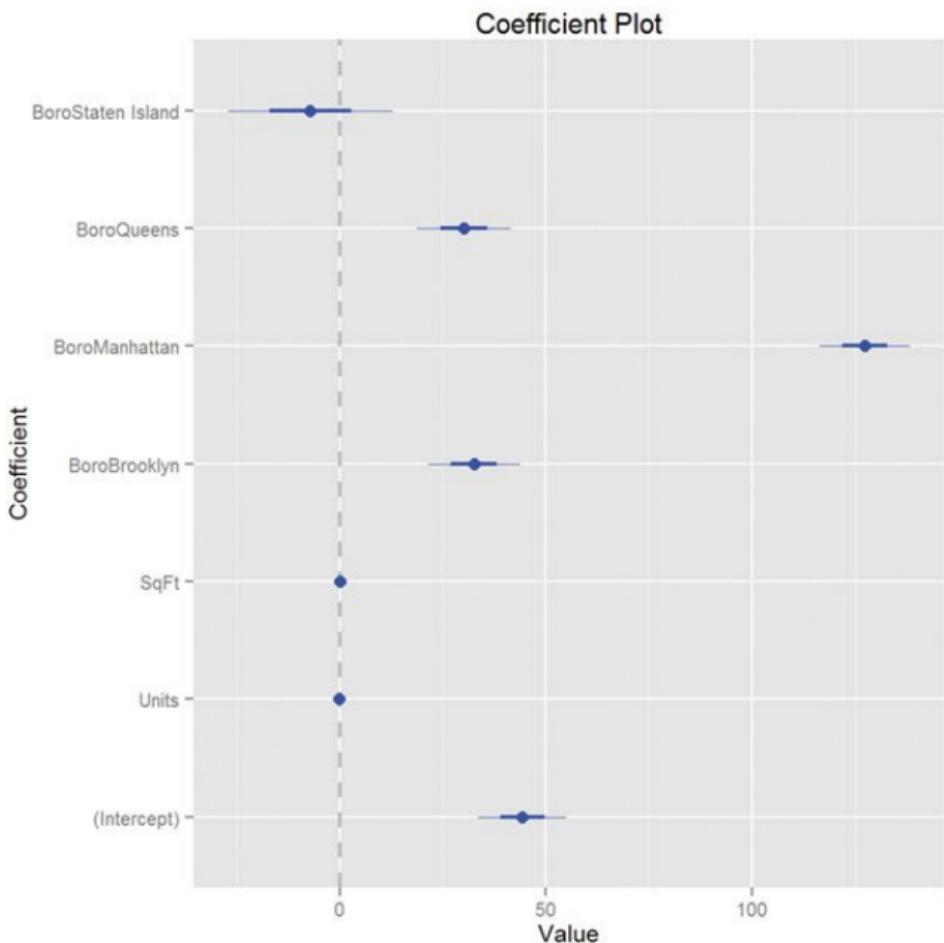
```
3.257554e+01    1.274259e+02    3.011000e+01  
BoroStaten Island  
-7.113688e+00  
> # works the same as coef  
> coefficients(house1)  


|                   | Units         | SqFt          |
|-------------------|---------------|---------------|
| (Intercept)       | 4.430325e+01  | -1.532405e-01 |
| BoroBrooklyn      | BoroManhattan | BoroQueens    |
| 3.257554e+01      | 1.274259e+02  | 3.011000e+01  |
| BoroStaten Island |               |               |
| -7.113688e+00     |               |               |


```

As a repeated theme, we prefer visualizations over tables of information, and a great way of visualizing regression results is a coefficient plot like the one shown in [Figure 16.2](#). Rather than build it from scratch, we use the convenient `coefplot` package that we wrote. [Figure 16.9](#) shows the result, where each coefficient is plotted as a point with a thick line representing the one standard error confidence interval and a thin line representing the two standard error confidence interval. There is a vertical line indicating 0. In general, a good rule of thumb is that if the two standard error confidence interval does not contain 0, it is statistically significant.

```
> require(coefplot)  
> coefplot(house1)
```



**Figure 16.9** Coefficient plot for condo value regression.

Figure 16.9 shows that, as expected, being located in Manhattan has the largest effect on value per square foot. Surprisingly, the number of units or square feet in a building has little effect on value. This is a model with purely additive terms. Interactions between variables can be equally powerful. To enter them in a formula, separate the desired variables with a \* instead of +. Doing so results in the individual variables plus the interaction term being included in the model. To include just the interaction term, and not the individual variables, use : instead. The results of interacting Units and SqFt are shown in Figure 16.10.

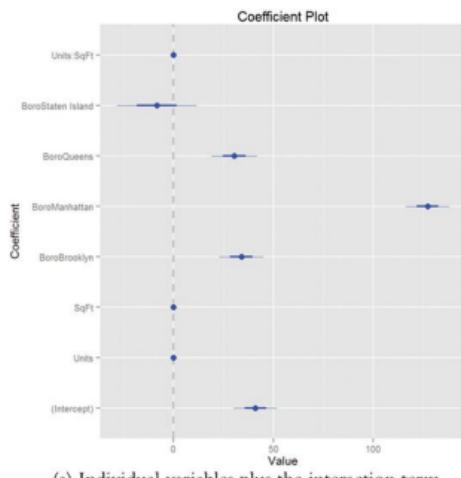
[Click here to view code image](#)

```
> house2 <- lm(ValuePerSqFt ~ Units * SqFt + Boro, data = housing)
> house3 <- lm(ValuePerSqFt ~ Units:SqFt + Boro, data = housing)
> house2$coefficients
  (Intercept)      Units       SqFt
  4.093685e+01 -1.024579e-01  2.362293e-04
  BoroBrooklyn   BoroManhattan BoroQueens
```

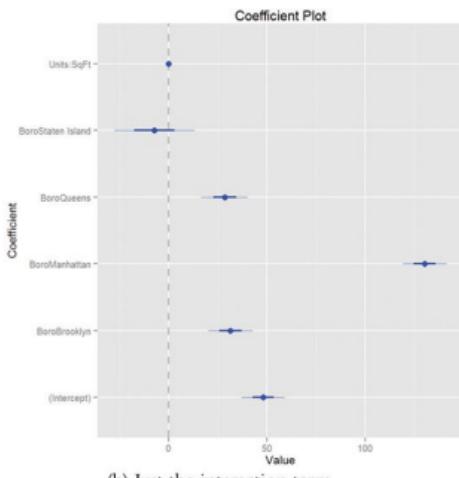
```

3.394544e+01    1.272102e+02    3.040115e+01
BoroStaten Island      Units:SqFt
-8.419682e+00   -1.809587e-07
> house3$coefficients
(Intercept)  BoroBrooklyn  BoroManhattan
4.804972e+01  3.141208e+01  1.302084e+02
BoroQueens  BoroStaten Island      Units:SqFt
2.841669e+01  -7.199902e+00  1.088059e-07
> coefplot(house2)
> coefplot(house3)

```



(a) Individual variables plus the interaction term



(b) Just the interaction term

**Figure 16.10** Coefficient plots for models with interaction terms. (a) includes individual variables and the interaction term, while (b) only includes the interaction term.

If three variables all interact together, the resulting coefficients will be the three individual terms, three two-way interactions and one three-way interaction.

[Click here to view code image](#)

```
> house4 <- lm(ValuePerSqFt ~ SqFt * Units * Income,  
housing)  
> house4$coefficients  


|               | (Intercept)       | SqFt          | Units |
|---------------|-------------------|---------------|-------|
| 1.116433e+02  | -1.694688e-03     | 7.142611e-03  |       |
| Income        | SqFt:Units        | SqFt:Income   |       |
| 7.250830e-05  | 3.158094e-06      | -5.129522e-11 |       |
| Units:Income  | SqFt:Units:Income |               |       |
| -1.279236e-07 | 9.107312e-14      |               |       |


```

Interacting (from now on, unless otherwise specified, interacting will refer to the `*` operator) a continuous variable like `SqFt` with a factor like `Boro` results in individual terms for the continuous variable and each non-baseline level of the factor plus an interaction term between the continuous variable and each non-baseline level of the factor. Interacting two (or more) factors yields terms for all the individual non-baseline

levels in both factors and an interaction term for every combination of non-baseline levels of the factors.

[Click here to view code image](#)

```
> house5 <- lm(ValuePerSqFt ~ Class * Boro, housing)
> house5$coefficients
  (Intercept)          47.041481
  ClassR4-CONDOMINIUM  4.023852
  ClassR9-CONDOMINIUM -2.838624
  ClassRR-CONDOMINIUM  3.688519
  BoroBrooklyn         27.627141
  BoroManhattan        89.598397
  BoroQueens           19.144780
  BoroStaten Island    -9.203410
  ClassR4-CONDOMINIUM:BoroBrooklyn 4.117977
  ClassR9-CONDOMINIUM:BoroBrooklyn  2.660419
  ClassRR-CONDOMINIUM:BoroBrooklyn
```

-25.607141

ClassR4-CONDOMINIUM:BoroManhattan  
47.198900

ClassR9-CONDOMINIUM:BoroManhattan  
33.479718

ClassRR-CONDOMINIUM:BoroManhattan  
10.619231

ClassR4-CONDOMINIUM:BoroQueens  
13.588293

ClassR9-CONDOMINIUM:BoroQueens  
-9.830637

ClassRR-CONDOMINIUM:BoroQueens  
34.675220

ClassR4-CONDOMINIUM:BoroStaten Island  
NA

ClassR9-CONDOMINIUM:BoroStaten Island  
NA

ClassRR-CONDOMINIUM:BoroStaten Island  
NA

Because neither SqFt nor Units appears to be significant in any model, it would be good to test their ratio. To simply divide one variable by another in a formula, the division must be wrapped in the I function.

[Click here to view code image](#)

```
> house6 <- lm(ValuePerSqFt ~ I(SqFt/Units) + Boro,  
housing)
```

```
> house6$coefficients
```

(Intercept)	I(SqFt/Units)	BoroBrooklyn
43.754838763	0.004017039	30.774343209
BoroManhattan	BoroQueens	BoroStaten Island
130.769502685	29.767922792	-6.134446417

The I function is used to preserve a mathematical relationship in a formula and prevent it from being interpreted according to formula rules. For instance, using  $(\text{Units} + \text{SqFt})^2$  in a formula is the same as using  $\text{Units} * \text{SqFt}$ , whereas  $I(\text{Units} + \text{SqFt})^2$  will include the square of the sum of the two variables as a term in the formula.

[Click here to view code image](#)

```
> house7 <- lm(ValuePerSqFt ~ (Units + SqFt)^2, housing)
```

```
> house7$coefficients
```

(Intercept)	Units	SqFt	Units:SqFt
1.070301e+02	-1.125194e-01	4.964623e-04	
-5.159669e-07			

```
> house8 <- lm(ValuePerSqFt ~ Units * SqFt, housing)
```

```
> identical(house7$coefficients, house8$coefficients)
```

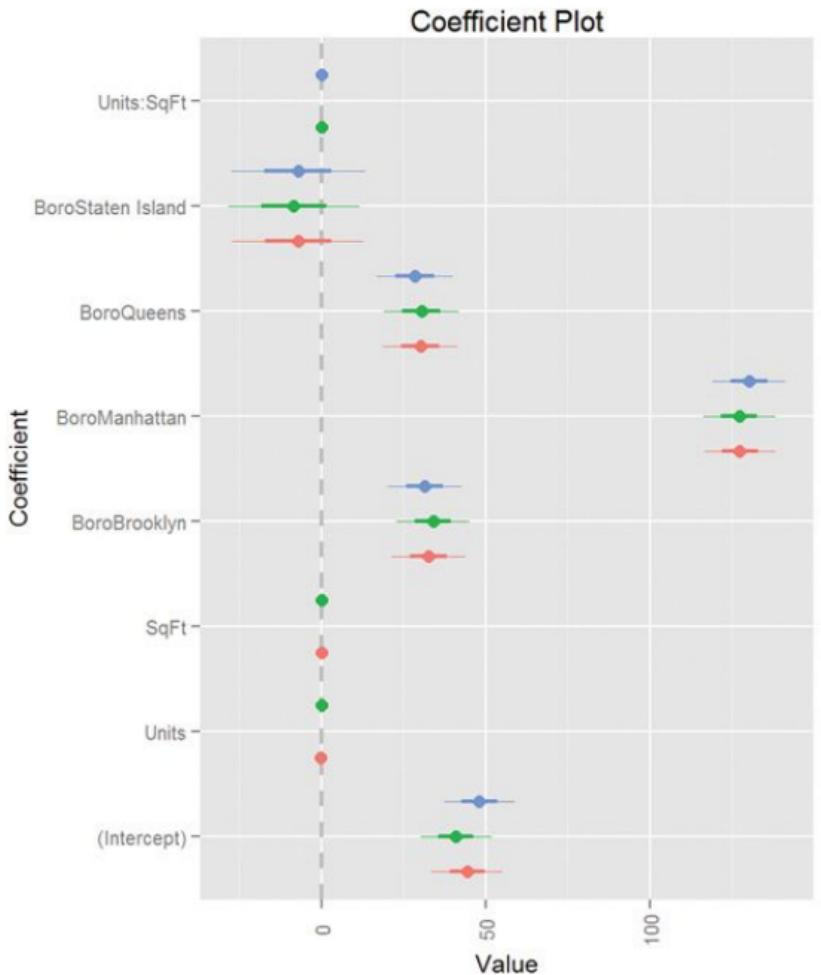
```
[1] TRUE
```

```
> house9 <- lm(ValuePerSqFt ~ I(Units + SqFt)^2, housing)
> house9$coefficients
  (Intercept) I(Units + SqFt)
  1.147034e+02  2.107231e-04
```

We have fit numerous models from which we need to pick the “best” one. Model selection is discussed in [Section 18.2](#). In the meantime, visualizing the coefficients from multiple models is a handy tool. [Figure 16.11](#) shows a coefficient plot for models house1, house2 and house3.

[Click here to view code image](#)

```
> # also from the coefplot package
> multiplot(house1, house2, house3)
```



**Figure 16.11** Coefficient plot for multiple condo models. The coefficients are plotted in the same spot on the  $y$ -axis for each model. If a model does not contain a particular coefficient, it is simply not plotted.

Regression is often used for prediction, which in R is enabled by the predict function. For this example, new data are available at <http://www.jaredlander.com/data/housingNew.csv>.

[Click here to view code image](#)

```
> housingNew <- read.table("http://www.jaredlander.com/  
data/  
+ housingNew.csv", sep = ",", header = TRUE, string-  
sAsFactors = FALSE)
```

Making the prediction can be as simple as calling predict, although caution must be used when dealing with factor predictors to ensure that they have the same levels as those used in building the model.

[Click here to view code image](#)

```
> # make prediction with new data and 95% confidence  
bounds  
> housePredict <- predict(house1, newdata = housingNew,  
se.fit = TRUE,  
+ interval = "prediction", level = .95)  
> # view predictions with upper and lower bounds based on  
> # standard errors  
> head(housePredict$fit)
```

```
    fit     lwr     upr
1 74.00645 -10.813887 158.8268
2 82.04988 -2.728506 166.8283
3 166.65975 81.808078 251.5114
4 169.00970 84.222648 253.7968
5 80.00129 -4.777303 164.7799
6 47.87795 -37.480170 133.2361
> # view the standard errors for the prediction
> head(housePredict$se.fit)
  1     2     3     4     5     6
2.118509 1.624063 2.423006 1.737799 1.626923 5.318813
```

## 16.3. Conclusion

Perhaps one of the most versatile tools in statistical analysis, regression is well handled using R's lm function. It takes the formula interface, where a response is modeled on a set of predictors. Other useful arguments to the function are weights, which specifies the weights attributed to observations (both probability and count weights), and subset, which will fit the model only on a subset of the data.

# Chapter 17. Generalized Linear Models

Not all data can be appropriately modeled with linear regression, because they are binomial (TRUE/FALSE) data, count data or some other form. To model these types of data, generalized linear models were developed. They are still modeled using a linear predictor,  $\mathbf{X}\beta$ , but they are transformed using some link function. To the R user, fitting a generalized linear model requires barely any more effort than running a linear regression.

## 17.1. Logistic Regression

A very powerful and common model—especially in fields such as marketing and medicine—is logistic regression. The examples in this section will use a subset of data from the 2010 American Community Survey (ACS) for New York State.<sup>1</sup> ACS data contain a lot of information, so we have made a subset of it with 22,745 rows and 18 columns available at [http://jaredlander.com/data/acs\\_ny.csv](http://jaredlander.com/data/acs_ny.csv).

1. The ACS is a large-scale survey very similar to the decennial census, except that is conducted on a more frequent basis.

[Click here to view code image](#)

```
> acs <- read.table("http://jaredlander.com/data/  
acs_ny.csv", sep = ",",  
+   header = TRUE, stringsAsFactors = FALSE)
```

Logistic regression models are formulated as

$$p(y_i = 1) = \text{logit}^{-1}(X_i\beta) \quad (17.1)$$

where  $y_i$  is the  $i$ th response and  $X_i\beta$  is the linear predictor. The inverse logit function

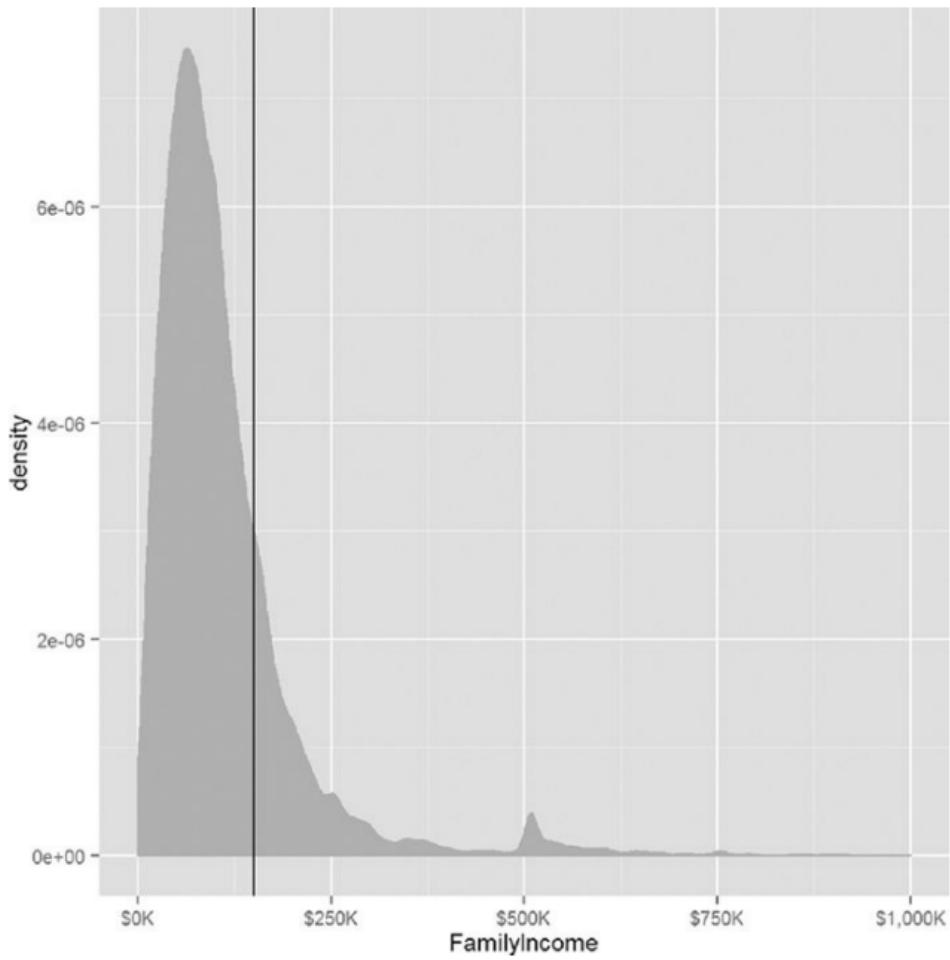
$$\text{logit}^{-1}(x) = \frac{e^x}{1 + e^x} = \frac{1}{1 + e^{-x}} \quad (17.2)$$

transforms the continuous output from the linear predictor to fall between 0 and 1. This is the inverse of the link function.

We now formulate a question that asks whether a household has an income greater than \$150,000 (See [Figure 17.1](#)). To do this we need to create a new binary variable with TRUE for income above that mark and FALSE for income below.

### [Click here to view code image](#)

```
> acs$Income <- with(acs, FamilyIncome >= 150000)
> require(ggplot2)
> require(useful)
> ggplot(acs, aes(x=FamilyIncome)) +
+   geom_density(fill="grey", color="grey") +
+   geom_vline(xintercept=150000) +
+   scale_x_continuous(label=multiple.dollar, limits=c(0,
1000000))
```



**Figure 17.1** Density plot of family income with a vertical line indicating the \$150,000 mark.

[Click here to view code image](#)

> **head(acs)**

	Acres	FamilyIncome	FamilyType	NumBedrooms		
	NumChildren	NumPeople				
1	1-10	150	Married	4	1	3
2	1-10	180	Female Head	3	2	4
3	1-10	280	Female Head	4	0	2
4	1-10	330	Female Head	2	1	2
5	1-10	330	Male Head	3	1	2
6	1-10	480	Male Head	0	3	4
	NumRooms	NumUnits	NumVehicles	NumWork-		
	ers	OwnRent				
1	9	Single detached	1	0	Mortgage	
2	6	Single detached	2	0	Rented	
3	8	Single detached	3	1	Mortgage	
4	4	Single detached	1	0	Rented	
5	5	Single attached	1	0	Mortgage	
6	1	Single detached	0	0	Rented	
	YearBuilt	HouseCosts	ElectricBill	FoodStamp	Heatin-	
	gFuel	Insurance				
1	1950-1959	1800	90	No	Gas	2500
2	Before 1939	850	90	No	Oil	0
3	2000-2004	2600	260	No	Oil	6600
4	1950-1959	1800	140	No	Oil	0
5	Before 1939	860	150	No	Gas	660
6	Before 1939	700	140	No	Gas	0
	Language	Income				
1	English	FALSE				
2	English	FALSE				
3	Other European	FALSE				
4	English	FALSE				
5	Spanish	FALSE				

Running a logistic regression is done very similarly to running a linear regression. It still uses the formula interface but the function is `glm` rather than `lm` (`glm` can actually fit linear regressions as well), and a few more options need to be set.

[Click here to view code image](#)

```
> income1 <- glm(Income ~ HouseCosts + NumWorkers +
  OwnRent +
  +           NumBedrooms + FamilyType,
  +           data=acs, family=binomial(link="logit"))
> summary(income1)
```

Call:

`glm(formula = Income ~ HouseCosts + NumWorkers +`  
`OwnRent + NumBedrooms +`

`FamilyType, family = binomial(link = "logit"), data =`  
`acs)`

Deviance Residuals:

Min	1Q	Median	3Q	Max
-2.8452	-0.6246	-0.4231	-0.1743	2.9503

Coefficients:

	Estimate	Std. Error	z value	Pr(> z )
(Intercept)	-5.738e+00	1.185e-01	-48.421	<2e-16
***				

HouseCosts	7.398e-04	1.724e-05	42.908	<2e-16
***				
NumWorkers	5.611e-01	2.588e-02	21.684	<2e-16
***				
OwnRentOutright	1.772e+00	2.075e-01	8.541	<2e-16
***				
OwnRentRented	-8.886e-01	1.002e-01	-8.872	<2e-16
***				
NumBedrooms	2.339e-01	1.683e-02	13.895	<2e-16
***				
FamilyTypeMale				
Head	3.336e-01	1.472e-01	2.266	0.0235 *
FamilyTypeMar-				
ried	1.405e+00	8.704e-02	16.143	<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: 22808 on 22744 degrees of freedom

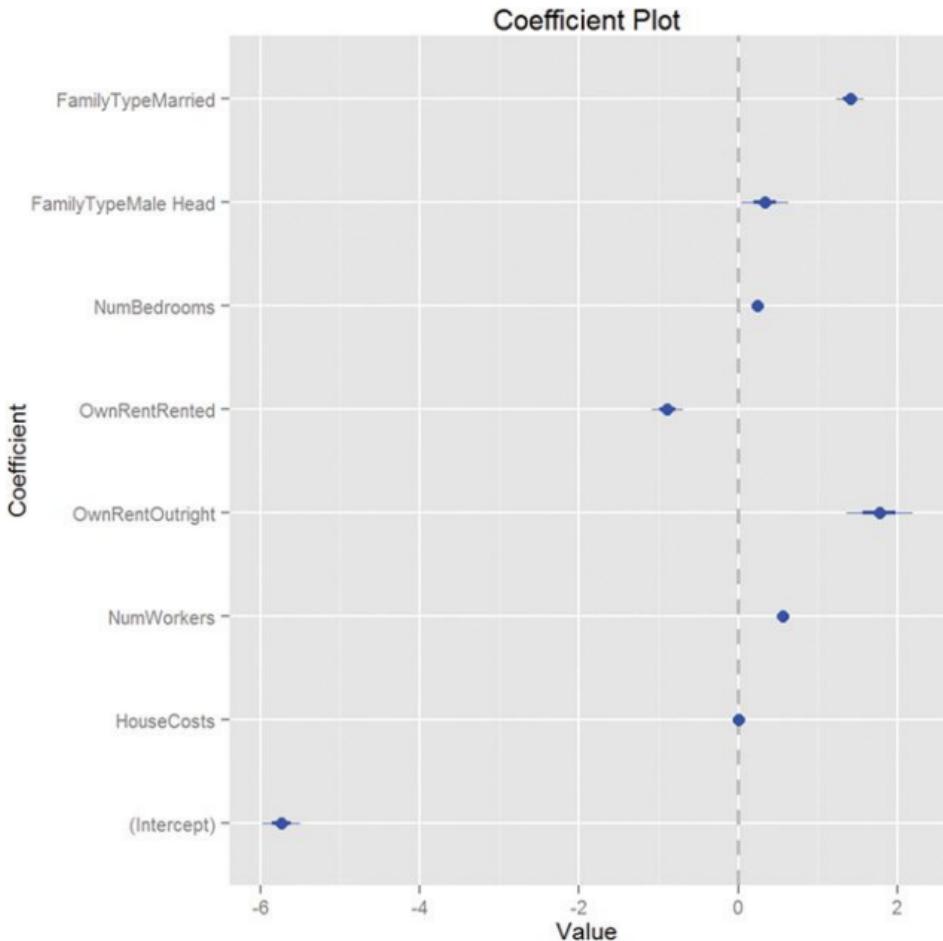
Residual deviance: 18073 on 22737 degrees of freedom

AIC: 18089

Number of Fisher Scoring iterations: 6

> **require**(coefplot)

> **coefplot**(income1)



**Figure 17.2** Coefficient plot for logistic regression on family income greater than \$150,000, based on the American Community Survey.

The output from summary and coefplot for glm is similar to that of lm. There are coefficient estimates, standard errors, p-values—both overall and for the coefficients—and a measure of correctness, which in this case is the deviance and AIC. A general rule of thumb is that adding a variable (or a level of a factor) to a model should result in a drop in deviance of two; otherwise, the variable is not useful in the model. Interactions and all the other formula concepts work the same.

Interpreting the coefficients from a logistic regression necessitates taking the inverse logit.

[Click here to view code image](#)

```
> invlogit <- function(x)
+ {
+   1/(1 + exp(-x))
+ }
> invlogit(income1$coefficients)
  (Intercept)    HouseCosts    NumWorkers
  0.003211572    0.500184950    0.636702036
  OwnRentOutright  OwnRentRented  NumBed-
rooms
  0.854753527    0.291408659    0.558200010
FamilyTypeMale Head FamilyTypeMarried
```

## 17.2. Poisson Regression

Another popular member of the generalized linear models is Poisson regression, which, much like the Poisson distribution, is used for count data. It, like all other generalized linear models, is called using `glm`. To illustrate we continue using the ACS data with the number of children (`NumChildren`) as the response.

The formulation for Poisson regression is

$$y_i \sim \text{pois}(\theta_i) \tag{17.3}$$

where  $y_i$  is the  $i$ th response and

$$\theta_i = e^{X_i \beta} \tag{17.4}$$

is the mean of the distribution for the  $i$ th observation.

Before fitting a model, we look at the histogram of the number of children in each household.

[Click here to view code image](#)

```
> ggplot(acs, aes(x = NumChildren)) +  
  geom_histogram(binwidth = 1)
```

While [Figure 17.3](#) does not show data that have a perfect Poisson distribution it is close enough to fit a good model. The coefficient plot is shown in [Figure 17.4](#).

[Click here to view code image](#)

```
> children1 <- glm(NumChildren ~ FamilyIncome + Fam-  
  ilyType + OwnRent,  
+                   data=acs, family=poisson(link="log"))  
> summary(children1)
```

Call:

```
glm(formula = NumChildren ~ FamilyIncome + Fam-  
  ilyType + OwnRent,
```

```
  family = poisson(link = "log"), data = acs)
```

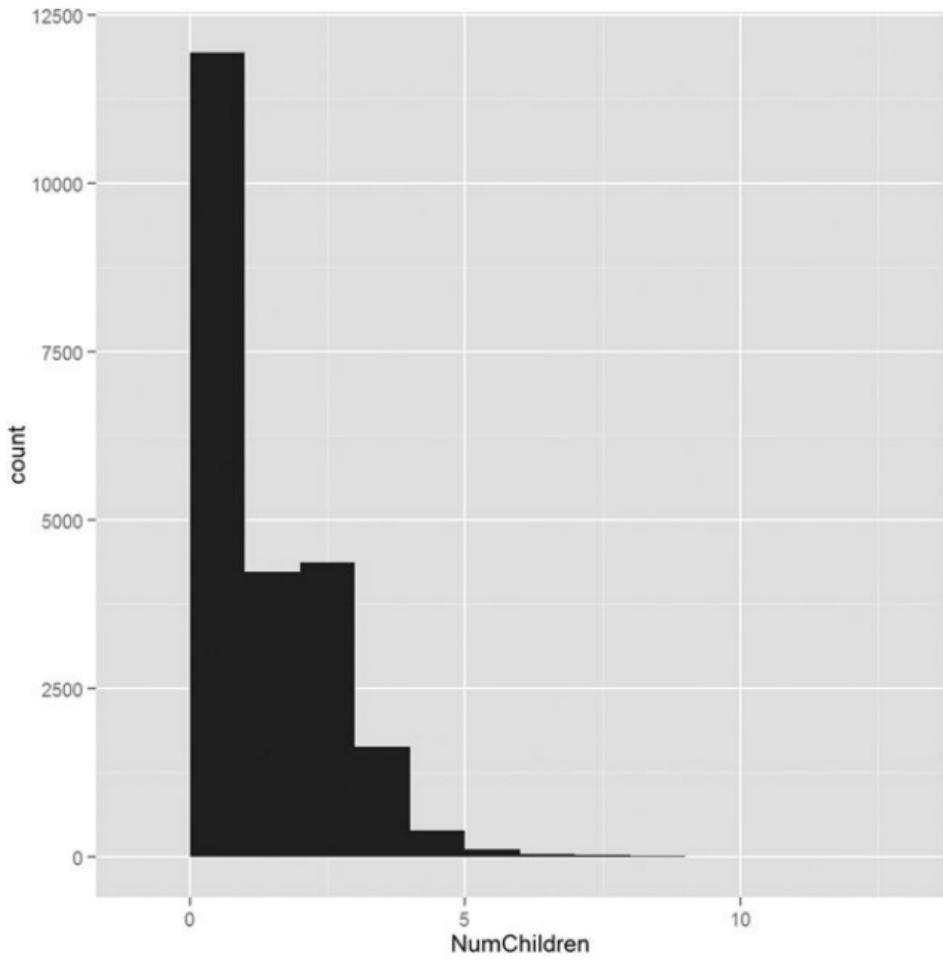
Deviance Residuals:

Min	1Q	Median	3Q	Max
-1.9950	-1.3235	-1.2045	0.9464	6.3781

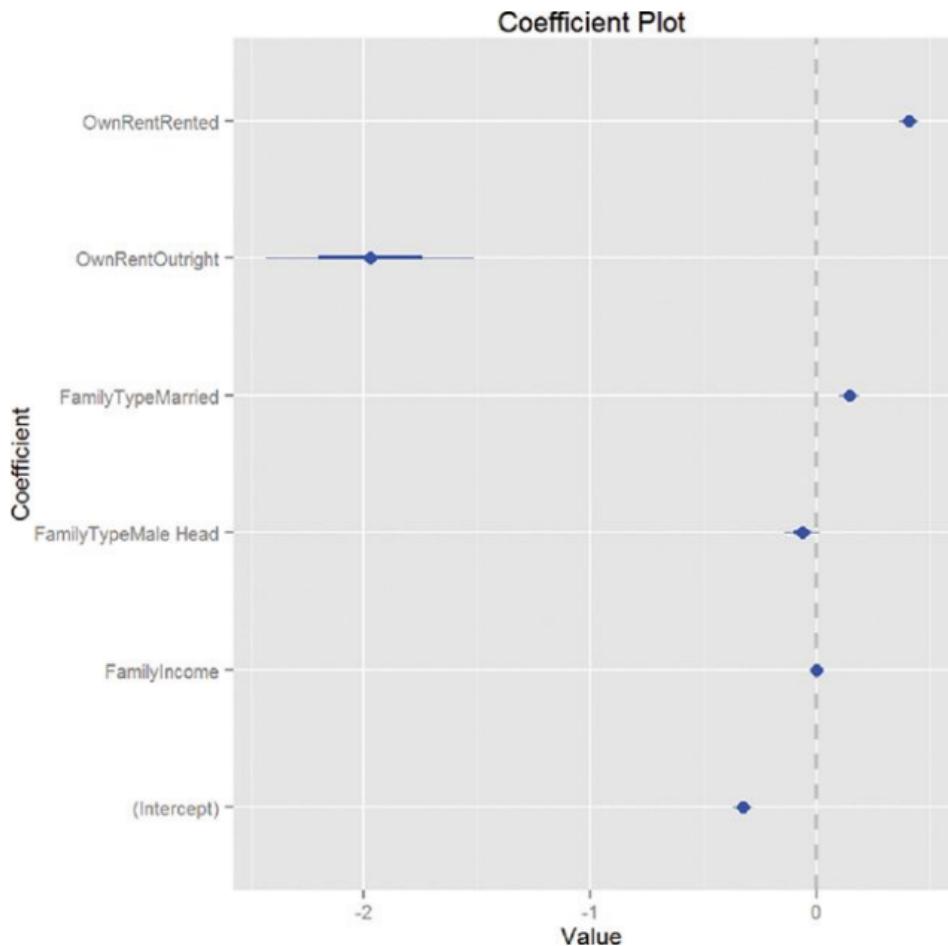
Coefficients:

	Estimate	Std. Error	z value	Pr(> z )
(Intercept)	-3.257e-01	2.103e-02	-15.491	< 2e-16
***				
FamilyIncome	5.420e-07	6.572e-08	8.247	< 2e-16
***				

FamilyTypeMale  
Head -6.298e-02 3.847e-02 -1.637 0.102  
FamilyTypeMarried 1.440e-01 2.147e-02 6.707  
1.98e-11 \*\*\*  
OwnRentOutright -1.974e+00 2.292e-01 -8.611 <  
2e-16 \*\*\*  
OwnRentRented 4.086e-01 2.067e-02 19.773 <  
2e-16 \*\*\*  
---  
Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1  
(Dispersion parameter for poisson family taken to be 1)  
Null deviance: 35240 on 22744 degrees of freedom  
Residual deviance: 34643 on 22739 degrees of freedom  
AIC: 61370  
Number of Fisher Scoring iterations: 5  
> **coefplot**(children1)



**Figure 17.3** Histogram of the number of children per household from the American Community Survey. The distribution is not perfectly Poisson but it is sufficiently so for modeling with Poisson regression.



**Figure 17.4** Coefficient plot for a logistic regression on ACS data.

The output here is similar to that for logistic regression, and the same rule of thumb for deviance applies.

A particular concern with Poisson regression is overdispersion, which means that the variability seen in the data is greater than is theorized by the Poisson distribution where the mean and variance are the same.

Overdispersion is defined as

$$OD = \frac{1}{n-p} \sum_{i=1}^n z_i^2 \quad (17.5)$$

where

$$z_i = \frac{\gamma_i - \hat{\gamma}_i}{sd(\hat{\gamma}_i)} = \frac{\gamma_i - u_i \hat{\theta}_i}{\sqrt{u_i \hat{\theta}_i}} \quad (17.6)$$

are the studentized residuals.

Calculating overdispersion in R is as follows.

[Click here to view code image](#)

```
> # the standardized residuals  
> z <- (acs$NumChildren - children1$fitted.values) /  
+   sqrt(children1$fitted.values)  
> # Overdispersion Factor  
> sum(z^2) / children1$df.residual  
[1] 1.469747  
> # Overdispersion p-value
```

```
> pchisq(sum(z^2), children1$df.residual)
[1] 1
```

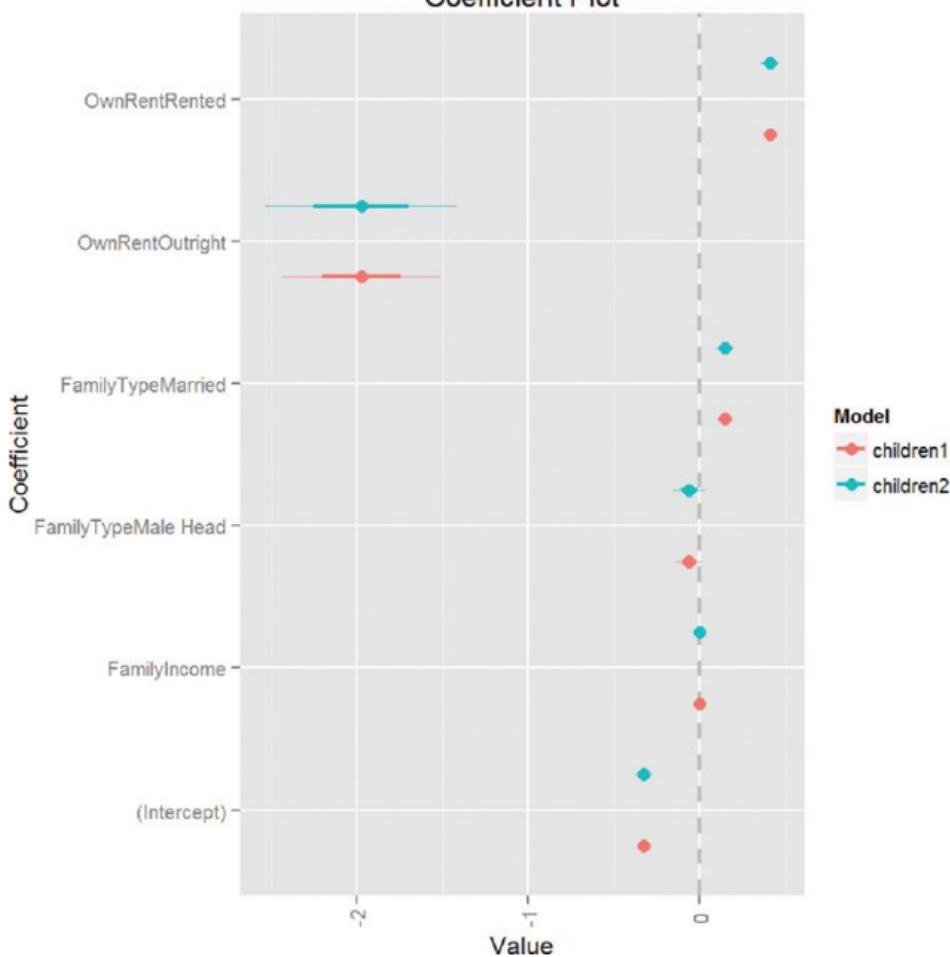
Generally an overdispersion ratio of 2 or greater indicates overdispersion. While this overdispersion ratio is less than 2, the p-value is 1, meaning that there is a statistically significant overdispersion. So we refit the model to account for the overdispersion using the quasipoisson family, which actually uses the negative binomial distribution.

[Click here to view code image](#)

```
> children2 <- glm(NumChildren ~ FamilyIncome + FamilyType + OwnRent,
+                     data=acs, family=quasipoisson(link="log"))
> multiplot(children1, children2)
```

[Figure 17.5](#) shows a coefficient plot for a model that accounts for overdispersion and one that does not. Since the overdispersion was not very large, the second model adds just a little uncertainty to the coefficient estimates.

### Coefficient Plot



**Figure 17.5** Coefficient plot for Poisson models. The first model, children1, does not account for overdispersion, while children2 does. Because the overdispersion was not too big, the coefficient estimates in the second model have just a bit more uncertainty.

### 17.3. Other Generalized Linear Models

Other common generalized linear models supported by the `glm` function are gamma, inverse gaussian and quasibinomial. Different link functions can be supplied, such as the following: logit, probit, cauchit, log and cloglog for binomial; inverse, identity and log for gamma; log, identity and sqrt for Poisson; and  $1/\mu^2$ , inverse, identity and log for inverse gaussian.

Multinomial regression, for classifying multiple categories, requires either running multiple logistic regressions (a tactic well supported in statistical literature) or using the `polr` function or the `multinom` function from the `nnet` package.

## 17.4. Survival Analysis

While not technically part of the family of generalized linear models, survival analysis is another important extension to regression. It has many applications, such as clinical medical trials, server failure times, number of accidents and time to death after a treatment or disease.

Data used for survival analysis are different from most other data in that they are censored, meaning there is unknown information, typically about what happens to a subject after a given amount of time. For an example, we look at the bladder data from the survival package.

[Click here to view code image](#)

```
> require(survival)
> head(bladder)
```

	id	rx	number	size	stop	event	enum
1	1	1	1	3	1	0	1
2	1	1	1	3	1	0	2
3	1	1	1	3	1	0	3
4	1	1	1	3	1	0	4
5	2	1	2	1	4	0	1
6	2	1	2	1	4	0	2

The columns of note are stop (when an event occurs or the patient leaves the study) and event (whether an event occurred at the time). Even if event is 0, we do not know if an event could have occurred later; this is why it is called censored. Making use of that structure requires the Surv function.

[Click here to view code image](#)

```
> # first look at a piece of the data
> bladder[100:105, ]
   id rx number size stop event enum
100 25 1     2    1   12    1    4
101 26 1     1    3   12    1    1
102 26 1     1    3   15    1    2
103 26 1     1    3   24    1    3
104 26 1     1    3   31    0    4
105 27 1     1    2   32    0    1
> # now look at the response variable built by build.y
> survObject <- with(bladder[100:105, ], Surv(stop,
  event))
> # nicely printed form
> survObject
[1] 12 12 15 24 31+ 32+
> # see its matrix form
> survObject[, 1:2]
   time status
[1,] 12     1
```

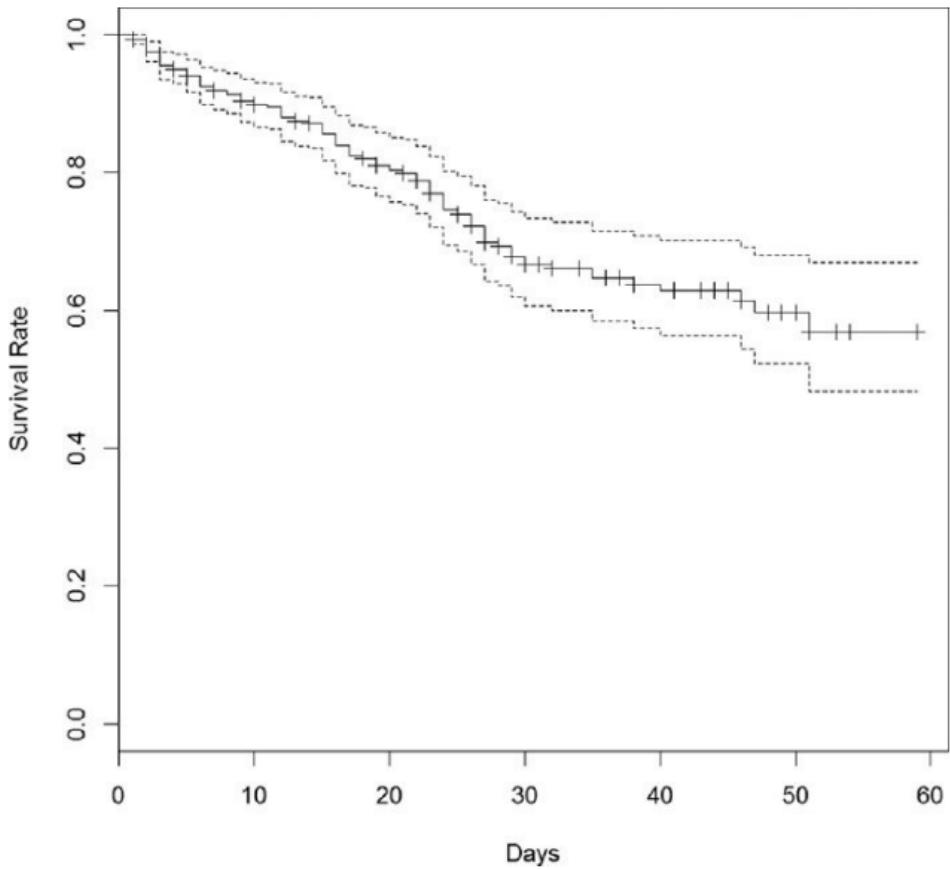
[2,]	12	1
[3,]	15	1
[4,]	24	1
[5,]	31	0
[6,]	32	0

This shows that for the first three rows where an event occurred, the time is known to be 12, whereas the bottom two rows had no event, so the time is censored because an event could have occurred afterward.

Perhaps the most common modeling technique in survival analysis is using a Cox proportional hazards model, which in R is done with `coxph`. The model is fitted using the familiar formula interface supplied to `coxph`. The `survfit` function builds the survival curve that can then be plotted as shown in [Figure 17.6](#). The survival curve shows the percentage of participants surviving at a given time. The summary is similar to other summaries but tailored to survival analysis.

[Click here to view code image](#)

```
> cox1 <- coxph(Surv(stop, event) ~ rx + number + size +
  enum,
+           data=bladder)
> summary(cox1)
Call:
coxph(formula = Surv(stop, event) ~ rx + number + size +
  enum,
  data = bladder)
n= 340, number of events= 112
      coef exp(coef) se(coef)   z Pr(>|z|)
rx    -0.59739  0.55024  0.20088 -2.974  0.00294 ***
number  0.21754  1.24301  0.04653  4.675 2.93e-06 ***
size    -0.05677  0.94481  0.07091 -0.801  0.42333
enum    -0.60385  0.54670  0.09401 -6.423 1.34e-10 ***
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1
      exp(coef) exp(-coef) lower .95 upper .95
rx      0.5502   1.8174   0.3712   0.8157
number  1.2430   0.8045   1.1347   1.3617
size    0.9448   1.0584   0.8222   1.0857
enum    0.5467   1.8291   0.4547   0.6573
Concordance= 0.753 (se = 0.029 )
Rsquare= 0.179 (max possible= 0.971 )
Likelihood ratio test= 67.21 on 4 df,  p=8.804e-14
Wald test       = 64.73 on 4 df,  p=2.932e-13
Score (logrank) test = 69.42 on 4 df,  p=2.998e-14
> plot(survfit(cox1), xlab="Days", ylab="Survival Rate",
+   conf.int=TRUE)
```

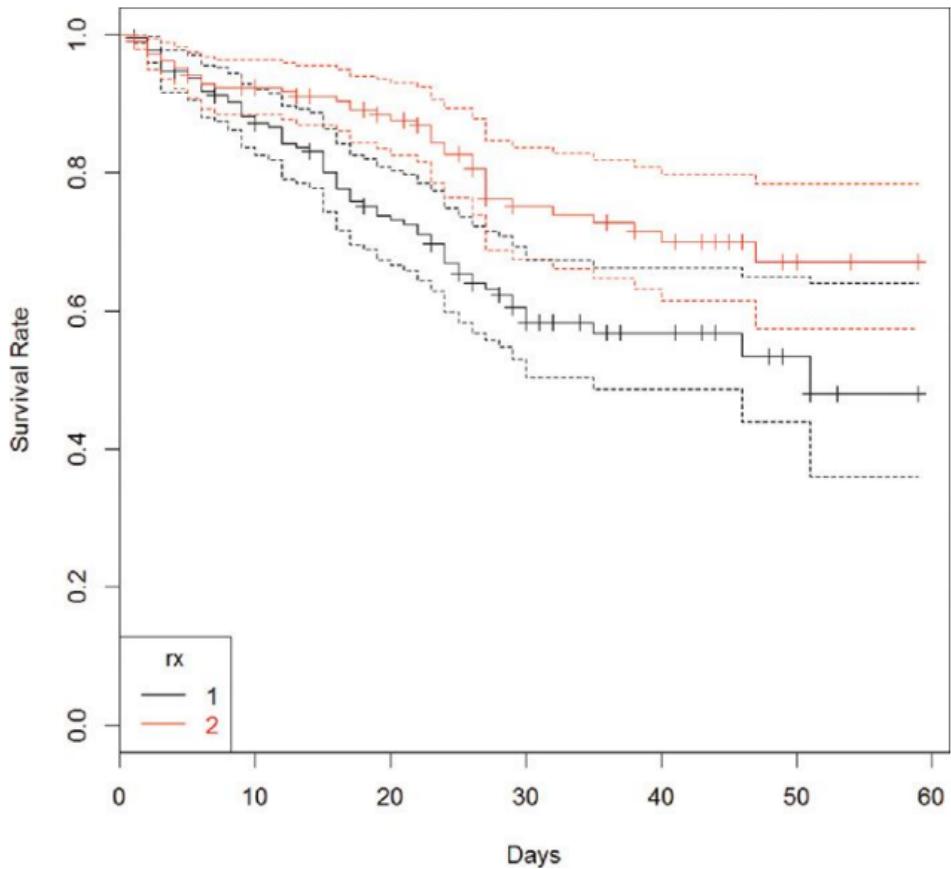


**Figure 17.6** Survival curve for Cox proportional hazards model fitted on bladder data.

In this data, the rx variable indicates placebo versus treatment, which is a natural stratification of the patients. Passing rx to strata in the formula splits the data into two for analysis and will result in two survival curves like those in [Figure 17.7](#).

[Click here to view code image](#)

```
> cox2 <- coxph(Surv(stop, event) ~ strata(rx) + number  
+ size + enum,  
+           data=bladder)  
> summary(cox2)  
Call:  
  
coxph(formula = Surv(stop, event) ~ strata(rx) + number +  
size +  
    enum, data = bladder)  
n= 340, number of events= 112  
      coef exp(coef) se(coef)   z Pr(>|z|)  
number  0.21371  1.23826  0.04648  4.598 4.27e-06 ***  
size   -0.05485  0.94662  0.07097 -0.773   0.44  
enum   -0.60695  0.54501  0.09408 -6.451 1.11e-10 ***  
---  
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1  
      exp(coef) exp(-coef) lower .95 upper .95  
number  1.2383   0.8076   1.1304   1.3564  
size    0.9466   1.0564   0.8237   1.0879  
enum    0.5450   1.8348   0.4532   0.6554  
Concordance= 0.74 (se = 0.04 )  
Rsquare= 0.166 (max possible= 0.954 )  
Likelihood ratio test= 61.84 on 3 df, p=2.379e-13  
Wald test       = 60.04 on 3 df, p=5.751e-13  
Score (logrank) test = 65.05 on 3 df, p=4.896e-14  
> plot(survfit(cox2), xlab="Days", ylab="Survival Rate",  
+     conf.int=TRUE, col=1:2)  
> legend("bottomleft", legend=c(1, 2), lty=1, col=1:2,  
+     text.col=1:2, title="rx")
```



**Figure 17.7** Survival curve for Cox proportional hazards model fitted on bladder data stratified on rx.

As an aside, this was a relatively simple legend to produce but it took a lot more effort than it would with ggplot2.

Testing the assumption of proportional hazards is done with cox.zph.

[Click here to view code image](#)

```
> cox.zph(cox1)
    rho  chisq      p
rx   0.0299 0.0957 7.57e-01
number 0.0900 0.6945 4.05e-01
size  -0.1383 2.3825 1.23e-01
enum   0.4934 27.2087 1.83e-07
GLOBAL   NA 32.2101 1.73e-06
> cox.zph(cox2)
    rho  chisq      p
number 0.0966 0.785 3.76e-01
size  -0.1331 2.197 1.38e-01
enum   0.4972 27.237 1.80e-07
GLOBAL   NA 32.101 4.98e-07
```

An Andersen-Gill analysis is similar to survival analysis, except it takes intervalized data and can handle multiple events such as counting the number of emergency room visits as opposed to whether or not there is an emergency room visit. It is also performed using coxph, except an additional variable is passed to Surv, and the data must be clustered on an identification column (id)

to keep track of multiple events. The corresponding survival curves are seen in [Figure 17.8](#).

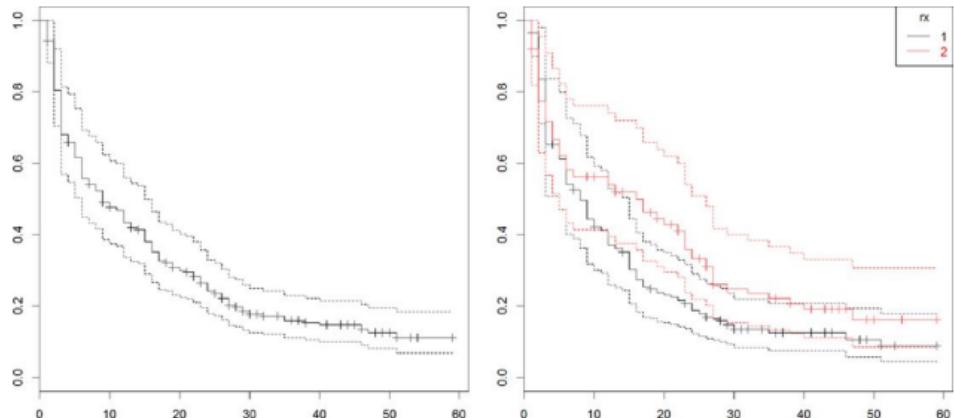
[Click here to view code image](#)

```
> head(bladder2)
  id rx number size start stop event enum
  1 1 1     1   3   0   1   0   1
  2 2 1     2   1   0   4   0   1
  3 3 1     1   1   0   7   0   1
  4 4 1     5   1   0  10   0   1
  5 5 1     4   1   0   6   1   1
  6 5 1     4   1   6  10   0   2

> ag1 <- coxph(Surv(start, stop, event) ~ rx + number +
  size + enum +
  +           cluster(id), data=bladder2)

> ag2 <- coxph(Surv(start, stop, event) ~ strata(rx) + num-
  ber + size +
  +           enum + cluster(id), data=bladder2)

> plot(survfit(ag1), conf.int=TRUE)
> plot(survfit(ag2), conf.int=TRUE, col=1:2)
> legend("topright", legend=c(1, 2), lty=1, col=1:2,
  +       text.col=1:2, title="rx")
```



**Figure 17.8** Andersen-Gill survival curves for bladder2 data.

## 17.5. Conclusion

Generalized linear models extend regression beyond linear relationships between the predictors and response. The most prominent types are logistic for binary data, Poisson for count data and survival analysis. Their uses go far beyond that, but those are by far the most common.

# Chapter 18. Model Diagnostics

Building a model can be a never-ending process in which we constantly improve the model by adding interactions, taking away variables, doing transformations and so on. However, at some point we need to confirm that we have the best model at the time, or even a good model. That leads to the question: How do we judge the quality of a model? In almost all cases the answer has to be: in relation to other models. This could be an analysis of residuals, the results of an ANOVA test or a Wald test, drop-in deviance, the AIC or BIC score, cross-validation error or bootstrapping.

## 18.1. Residuals

One of the first-taught ways of assessing model quality is an analysis of the residuals, which is the difference between the actual response and the fitted values, values predicted by the model. This is a direct result of the formulation in [Equation 16.1](#) where the errors, akin to residuals, are normally distributed. The basic idea is that if the model is appropriately fitted to the data, the residuals should be normally distributed as well. To see this, we start with the housing data to which we fit a regression and visualize with a coefficient plot, as shown in [Figure 18.1](#).

[Click here to view code image](#)

```
> # read in the data
> housing <- read.table("data/housing.csv", sep=",", header=TRUE,
+                           stringsAsFactors=FALSE)
> # give the data good names
> names(housing) <- c("Neighborhood", "Class", "Units",
+ "YearBuilt",
+                           "SqFt", "Income", "IncomePerSqFt", "Expense",
+                           "ExpensePerSqFt", "NetIncome", "Value",
```

```
+ "ValuePerSqFt", "Boro")
```

```
> # eliminate some outliers
```

```
> housing <- housing[housing$Units < 1000, ]
```

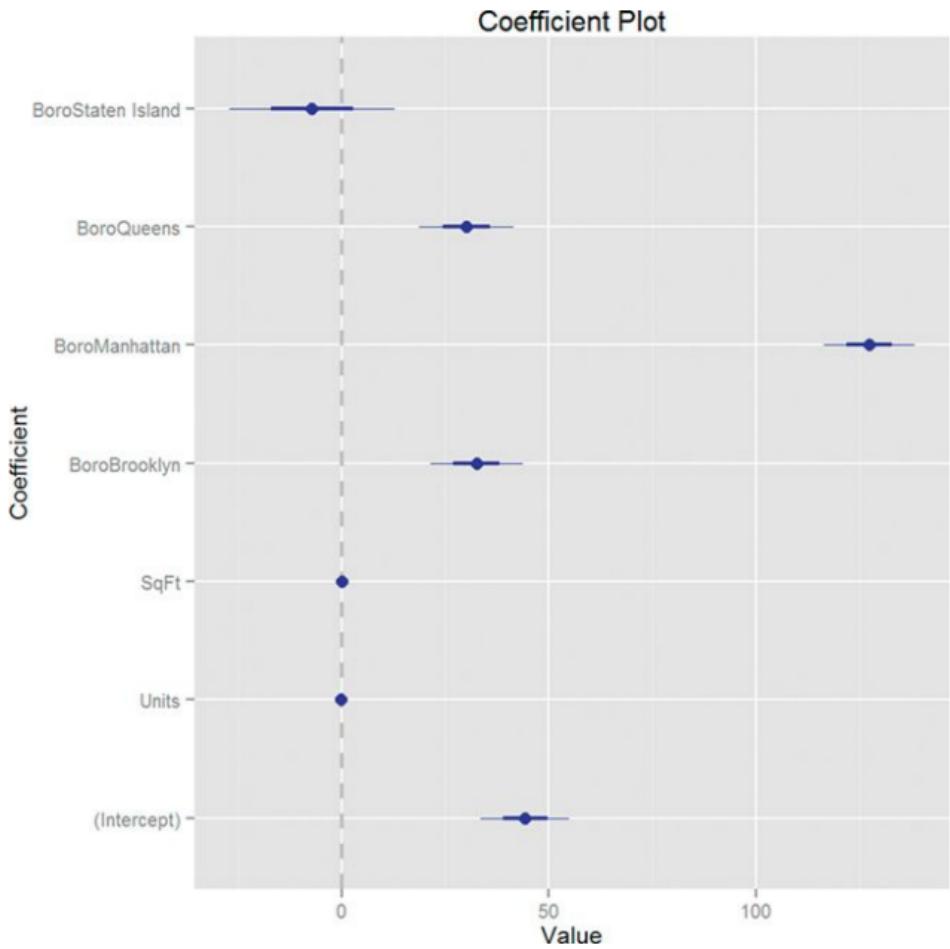
```
> head(housing)
```

	Neighborhood	Class	Units	YearBuilt	SqFt	Income
1	FINANCIAL					
2	R9-CONDOMINIUM	42	1920	36500	1332615	
3	FINANCIAL R4-CONDOMINIUM	78		1985		
4	126420	6633257				
5	RR-CONDOMINIUM	500		NA		
6	554174	17310000				
7	FINANCIAL R4-CONDOMINIUM	282		1930		
8	249076	11776313				
9	TRIBECA R4-CONDOMINIUM	239		1985		
10	219495	10004582				
11	TRIBECA R4-CONDOMINIUM	133		1986		
12	139719	5127687				

	IncomePerSqFt	Expense	ExpensePerSqFt	NetIncome	Value
1	36.51	342005	9.37	990610	7300000
2	52.47	1762295	13.94	4870962	30690000
3	31.24	3543000	6.39	13767000	90970000
4	47.28	2784670	11.18	8991643	67556006
5	45.58	2783197	12.68	7221385	54320996
6	36.70	1497788	10.72	3629899	26737996

```
5     247.48 Manhattan
6     191.37 Manhattan
>
> # fit a model
> house1 <- lm(ValuePerSqFt ~ Units + SqFt + Boro,
+ data=housing)
> summary(house1)
Call:
lm(formula = ValuePerSqFt ~ Units + SqFt + Boro, data =
housing)
Residuals:
    Min      1Q  Median      3Q      Max 
-168.458 -22.680   1.493  26.290  261.761 
Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) 4.430e+01 5.342e+00  8.293 < 2e-16 ***
Units       -1.532e-01 2.421e-02 -6.330 2.88e-10 ***
SqFt        2.070e-04 2.129e-05  9.723 < 2e-16 ***
BoroBrooklyn 3.258e+01 5.561e+00  5.858 5.28e-09 ***
BoroManhattan 1.274e+02 5.459e+00 23.343 < 2e-16 ***
BoroQueens   3.011e+01 5.711e+00  5.272 1.46e-07 ***
BoroStaten Island -7.114e+00 1.001e+01 -0.711   0.477 
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 43.2 on 2613 degrees of freedom
```

```
Multiple R-squared: 0.6034, Adjusted R-squared: 0.6025  
F-statistic: 662.6 on 6 and 2613 DF, p-value: <2.2e-16  
>  
> # visualize the model  
> require(coefplot)  
> coefplot(house1)
```



**Figure 18.1** Coefficient plot for condo value data regression in house1.

For linear regression, three important residual plots are fitted values against residuals, Q-Q plots and the histogram of the residuals. The first is

easy enough with `ggplot2`. Fortunately, `ggplot2` has a handy trick for dealing with `lm` models. We can use the model as the data source and `ggplot2` “fortifies” it, creating new columns, for easy plotting.

[Click here to view code image](#)

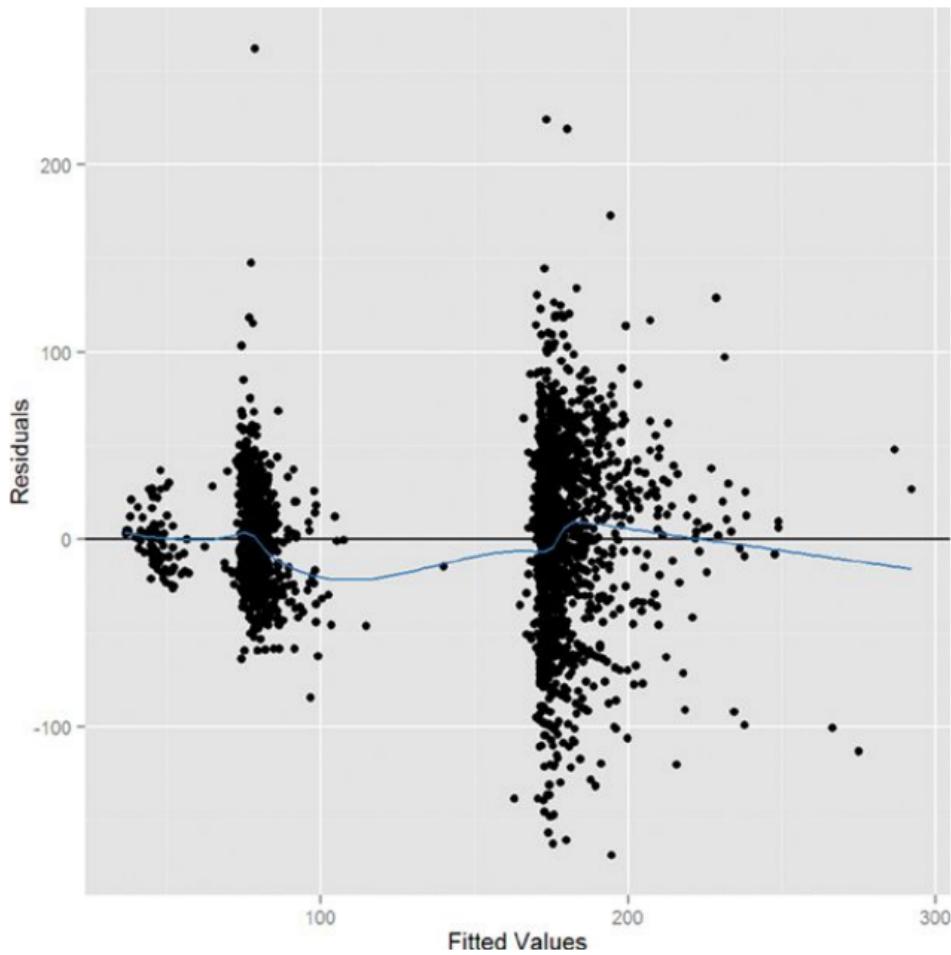
```
> require(ggplot2)
> # see what a fortified lm model looks like
> head(fortify(house1))
  ValuePerSqFt Units SqFt      Boro     .hat   .sigma
1    200.00     42 36500 Manhattan 0.0009594821
43.20952
2    242.76     78 126420 Manhattan 0.0009232393
43.19848
3    164.15     500 554174 Manhattan 0.0089836758
43.20347
4    271.23     282 249076 Manhattan 0.0035168641
43.17583
5    247.48     239 219495 Manhattan 0.0023865978
43.19289
6    191.37     133 139719 Manhattan 0.0008934957
43.21225
       .cooksD .fitted .resid   .stdresid
1 5.424169e-05 172.8475 27.15248  0.6287655
2 2.285253e-04 185.9418 56.81815  1.3157048
3 1.459368e-03 209.8077 -45.65775 -1.0615607
4 2.252653e-03 180.0672  91.16278  2.1137487
```

```
5 8.225193e-04 180.5341 66.94589 1.5513636
6 8.446170e-06 180.2661 11.10385 0.2571216
> # save a plot to an object
> # notice we are using the created columns for the x- and
y-axes
> # they are .fitted and .resid
> h1 <- ggplot(aes(x=.fitted, y=.resid), data = house1) +
+   geom_point() +
+   geom_hline(yintercept = 0) +
+   geom_smooth(se = FALSE) +
+   labs(x="Fitted Values", y="Residuals")
>
> # print the plot
> h1
```

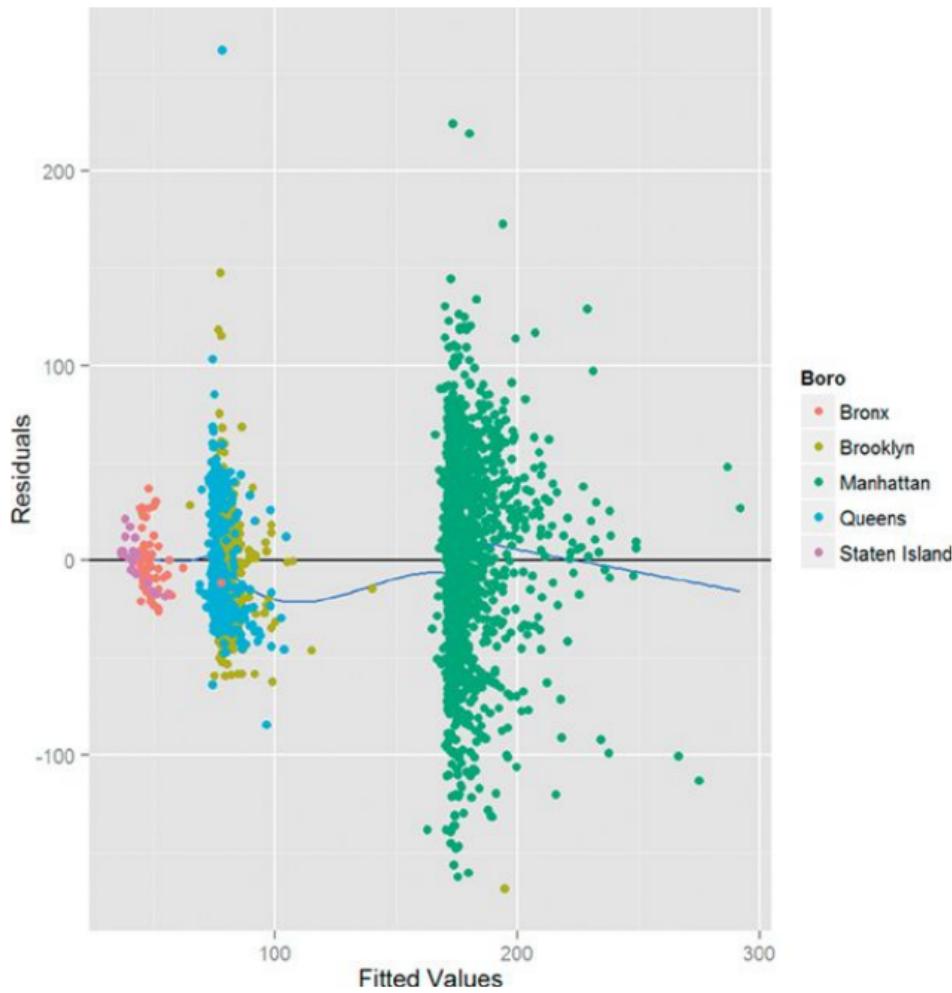
The plot of residuals versus fitted values shown in [Figure 18.2](#) is at first glance disconcerting, because the pattern in the residuals shows that they are not as randomly dispersed as desired. However, further investigation reveals that this is due to the structure that Boro gives the data, as seen in [Figure 18.3](#).

[Click here to view code image](#)

```
> h1 + geom_point(aes(color = Boro))
```



**Figure 18.2** Plot of residuals versus fitted values for house1. This clearly shows a pattern in the data that does not appear to be random.



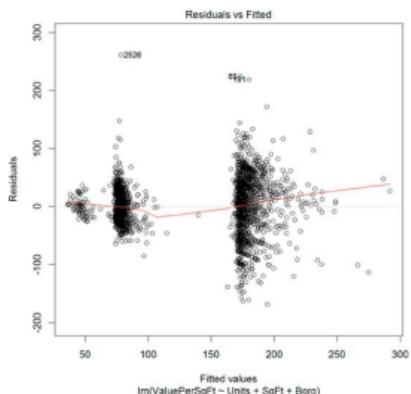
**Figure 18.3** Plot of residuals versus fitted values for house1 colored by Boro. The pattern in the residuals is revealed to be the result of the effect of Boro on the model. Notice that the points sit above the  $x$ -axis and the smoothing curve because geom point was added after the other geoms, meaning it gets layered on top.

This plot could have been easily, although less attractively, plotted using the built-in plotting function, as shown in [Figure 18.4](#).

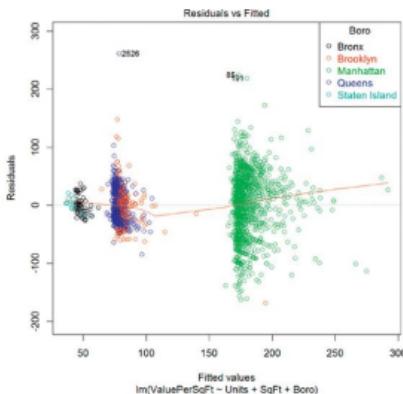
[Click here to view code image](#)

```
> # basic plot  
> plot(house1, which=1)  
> # same plot but colored by Boro  
> plot(house1, which=1, col=as.numeric(factor(house1$  
model$Boro)))  
> # corresponding legend  
> legend("topright", legend=levels(factor(house1$mod-  
el$Boro)), pch=1,  
+       col=as.numeric(factor(levels(factor(house1$mod-  
el$Boro)))),  
+       text.col=as.numeric(factor(levels(factor(house1$-  
model$Boro)))),
```

```
+      title="Boro")
```



(a) Residuals versus fitted values



(b) Residuals versus fitted values colored by *Boro*

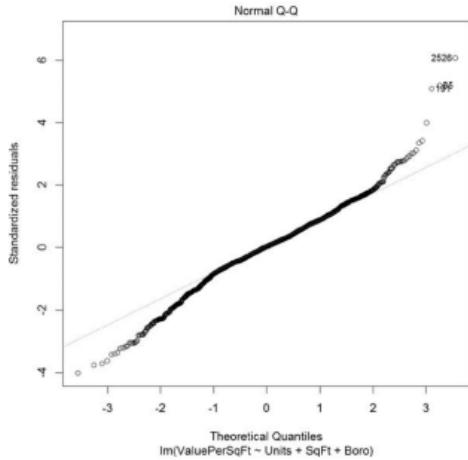
## Figure 18.4 Base graphics plots for residuals versus fitted values.

Next up is the Q-Q plot. If the model is a good fit, the standardized residuals should all fall along a straight line when plotted against the theoretical quantiles of the normal distribution. Both the base graphics and ggplot2 versions are shown in [Figure 18.5](#).

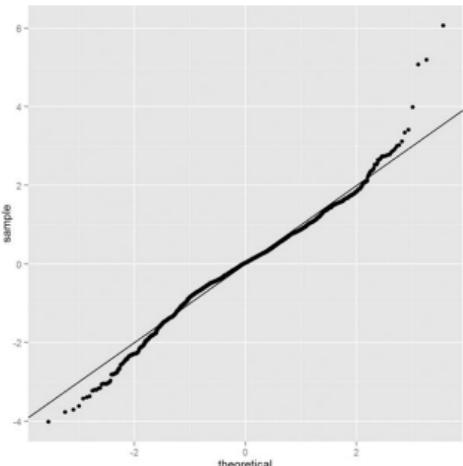
[Click here to view code image](#)

```
> plot(house1, which = 2)
```

```
> ggplot(house1, aes(sample = .stdresid)) + stat_qq() +  
  geom_abline()
```



(a) Base graphics



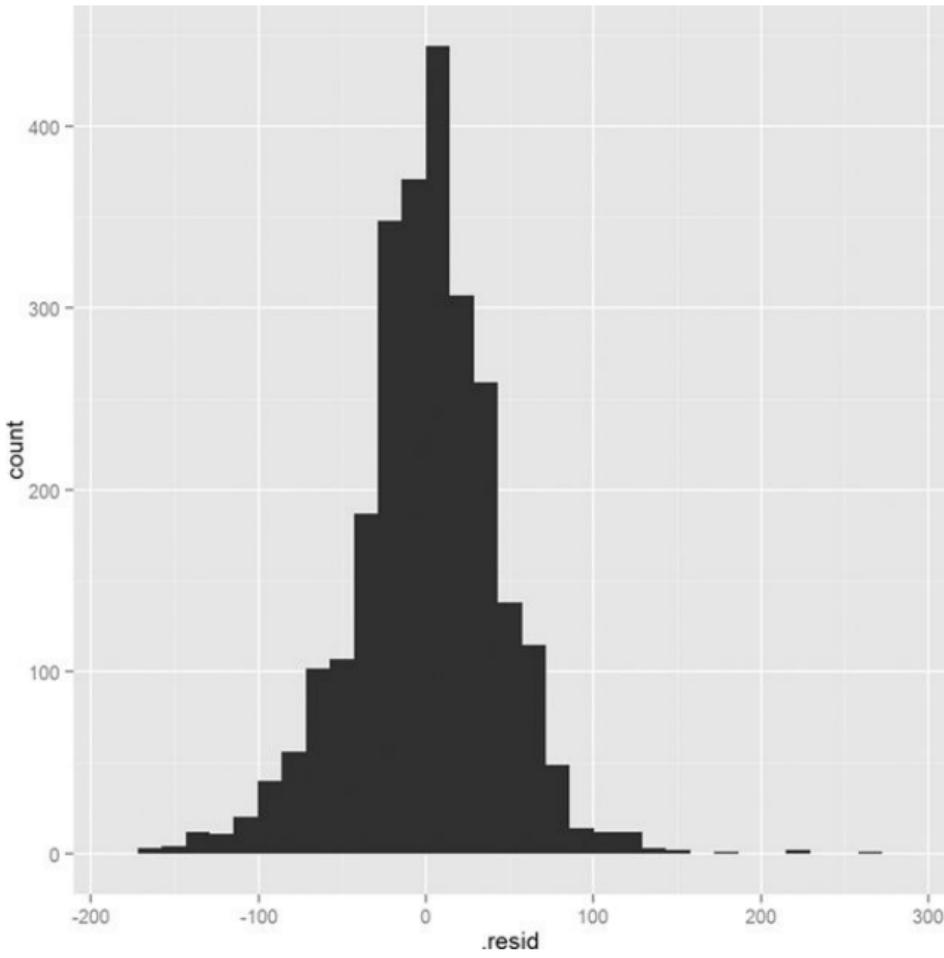
(b) ggplot2

**Figure 18.5** Q-Q plot for house1. The tails drift away from the ideal theoretical line, indicating that we do not have the best fit.

Another diagnostic is a histogram of the residuals. This time we will not be showing the base graphics alternative because a histogram is a standard plot that we have shown repeatedly. The histogram in [Figure 18.6](#) is not normally distributed, meaning that our model is not an entirely correct specification.

[Click here to view code image](#)

```
> ggplot(house1, aes(x = .resid)) + geom_histogram()
```



**Figure 18.6** Histogram of residuals from house1. This does not look normally distributed, meaning our model is incomplete.

## 18.2. Comparing Models

All of this measuring of model fit only really makes sense when comparing multiple models, because all of these measures are relative. So we will fit a number of models in order to compare them to each other.

[Click here to view code image](#)

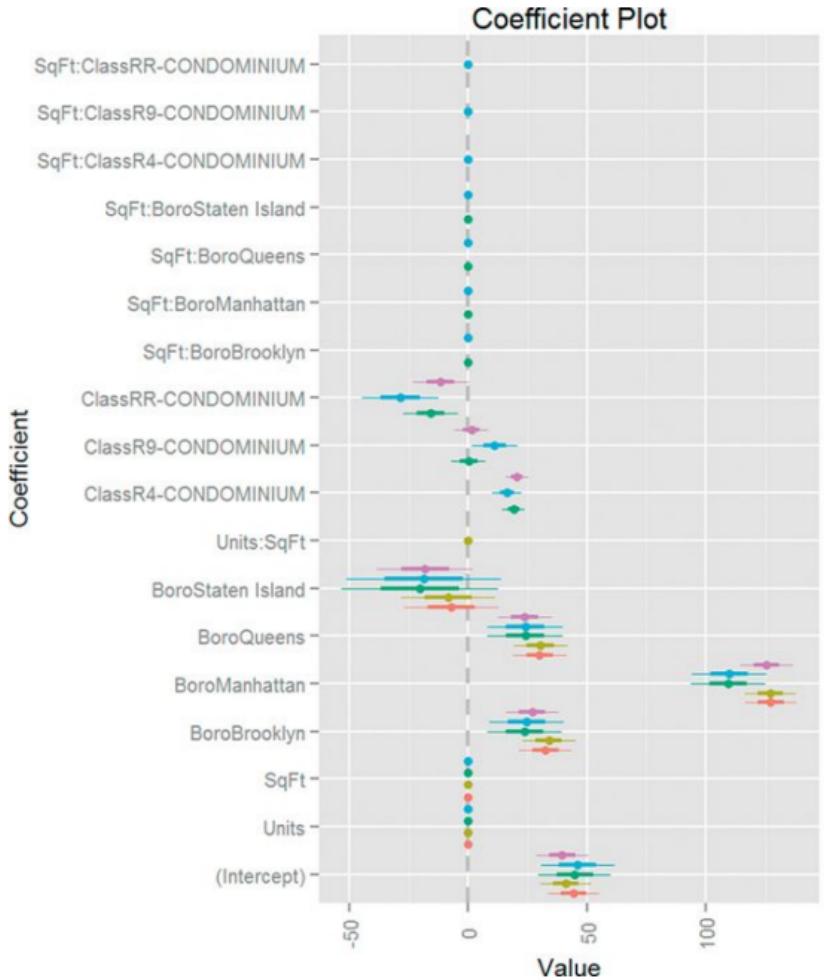
```
> house2 <- lm(ValuePerSqFt ~ Units * SqFt + Boro,  
+                 data=housing)  
  
> house3 <- lm(ValuePerSqFt ~ Units + SqFt * Boro +  
+                 Class,  
+                 data=housing)  
  
> house4 <- lm(ValuePerSqFt ~ Units + SqFt * Boro +  
+                 SqFt*Class,  
+                 data=housing)  
  
> house5 <- lm(ValuePerSqFt ~ Boro + Class, data=hous-  
+                 ing)
```

As usual, our first step is to visualize the models together using multiplot from the coefplot package. The result is in [Figure 18.7](#) and shows that Boro is the only variable with a significant

effect on ValuePerSqFt as do certain condominium types.

[Click here to view code image](#)

```
> multiplot(house1, house2, house3, house4, house5,  
  pointSize = 2)
```



**Figure 18.7** Coefficient plot of various models based on housing data. This shows that only Boro and some condominium types matter.

While we do not promote using ANOVA for a multisample test, we do believe it serves a useful purpose in testing the relative merits of different models. Simply passing multiple model objects to `anova` will return a table of results including the residual sum of squares (RSS), which is a measure of error, the lower the better.

[Click here to view code image](#)

```
> anova(house1, house2, house3, house4, house5)  
Analysis of Variance Table
```

Model 1:  $\text{ValuePerSqFt} \sim \text{Units} + \text{SqFt} + \text{Boro}$

Model 2:  $\text{ValuePerSqFt} \sim \text{Units} * \text{SqFt} + \text{Boro}$

Model 3:  $\text{ValuePerSqFt} \sim \text{Units} + \text{SqFt} * \text{Boro} + \text{Class}$

Model 4:  $\text{ValuePerSqFt} \sim \text{Units} + \text{SqFt} * \text{Boro} + \text{SqFt} * \text{Class}$

Model 5:  $\text{ValuePerSqFt} \sim \text{Boro} + \text{Class}$

Res.Df	RSS	Df	Sum of Sq	F	Pr(>F)
--------	-----	----	-----------	---	--------

1	2613	4877506
---	------	---------

2	2612	4847886	1	29620	17.0360	3.783e-05	***
---	------	---------	---	-------	---------	-----------	-----

3	2606	4576769	6	271117	25.9888	< 2.2e-16	***
---	------	---------	---	--------	---------	-----------	-----

4	2603	4525783	3	50986	9.7749	2.066e-06	***
---	------	---------	---	-------	--------	-----------	-----

5	2612	4895630	-9	-369847	23.6353	< 2.2e-16	***
---	------	---------	----	---------	---------	-----------	-----

---

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

This shows that the fourth model, house4, has the lowest RSS, meaning it is the best model of the bunch. The problem with RSS is that it always improves when an additional variable is added to the model. This can lead to excessive model complexity and overfitting. Another metric, which penalizes model complexity, is the Akaike Information Criterion (AIC). As with RSS, the model with the lowest AIC—even negative values—is considered optimal. The BIC (Bayesian Information Criterion) is a similar measure where, once again, lower is better.

The formula for AIC is

$$\text{AIC} = -2\ln(\mathcal{L}) + 2p \quad (18.1)$$

where  $\ln(\mathcal{L})$  is the maximized log-likelihood and  $p$  is the number of coefficients in the model. As the model improves the log-likelihood gets bigger, and because that term is negated the AIC gets lower. However, adding coefficients increases the AIC; this penalizes model complexity. The formula for BIC is similar except that instead of multiplying the number of coefficients by 2 it

multiplies it by the natural log of the number of rows. This is seen in [Equation 18.2](#).

$$\text{BIC} = -2\ln(\mathcal{L}) + \ln(n) \cdot p \quad (18.2)$$

The AIC and BIC for our models are calculated using the AIC and BIC functions, respectively.

[Click here to view code image](#)

```
> AIC(house1, house2, house3, house4, house5)
      df    AIC
house1 8 27177.78
house2 9 27163.82
house3 15 27025.04
house4 18 27001.69
house5 9 27189.50
> BIC(house1, house2, house3, house4, house5)
      df    BIC
house1 8 27224.75
house2 9 27216.66
house3 15 27113.11
house4 18 27107.37
house5 9 27242.34
```

When called on `glm` models, `anova` returns the deviance of the model, which is another measure of error. The general rule of thumb—according

to Andrew Gelman—is that for every added variable in the model, the deviance should drop by two. For categorical (factor) variables, the deviance should drop by two for each level.

To illustrate we make a binary variable out of ValuePerSqFt and fit a few logistic regression models.

[Click here to view code image](#)

```
> # create the binary variable based on whether ValuePer-SqFt is above 150  
> housing$HighValue <- housing$ValuePerSqFt >= 150  
>  
> # fit a few models  
  
> high1 <- glm(HighValue ~ Units + SqFt + Boro,  
+           data=housing, family=binomial(link="logit"))  
  
> high2 <- glm(HighValue ~ Units * SqFt + Boro,  
+           data=housing, family=binomial(link="logit"))  
  
> high3 <- glm(HighValue ~ Units + SqFt * Boro + Class,  
+           data=housing, family=binomial(link="logit"))  
  
> high4 <- glm(HighValue ~ Units + SqFt * Boro +  
SqFt*Class,  
+           data=housing, family=binomial(link="logit"))  
  
> high5 <- glm(HighValue ~ Boro + Class,  
+           data=housing, family=binomial(link="logit"))
```

```
>  
> # test the models using ANOVA (deviance), AIC and BIC  
> anova(high1, high2, high3, high4, high5)
```

### Analysis of Deviance Table

Model 1: HighValue ~ Units + SqFt + Boro

Model 2: HighValue ~ Units \* SqFt + Boro

Model 3: HighValue ~ Units + SqFt \* Boro + Class

Model 4: HighValue ~ Units + SqFt \* Boro + SqFt \* Class

Model 5: HighValue ~ Boro + Class

Resid.	Df	Resid.	Dev	Df	Deviance
--------	----	--------	-----	----	----------

1	2613	1687.5			
---	------	--------	--	--	--

2	2612	1678.8	1	8.648	
---	------	--------	---	-------	--

3	2606	1627.5	6	51.331	
---	------	--------	---	--------	--

4	2603	1606.1	3	21.420	
---	------	--------	---	--------	--

5	2612	1662.3	-9	-56.205	
---	------	--------	----	---------	--

> **AIC**(high1, high2, high3, high4, high5)

df	AIC
----	-----

high1	7	1701.484
-------	---	----------

high2	8	1694.835
-------	---	----------

high3	14	1655.504
-------	----	----------

high4	17	1640.084
-------	----	----------

high5	8	1678.290
-------	---	----------

> **BIC**(high1, high2, high3, high4, high5)

df	BIC
----	-----

high1	7	1742.580
-------	---	----------

high2	8	1741.803
-------	---	----------

high3	14	1737.697
-------	----	----------

high4	17	1739.890
-------	----	----------

Here, once again, the fourth model is the best. Notice that the fourth model added three variables (the three indicator variables for Class interacted with SqFt) and its deviance dropped by 21, which is greater than two for each additional variable.

## 18.3. Cross-Validation

Residual diagnostics and model tests such as ANOVA and AIC are a bit old fashioned and came along before modern computing horsepower. The preferred method to assess model quality—at least by most data scientists—is cross-validation, sometimes called  $k$ -fold cross-validation. The data are broken into  $k$  (usually five or ten) non-overlapping sections. Then a model is fitted on  $k - 1$  sections of the data, which is then used to make predictions based on the  $k$ th section. This is repeated  $k$  times until every section has been held out for testing once and included in model fitting  $k - 1$  times. Cross-validation provides a measure of the predictive accuracy of a model, which is largely considered a good means of assessing model quality.

There are a number of packages and functions that assist in performing cross-validation. Each has its own limitations or quirks, so rather than going through a number of incomplete functions, we show one that works well for generalized lin-

ear models (including linear regression), and then build a generic framework that can be used generally for an arbitrary model type.

The boot package by Brian Ripley has cv.glm for performing cross-validation on. As the name implies, it works only for generalized linear models, which will suffice for a number of situations.

[Click here to view code image](#)

```
> require(boot)
> # refit house1 using glm instead of lm
> houseG1 <- glm(ValuePerSqFt ~ Units + SqFt + Boro,
+                   data=housing, family=gaussian(link="identity"))
>
> # ensure it gives the same results as lm
> identical(coef(house1), coef(houseG1))
[1] TRUE
>
> # run the cross-validation with 5 folds
> houseCV1 <- cv.glm(housing, houseG1, K=5)
> # check the error
> houseCV1$delta
[1] 1878.596 1876.691
```

The results from cv.glm include delta, which has two numbers, the raw cross-validation error based on the cost function (in this case the mean squared error, which is a measure of correctness for an estimator and is defined in [Equation 18.3](#)) for all the folds and the adjusted cross-validation error. This second number compensates for not using leave-one-out cross-validation, which is like k-fold cross-validation except that each fold is the all but one data point with one point held out. This is very accurate but highly computationally intensive.

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2 \quad (18.3)$$

While we got a nice number for the error, it helps us only if we can compare it to other models, so we run the same process for the other models we built, rebuilding them with glm first.

[Click here to view code image](#)

```
> # refit the models using glm
```

```
> houseG2 <- glm(ValuePerSqFt ~ Units * SqFt + Boro,  
  data=housing)
```

```
> houseG3 <- glm(ValuePerSqFt ~ Units + SqFt * Boro +
  Class,
+           data=housing)

> houseG4 <- glm(ValuePerSqFt ~ Units + SqFt * Boro +
  SqFt*Class,
+           data=housing)

> houseG5 <- glm(ValuePerSqFt ~ Boro + Class,
  data=housing)
>
> # run cross-validation
> houseCV2 <- cv.glm(housing, houseG2, K=5)
> houseCV3 <- cv.glm(housing, houseG3, K=5)
> houseCV4 <- cv.glm(housing, houseG4, K=5)
> houseCV5 <- cv.glm(housing, houseG5, K=5)
>
> ## check the error results
> # build a data.frame of the results
> cvResults <- as.data.frame(rbind(houseCV1$delta,
  houseCV2$delta,
+           houseCV3$delta, houseCV4$delta,
+           houseCV5$delta))
> ## do some cleaning up to make the results more present-
  able
> # give better column names
> names(cvResults) <- c("Error", "Adjusted.Error")
> # add model name
> cvResults$Model <- sprintf("houseG%s", 1:5)
>
> # check the results
```

```
> cvResults
```

	Error	Adjusted.Error	Model
1	1878.596	1876.691	houseG1
2	1862.247	1860.900	houseG2
3	1767.268	1764.953	houseG3
4	1764.370	1760.102	houseG4
5	1882.631	1881.067	houseG5

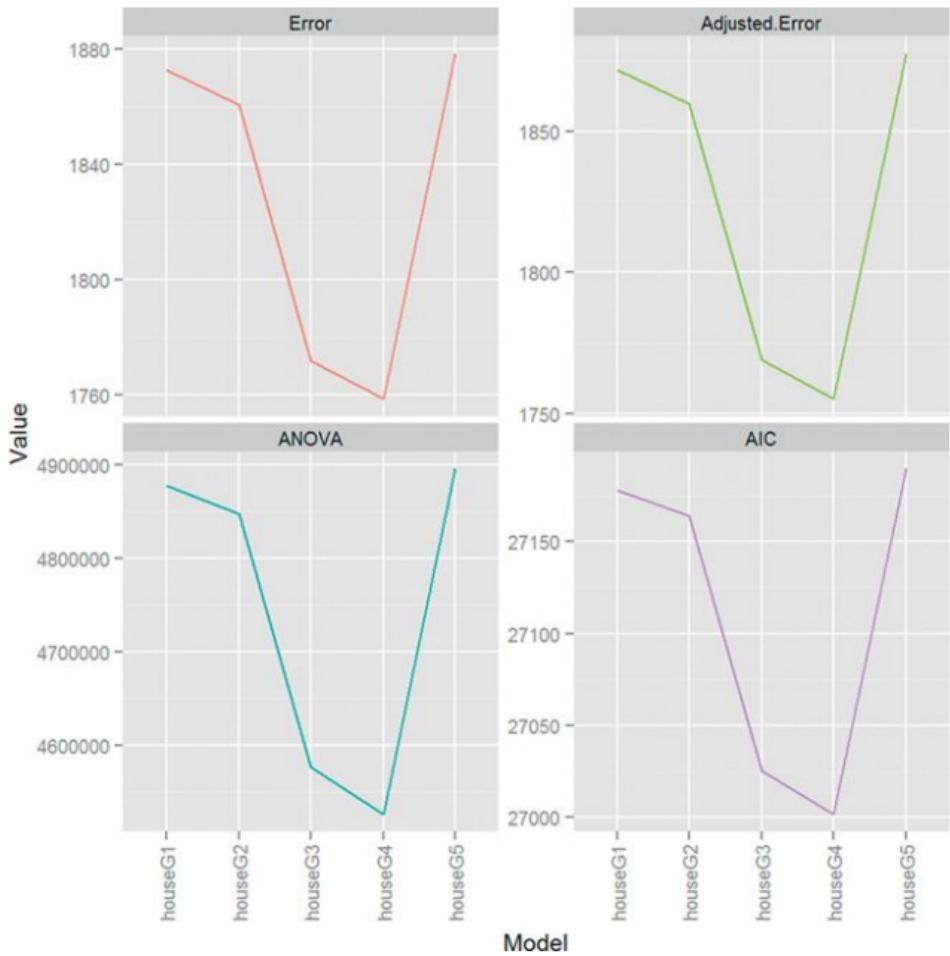
Once again, the fourth model, houseG4, is the superior model. [Figure 18.8](#) shows how much ANOVA, AIC and cross-validation agree on the relative merits of the different models. The scales are all different but the shapes of the plots are identical.

[Click here to view code image](#)

```
> # visualize the results  
> # test with ANOVA  
> cvANOVA <- anova(houseG1, houseG2, houseG3,  
houseG4, houseG5)  
> cvResults$ANOVA <- cvANOVA$`Resid. Dev'  
> # measure with AIC  
> cvResults$AIC <- AIC(houseG1, houseG2, houseG3,  
houseG4, houseG5)$AIC  
>  
> # make the data.frame suitable for plotting  
> require(reshape2)
```

```
> cvMelt <- melt(cvResults, id.vars="Model", variable.name="Measure",
+           value.name="Value")
> cvMelt
   Model     Measure    Value
1 houseG1      Error 1878.596
2 houseG2      Error 1862.247
3 houseG3      Error 1767.268
4 houseG4      Error 1764.370
5 houseG5      Error 1882.631
6 houseG1 Adjusted.Error 1876.691
7 houseG2 Adjusted.Error 1860.900
8 houseG3 Adjusted.Error 1764.953
9 houseG4 Adjusted.Error 1760.102
10 houseG5 Adjusted.Error 1881.067
11 houseG1      ANOVA 4877506.411
12 houseG2      ANOVA 4847886.327
13 houseG3      ANOVA 4576768.981
14 houseG4      ANOVA 4525782.873
15 houseG5      ANOVA 4895630.307
16 houseG1       AIC  27177.781
17 houseG2       AIC  27163.822
18 houseG3       AIC  27025.042
19 houseG4       AIC  27001.691
20 houseG5       AIC  27189.499
>
> ggplot(cvMelt, aes(x=Model, y=Value)) +
+   geom_line(aes(group=Measure, color=Measure)) +
+   facet_wrap(~Measure, scales="free_y") +
```

```
+   theme(axis.text.x=element_text(angle=90, vjust=.5))  
+  
+   guides(color=FALSE)
```



**Figure 18.8** Plots for cross-validation error (raw and adjusted), ANOVA and AIC for housing models. The scales are different, as they should be, but the shapes are identical, indicating that houseG4 truly is the best model.

We now present a general framework (loosely borrowed from `cv.glm`) for running our own cross-validation on models other than `glm`. This is not universal and will not work for all models, but gives a general idea for how it should be done. In practice it should be abstracted into smaller parts and made more robust.

[Click here to view code image](#)

```
> cv.work <- function(fun, k = 5, data,
+                      cost = function(y, yhat) mean((y - yhat)^2),
+                      response="y", ...)
+ {
+   # generate folds
+   folds <- data.frame(Fold=sample(rep(x=1:k,
length.out=nrow(data))),
+                      Row=1:nrow(data))
+
+   # start the error at 0
+   error <- 0
+
+   ## loop through each of the folds
+   ## for each fold:
+   ## fit the model on the training data
+   ## predict on the test data
+   ## compute the error and accumulate it
+   for(f in 1:max(folds$Fold))
+   {
```

```
+ # rows that are in test set
+ theRows <- folds$Row[folds$Fold == f]
+
+ ## call fun on data[-theRows, ]
+ ## predict on data[theRows, ]
+ mod <- fun(data=data[-theRows, ], ...)
+ pred <- predict(mod, data[theRows, ])
+
+ # add new error weighted by the number of rows in
this fold
+ error <- error +
+ cost(data[theRows, response], pred) *
+ (length(theRows)/nrow(data))
+
}
+
+ return(error)
+ }
```

Applying that function to the various housing models we get their cross-validation errors.

[Click here to view code image](#)

```
> cv1 <- cv.work(fun=lm, k=5, data=housing, re-
sponse="ValuePerSqFt",
+ formula=ValuePerSqFt ~ Units + SqFt + Boro)
> cv2 <- cv.work(fun=lm, k=5, data=housing, re-
sponse="ValuePerSqFt",
+ formula=ValuePerSqFt ~ Units * SqFt + Boro)
```

```
> cv3 <- cv.work(fun=lm, k=5, data=housing, re-
  sponse="ValuePerSqFt",
+           formula=ValuePerSqFt ~ Units + SqFt * Boro +
  Class)
> cv4 <- cv.work(fun=lm, k=5, data=housing, re-
  sponse="ValuePerSqFt",
+           formula=ValuePerSqFt ~ Units + SqFt * Boro +
  SqFt*Class)
> cv5 <- cv.work(fun=lm, k=5, data=housing, re-
  sponse="ValuePerSqFt",
+           formula=ValuePerSqFt ~ Boro + Class)
> cvResults <- data.frame(Model=sprintf("house%0S",
  1:5),
+           Error=c(cv1, cv2, cv3, cv4, cv5))
> cvResults
  Model   Error
1 house1 1875.582
2 house2 1859.388
3 house3 1766.066
4 house4 1764.343
5 house5 1880.926
```

This gives very similar results to `cv.glm` and again shows that the fourth parameterization is still the best. These measures do not always agree so nicely but it is great when they do.

## 18.4. Bootstrap

Sometimes, for one reason or another, there is not a good analytic solution to a problem and another tactic is needed. This is especially true for measuring uncertainty for confidence intervals. To overcome this, Bradley Efron introduced the bootstrap in 1979. Since then the bootstrap has grown to revolutionize modern statistics and is indispensable.

The idea is that we start with  $n$  rows of data. Some statistic (whether a mean, regression or some arbitrary function) is applied to the data. Then the data are sampled, creating a new dataset. This new set still has  $n$  rows except that there are repeats and other rows are entirely missing. The statistic is applied to this new dataset. The process is repeated  $R$  times (typically around 1,200), which generates an entire distribution for the statistic. This distribution can then be used to find the mean and confidence interval (typically 95%) for the statistic.

The boot package is a very robust set of tools for making the bootstrap easy to compute. Some care is needed when setting up the function call, but that can be handled easily enough.

Starting with a simple example, we analyze the batting average of Major League Baseball as a whole since 1990. The baseball data have information such as at bats (ab) and hits (h).

[Click here to view code image](#)

```
> require(plyr)
> baseball <- baseball[baseball$year >= 1990, ]
> head(baseball)
   id year stint team lg g ab r h X2b X3b hr rbi sb
67412 alomasa02 1990 1 CLE AL 132 445 60
129 26 2 9 66 4
67414 anderbr01 1990 1 BAL AL 89 234
24 54 5 2 3 24 15
67422 baergca01 1990 1 CLE AL 108 312
46 81 17 2 7 47 0
67424 baineha01 1990 1 TEX AL 103 321 41 93 10 1
13 44 0
67425 baineha01 1990 2 OAK AL 32 94
11 25 5 0 3 21 0
67442 bergmda01 1990 1 DET AL 100 205
21 57 10 1 2 26 3
   cs bb so ibb hbp sh sf gidp      OBP
```

67412	1	25	46	2	2	5	6	10	0.3263598
67414	2	31	46	2	5	4	5	4	0.3272727
67422	2	16	57	2	4	1	5	4	0.2997033
67424	1	47	63	9	0	0	3	13	0.3773585
67425	2	20	17	1	0	0	4	4	0.3813559
67442	2	33	17	3	0	1	2	7	0.3750000

The proper way to compute the batting average is to divide total hits by total at bats. This means we cannot simply run  $\text{mean}(h/\text{ab})$  and  $\text{sd}(h/\text{ab})$  to get the mean and standard deviation. Rather, the batting average is calculated as  $\text{sum}(h)/\text{sum}(\text{ab})$  and its standard deviation is not easily calculated. This problem is a great candidate for using the bootstrap.

We calculate the overall batting average with the original data. Then we sample  $n$  rows with replacement and calculate the batting average again. We do this repeatedly until a distribution is formed. Rather than doing this manually, though, we use `boot`.

The first argument to `boot` is the data. The second argument is the function that is to be computed on the data. This function must take at

least two arguments (unless sim="parametric" in which case only the first argument is necessary). The first is the original data and the second is a vector of indices, frequencies or weights. Additional named arguments can be passed into the function from boot.

[Click here to view code image](#)

```
> ## build a function for calculating batting average
> # data is the data
> # boot will pass varying sets of indices
> # some rows will be represented multiple times in a
single pass
> # other rows will not be represented at all
> # on average about 63% of the rows will be present
> # this funciton is called repeatedly by boot
> bat.avg <- function(data, indices=1:NROW(data),
hits="h",
+                   at.bats="ab"))
+ {
+   sum(data[indices, hits], na.rm=TRUE) /
+   sum(data[indices, at.bats], na.rm=TRUE)
+ }
>
> # test it on the original data
> bat.avg(baseball)
[1] 0.2745988
>
```

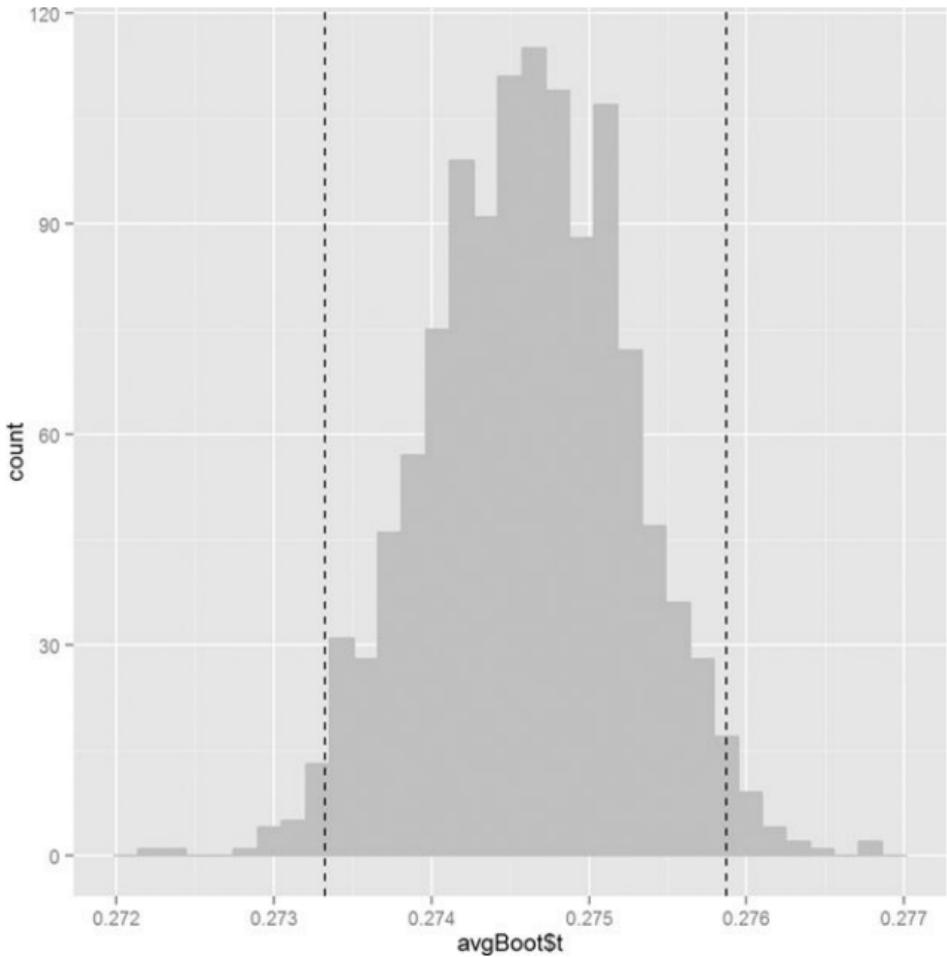
```
> # bootstrap it
> # using the baseball data, call bat.avg 1,200 times
> # pass indices to the function
> avgBoot <- boot(data=baseball, statistic=bat.avg,
R=1200, stype="i")
>
> # print original measure and estimates of bias and stand-
ard error
> avgBoot
ORDINARY NONPARAMETRIC BOOTSTRAP
Call:
boot(data = baseball, statistic = bat.avg, R = 1200, stype =
"i")
Bootstrap Statistics :
      original     bias   std. error
t1*  0.2745988 1.071011e-05 0.0006843765
> # print the confidence interval
> boot.ci(avgBoot, conf=.95, type="norm")
BOOTSTRAP CONFIDENCE INTERVAL
CALCULATIONS
Based on 1200 bootstrap replicates
CALL :
boot.ci(boot.out = avgBoot, conf = 0.95, type = "norm")
Intervals :
Level  Normal
95% ( 0.2732, 0.2759 )
Calculations and Intervals on Original Scale
```

Visualizing the distribution is as simple as plotting a histogram of the replicate results. [Fig-](#)

ure 18.9 shows the histogram for the batting average with vertical lines two standard errors on either side of the original estimate. These mark the (roughly) 95% confidence interval.

[Click here to view code image](#)

```
> ggplot() +  
+   geom_histogram(aes(x=avgBoot$t), fill="grey", col-  
or="grey") +  
+   geom_vline(xintercept=avgBoot$t0 + c(-1,  
1)*2*sqrt(var(avgBoot$t)),  
+               linetype=2)
```



**Figure 18.9** Histogram of the batting average bootstrap. The vertical lines are two standard errors from the original estimate in each direction. They make up the bootstrapped 95% confidence interval.

The bootstrap is an incredibly powerful tool that holds a great deal of promise. The boot package offers far more than what we have shown here, including the ability to bootstrap time series and censored data. The beautiful thing about the bootstrap is its near universal applicability. It can be used in just about any situation where an analytical solution is impractical or impossible. There are some instances where the bootstrap is inappropriate, such as for measuring uncertainty of biased estimators like those from the lasso, although such limitations are rare.

## 18.5. Stepwise Variable Selection

A common, though becoming increasingly discouraged, way to select variables for a model is stepwise selection. This is the process of iteratively adding and removing variables from a model and testing the model at each step, usually using AIC.

The step function iterates through possible models. The scope argument specifies a lower

and upper bound on possible models. The direction argument specifies whether variables are just added into the model, just subtracted from the model or added and subtracted as necessary. When run, step prints out all the iterations it has taken to arrive at what it considers the optimal model.

[Click here to view code image](#)

```
> # the lowest model is the null model, basically the
straight average
> nullModel <- lm(ValuePerSqFt ~ 1, data=housing)
> # the largest model we will accept
> fullModel <- lm(ValuePerSqFt ~ Units + SqFt*Boro +
Boro*Class,
+                   data=housing)
> # try different models
> # start with nullModel
> # do not go above fullModel
> # work in both directions
> houseStep <- step(nullModel,
+                     scope=list(lower=nullModel, upper=-
fullModel),
+                     direction="both")
Start: AIC=22151.56
ValuePerSqFt ~ 1
```

	Df	Sum of Sq	RSS	AIC
+ Boro	4	7160206	5137931	19873
+ SqFt	1	1310379	10987758	21858
+ Class	3	1264662	11033475	21873
+ Units	1	778093	11520044	21982
<none>		12298137	22152	
Step:		AIC=19872.83		

ValuePerSqFt ~ Boro

	Df	Sum of Sq	RSS	AIC
+ Class	3	242301	4895630	19752
+ SqFt	1	185635	4952296	19778
+ Units	1	83948	5053983	19832
<none>		5137931	19873	
- Boro	4	7160206	12298137	22152
Step:		AIC=19752.26		

ValuePerSqFt ~ Boro + Class

	Df	Sum of Sq	RSS	AIC
+ SqFt	1	182170	4713460	19655
+ Units	1	100323	4795308	19700
+ Boro:Class	9	111838	4783792	19710
<none>		4895630	19752	
- Class	3	242301	5137931	19873
- Boro	4	6137845	11033475	21873
Step:		AIC=19654.91		

ValuePerSqFt ~ Boro + Class + SqFt

	Df	Sum of Sq	RSS	AIC
+ SqFt:Boro	4	113219	4600241	19599
+ Boro:Class	9	94590	4618870	19620
+ Units	1	37078	4676382	19636

<none> 4713460 19655  
- SqFt 1 182170 4895630 19752  
- Class 3 238836 4952296 19778  
- Boro 4 5480928 10194388 21668

Step: AIC=19599.21

ValuePerSqFt ~ Boro + Class + SqFt + Boro:SqFt  
Df Sum of Sq RSS AIC

+ Boro:Class 9 68660 4531581 19578  
+ Units 1 23472 4576769 19588  
<none> 4600241 19599

- Boro:SqFt 4 113219 4713460 19655  
- Class 3 258642 4858883 19737

Step: AIC=19577.81

ValuePerSqFt ~ Boro + Class + SqFt + Boro:SqFt +  
Boro:Class

Df Sum of Sq RSS AIC  
+ Units 1 20131 4511450 19568  
<none> 4531581 19578  
- Boro:Class 9 68660 4600241 19599  
- Boro:SqFt 4 87289 4618870 19620

Step: AIC=19568.14

ValuePerSqFt ~ Boro + Class + SqFt + Units + Boro:SqFt +  
Boro:Class

Df Sum of Sq RSS AIC  
<none> 4511450 19568  
- Units 1 20131 4531581 19578  
- Boro:Class 9 65319 4576769 19588  
- Boro:SqFt 4 75955 4587405 19604

> # reveal the chosen model

> houseStep

Call:

```
lm(formula = ValuePerSqFt ~ Boro + Class + SqFt + Units  
+ Boro:SqFt +  
Boro:Class, data = housing)
```

Coefficients:

(Intercept)

4.848e+01

BoroBrooklyn

2.655e+01

BoroManhattan

8.672e+01

BoroQueens

1.999e+01

BoroStaten Island

-1.132e+01

ClassR4-CONDOMINIUM

6.586e+00

ClassR9-CONDOMINIUM

4.553e+00

ClassRR-CONDOMINIUM

8.130e+00

SqFt

1.373e-05

Units

-8.296e-02

BoroBrooklyn:SqFt

3.798e-05

BoroManhattan:SqFt

1.594e-04

BoroQueens:SqFt  
2.753e-06

BoroStaten Island:SqFt  
4.362e-05

BoroBrooklyn:ClassR4-CONDOMINIUM  
1.933e+00

BoroManhattan:ClassR4-CONDOMINIUM  
3.436e+01

BoroQueens:ClassR4-CONDOMINIUM  
1.274e+01

BoroStaten Island:ClassR4-CONDOMINIUM  
NA

BoroBrooklyn:ClassR9-CONDOMINIUM  
-3.440e+00

BoroManhattan:ClassR9-CONDOMINIUM  
1.497e+01

BoroQueens:ClassR9-CONDOMINIUM  
-9.967e+00

BoroStaten Island:ClassR9-CONDOMINIUM  
NA

BoroBrooklyn:ClassRR-CONDOMINIUM  
-2.901e+01

BoroManhattan:ClassRR-CONDOMINIUM  
-6.850e+00

BoroQueens:ClassRR-CONDOMINIUM  
2.989e+01

BoroStaten Island:ClassRR-CONDOMINIUM  
NA

Ultimately, step decided that fullModel was optimal with the lowest AIC. While this works, it is a bit of a brute force method and has its own theoretical problems. Lasso regression arguably does a better job of variable selection and is discussed in [Section 19.1](#).

## 18.6. Conclusion

Determining the quality of a model is an important step in the model-building process. This can take the form of traditional tests of fit such as ANOVA or more modern techniques like cross-validation. The bootstrap is another means of determining model uncertainty, especially for models where confidence intervals are impractical to calculate. These can all be shaped by helping select which variables are included in a model and which are excluded.

# Chapter 19. Regularization and Shrinkage

In today's era of high dimensional (many variables) data, methods are needed to prevent overfitting. Traditionally, this has been done with variable selection, as described in [Chapter 18](#), although with a large number of variables that can become computationally prohibitive. These methods can take a number of forms; we focus on regularization and shrinkage. For these we will use `glmnet` from the `glmnet` package and `bayesglm` from the `arm` package.

## 19.1. Elastic Net

One of the most exciting algorithms to be developed in the past five years is the Elastic Net, which is a dynamic blending of lasso and ridge regression. The lasso uses an  $L1$  penalty to perform variable selection and dimension reduction, while the ridge uses an  $L2$  penalty to shrink the coefficients for more stable predictions. The formula for the Elastic Net is

$$\min_{\beta_0, \beta \in \mathbb{R}^{p+1}} \left[ \frac{1}{2N} \sum_{i=1}^N (\gamma_i - \beta_0 - x_i^T \beta)^2 + \lambda P_\alpha(\beta) \right] \quad (19.1)$$

where

$$P_\alpha(\beta) = (1 - \alpha) \frac{1}{2} \|\beta\|_2^2 + \alpha \|\beta\|_1 \quad (19.2)$$

where  $\lambda$  is a complexity parameter controlling the amount of shrinkage (0 is no penalty and  $\infty$  is complete penalty) and  $\alpha$  regulates how much of the solution is ridge versus lasso with  $\alpha = 0$  being complete ridge and  $\alpha = 1$  being complete lasso.  $\Gamma$ , not seen here, is a vector of penalty factors—one value per variable—that multiplies  $\lambda$  for fine tun-

ing of the penalty applied to each variable; again 0 is no penalty and  $\infty$  is complete penalty.

A fairly new package (this is a relatively new algorithm) is `glmnet`, which fits generalized linear models with the Elastic Net. It is written by Trevor Hastie, Robert Tibshirani and Jerome Friedman from Stanford University who also published the landmark papers on the Elastic Net.

Because it is designed for speed and larger, sparser data, `glmnet` requires a little more effort to use than most other modeling functions in R. Where functions like `lm` and `glm` take a formula to specify the model, `glmnet` requires a matrix of predictors (including an intercept) and a response matrix.

Even though it is not incredibly high dimensional, we will look at the American Community Survey (ACS) data for New York State. We will throw every possible predictor into the model and see which are selected.

[Click here to view code image](#)

```
> acs <- read.table("http://jaredlander.com/data/  
acs_ny.csv", sep = ",",  
+   header = TRUE, stringsAsFactors = FALSE)
```

Because glmnet requires a predictor matrix, it will be good to have a convenient way of building that matrix. This can be done simply enough using model.matrix, which at its most basic takes in a formula and a data.frame and returns a design matrix. As an example we create some fake data and run model.matrix on it.

[Click here to view code image](#)

```
> # build a data.frame where the first three columns are numeric  
> testFrame <-  
+   data.frame(First=sample(1:10, 20, replace=TRUE),  
+     Second=sample(1:20, 20, replace=TRUE),  
+     Third=sample(1:10, 20, replace=TRUE),  
+     Fourth=factor(rep(c("Alice", "Bob", "Charlie",  
"David"),  
+                           5)),  
+     Fifth=ordered(rep(c("Edward", "Frank", "Georgia",  
+                           "Hank", "Isaac"), 4)),  
+     Sixth=rep(c("a", "b"), 10), stringsAsFactors=F)
```

```

> head(testFrame)
First Second Third Fourth Fifth Sixth
1   3     8     6 Alice Edward  a
2   3    16     4 Bob Frank   b
3   9    14     6 Charlie Georgia a
4   9     2     2 David Hank   b
5   5    17     6 Alice Isaac  a
6   6     3     4 Bob Edward  b
>
> head(model.matrix(First ~ Second + Fourth + Fifth,
testFrame))
(Intercept) Second FourthBob FourthCharlie
FourthDavid Fifth.L
1           1     8     0      0      0 -0.6324555
2           1    16     1      0      0 -0.3162278
3           1    14     0      1      0  0.0000000
4           1     2     0      0      1  0.3162278
5           1    17     0      0      0  0.6324555
6           1     3     1      0      0 -0.6324555
Fifth.Q   Fifth.C   Fifth^4
1 0.5345225 -3.162278e-01  0.1195229
2 -0.2672612  6.324555e-01 -0.4780914
3 -0.5345225 -4.095972e-16  0.7171372
4 -0.2672612 -6.324555e-01 -0.4780914
5  0.5345225  3.162278e-01  0.1195229
6  0.5345225 -3.162278e-01  0.1195229

```

This works very well and is simple, but first there are a few things to notice. As expected,

Fourth gets converted into indicator variables with one less column than levels in Fourth. Initially, the parameterization of Fifth might seem odd, as there is one less column than there are levels, but their values are not just 1s and 0s. This is because Fifth is an ordered factor where one level is greater or less than another level.

Not creating an indicator variable for the base level of a factor is essential for most linear models to avoid multicollinearity.<sup>1</sup> However, it is generally considered undesirable for the predictor matrix to be designed this way for the Elastic Net. It is possible to have `model.matrix` return indicator variables for all levels of a factor, although doing so can take some creative coding.<sup>2</sup> To make the process easier we incorporated a solution in the `build.x` function in the useful package.

- <sup>1</sup> This is a characteristic of a matrix in linear algebra where the columns are not linearly independent. While this is an important concept, we do not need to concern ourselves with it much in the context of this book.
- <sup>2</sup> The difficulty is evidenced in this Stack Overflow question asked by us: <http://stackoverflow.com/questions/>

[4560459/all-levels-of-a-factor-in-a-model-matrix-in-r/](https://4560459/all-levels-of-a-factor-in-a-model-matrix-in-r/)  
15400119

[Click here to view code image](#)

```
> require(useful)
> # always use all levels
> head(build.x(First ~ Second + Fourth + Fifth, testFrame,
+               contrasts=FALSE))
(Intercept) Second FourthAlice FourthBob FourthCharlie
FourthDavid
 1       1     8      1      0      0      0
 2       1    16      0      1      0      0
 3       1    14      0      0      1      0
 4       1     2      0      0      0      1
 5       1    17      1      0      0      0
 6       1     3      0      1      0      0
FifthEdward FifthFrank FifthGeorgia FifthHank
FifthIsaac
 1       1     0      0      0      0
 2       0     1      0      0      0
 3       0     0      1      0      0
 4       0     0      0      1      0
 5       0     0      0      0      1
 6       1     0      0      0      0
> # just use all levels for Fourth
> head(build.x(First ~ Second + Fourth + Fifth, testFrame,
+               contrasts=c(Fourth=FALSE, Fifth=TRUE)))
(Intercept) Second FourthAlice FourthBob FourthCharlie
FourthDavid
```

1	1	8	1	0	0	0
2	1	16	0	1	0	0
3	1	14	0	0	1	0
4	1	2	0	0	0	1
5	1	17	1	0	0	0
6	1	3	0	1	0	0
	Fifth.L	Fifth.Q	Fifth.C	Fifth^4		
1	-0.6324555	0.5345225	-3.162278e-01	0.1195229		
2	-0.3162278	-0.2672612	6.324555e-01	-0.4780914		
3	0.0000000	-0.5345225	-4.095972e-16	0.7171372		
4	0.3162278	-0.2672612	-6.324555e-01	-0.4780914		
5	0.6324555	0.5345225	3.162278e-01	0.1195229		
6	-0.6324555	0.5345225	-3.162278e-01	0.1195229		

Using build.x appropriately on acs builds a nice predictor matrix for use in glmnet. We control the desired matrix by using a formula for our model specification just like we would in lm, interactions and all.

[Click here to view code image](#)

```
> # make a binary Income variable for building a logistic
  regression
> acs$Income <- with(acs, FamilyIncome >= 150000)
>
> head(acs)
  Acres FamilyIncome FamilyType NumBedrooms
  NumChildren NumPeople
```

1	1-10	150	Married	4	1	3
2	1-10	180	Female Head	3	2	4
3	1-10	280	Female Head	4	0	2
4	1-10	330	Female Head	2	1	2
5	1-10	330	Male Head	3	1	2
6	1-10	480	Male Head	0	3	4

NumRooms      NumUnits    NumVehicles    NumWorkers    NumWork-  
ers    OwnRent

1	9	Single detached	1	0	Mortgage
2	6	Single detached	2	0	Rented
3	8	Single detached	3	1	Mortgage
4	4	Single detached	1	0	Rented
5	5	Single attached	1	0	Mortgage
6	1	Single detached	0	0	Rented

YearBuilt HouseCosts ElectricBill FoodStamp HeatIn-  
gFuel Insurance

1	1950-1959	1800	90	No	Gas	2500
2	Before 1939	850	90	No	Oil	0
3	2000-2004	2600	260	No	Oil	6600
4	1950-1959	1800	140	No	Oil	0
5	Before 1939	860	150	No	Gas	660
6	Before 1939	700	140	No	Gas	0

Language Income  
 1 English FALSE  
 2 English FALSE  
 3 Other European FALSE  
 4 English FALSE  
 5 Spanish FALSE  
 6 English FALSE  
 >

```
> # build predictor matrix
> # do not include the intercept as glmnet will add that
  automatically

> acsX <- build.x(Income ~ NumBedrooms + NumChil-
  dren + NumPeople +
+           NumRooms + NumUnits + NumVehicles +
  NumWorkers +
+           OwnRent + YearBuilt + ElectricBill +
  FoodStamp +
+           HeatingFuel + Insurance + Language - 1,
+           data=acs, contrasts=FALSE)
>
> # check class and dimensions
> class(acsX)
[1] "matrix"
> dim(acsX)
[1] 22745  44
>
> # view the top left and top right of the data
> topleft(acsX, c=6)
  NumBedrooms NumChildren NumPeople NumRooms
  NumUnitsMobile home
  1          4          1          3          9          0
  2          3          2          4          6          0
  3          4          0          2          8          0
  4          2          1          2          4          0
  5          3          1          2          5          0
  NumUnitsSingle attached
  1                  0
  2                  0
```

```
3          0  
4          0  
5          1
```

```
> topright(acsX, c=6)
```

```
Insurance LanguageAsian Pacific LanguageEnglish Lan-  
guageOther
```

1	2500	0	1	0
2	0	0	1	0
3	6600	0	0	0
4	0	0	1	0
5	660	0	0	0

```
LanguageOther European LanguageSpanish
```

1	0	0
2	0	0
3	1	0
4	0	0
5	0	1

```
>
```

```
> # build response predictor
```

```
> acsY <- build.y(Income ~ NumBedrooms + NumChil-  
dren + NumPeople +  
+           NumRooms + NumUnits + NumVehicles +  
NumWorkers +  
+           OwnRent + YearBuilt + ElectricBill +  
FoodStamp +  
+           HeatingFuel + Insurance + Language - 1,  
data=acs)
```

```
>
```

```
> head(acsY)
```

```
[1] FALSE FALSE FALSE FALSE FALSE FALSE
```

```
> tail(acsY)
```

```
[1] TRUE TRUE TRUE TRUE TRUE TRUE
```

Now that the data are properly stored we can run `glmnet`. As seen in [Equation 19.1](#),  $\lambda$  controls the amount of shrinkage. By default `glmnet` fits the regularization path on 100 different values of  $\lambda$ . The decision of which is best then falls upon the user with cross-validation being a good measure. Fortunately the `glmnet` package has a function, `cv.glmnet`, that computes the cross-validation automatically. By default  $\alpha = 1$ , meaning only the lasso is calculated. Selecting the best  $\alpha$  requires an additional layer of cross-validation.

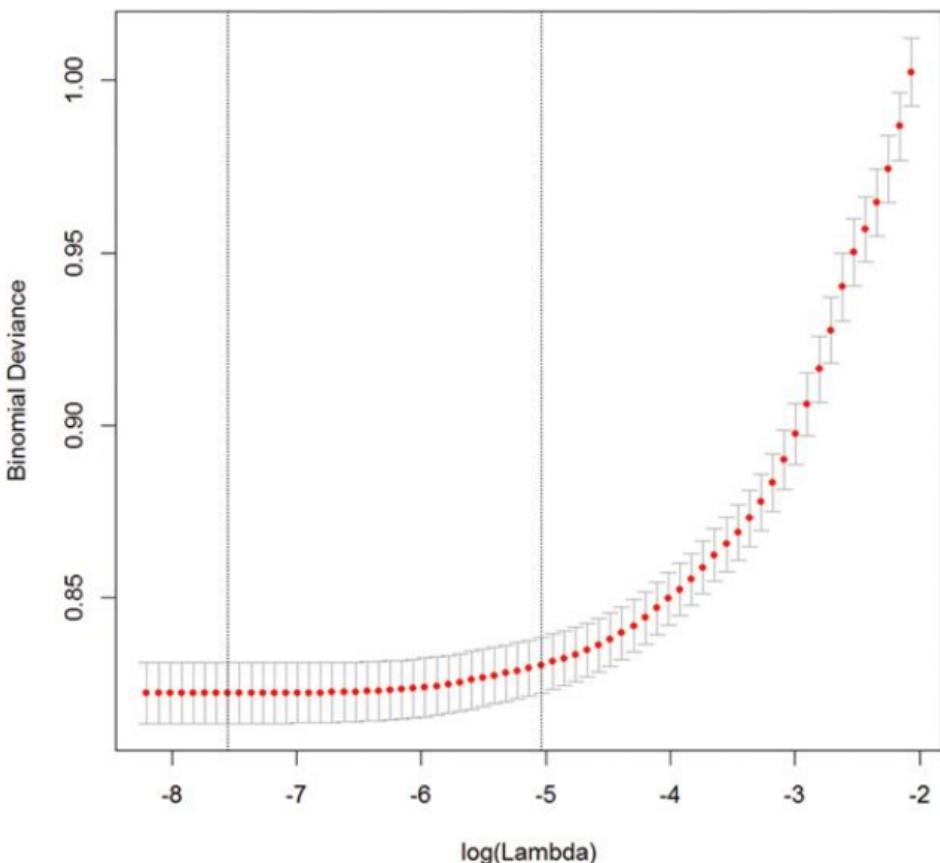
[Click here to view code image](#)

```
> require(glmnet)
> set.seed(1863561)
> # run the cross-validated glmnet
> acsCV1 <- cv.glmnet(x = acsX, y = acsY, family = "binomial",
  nfold = 5)
```

The most important information returned from `cv.glmnet` are the cross-validation and which value of  $\lambda$  minimizes the cross-validation error.

Additionally, it also returns the largest value of  $\lambda$  with a cross-validation error that is within one standard error of the minimum. Theory suggests that the simpler model, even though it is slightly less accurate, should be preferred due to its parsimony. The cross-validation errors for differing values of  $\lambda$  are seen in [Figure 19.1](#). The top row of numbers indicates how many variables (factor levels are counted as individual variables) are in the model for a given value of  $\log(\lambda)$ .

38 38 37 36 36 33 28 17 12 10 7 5 5 4 1 1



**Figure 19.1** Cross-validation curve for the `glmnet` fitted on the American Community Survey data. The top row of numbers indicates how many variables (factor levels are counted as individual variables) are in the model for a given value of  $\log(\lambda)$ . The dots represent the cross-validation error at that point and the vertical lines are the confidence interval for the error. The leftmost vertical line indicates the value of  $\lambda$  where the error is minimized and the rightmost vertical line is the next largest value of  $\lambda$  error that is within one standard error of the minimum.

```
> acsCV1$lambda.min  
[1] 0.0005258299  
> acsCV1$lambda.1se  
[1] 0.006482677  
> plot(acsCV1)
```

Extracting the coefficients is done as with any other model, by using `coef`, except that a specific level of  $\lambda$  should be specified; otherwise, the en-

tire path is returned. Dots represent variables that were not selected.

[Click here to view code image](#)

```
> coef(acsCV1, s = "lambda.1se")
45 x 1 sparse Matrix of class "dgCMatrix"
           1
(Intercept) -5.0552170103
NumBedrooms  0.0542621380
NumChildren   .
NumPeople     .
NumRooms      0.1102021934
NumUnitsMobile home -0.8960712560
NumUnitsSingle attached .
NumUnitsSingle detached .
NumVehicles    0.1283171343
NumWorkers     0.4806697219
OwnRentMortgage .
OwnRentOutright 0.2574766773
OwnRentRented  -0.1790627645
YearBuilt15    .
YearBuilt1940-1949 -0.0253908040
YearBuilt1950-1959 .
YearBuilt1960-1969 .
YearBuilt1970-1979 -0.0063336086
YearBuilt1980-1989  0.0147761442
YearBuilt1990-1999 .
YearBuilt2000-2004 .
YearBuilt2005    .
```

YearBuilt2006	.
YearBuilt2007	.
YearBuilt2008	.
YearBuilt2009	.
YearBuilt2010	.
YearBuiltBefore 1939	-0.1829643904
ElectricBill	0.0018200312
FoodStampNo	0.7071289660
FoodStampYes	.
HeatingFuelCoal	-0.2635263281
HeatingFuelElectricity	.
HeatingFuelGas	.
HeatingFuelNone	.
HeatingFuelOil	.
HeatingFuelOther	.
HeatingFuelSolar	.
HeatingFuelWood	-0.7454315355
Insurance	0.0004973315
LanguageAsian Pacific	0.3606176925
LanguageEnglish	.
LanguageOther	.
LanguageOther European	0.0389641675
LanguageSpanish	.

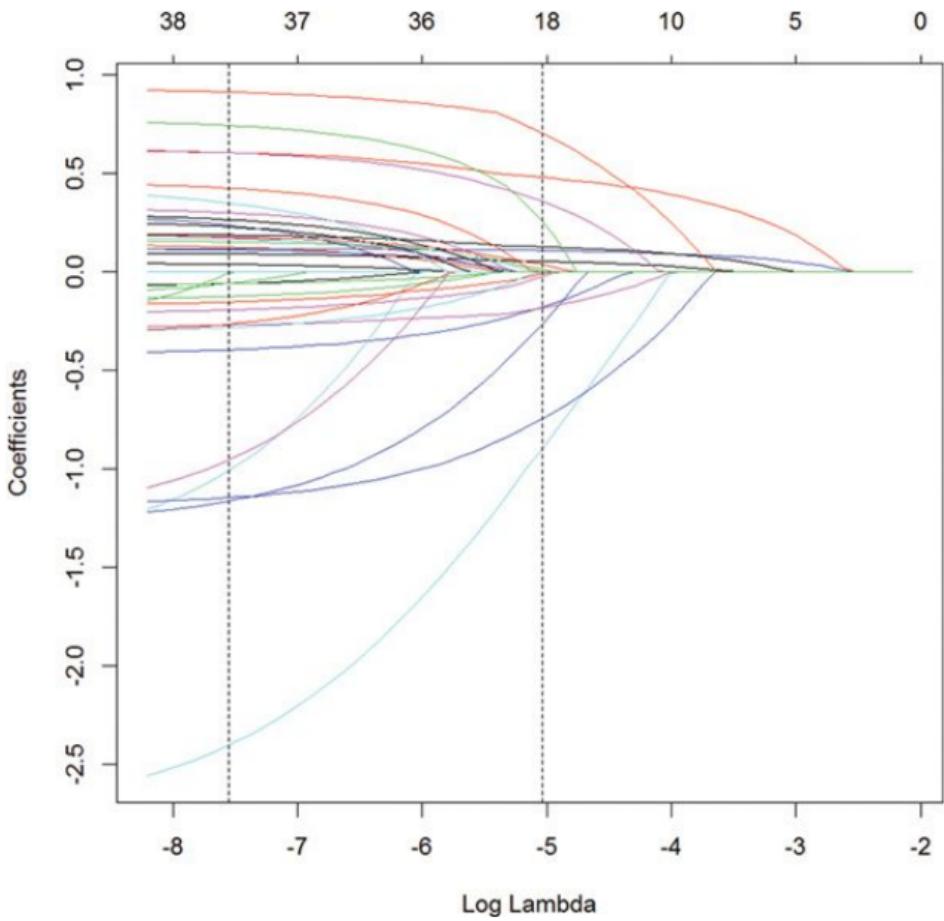
It might seem weird that some levels of a factor were selected and others were not, but it ultimately makes sense because the lasso eliminates variables that are highly correlated with each other.

Another thing to notice is that there are no standard errors and hence no confidence intervals for the coefficients. The same is true of any predictions made from a `glmnet` model. This is due to the theoretical properties of the lasso and ridge, and is an open problem. Recent advancements have led to the ability to perform significance tests on lasso regressions, although the existing R package requires that the model be fitted using the `lars` package, not `glmnet`, at least until the research extends the testing ability to cover the Elastic Net as well.

Visualizing where variables enter the model along the  $\lambda$  path can be illuminating and is seen in [Figure 19.2](#).

[Click here to view code image](#)

```
> # plot the path  
> plot(acsCV1$glmnet.fit, xvar = "lambda")  
> # add in vertical lines for the optimal values of lambda  
> abline(v = log(c(acsCV1$lambda.min, ac-  
sCV1$lambda.1se)), lty = 2)
```



**Figure 19.2** Coefficient profile plot of the `glmnet` model fitted on the ACS data. Each line represents a coefficient's value at different values of  $\lambda$ . The leftmost vertical line indicates the value of  $\lambda$  where the error is minimized and the rightmost vertical line is the next largest value of  $\lambda$  error that is within one standard error of the minimum.

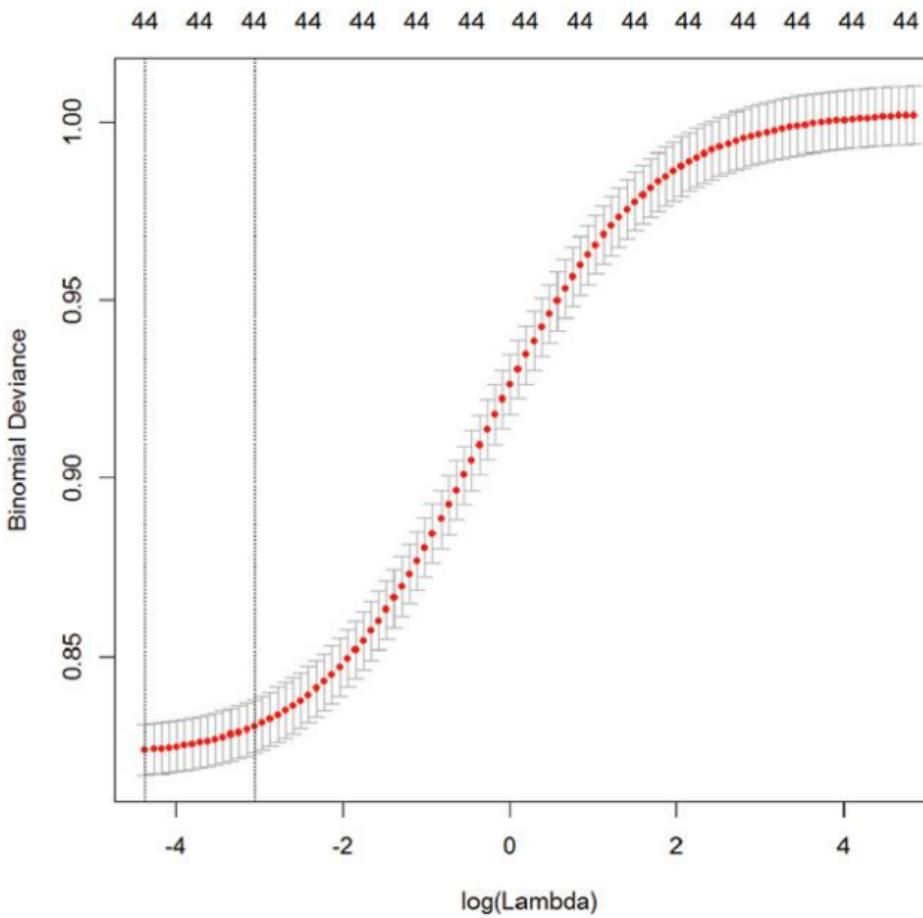
Setting  $\alpha$  to 0 causes the results to be from the ridge. In this case, every variable is kept in the model but is just shrunk closer to 0. [Figure 19.3](#), on page [283](#), shows the cross-validation curve. Notice in [Figure 19.4](#), on page [284](#), that for every value of  $\lambda$  there are still all the variables, just at different sizes.

[Click here to view code image](#)

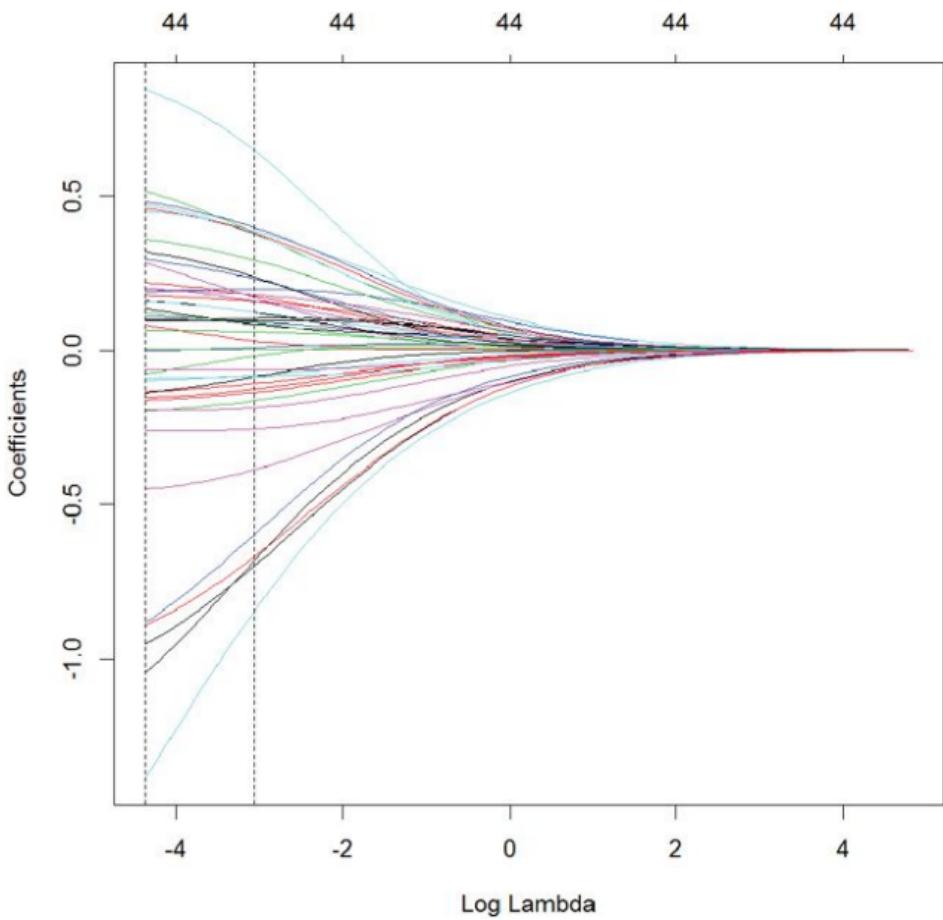
```
> # fit the ridge model  
> set.seed(71623)  
> acsCV2 <- cv.glmnet(x = acsX, y = acsY, family = "binomial", nfold = 5,  
+   alpha = 0)  
> # look at the lambda values  
> acsCV2$lambda.min
```

```
[1] 0.01272576
> acsCV2$lambda.1se
[1] 0.04681018
>
> # look at the coefficients
> coef(acsCV2, s = "lambda.1se")
45 x 1 sparse Matrix of class "dgCMatrix"
   1
(Intercept) -4.8197810188
NumBedrooms  0.1027963294
NumChildren   0.0308893447
NumPeople     -0.0203037177
NumRooms      0.0918136969
NumUnitsMobile home -0.8470874369
NumUnitsSingle attached 0.1714879712
NumUnitsSingle detached 0.0841095530
NumVehicles   0.1583881396
NumWorkers    0.3811651456
OwnRentMortgage 0.1985621193
OwnRentOutright 0.6480126218
OwnRentRented -0.2548147427
YearBuilt15    -0.6828640400
YearBuilt1940-1949 -0.1082928305
YearBuilt1950-1959  0.0602009151
YearBuilt1960-1969  0.0081133932
YearBuilt1970-1979 -0.0816541923
YearBuilt1980-1989  0.1593567244
YearBuilt1990-1999  0.1218212609
YearBuilt2000-2004  0.1768690849
YearBuilt2005      0.2923210334
```

YearBuilt2006	0.2309044444
YearBuilt2007	0.3765019705
YearBuilt2008	-0.0648999685
YearBuilt2009	0.2382560699
YearBuilt2010	0.3804282473
YearBuiltBefore 1939	-0.1648659906
ElectricBill	0.0018576432
FoodStampNo	0.3886474609
FoodStampYes	-0.3886013004
HeatingFuelCoal	-0.7005075763
HeatingFuelElectricity	-0.1370927269
HeatingFuelGas	0.0873505398
HeatingFuelNone	-0.5983944720
HeatingFuelOil	0.1241958119
HeatingFuelOther	-0.1872564710
HeatingFuelSolar	-0.0870480957
HeatingFuelWood	-0.6699727752
Insurance	0.0003881588
LanguageAsian Pacific	0.3982023046
LanguageEnglish	-0.0851389569
LanguageOther	0.1804675114
LanguageOther European	0.0964194255
LanguageSpanish	-0.1274688978
>	
> # plot the cross-validation error path	
> <b>plot</b> (acsCV2)	
> # plot the coefficient path	
> <b>plot</b> (acsCV2\$glmnet.fit, xvar = "lambda")	
> <b>abline</b> (v = <b>log</b> ( <b>c</b> (acsCV2\$lambda.min, acsCV2\$lambda.1se)), lty = 2)	



**Figure 19.3** Cross-validation curve for ridge regression fitted on ACS data.



**Figure 19.4** Coefficient profile plot for ridge regression fitted on ACS data.

Finding the optimal value of  $\alpha$  requires an additional layer of cross-validation, and unfortunately `glmnet` does not do that automatically. This will require us to run `cv.glmnet` at various

levels of  $\alpha$ , which will take a fairly large chunk of time if performed sequentially, making this a good time to use parallelization. The most straightforward way to run code in parallel is to use the parallel, doParallel and foreach packages.

[Click here to view code image](#)

```
> require(parallel)
```

Loading required package: parallel

```
> require(doParallel)
```

Loading required package: doParallel

```
 Loading required package: foreach
```

```
 Loading required package: iterators
```

First, we build some helper objects to speed along the process. When a two-layered cross-validation is run, an observation should fall in the same fold each time, so we build a vector specifying fold membership. We also specify the sequence of  $\alpha$  values that foreach will loop over. It is generally considered better to lean toward the lasso rather than the ridge, so we consider only  $\alpha$  values greater than 0.5.

## [Click here to view code image](#)

```
> # set the seed for repeatability of random results  
> set.seed(2834673)  
>  
> # create folds, we want observations to be in the same  
fold each time  
> # it is run  
> theFolds <- sample(rep(x = 1:5, length.out = nrow(ac-  
sX)))  
>  
> # make sequence of alpha values  
> alphas <- seq(from = 0.5, to = 1, by = 0.05)
```

Before running a parallel job, a cluster (even on a single machine) must be started and registered with `makeCluster` and `registerDoParallel`. After the job is done the cluster should be stopped with `stopCluster`. Setting `.errorhandling` to "remove" means that if an error occurs, that iteration will be skipped. Setting `.inorder` to FALSE means that the order of combining the results does not matter and they can be combined whenever returned, which yields significant speed improvements. Because we are using the default combination function, `list`, which takes

multiple arguments at once, we can speed up the process by setting `.multicombine` to TRUE. We specify in `.packages` that `glmnet` should be loaded on each of the workers, again leading to performance improvements. The operator `%dopar%` tells `foreach` to work in parallel. Parallel computing can be dependent on the environment, so we explicitly load some variables into the `foreach` environment using `.export`, namely, `acsX`, `acsY`, `alphas` and `theFolds`.

### [Click here to view code image](#)

```
> # set the seed for repeatability of random results
> set.seed(5127151)
>
> # start a cluster with two workers
> cl <- makeCluster(2)
> # register the workers
> registerDoParallel(cl)
>
> # keep track of timing
> before <- Sys.time()
>
> # build foreach loop to run in parallel
> ## several arguments
> acsDouble <- foreach(i=1:length(alphas), .errorhandling="remove",
> .packages=c("glmnet", "gridExtra"), .multicombine=TRUE, .export=c("acsX", "acsY", "theFolds")) %dopar% {
>   # do something
> }
```

```
+           .inorder=FALSE, .multicombine=TRUE,
+           .export=c("acsX", "acsY", "alphas",
+ "theFolds"),
+           .packages="glmnet") %dopar%
+ {
+   print(alphas[i])
+   cv.glmnet(x=acsX, y=acsY, family="binomial", nfold-
s=5,
+             foldid=theFolds, alpha=alphas[i])
+ }
>
> # stop timing
> after <- Sys.time()
>
> # make sure to stop the cluster when done
> stopCluster(cl)
>
> # time difference
> # this will depend on speed, memory & number of cores
of the machine
> after - before
Time difference of 1.443783 mins
```

The results in acsDouble should be a list with 11 instances of cv.glmnet objects. We can use sapply to check the class of each element of the list.

## [Click here to view code image](#)

```
> sapply(acsDouble, class)
[1] "cv.glmnet" "cv.glmnet" "cv.glmnet" "cv.glmnet"
"cv.glmnet"
[6] "cv.glmnet" "cv.glmnet" "cv.glmnet" "cv.glmnet"
"cv.glmnet"
[11] "cv.glmnet"
```

The goal is to find the best combination of  $\lambda$  and  $\alpha$ , so we need to build some code to extract the cross-validation error (including the confidence interval) and  $\lambda$  from each element of the list.

## [Click here to view code image](#)

```
> # function for extracting info from cv.glmnet object
> extractGlmnetInfo <- function(object)
+ {
+   # find lambdas
+   lambdaMin <- object$lambda.min
+   lambda1se <- object$lambda.1se
+
+   # figure out where those lambdas fall in the path
+   whichMin <- which(object$lambda == lambdaMin)
+   which1se <- which(object$lambda == lambda1se)
+
+   # build a one line data.frame with each of the selected
lambdas and
+   # its corresponding error figures
```

```
+ data.frame(lambda.min=lambdaMin, er-
ror.min=object$cvm[whichMin],
+           lambda.1se=lambda1se, er-
ror.1se=object$cvm[which1se])
+ }
>
> # apply that function to each element of the list
> # combine it all into a data.frame
> alphaInfo <- Reduce(rbind, lapply(acsDouble, ex-
tractGlmnetInfo))
>
> # could also be done with ldply from plyr
> alphaInfo2 <- plyr::ldply(acsDouble, extractGlmnetInfo)
> identical(alphaInfo, alphaInfo2)
[1] TRUE
>
> # make a column listing the alphas
> alphaInfo$Alpha <- alphas
> alphaInfo
   lambda.min error.min lambda.1se error.1se Alpha
1  0.0009582333 0.8220267 0.008142621 0.8275331  0.50
2  0.0009560545 0.8220226 0.007402382 0.8273936  0.55
3  0.0008763832 0.8220197 0.006785517 0.8272771  0.60
4  0.0008089692 0.8220184 0.006263554 0.8271786  0.65
5  0.0008244253 0.8220168 0.005816158 0.8270917  0.70
6  0.0007694636 0.8220151 0.005428414 0.8270161  0.75
7  0.0007213721 0.8220139 0.005585323 0.8276118  0.80
8  0.0006789385 0.8220130 0.005256774 0.8275519  0.85
9  0.0006412197 0.8220123 0.004964731 0.8274993  0.90
10 0.0006074713 0.8220128 0.004703430 0.8274524  0.95
```

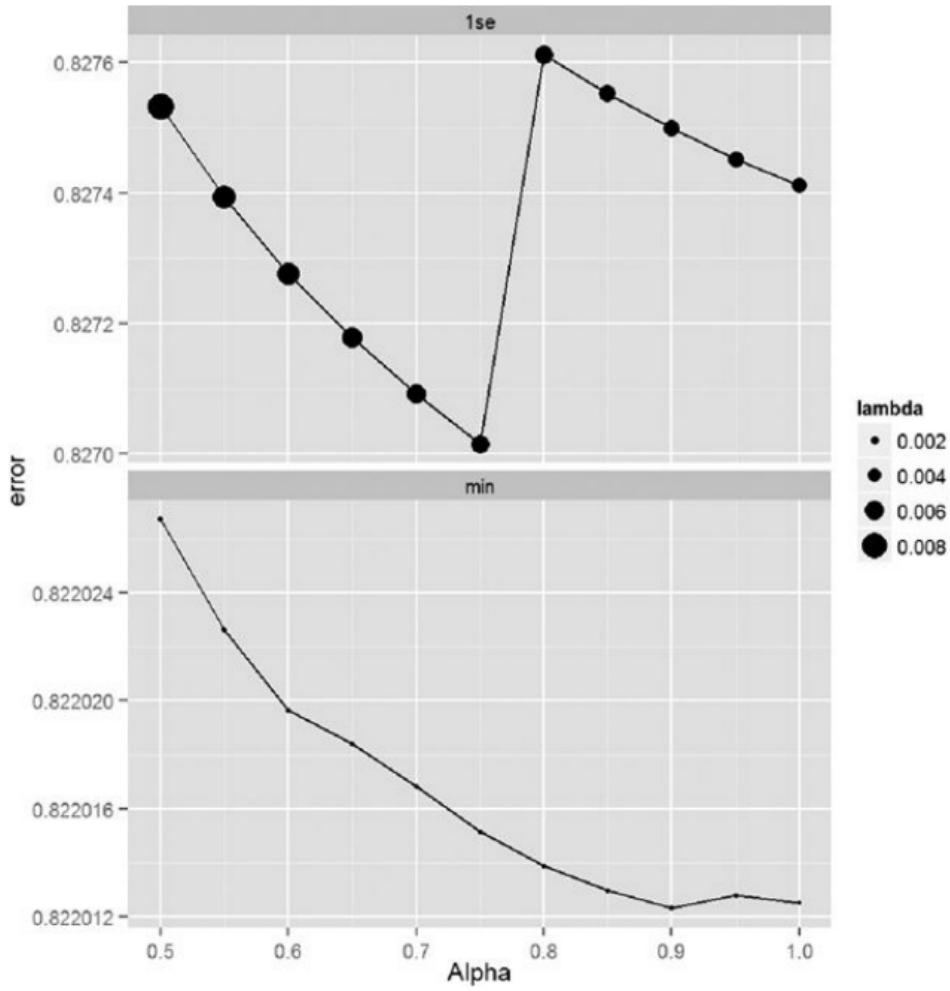
11 0.0005770977 0.8220125 0.004468258 0.8274120 1.00

Now that we have this nice unintelligible set of numbers, we should plot it to easily pick out the best combination of  $\alpha$  and  $\lambda$ , which is where the plot shows minimum error. [Figure 19.5](#) indicates that by using the one standard error methodology, the optimal  $\alpha$  and  $\lambda$  are 0.75 and 0.0054284, respectively.

[Click here to view code image](#)

```
> ## prepare the data.frame for plotting multiple pieces of  
information  
> require(reshape2)  
> require(stringr)  
>  
> # melt the data into long format  
> alphaMelt <- melt(alphaInfo, id.vars="Alpha",  
value.name="Value",  
+ variable.name="Measure")  
> alphaMelt$Type <- str_extract(string=alphaMelt$Measure,  
+ pattern="(min)|(1se)")  
>  
> # some housekeeping  
> alphaMelt$Measure <- str_replace(string=al-  
phaMelt$Measure,  
+ pattern="\.(min|1se)",
```

```
+           replacement=""))
> alphaCast <- dcast(alphaMelt, Alpha + Type ~ Measure,
+                      value.var="Value")
>
> ggplot(alphaCast, aes(x=Alpha, y=error)) +
+   geom_line(aes(group=Type)) +
+   facet_wrap(~Type, scales="free_y", ncol=1) +
+   geom_point(aes(size=lambda))
```



**Figure 19.5** Plot of  $\alpha$  versus error for glmnet cross-validation on the ACS data. The lower the error the better. The size of the dot represents the value of lambda. The top pane shows the error using the one standard error methodology (0.0054) and the bottom pane shows the error by selecting the  $\lambda$  (6e-04) that minimizes the error. In the top pane the error is minimized for an  $\alpha$  of 0.75 and in the bottom pane the optimal  $\alpha$  is 0.9.

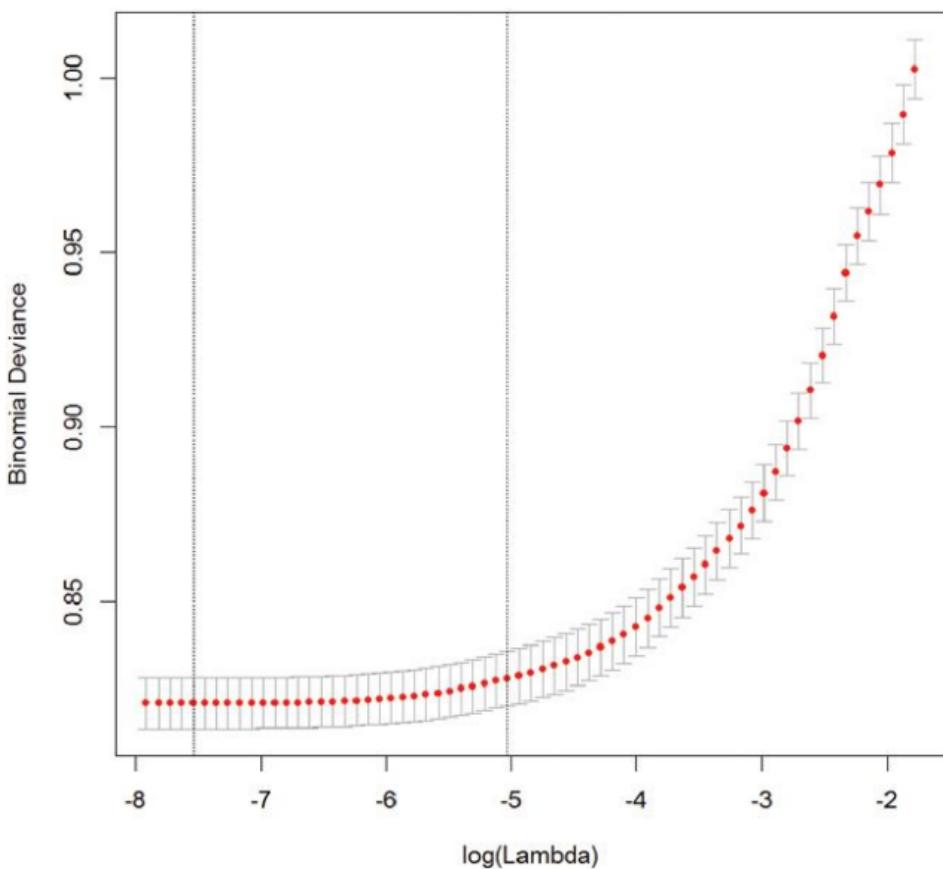
Now that we have found the optimal value of  $\alpha$  (0.75), we refit the model and check the results.

[Click here to view code image](#)

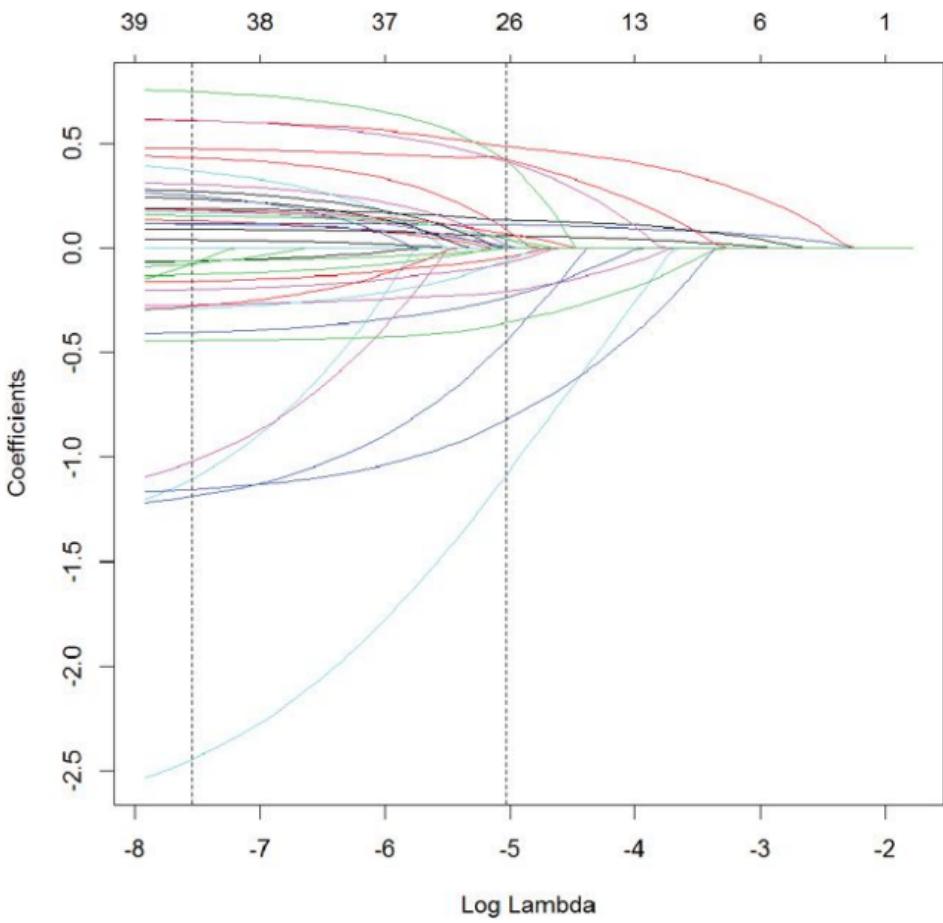
```
> set.seed(5127151)
> acsCV3 <- cv.glmnet(x = acsX, y = acsY, family = "binomial",
+   nfold = 5,
+   alpha = alphaInfo$Alpha[which.min(alphaInfo$error.1se)])
```

After fitting the model we check the diagnostic plots shown in [Figures 19.6](#) and [19.7](#).

39 39 38 37 37 34 28 18 13 11 8 6 5 4 2 1



**Figure 19.6** Cross-validation curve for `glmnet` with  $\alpha = 0.75$ .



**Figure 19.7** Coefficient path for `glmnet` with  $\alpha = 0.75$ .

[Click here to view code image](#)

```
> plot(acsCV3)
> plot(acsCV3$glmnet.fit, xvar = "lambda")
```

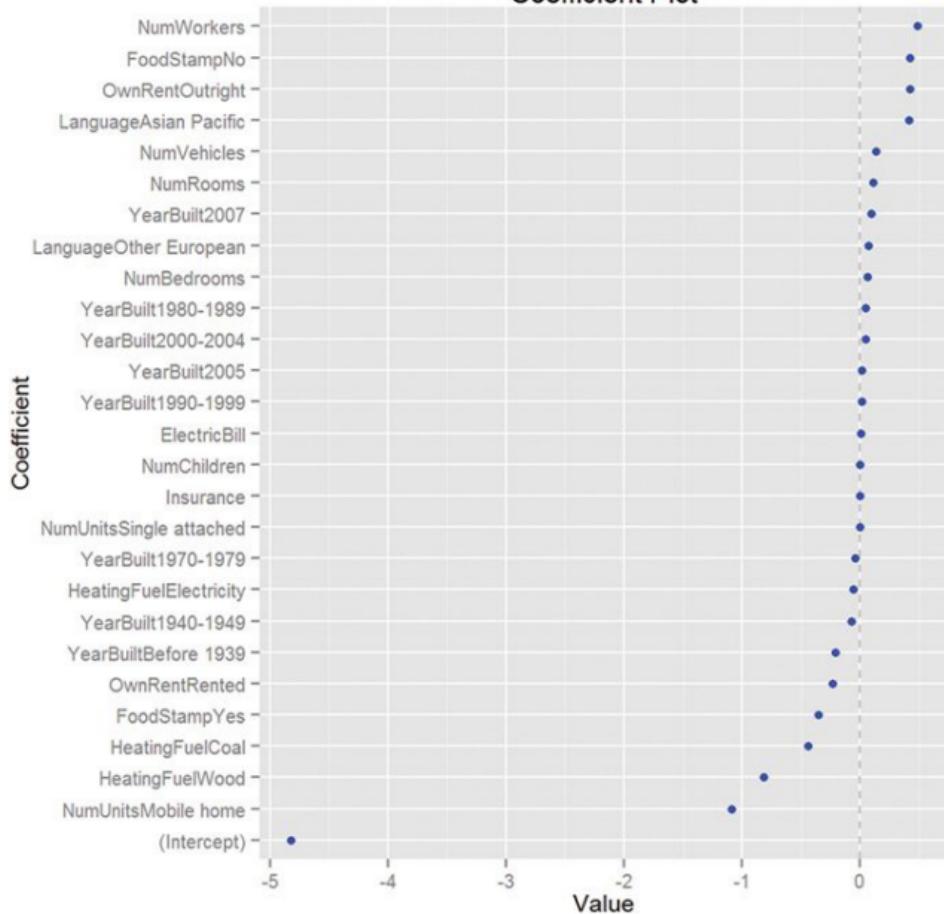
```
> abline(v = log(c(acsCV3$lambda.min, acsCV3$lambda.1se)), lty = 2)
```

Viewing the coefficient plot for a `glmnet` object is not yet implemented in `coefplot`, so we build it manually. [Figure 19.8](#) shows that the number of workers in the family and not being on foodstamps are the strongest indicators of having high income, and using coal heat and living in a mobile home are the strongest indicators of having low income. There are no standard errors because `glmnet` does not calculate them.

[Click here to view code image](#)

```
> theCoef <- as.matrix(coef(acsCV3, s = "lambda.1se"))
> coefDF <- data.frame(Value = theCoef,
+   Coefficient = rownames(theCoef))
> coefDF <- coefDF[nonzeroCoef(coef(acsCV3, s =
+ "lambda.1se")), ]
> ggplot(coefDF, aes(x = X1, y = reorder(Coefficient,
+ X1))) +
+   geom_vline(xintercept = 0, color = "grey", linetype =
+ 2) +
+   geom_point(color = "blue") + labs(x = "Value",
+   y = "Coefficient", title = "Coefficient Plot")
```

### Coefficient Plot



**Figure 19.8** Coefficient plot for glmnet on ACS data. This shows that the number of workers in the family and not being on foodstamps are the strongest indicators of having high income, and using coal heat and living in a mobile home are the strongest indicators of having low income. There are no standard errors because glmnet does not calculate them.

## 19.2. Bayesian Shrinkage

For Bayesians, shrinkage can come in the form of weakly informative priors.<sup>3</sup> This can be particularly useful when a model is built on data that does not have a large enough number of rows for some combinations of the variables. For this example, we blatantly steal an example from Andrew Gelman's and Jennifer Hill's book, *Data Analysis Using Regression and Multilevel/Hierarchical Models*, examining voter preference. The data have been cleaned up and posted at <http://jaredlander.com/data/ideo.rdata>.

3. From a Bayesian point of view, the penalty terms in the Elastic Net could be considered log-priors as well.

[Click here to view code image](#)

```
> load("data/ideo.rdata")
> head(ideo)
  Year   Vote Age Gender Race
  1 1948 democrat NA male white
  2 1948 republican NA female white
  3 1948 democrat NA female white
  4 1948 republican NA female white
  5 1948 democrat NA male white
  6 1948 republican NA female white
                               Education           Income
  1 grade school of less (0-8 grades) 34 to 67 percentile
  2 high school (12 grades or fewer, incl 96 to 100 percentile
  3 high school (12 grades or fewer, incl 68 to 95 percentile
  4 some college(13 grades or more, but no 96 to 100 percent-
    ile
  5 some college(13 grades or more, but no 68 to 95 percent-
    ile
  6 high school (12 grades or fewer, incl 96 to 100 percentile
                    Religion
  1      protestant
  2      protestant
  3 catholic (roman catholic)
  4      protestant
  5 catholic (roman catholic)
  6      protestant
```

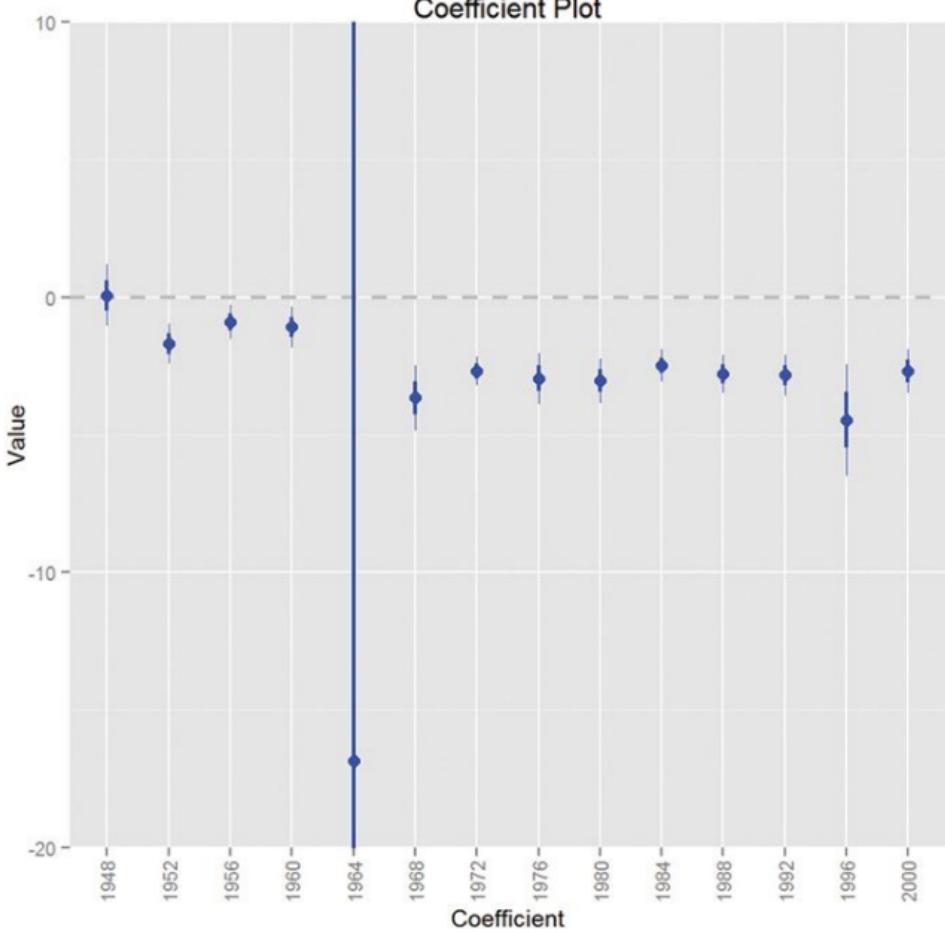
To show the need for shrinkage, we fit a separate model for each election year and then display the resulting coefficients for the black level of Race.

[Click here to view code image](#)

```
> ## fit a bunch of models
> # figure out the years we will be fitting the models on
> theYears <- unique(ideo$Year)
>
> # create an empty list
> # as many elements as years
> # it holds the results
> # preallocating the object makes the code run faster
> results <- vector(mode="list", length=length(theYears))
> # give good names to the list
> names(results) <- theYears
>
> ## loop through the years
> # fit a model on the subset of data for that year
> for(i in theYears)
+ {
  +   results[[as.character(i)]] <- glm(Vote ~ Race + Income + Gender +
  +                                         Education,
  +                                         data=ideo, subset=Year==i,
  +                                         family=binomial(link="logit"))
  + }
```

Now that we have all of these models, we can plot the coefficients with multiplot. [Figure 19.9](#) shows the coefficient for the black level of Race for each model. The result for the model from 1964 is clearly far different from the other models. [Figure 19.9](#) shows standard errors, which threw off the scale so much that we had to restrict the plot window to still see variation in the other points. Fitting a series of models like this and then plotting the coefficients over time has been termed the “secret weapon” by Gelman due to its usefulness and simplicity.

### Coefficient Plot



**Figure 19.9** Plot showing the coefficient for the black level of Race for each of the models. The coefficient for 1964 has a standard error that is orders of magnitude bigger than for the other years. It is so out of proportion that the plot had to be truncated to still see variation in the other data points.

[Click here to view code image](#)

```
> require(coefplot)
> # get the coefficient information
> voteInfo <- multiplot(results, coefficients="Raceblack",
  plot=FALSE)
> head(voteInfo)
      Value Coefficient HighInner LowIn-
      ner HighOuter
1 0.07119541 Race-
black 0.6297813 -0.4873905 1.1883673
2 -1.68490828 Race-
black -1.3175506 -2.0522659 -0.9501930
3 -0.89178359 Race-
black -0.5857195 -1.1978476 -0.2796555
4 -1.07674848 Race-
black -0.7099648 -1.4435322 -0.3431811
5 -16.85751152 Raceblack 382.1171424 -415.8321655
781.0917963
```

```
6 -3.65505395 Race-
black -3.0580572 -4.2520507 -2.4610605
LowOuter Model
1 -1.045976 1948
2 -2.419624 1952
3 -1.503912 1956
4 -1.810316 1960
5 -814.806819 1964
6 -4.849047 1968
>
> # plot it restricting the window to (-20, 10)
> multiplot(results, coefficients="Raceblack",
secret.weapon=TRUE) +
+ coord_flip(xlim=c(-20, 10))
```

By comparing the model for 1964 to the other models, we can see that something is clearly wrong with the estimate. To fix this we put a prior on the coefficients in the model. The simplest way to do this is to use Gelman's bayesglm function in the arm package. By default it sets a Cauchy prior with scale 2.5. Because the arm package namespace interferes with the coefplot namespace, we do not load the package but rather just call the function using the :: operator.

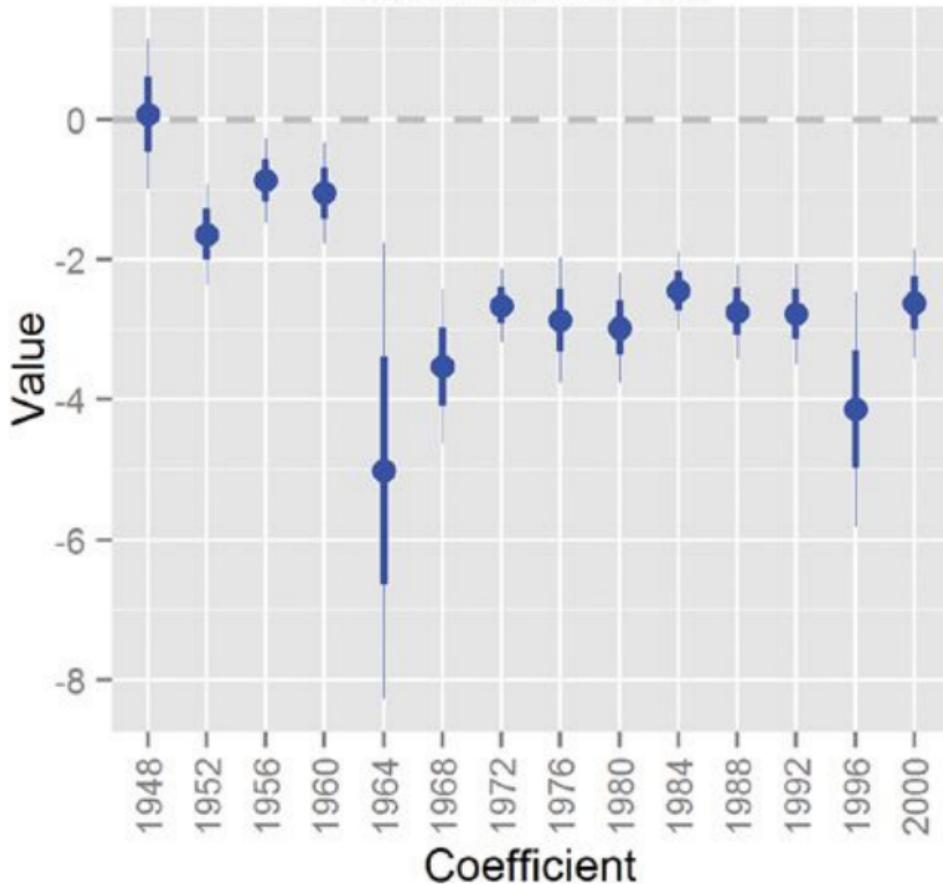
## [Click here to view code image](#)

```
> resultsB <- vector(mode="list", length=length(theYears))
> # give good names to the list
> names(resultsB) <- theYears
>
> ## loop through the years
> ## fit a model on the subset of data for that year
> for(i in theYears)
+ {
+   # fit model with Cauchy priors with a scale of 2.5
+   resultsB[[as.character(i)]] <-
+     arm::bayesglm(Vote ~ Race + Income + Gender +
Education,
+     data=ideo, subset=Year==i,
+     family=binomial(link="logit"),
+     prior.scale=2.5, prior.df=1)
+ }
>
> # build the coefficient plot
> multiplot(resultsB, coefficients="Raceblack",
secret.weapon=TRUE)
```

Simply adding Cauchy priors dramatically shrinks both the estimate and the standard error of the coefficient, as seen in [Figure 19.10](#). Remember, the models were fitted independently, meaning that it was simply the prior that did the fix and

not information from the other years. It turns out that the survey conducted in 1964 underrepresented black respondents, which led to a highly inaccurate measure.

## Coefficient Plot



**Figure 19.10** Coefficient plot (the secret weapon) for the black level of Race for each of the models with a Cauchy prior. A simple change like adding a prior dramatically changed the point estimate and standard error.

The default prior is a Cauchy with scale 2.5, which is the same as a t distribution with 1 degree of freedom. These arguments, `prior.scale` and `prior.df`, can be changed to represent a t distribution with any degrees of freedom. Setting both to infinity (`Inf`) makes them normal priors, which is identical to running an ordinary `glm`.

## 19.3. Conclusion

Regularization and shrinkage play important roles in modern statistics. They help fit models to poorly designed data, and prevent overfitting of complex models. The former is done using Bayesian methods, in this case the simple `bayesglm`; the latter is done with the lasso, ridge or Elastic Net using `glmnet`. Both are useful tools to have.

# Chapter 20. Nonlinear Models

A key tenet of linear models is a linear relationship, which is actually reflected in the coefficients, not the predictors. While this is a nice simplifying assumption, in reality nonlinearity often holds. Fortunately, modern computing makes fitting nonlinear models not much more difficult than fitting linear models. Typical implementations are nonlinear least squares, splines, decision trees and random forests and generalized additive models (GAMs).

## 20.1. Nonlinear Least Squares

The nonlinear least squares model uses squared error loss to find the optimal parameters of a generic (nonlinear) function of the predictors.

$$y_i = f(x_i, \beta) \tag{20.1}$$

A common application for a nonlinear model is using the location of WiFi-connected devices to

determine the location of the WiFi hotspot. In a problem like this, the locations of the devices in a two-dimensional grid are known, and they report their distance to the hotspot but with some random noise due to the fluctuation of the signal strength. A sample dataset is available at [ht-tp://jaredlander.com/data/wifi.rdata](http://jaredlander.com/data/wifi.rdata).

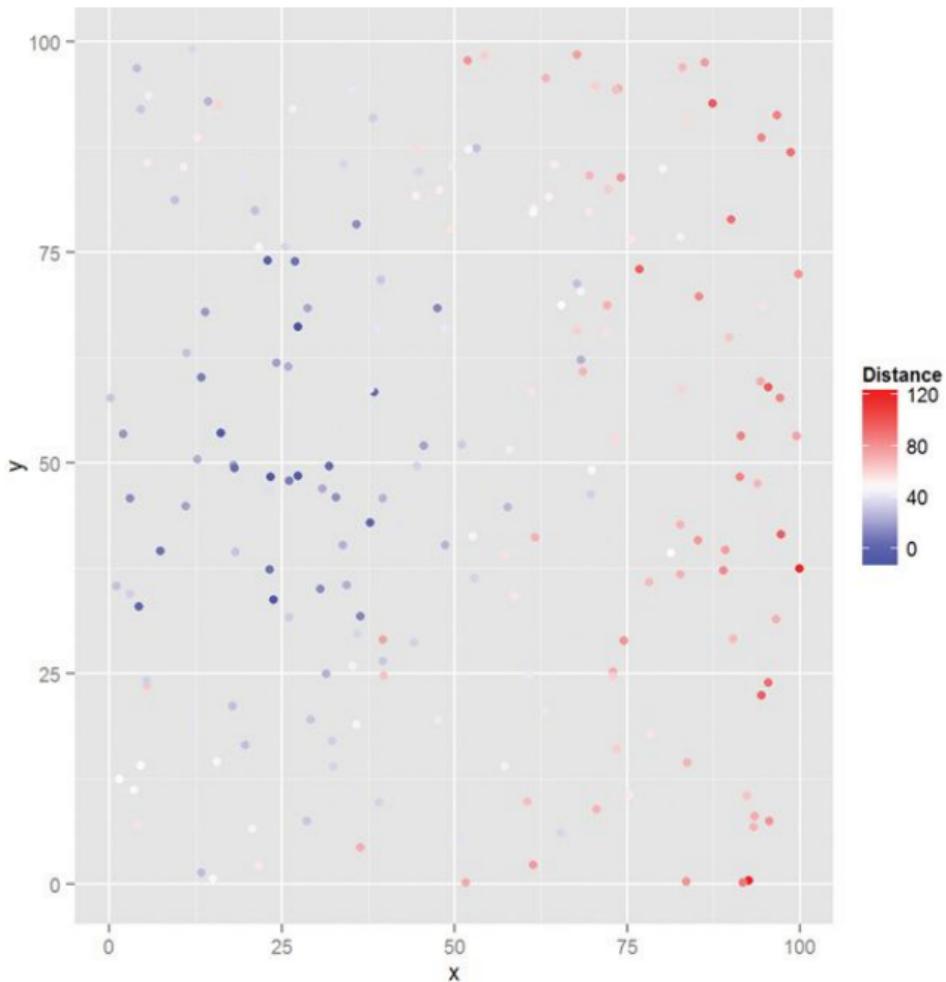
[Click here to view code image](#)

```
> load("data/wifi.rdata")
> head(wifi)
  Distance      x      y
1 21.87559 28.60461 68.429628
2 67.68198 90.29680 29.155945
3 79.25427 83.48934  0.371902
4 44.73767 61.39133 80.258138
5 39.71233 19.55080 83.805855
6 56.65595 71.93928 65.551340
```

This dataset is easy to plot with ggplot2. The *x*- and *y*-axes are the device's positions in the grid and the color represents how far the device is from the hotspot, blue being closer and red being farther (see [Figure 20.1](#)).

[Click here to view code image](#)

```
> require(ggplot2)
> ggplot(wifi, aes(x=x, y=y, color=Distance)) +
  geom_point() +
  scale_color_gradient2(low="blue", mid="white",
  high="red",
  midpoint=mean(wifi$Distance))
```



**Figure 20.1** Plot of WiFi device position colored by distance from the hotspot. Blue points are closer and red points are farther.

The distance between a device  $i$  and the hotspot is

$$d_i = \sqrt{(\beta_x - x_i)^2 + (\beta_y - y_i)^2} \quad (20.2)$$

where  $\beta_x$  and  $\beta_y$  are the unknown  $x$ - and  $y$ -coordinates of the hotspot.

A standard function in R for computing non-linear least squares is `nls`. Since these problems are usually intractable, numerical methods are used, which can be sensitive to starting values, so best guesses need to be specified. The function takes a formula—just like `lm`—except the equation and coefficients are explicitly specified. The starting values for the coefficients are given in a named list.

[Click here to view code image](#)

```
> # specify the square root model  
> # starting values are at the center of the grid  
  
> wifiMod1 <- nls(Distance ~ sqrt((betaX - x)^2 + (betaY  
- y)^2),  
+   data = wifi, start = list(betaX = 50, betaY = 50))  
> summary(wifiMod1)
```

Formula: Distance ~ sqrt((betaX - x)^2 + (betaY - y)^2)

Parameters:

	Estimate	Std. Error	t value	Pr(> t )
betaX	17.851	1.289	13.85	<2e-16 ***

```
betaY 52.906   1.476 35.85 <2e-16 ***
```

---

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

Residual standard error: 13.73 on 198 degrees of freedom

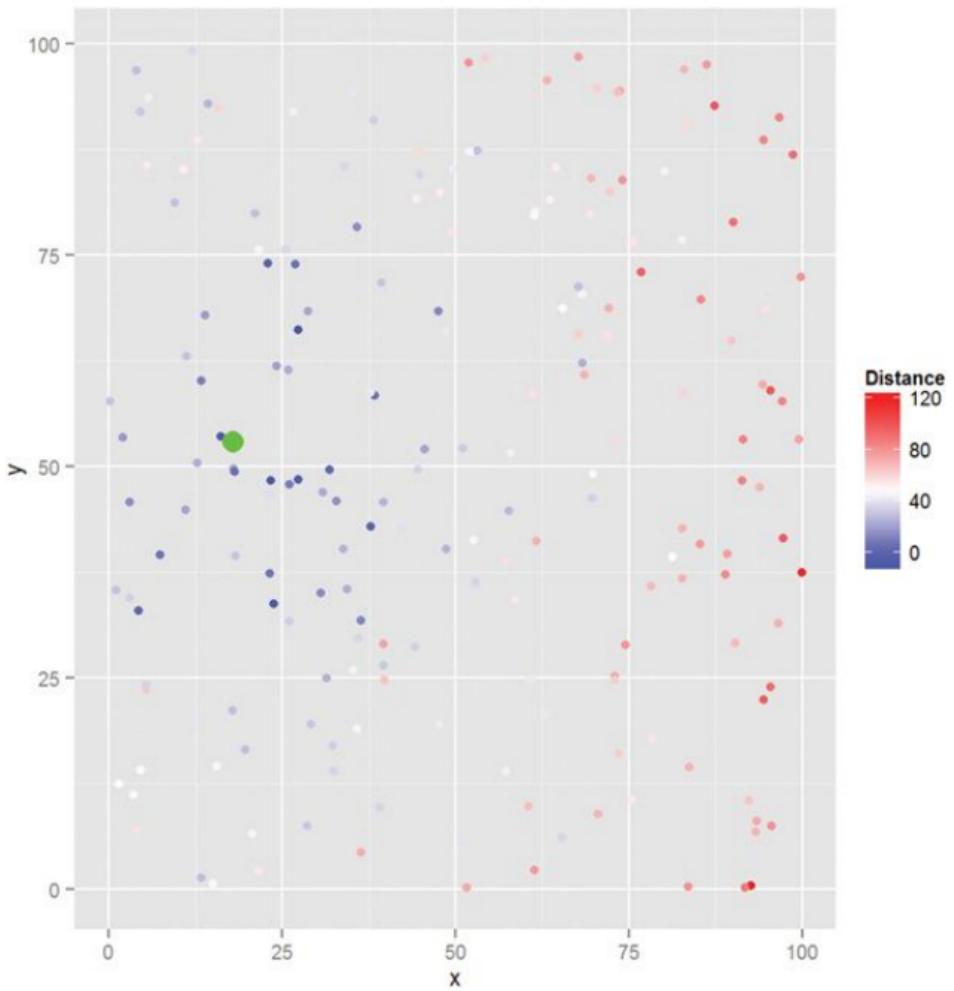
Number of iterations to convergence: 6

Achieved convergence tolerance: 3.846e-06

This estimates that the hotspot is located at 17.8506668, 52.9056438. Plotting this in [Figure 20.2](#), we see that the hotspot is located amidst the “close” blue points, indicating a good fit.

[Click here to view code image](#)

```
> ggplot(wifi, aes(x = x, y = y, color = Distance)) +  
  geom_point() +  
  +  scale_color_gradient2(low = "blue", mid = "white",  
  high = "red",  
  +                      midpoint = mean(wifi$Distance)) +  
  +  geom_point(data = as.data.frame(t(coef(wifiMod1))),  
  +             aes(x = betaX, y = betaY), size = 5, color =  
  "green")
```



**Figure 20.2** Plot of WiFi devices. The hot-spot is the large green dot. Its position in the middle of the blue dots indicates a good fit.

## 20.2. Splines

A smoothing spline can be used to fit a smooth to data that exhibit nonlinear behavior and even make predictions on new data. A spline is a function  $f$  that is a linear combination of  $N$  functions (one for each unique data point) that are transformations of the variable  $x$ .

$$f(x) = \sum_{j=1}^N N_j(x)\theta_j \quad (20.3)$$

The goal is to find the function  $f$  that minimizes

$$RSS(f, \lambda) = \sum_{i=1}^N \{\gamma_i - f(x_i)\}^2 + \lambda \int \{f''(t)\}^2 dt \quad (20.4)$$

where  $\lambda$  is the smoothing parameter. Small  $\lambda$ s make for a rough smooth and large  $\lambda$ s make for a smooth smooth.

This is accomplished in R using `smooth.spline`. It returns a list of items where `x` holds the unique values of the data, `y` are the corresponding fitted values and `df` is the degrees

of freedom used. We demonstrate with the diamonds data.

[Click here to view code image](#)

```
> data(diamonds)
> # fit with a few different degrees of freedom
> # the degrees of freedom must be greater than 1
> # but less than the number of unique x values in the data
> diaSpline1 <- smooth.spline(x=diamonds$carat, y=diamonds$price)
> diaSpline2 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                                df=2)
> diaSpline3 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                                df=10)
> diaSpline4 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                                df=20)
> diaSpline5 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                                df=50)
> diaSpline6 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                                df=100)
```

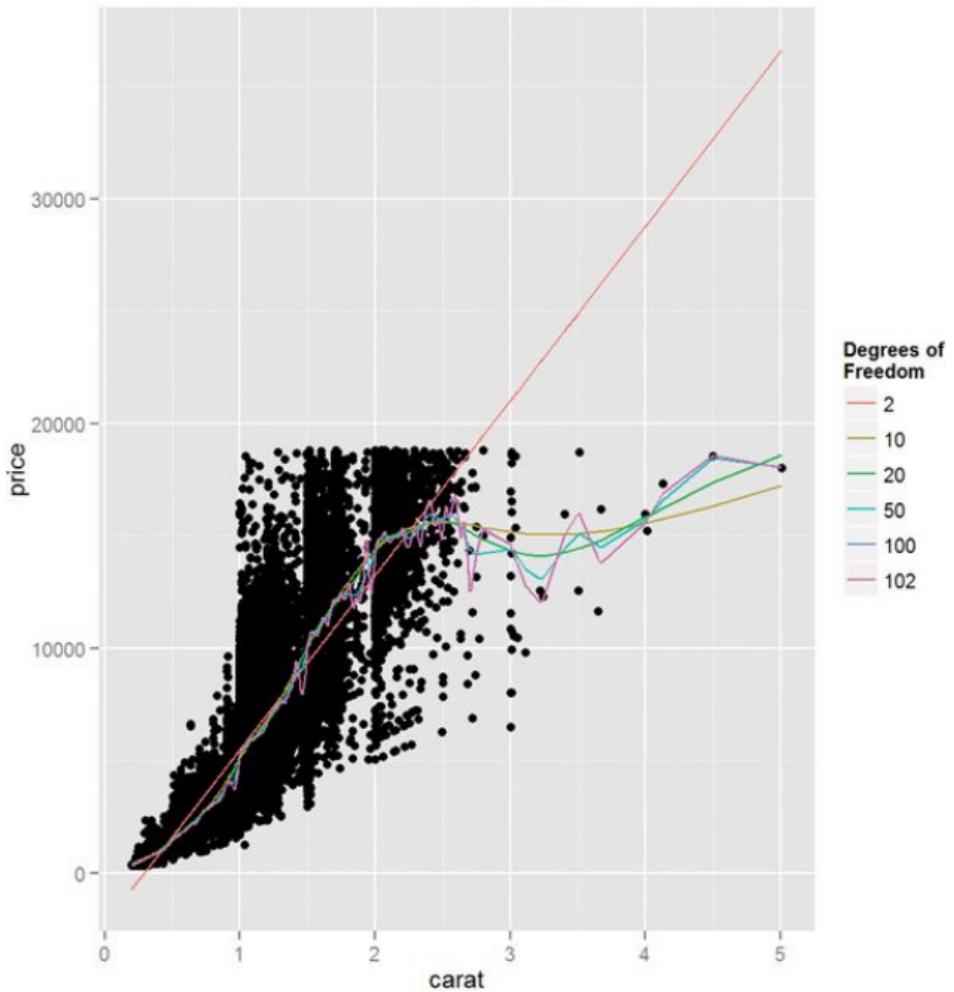
To plot these we extract the information from the objects, build a data.frame, then add a new

layer on top of the standard scatterplot of the diamonds data. [Figure 20.3](#) shows this. Fewer degrees of freedom leads to straighter fits while higher degrees of freedom leads to more interpolating lines.

[Click here to view code image](#)

```
> get.spline.info <- function(object)
+ {
+   data.frame(x=object$x, y=object$y, df=object$df)
+ }
>
> require(plyr)
> # combine results into one data.frame
> splineDF <- ldply(list(diaSpline1, diaSpline2, diaSpline3,
+                               diaSpline4, diaSpline5, diaSpline6),
+                               get.spline.info)
> head(splineDF)
      x     y     df
1 0.20 361.9112 101.9053
2 0.21 397.1761 101.9053
3 0.22 437.9095 101.9053
4 0.23 479.9756 101.9053
5 0.24 517.0467 101.9053
6 0.25 542.2470 101.9053
>
```

```
> g <- ggplot(diamonds, aes(x=carat, y=price)) +  
  geom_point()  
> g + geom_line(data=splineDF,  
+   aes(x=x, y=y, color=factor(round(df, 0)),  
+   group=df)) + scale_color_discrete("Degrees of\nFreedom")
```



**Figure 20.3** Diamonds data with a number of different smoothing splines.

Making predictions on new data is done, as usual, with `predict`.

Another type of spline is the basis spline, which creates new predictors based on transformations of the original predictors. The best basis spline is the natural cubic spline because it creates smooth transitions at interior breakpoints and forces linear behavior beyond the endpoints of the input data. A natural cubic spline with  $K$  breakpoints (knots) is made of  $K$  basis functions

$$N_1(X) = 1, N_2(X) = X, N_{k+2} = d_k(X) - d_{K-1}(X) \quad (20.5)$$

where

$$d_k(X) = \frac{(X - \xi_k)_+^3 - (X - \xi_K)_+^3}{\xi_K - \xi_k} \quad (20.6)$$

and  $\xi$  is the location of a knot and  $t_+$  denotes the positive part of  $t$ .

While the math may seem complicated, natural cubic splines are easily fitted using `ns` from the `splines` package. It takes a predictor variable and the number of new variables to return.

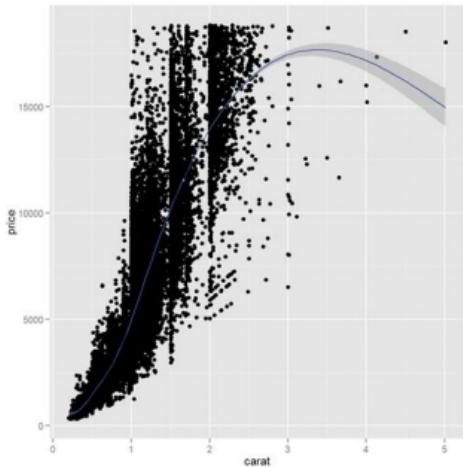
[Click here to view code image](#)

```
> require(splines)
> head(ns(diamonds$carat, df = 1))
```

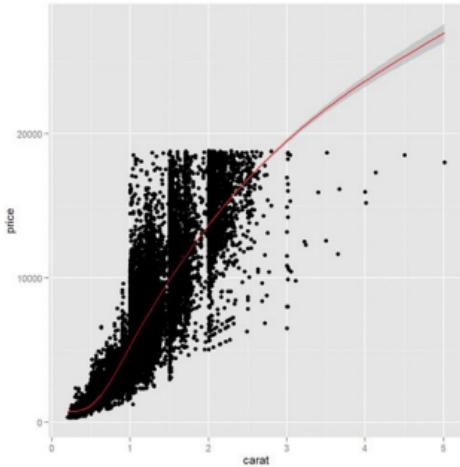
```
1  
[1,] 0.00500073  
[2,] 0.00166691  
[3,] 0.00500073  
[4,] 0.01500219  
[5,] 0.01833601  
[6,] 0.00666764  
> head(ns(diamonds$carat, df = 2))  
 1     2  
[1,] 0.013777685 -0.007265289  
[2,] 0.004593275 -0.002422504  
[3,] 0.013777685 -0.007265289  
[4,] 0.041275287 -0.021735857  
[5,] 0.050408348 -0.026525299  
[6,] 0.018367750 -0.009684459  
> head(ns(diamonds$carat, df = 3))  
 1     2     3  
[1,] -0.03025012 0.06432178 -0.03404826  
[2,] -0.01010308 0.02146773 -0.01136379  
[3,] -0.03025012 0.06432178 -0.03404826  
[4,] -0.08915435 0.19076693 -0.10098109  
[5,] -0.10788271 0.23166685 -0.12263116  
[6,] -0.04026453 0.08566738 -0.04534740  
> head(ns(diamonds$carat, df = 4))  
 1     2     3     4  
[1,] 3.214286e-04 -0.04811737 0.10035562 -0.05223825  
[2,] 1.190476e-05 -0.01611797 0.03361632 -0.01749835  
[3,] 3.214286e-04 -0.04811737 0.10035562 -0.05223825  
[4,] 8.678571e-03 -0.13796549 0.28774667 -0.14978118  
[5,] 1.584524e-02 -0.16428790 0.34264579 -0.17835789
```

[6,] 7.619048e-04 -0.06388053 0.13323194 -0.06935141

These new predictors can then be used in any model just like any other predictor. More knots means a more interpolating fit. Plotting the result of a natural cubic spline overlaid on data is easy with ggplot2. [Figure 20.4a](#) shows this for the diamonds data and



(a) Six knots



(b) Three knots

**Figure 20.4** Scatterplot of price versus carat with a regression fitted on a natural cubic spline.

six knots, and [Figure 20.4b](#) shows it with three knots. Notice that having six knots fits the data more smoothly.

[Click here to view code image](#)

```
> g <- ggplot(diamonds, aes(x = carat, y = price)) +  
  geom_point()  
  
> g + stat_smooth(method = "lm", formula = y ~ ns(x, 6),  
  color = "blue")  
  
> g + stat_smooth(method = "lm", formula = y ~ ns(x, 3),  
  color = "red")
```

## 20.3. Generalized Additive Models

Another method for fitting nonlinear models is generalized additive models (GAMs), which fit a separate smoothing function on each predictor independently. As the name implies, these are general and work in a number of regression contexts, meaning the response can be continuous, binary, count and other types. Like many of the best modern techniques in machine learning, this is the brainchild of Trevor Hastie and Robert Tibshirani based on work from John Chambers, the creator of S, the precursor of R.

They are specified as

$$E(Y|X_1, X_2, \dots, X_p) = \alpha + f_1(X_1) + f_2(X_2) + \dots + f_p(X_p) \quad (20.7)$$

where  $X_1, X_2, \dots, X_p$  are ordinary predictors and the  $f_j$ 's are any smoothing functions.

The mgcv package fits GAMs with a syntax very similar to glm. To illustrate we use data on credit scores from the University of California–Irvine Machine Learning Repository at [ht-  
tp://archive.ics.uci.edu/ml/datasets/Statlo-](http://archive.ics.uci.edu/ml/datasets/Statlog+Credit+Approval)

[g+\(German+Credit+Data\)](#). The data are stored in a space-separated text file with no headers where categorical data have been labeled with nonobvious codes. This arcane file format goes back to a time when data storage was more limited but has, for some reason, persisted.

The first step is reading the data like any other file except that the column names need to be specified.

[Click here to view code image](#)

```
> # make vector of column names
> creditNames <- c("Checking", "Duration", "CreditHistory",
+   "Purpose", "CreditAmount", "Savings", "Employ-
ment",
+   "InstallmentRate", "GenderMarital", "OtherDebtors",
+   "YearsAtResidence", "RealEstate", "Age",
+   "OtherInstallment", "Housing", "ExistingCredits",
"Job",
+   "NumLiable", "Phone", "Foreign", "Credit")
>
> # use read.table to read the file
> # specify that headers are not included
> # the col.names are from creditNames
> theURL <- "http://archive.ics.uci.edu/ml/
```

```
+      machine-learning-databases/statlog/german/ger-
man.data
> credit <- read.table(the URL sep = " ", header = FALSE,
+                         col.names = creditNames,
+                         stringsAsFactors = FALSE)
>
> head(credit)
  Checking Duration CreditHistory Purpose CreditAmount
Savings
  1   A11     6       A34    A43      1169    A65
  2   A12    48       A32    A43      5951    A61
  3   A14    12       A34    A46      2096    A61
  4   A11    42       A32    A42      7882    A61
  5   A11    24       A33    A40      4870    A61
  6   A14    36       A32    A46      9055    A65
  Employment InstallmentRate Gender Marital OtherDebt-
ors
  1   A75        4       A93    A101
  2   A73        2       A92    A101
  3   A74        2       A93    A101
  4   A74        2       A93    A103
  5   A73        3       A93    A101
  6   A73        2       A93    A101
  YearsAtResidence RealEstate Age OtherInstallment Hous-
ing
  1       4     A121 67      A143    A152
  2       2     A121 22      A143    A152
  3       3     A121 49      A143    A152
  4       4     A122 45      A143    A153
  5       4     A124 53      A143    A153
```

6	4	A124	35		A143	A153
	ExistingCredits	Job	NumLiable	Phone	Foreign	Credit
1	2	A173	1	A192	A201	1
2	1	A173	1	A191	A201	2
3	1	A172	2	A191	A201	1
4	1	A173	2	A191	A201	1
5	2	A173	2	A191	A201	2
6	1	A172	2	A192	A201	1

Now comes the unpleasant task of translating the codes to meaningful data. To save time and effort we decode only the variables we care about for a simple model. The simplest way of decoding is to create named vectors where the name is the code and the value is the new data.

[Click here to view code image](#)

	CreditHistory	Purpose	Employment	Credit
1	A34	A43	A75	1
2	A32	A43	A73	2
3	A34	A46	A74	1
4	A32	A42	A74	1
5	A33	A40	A73	2
6	A32	A46	A73	1

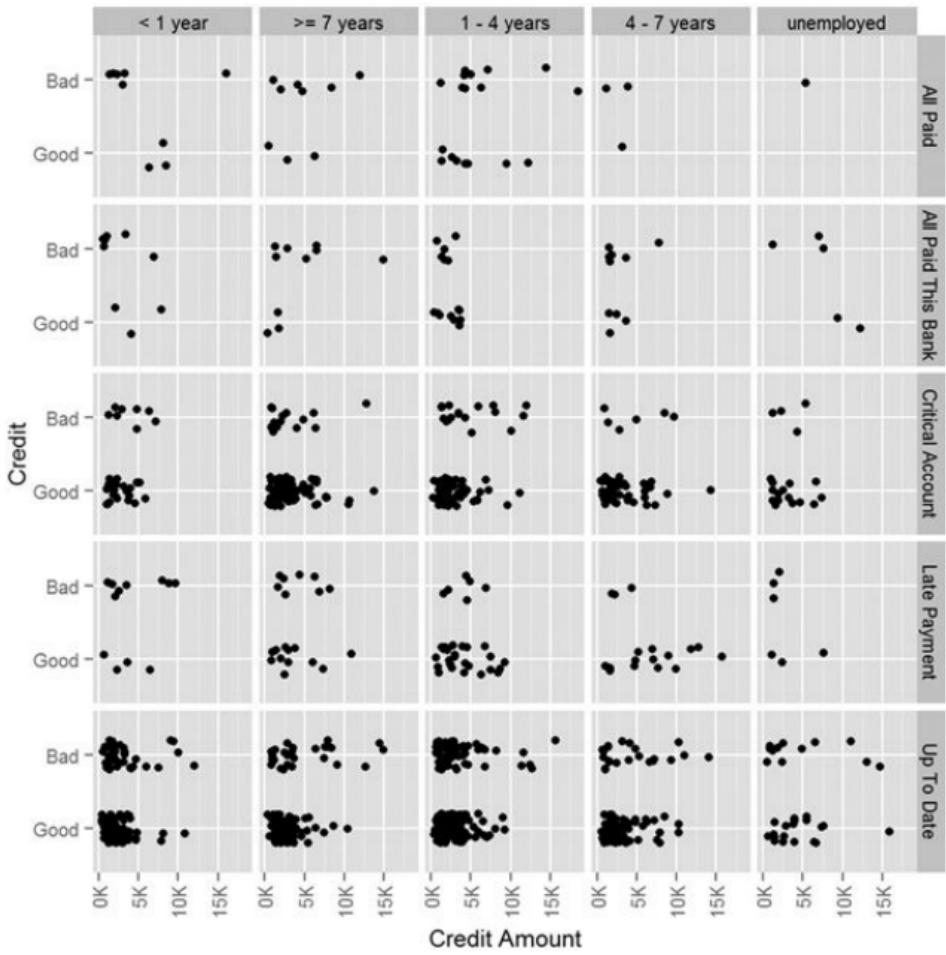
>

```
> creditHis-
tory <- c(A30 = "All Paid", A31 = "All Paid This Bank",
+   A32 = "Up To Date", A33 = "Late Payment",
+   A34 = "Critical Account")
>
> purpose <- c(A40 = "car (new)", A41 = "car (used)",
+   A42 = "furniture/equipment", A43 = "radio/television",
+   A44 = "domestic appliances", A45 = "repairs",
+   A46 = "education", A47 = "(vacation - does not ex-
ist?)",
+   A48 = "retraining", A49 = "business", A410 = "oth-
ers")
>
> employment <- c(A71 = "unem-
ployed", A72 = "< 1 year",
+   A73 = "1 - 4 years", A74 = "4 - 7 years", A75 = ">= 7 year
">
> credit$CreditHistory <- creditHis-
tory[credit$CreditHistory]
> credit$Purpose <- purpose[credit$Purpose]
> credit$Employment <- employment[credit$Employment]
>
> # code credit as good/bad
> credit$Credit <- ifelse(credit$Cred-
it == 1, "Good", "Bad")
> # make good the base levels
> credit$Credit <- factor(credit$Cred-
it, levels = c("Good", "Bad"))
>
> # after
```

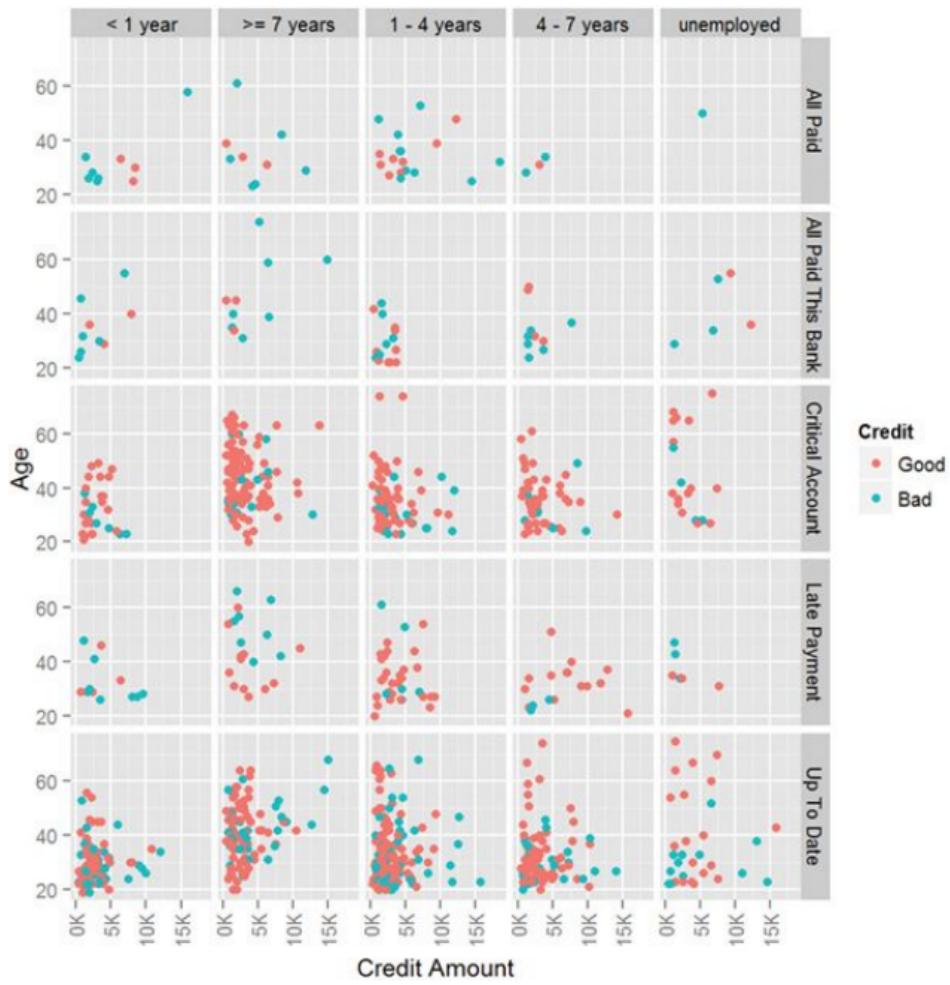
```
> head(credit[, c("CreditHistory", "Purpose", "Employ-  
ment",  
"Credit")])
```

	CreditHistory	Purpose	Employment	Credit
1	Critical Account	radio/television	$\geq 7$ years	Good
2	Up To Date	radio/television	1 - 4 years	Bad
3	Critical Account	education	4 - 7 years	Good
4	Up To Date	furniture/equipment	4 - 7 years	Good
5	Late Payment	car (new)	1 - 4 years	Bad
6	Up To Date	education	1 - 4 years	Good

Viewing the data will help give a sense of the relationship between the variables. [Figures 20.5](#) and [20.6](#) show that there is not a clear linear relationship, so a GAM may be appropriate.



**Figure 20.5** Plot of good credit versus bad based on credit amount, credit history and employment status.



**Figure 20.6** Plot of age versus credit amount faceted by credit history and employment status, color coded by credit.

## [Click here to view code image](#)

```
> require(useful)
> ggplot(credit, aes(x=CreditAmount, y=Credit)) +
+   geom_jitter(position = position_jitter(height = .2)) +
+   facet_grid(CreditHistory ~ Employment) +
+   xlab("Credit Amount") +
+   theme(axis.text.x=element_text(angle=90, hjust=1, vjust=.5)) +
+   scale_x_continuous(labels=multiple)
>
> ggplot(credit, aes(x=CreditAmount, y=Age)) +
+   geom_point(aes(color=Credit)) +
+   facet_grid(CreditHistory ~ Employment) +
+   xlab("Credit Amount") +
+   theme(axis.text.x=element_text(angle=90, hjust=1, vjust=.5)) +
+   scale_x_continuous(labels=multiple)
```

Using gam is very similar to using other modeling functions like lm and glm that take a formula argument. The difference is that continuous variables, such as CreditAmount and Age, can be transformed using a nonparametric smoothing function such as a spline or tensor product.<sup>1</sup>

1. Tensor products are a way of representing transformation functions of predictors, possibly measured on different units.

[Click here to view code image](#)

```
> require(mgcv)
> # fit a logistic GAM
> # apply a tensor product on CreditA-
mount and a spline on Age
> creditGam <- gam(Credit ~ te(CreditA-
mount) + s(Age) + CreditHistory +
+                 Employment,
+                 data=credit, family=binomial(link="logit"))
> summary(creditGam)
Family: binomial
Link function: logit
Formula:
Credit ~ te(CreditAmount) + s(Age) + CreditHistory + Em-
ployment
Parametric coefficients:
Estimate Std. Error z value Pr(>|z|)
(Inter-
cept)          0.662840  0.372377  1.780 0.07507
CreditHis-
toryAll Paid This Bank  0.008412  0.453267  0.019 0.98519
CreditHistoryCritical Ac-
count -1.809046  0.376326 -4.807 1.53e-06
CreditHistoryLate Pay-
ment -1.136008  0.412776 -2.752 0.00592
```

CreditHistoryUp To Date -1.104274 0.355208 -3.109 0.00188  
 Employment>= 7 years -0.388518 0.240343 -1.617 0.10598  
 Employment1 - 4 years -0.380981 0.204292 -1.865 0.06220  
 Employment4 - 7 years -0.820943 0.252069 -3.257 0.00113  
 Employmentunemployed -0.092727 0.334975 -0.277 0.78192  
 (Intercept) .  
 CreditHistoryAll Paid This Bank  
 CreditHistoryCritical Account \*\*\*  
 CreditHistoryLate Payment \*\*  
 CreditHistoryUp To Date \*\*  
 Employment>= 7 years  
 Employment1 - 4 years .  
 Employment4 - 7 years \*\*  
 Employmentunemployed

---

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

Approximate significance of smooth terms:

	edf	Ref.df	Chi.sq	p-value
te(CreditAmount)	2.415	2.783	20.79	0.000112 ***
s(Age)	1.932	2.435	6.13	0.068957 .

---

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

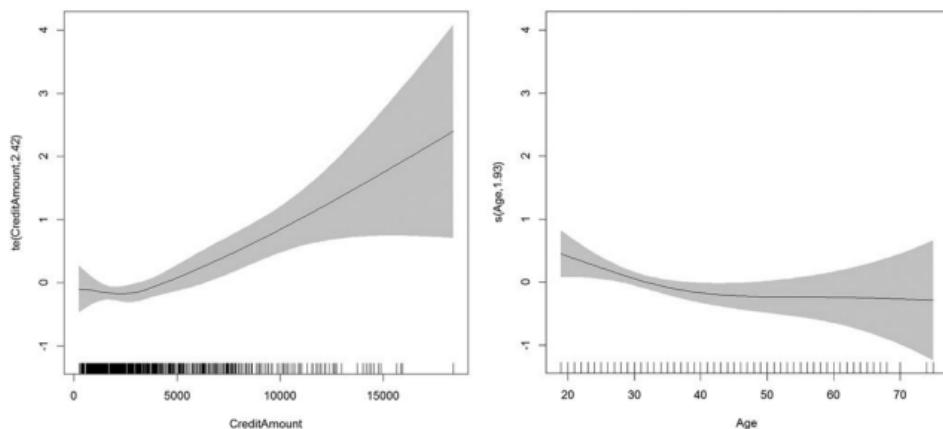
R-sq.(adj) = 0.0922 Deviance explained = 8.57%

UBRE score = 0.1437 Scale est. = 1 n = 1000

The smoother is fitted automatically in the fitting process and can be viewed after the fact. [Figure 20.7](#) shows CreditAmount and Age with their applied smoothers, a tensor product and a spline, respectively. The gray, shaded area represents the confidence interval for the smooths.

[Click here to view code image](#)

```
> plot(creditGam, select = 1, se = TRUE, shade = TRUE)  
> plot(creditGam, select = 2, se = TRUE, shade = TRUE)
```



**Figure 20.7** The smoother result for fitting a GAM on credit data. The shaded region represents two pointwise standard deviations.

## 20.4. Decision Trees

A relatively modern technique for fitting nonlinear models is the decision tree. Decision trees work for both regression and classification by performing binary splits on the recursive predictors.

For regression trees, the predictors are partitioned into  $M$  regions  $R_1, R_2, \dots, R_M$  and the response  $y$  is modeled as the average for a region with

$$\hat{f}(x) = \sum_{m=1}^M \hat{c}_m I(x \in R_m) \quad (20.8)$$

where

$$\hat{c}_m = \text{avg}(\gamma_i | x_i \in R_m) \quad (20.9)$$

is the average  $y$  value for the region.

The method for classification trees is similar. The predictors are partitioned into  $M$  regions and the proportion of each class in each of the regions,  $\hat{p}_{mk}$ , is calculated as

$$\hat{p}_{mk} = \frac{1}{N_m} \sum_{x_i \in R_m} I(y_i = k) \quad (20.10)$$

where  $N_m$  is the number of items in region  $m$  and the summation counts the number of observations of class  $k$  in region  $m$ .

Trees can be calculated with the rpart function in rpart. Like other modeling functions, it uses the formula interface but does not take interactions.

[Click here to view code image](#)

```
> require(rpart)  
> creditTree <- rpart(Credit ~ CreditAmount + Age +  
+   CreditHistory + Employment, data = credit)
```

Printing the object displays the tree in text form.

```
> creditTree  
n= 1000  
node), split, n, loss, yval, (yprob)  
* denotes terminal node  
1) root 1000 300 Good (0.7000000 0.3000000)  
2) CreditHistory=Critical Account,Late Payment,Up To  
Date 911 247 Good (0.7288694 0.2711306)
```

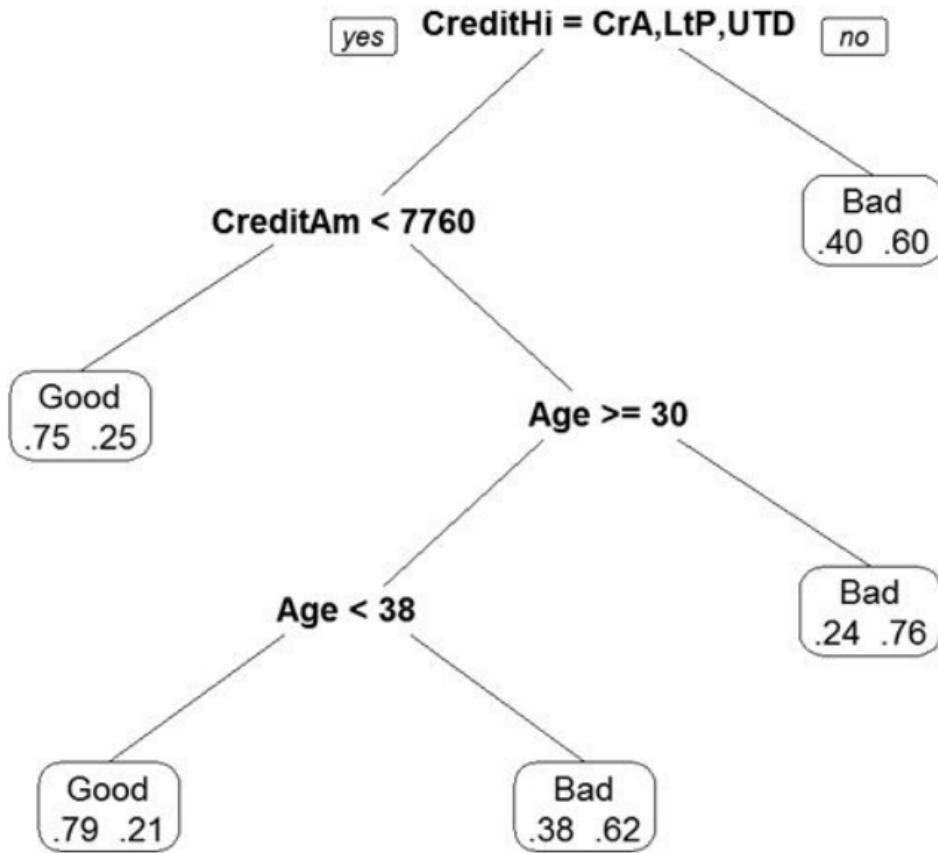
```
4) CreditAmoun-
t< 7760.5 846 211 Good (0.7505910 0.2494090) *
5) CreditAmoun-
t>=7760.5 65 29 Bad (0.4461538 0.5538462)
   10) Age>=29.5 40 17 Good (0.5750000 0.4250000)
       20) Age< 38.5 19 4 Good (0.7894737 0.2105263) *
       21) Age>=38.5 21 8 Bad (0.3809524 0.6190476) *
   11) Age< 29.5 25 6 Bad (0.2400000 0.7600000) *
3) CreditHistory=All Paid,All Paid This Bank 89 36
   Bad (0.4044944 0.5955056) *
```

The printed tree has one line per node. The first node is the root for all the data and shows that there are 1,000 observations of which 300 are considered “Bad.” The next level of indentation is the first split, which is on CreditHistory. One direction—where CreditHistory equals either “Critical Account,” “Late Payment” or “Up To Date”—contains 911 observations of which 247 are considered “Bad.” This has a 73% probability of having good credit. The other direction—where CreditHistory equals either “All Paid” or “All Paid This Bank”—has a 60% probability of having bad credit. The next level of indentation represents the next split.

Continuing to read the results this way could be laborious; plotting will be easier. [Figure 20.8](#) shows the splits. Nodes split to the left meet the criteria while nodes to the right do not. Each terminal node is labelled by the predicted class, either “Good” or “Bad.” The percentage is read from left to right, with the probability of being “Good” on the left.

[Click here to view code image](#)

```
> require(rpart.plot)
> rpart.plot(creditTree, extra = 4)
```



**Figure 20.8** Display of decision tree based on credit data. Nodes split to the left meet the criteria while nodes to the right do not. Each terminal node is labeled by the predicted class, either “Good” or “Bad.” The percentage is read from left to right, with the probability of being “Good” on the left.

While trees are easy to interpret and fit data nicely, they tend to be unstable with high variance due to overfitting. A slight change in the training data can cause a significant difference in the model.

## 20.5. Random Forests

Random forests are a type of ensemble method. An ensemble method is a process in which numerous models are fitted and the results are combined for stronger predictions. While this provides great predictions, inference and explainability are often limited. Random forests are composed of a number of decision trees where the included predictors are chosen at random. The name comes from randomly building trees to make a forest.

In the case of the credit data we will use CreditHistory, Purpose, Employment, Duration, Age and CreditAmount. Some trees will have just CreditHistory and Employment, another will have Purpose, Employment and Age, while an-

other will have CreditHistory, Purpose, Employment and Age. All of these different trees cover all the bases and make for a random forest that should have strong predictive power.

Fitting the random forest is done with randomForest from the randomForest package. Normally, randomForest can be used with a formula, but sometimes that fails and individual predictor and response matrices should be supplied.

[Click here to view code image](#)

```
> require(useful)
> require(randomForest)
> # build the predictor and response matrices
> creditFormula <- Credit ~ CreditHistory + Purpose + Employment +
+ Duration + Age + CreditAmount
> creditX <- build.x(creditFormula, data=credit)
> creditY <- build.y(creditFormula, data=credit)
>
> # fit the random forest
> creditForest <- randomForest(x=creditX, y=creditY)
>
> creditForest
Call:
randomForest(x = creditX, y = creditY)
```

Type of random forest: classification

Number of trees: 500

No. of variables tried at each split: 4

OOB estimate of error rate: 28.2%

Confusion matrix:

	Good	Bad	class.error
Good	649	51	0.07285714
Bad	231	69	0.77000000

The displayed information shows that 500 trees were built and four variables were assessed at each split; the confusion matrix shows that this is not exactly the best fit and that there is room for improvement.

## 20.6. Conclusion

With modern computing power, the previously necessary simplifying assumptions of linearity and normality are starting to give way to nonparametric techniques. Popular implementations are nonlinear least squares, splines, generalized additive models, decision trees and random forests. As with every other method, these all have their benefits and costs.

# Chapter 21. Time Series and Autocorrelation

A big part of statistics, particularly for financial and econometric data, is analyzing time series, data that are autocorrelated over time. That is, one observation depends on previous observations and the order matters. Special care needs to be taken to account for this dependency. R has a number of built-in functions and packages to make working with time series easier.

## 21.1. Autoregressive Moving Average

One of the most common ways of fitting time series models is to use autoregressive (AR), moving average (MA) or both (ARMA). These models are well represented in R and are fairly easy to work with. The formula for an ARMA(p, q) is

$$X_t - \Phi_1 X_{t-1} - \cdots - \Phi_p X_{t-p} = Z_t + \theta_1 Z_{t-1} + \cdots + \theta_q Z_{t-q} \quad (21.1)$$

where

$$Z_t \sim \text{WN}(0, \sigma^2) \quad (21.2)$$

is white noise, which is essentially random data.

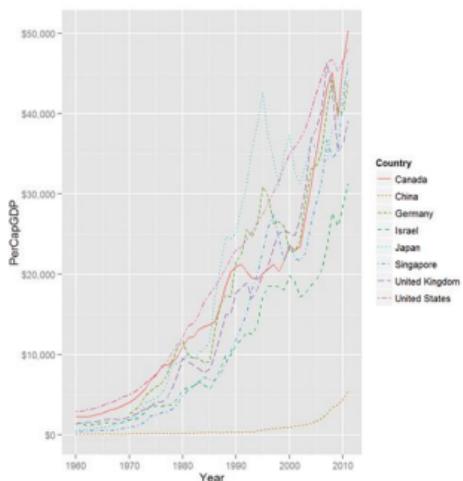
AR models can be thought of as linear regressions of the current value of the time series against previous values. MA models are, similarly, linear regressions of the current value of the time series against current and previous residuals.

For an illustration, we will make use of the World Bank API to download gross domestic product (GDP) for a number of countries from 1960 through 2011.

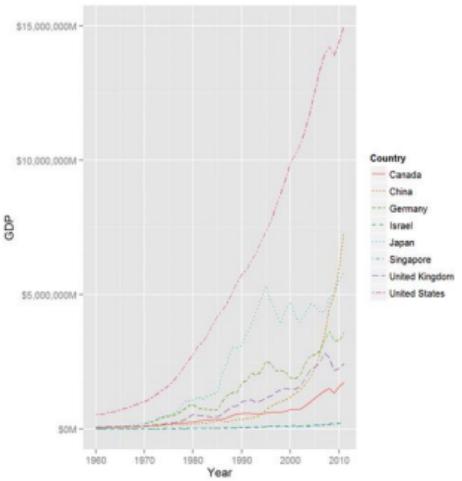
[Click here to view code image](#)

```
> # load the World Bank API package
> require(WDI)
> # pull the data
> gdp <- WDI(country=c("US", "CA", "GB", "DE", "CN",
+ "JP", "SG", "IL"),
+ indicator=c("NY.GDP.PCAP.CD",
+ "NY.GDP.MKTP.CD"),
+ start=1960, end=2011)
> # give it good names
> names(gdp) <- c("iso2c", "Country", "Year", "Per-
CapGDP", "GDP")
```

After downloading, we can inspect the data, which are stored in long country-year format with a plot of per capita GDP shown in [Figure 21.1a](#). [Figure 21.1b](#) shows absolute GDP, illustrating that while China's GDP has jumped significantly in the past ten years, its per capita GDP has only marginally increased.



(a) Per capita GDP



(b) Absolute GDP in millions

**Figure 21.1** GDP for a number of nations from 1960 to 2011.

> `head(gdp)`

	iso2c	Country	Year	PerCapGDP	GDP
1	CA	Canada	1960	2294.569	41093453545
2	CA	Canada	1961	2231.294	40767969454

```
3 CA Canada 1962 2255.230 41978852041
4 CA Canada 1963 2354.839 44657169109
5 CA Canada 1964 2529.518 48882938810
6 CA Canada 1965 2739.586 53909570342
> require(ggplot2)
> require(scales)
> # per capita GDP
> ggplot(gdp, aes(Year, PerCapGDP, color=Country, line-
type=Country)) +
+   geom_line() + scale_y_continuous(label=dollar)
>
> require(useful)
> # absolute GDP
> ggplot(gdp, aes(Year, GDP, color=Country, line-
type=Country)) +
+   geom_line() +
+   scale_y_continuous(label=multiple_format(extra=dol-
lar,
+                                         multiple="M"))
```

First we will only look at only one time series, so we extract the data for the United States. See [Figure 21.2](#).

```
> # get US data
> us <- gdp$PerCapGDP[gdp$Country == "United States"]
> # convert it to a time series
> us <- ts(us, start = min(gdp$Year), end =
max(gdp$Year))
```

```
> us
```

Time Series:

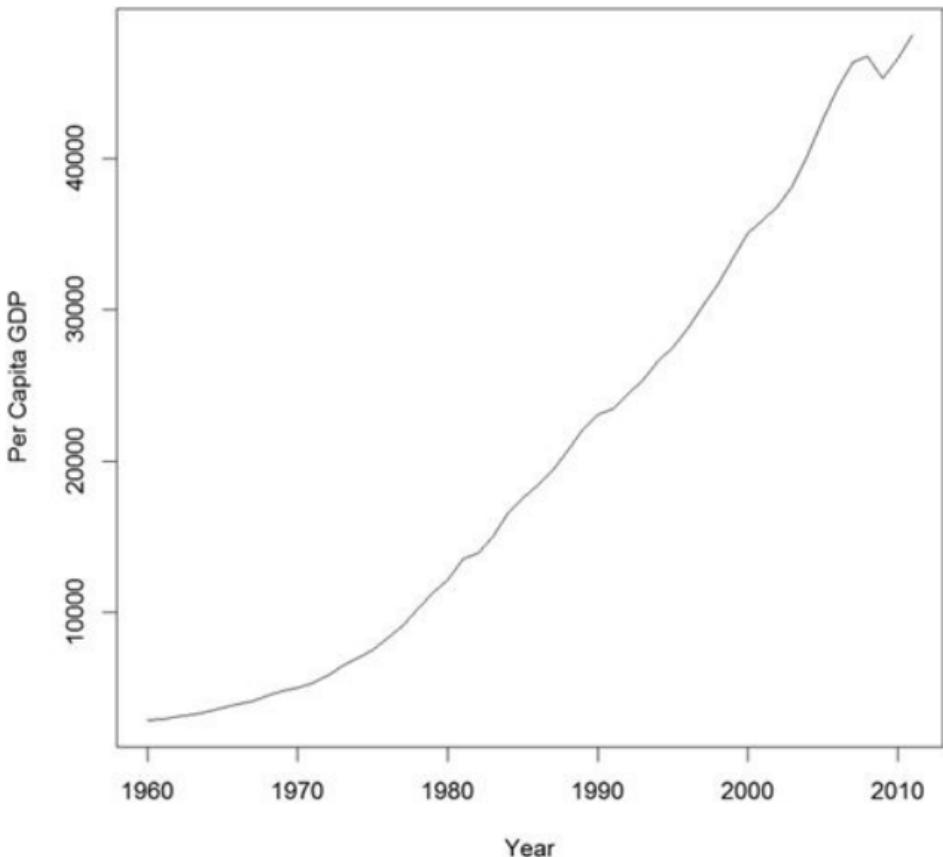
Start = 1960

End = 2011

Frequency = 1

```
[1] 2881.100 2934.553 3107.937 3232.208 3423.396 3664.  
[7] 3972.123 4152.020 4491.424 4802.642 4997.757 5360.  
[13] 5836.224 6461.736 6948.198 7516.680 8297.292 9142.  
[19] 10225.307 11301.682 12179.558 13526.187  
13932.678 15000.086  
[25] 16539.383 17588.810 18427.288 19393.782  
20703.152 22039.227  
[31] 23037.941 23443.263 24411.143 25326.736  
26577.761 27559.167  
[37] 28772.356 30281.636 31687.052 33332.139  
35081.923 35912.333  
[43] 36819.445 38224.739 40292.304 42516.393  
44622.642 46349.115  
[49] 46759.560 45305.052 46611.975 48111.967
```

> **plot**(us, ylab = "Per Capita GDP", xlab = "Year")



**Figure 21.2** Time series plot of U.S. Per Capita GDP.

Another way to assess a time series is to view its autocovariance function (ACF) and partial autocovariance function (PACF). In R this is done with the appropriately named `acf` and `pacf` functions.

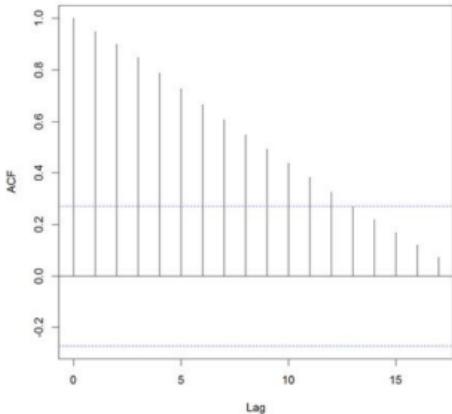
The ACF shows the correlation of a time series with lags of itself. That is, how much the time series is correlated with itself at one lag, at two lags, at three lags and so on.

The PACF is a little more complicated. The autocorrelation at lag one can have lingering effects on the autocorrelation at lag two and onward. The partial autocorrelation is the amount of correlation between a time series and lags of itself that is not explained by a previous lag. So, the partial autocorrelation at lag two is the correlation between the time series and its second lag that is not explained by the first lag.

The ACF and PACF for the U.S. Per Capita GDP data are shown in [Figure 21.3](#). Vertical lines that extend beyond the horizontal line indicate autocorrelations and partial autocorrelations that are significant at those lags.

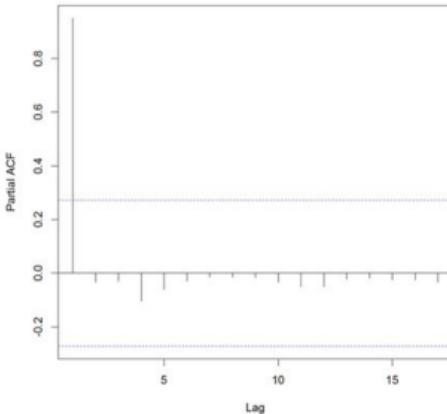
```
> acf(us)  
> pacf(us)
```

Series us



(a) ACF

Series us



(b) PACF

**Figure 21.3** ACF and PACF of U.S. Per Capita GDP. These plots are indicative of a time series that is not stationary.

This time series needs a number of transformations before it can be properly modeled. Its upward trend shows that it is not stationary<sup>1</sup> (the data are in current U.S. dollars, so inflation is not the cause). That can be fixed by differencing the series or applying some other transformation. Differencing is the process of subtracting one observation from another and can be done on any number of observations. For instance, we start with a series

1. Being stationary requires that the mean and variance of a time series are constant for the whole series.

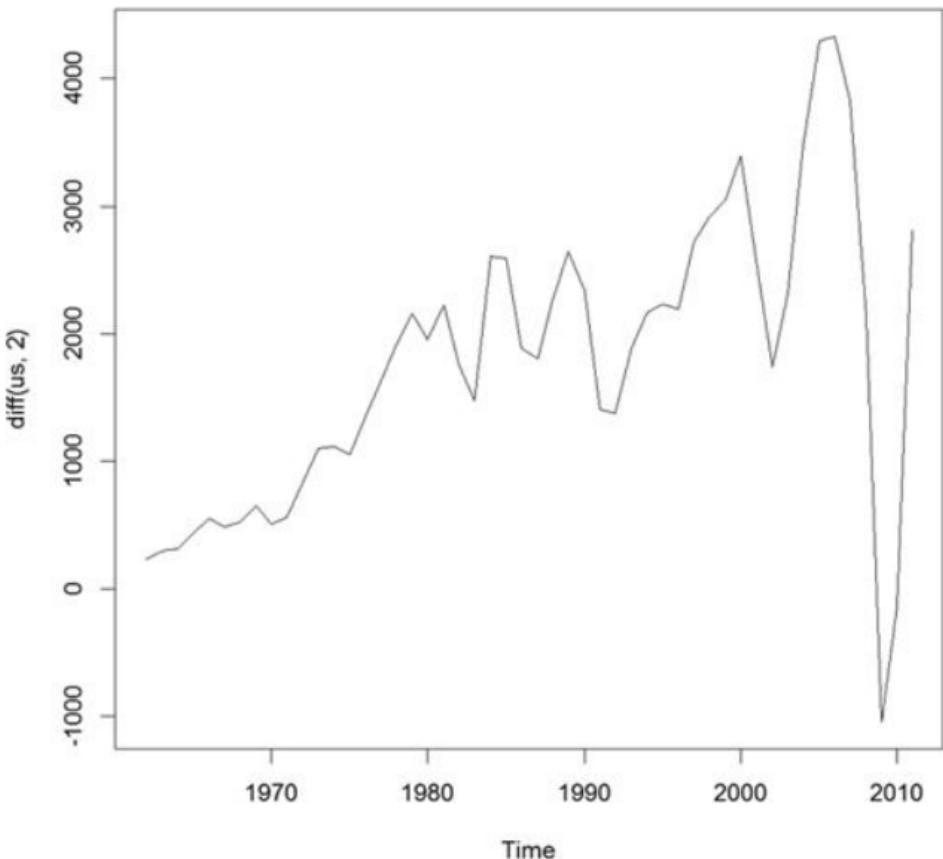
$x = [1 \ 4 \ 8 \ 2 \ 6 \ 6 \ 5 \ 3]$ . Differencing it yields  $x^{(1)} = [3 \ 4 \ -6 \ 4 \ 0 \ -1 \ -2]$ , which is the difference between successive elements. Differencing twice iteratively differs the differents, so  $x^{(2)} = [1 \ -10 \ 10 \ -4 \ -1 \ -1]$ . Observe that for each level of differencing, there is one fewer element in the series. Doing this in R involves the `diff` function. The `differences` argument controls how many differents are iteratively calculated. The `lag` determines which elements get subtracted from each other. A lag of 1 subtracts successive elements, while a lag of 2 subtracts elements that are two indices away from each other.

```
> x <- c(1, 4, 8, 2, 6, 6, 5, 3)
> # one diff
> diff(x, differences = 1)
[1] 3 4 -6 4 0 -1 -2
> # two iterative differents
> diff(x, differences = 2)
[1] 1 -10 10 -4 -1 -1
> # equivalent to one diff
> diff(x, lag = 1)
```

```
[1] 3 4 -6 4 0 -1 -2  
> # diff elements that are two indices apart  
> diff(x, lag = 2)  
[1] 7 -2 -2 4 -1 -3
```

Figuring out the correct number of diffs can be a tiresome process. Fortunately, the forecast package has a number of functions to make working with time series data easier, including determining the optimal number of diffs. The result is shown in [Figure 21.4](#).

```
> require(forecast)  
> ndiffs(x = us)  
[1] 2  
> plot(diff(us, 2))
```



**Figure 21.4** Plot of the U.S. Per Capita GDP diffed twice.

While R offers individual ar and ma functions, a better option is the arima function, which can fit both AR and MA models and the combined ARMA model. It is even more robust in that it can diff the series and fit seasonal effects. Tra-

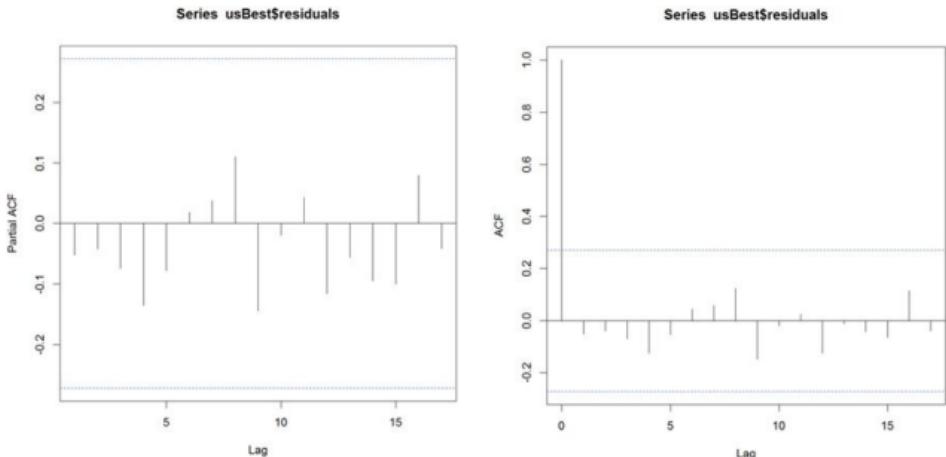
ditionally, the right order of each component of the model is determined by analyzing the ACF and PACF. This can be highly subjective, so fortunately `forecast` contains `auto.arima`, which will figure out the best specification.

```
> usBest <- auto.arima(x = us)
> usBest
Series: us
ARIMA(2,2,1)
Coefficients:
ar1    ar2    ma1
0.4181 -0.2567 -0.8102
s.e. 0.1632  0.1486  0.1111
sigma^2 estimated as 269726: log likelihood=-384.05
AIC=776.1  AICc=776.99  BIC=783.75
```

The function determined that an ARMA(2,1) (an AR(2) component and an MA(1) component) with two diffs is the optimal model based on minimum AICC (that is, AIC that is “corrected” to give a greater penalty to model complexity). The two diffs actually make this an ARIMA model rather than an ARMA model where the I stands for integrated. If this model is a good fit, then the residuals should resemble white noise. [Figure](#)

[21.5](#) shows the ACF and PACF of the residuals for the ideal model. They resemble the pattern for white noise, confirming our model selection.

```
> acf(usBest$residuals)  
> pacf(usBest$residuals)
```



**Figure 21.5** ACF and PACF plots for the residuals of ideal model chosen by `auto.arima`.

The coefficients for an ARIMA model are the AR and MA components.

```
> coef(usBest)  
ar1      ar2      ma1  
0.4181109 -0.2567494 -0.8102419
```

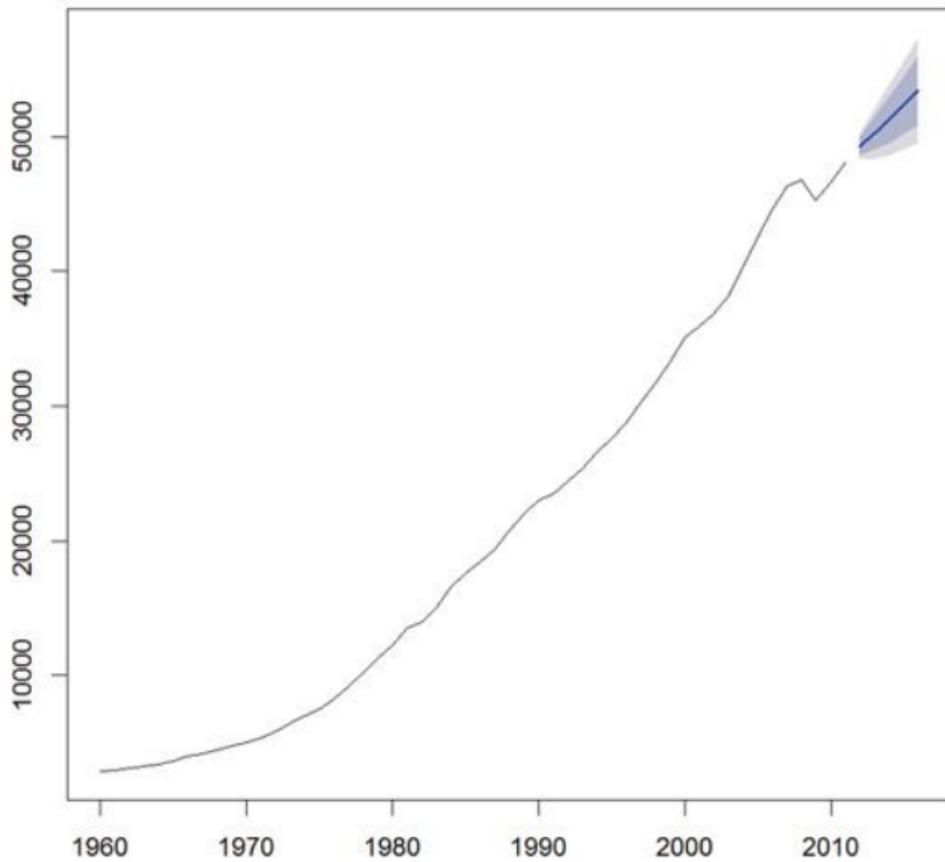
Making predictions based on an ARIMA model is much the same as with any other model type, using the predict function.

```
> # predict 5 years into the future and include the standard error  
> predict(usBest, n.ahead = 5, se.fit = TRUE)  
$pred  
Time Series:  
Start = 2012  
End = 2016  
Frequency = 1  
[1] 49292.41 50289.69 51292.41 52344.45 53415.70  
$se  
Time Series:  
Start = 2012  
End = 2016  
Frequency = 1  
[1] 519.3512 983.3778 1355.0380 1678.3930 2000.3464
```

Visualizing this is easy enough but using the forecast function makes it even easier, as seen in [Figure 21.6](#).

```
> # make a prediction for 5 years out  
> theForecast <- forecast(object = usBest, h = 5)  
> # plot it  
> plot(theForecast)
```

### Forecasts from ARIMA(2,2,1)



**Figure 21.6** Five year prediction of U.S. GDP. The think line is the point estimate and the shaded regions represent the confidence intervals.

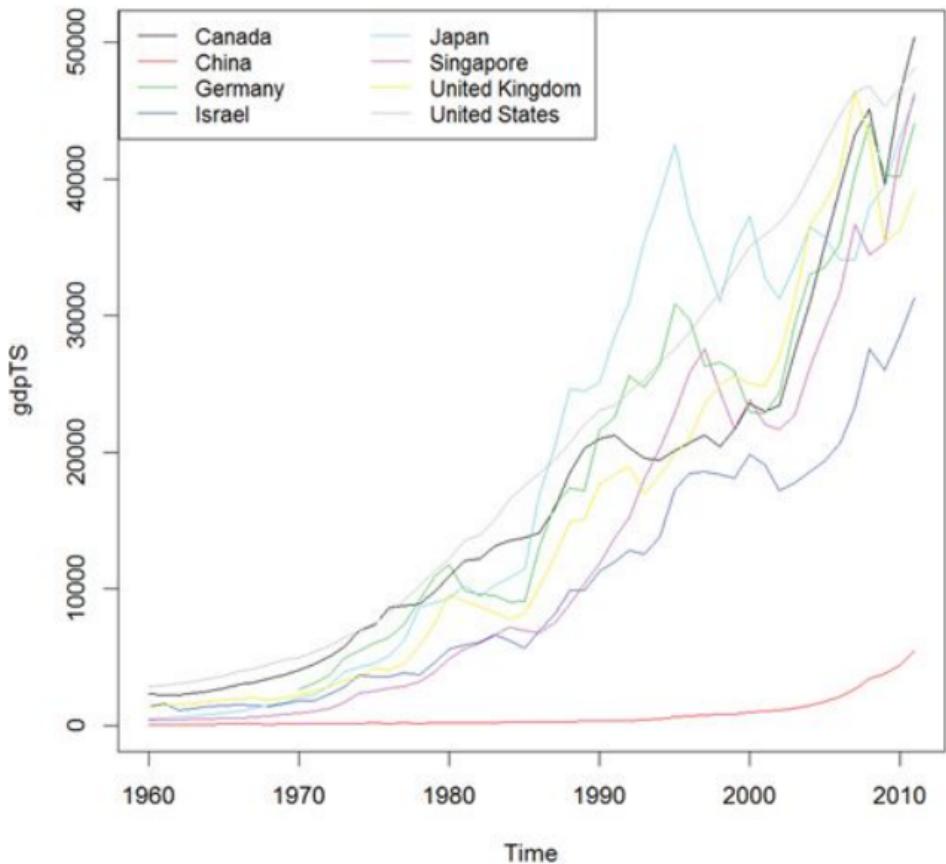
## 21.2. VAR

When dealing with multiple time series where each depends on its own past, others' pasts and others' presents, things get more complicated. The first thing we will do is convert all of the GDP data into a multivariate time series. To do this we first cast the data.frame to wide format then call ts to convert it. The result is shown in [Figure 21.7](#).

```
> # load reshape2  
> require(reshape2)  
> # cast the data.frame to wide format  
  
> gdpCast <- dcast(Year ~ Country,  
+                   data=gdp[, c("Country", "Year", "Per-  
CapGDP")],  
+                   value.var="PerCapGDP")  
> head(gdpCast)  
  
   Year Canada  China Germany Israel Japan Singapore  
1 1960 2294.569 92.01123    NA 1365.683  
478.9953 394.6489  
2 1961 2231.294 75.87257    NA 1595.860  
563.5868 437.9432  
3 1962 2255.230 69.78987    NA 1132.383  
633.6403 429.5377
```

4	1963	2354.839	73.68877	NA	1257.743
	717.8669	472.1830			
5	1964	2529.518	83.93044	NA	1375.943
	835.6573	464.3773			
6	1965	2739.586	97.47010	NA	1429.319
	919.7767	516.2622			
	United Kingdom	United States			
1	1380.306	2881.100			
2	1452.545	2934.553			
3	1513.651	3107.937			
4	1592.614	3232.208			
5	1729.400	3423.396			
6	1850.955	3664.802			

```
> # remove first 10 rows since Germany did not have
>
> # convert to time series
> gdpTS <- ts(data=gdpCast[, -1],
+ start=min(gdpCast$Year),
+ end=max(gdpCast$Year))
>
> # build a plot and legend using base graphics
> plot(gdpTS, plot.type="single", col=1:8)
> legend("topleft", legend=colnames(gdpTS), ncol=2,
+ lty=1,
+ col=1:8, cex=.9)
```



**Figure 21.7** Time series plot of GDP data for all countries in the data. This is the same information as in [Figure 21.1a](#), but this was built using base graphics.

Before proceeding we have to deal with the NAs for Germany. For some reason the World Bank does not have data on Germany's GDP be-

fore 1970. There are other resources, such as the St. Louis Federal Reserve Economic Data (FRED), but their data do not agree well with the World Bank data, so we remove Germany from our data.

```
> gdpTS <- gdpTS[, which(colnames(gdpTS) != "Germany")]
```

The most common way of fitting a model to multiple time series is to use a vector autoregressive (VAR) model. The equation for a VAR is

$$\mathbf{X}_t = \Phi_1 \mathbf{X}_{t-1} + \cdots + \Phi_p \mathbf{X}_{t-p} + \mathbf{Z}_t \quad (21.3)$$

where

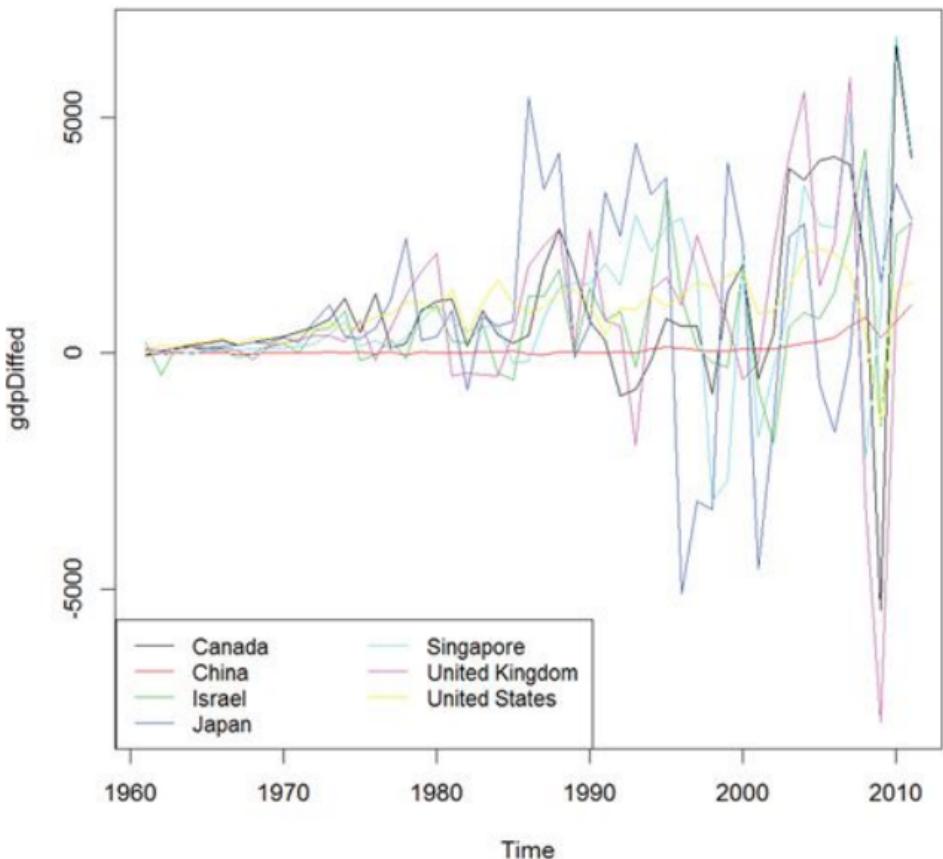
$$\{\mathbf{Z}_t\} \sim \text{WN}(0, \Sigma) \quad (21.4)$$

is white noise.

While `ar` can compute a VAR, it often has problems with singular matrices when the AR order is high, so it is better to use VAR from the `vars` package. To check whether the data should be diffed, we use the `ndiffs` function on `gdpTS` and then apply that number of diffs. The diffed

data are shown in [Figure 21.8](#), which exhibits greater stationarity than [Figure 21.7](#).

```
> numDiffs <- ndiffs(gdpTS)
> numDiffs
[1] 1
> gdpDiffed <- diff(gdpTS, differences=numDiffs)
> plot(gdpDiffed, plot.type="single", col=1:7)
> legend("bottomleft", legend=colnames(gdpDiffed),
  ncol=2, lty=1,
+     col=1:7, cex=.9)
```



**Figure 21.8** Differenced GDP data.

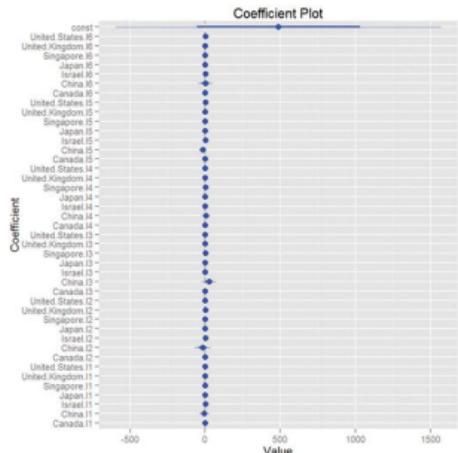
Now that the data are prepared, we can fit a VAR using VAR. This essentially fits a separate regression using  $\text{lm}$  of each time series on the lags of itself and the other series. This is evidenced in the coefficient plot for the Canada and Japan models, shown in [Figure 21.9](#).

```
> require(vars)
> # fit the model

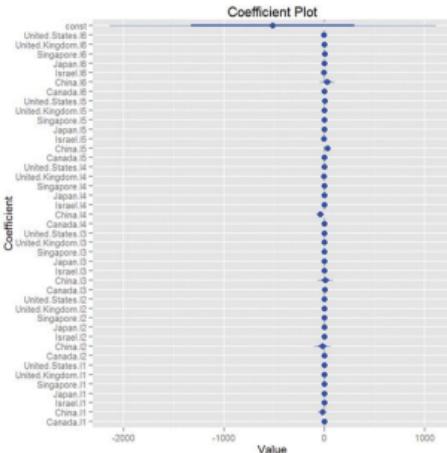
> gdpVar <- VAR(gdpDifffed, lag.max = 12)
> # chosen order
> gdpVar$p
AIC(n)
 6
>
> # names of each of the models
> names(gdpVar$varresult)
[1] "Canada"      "China"       "Israel"
[4] "Japan"        "Singapore"   "United.Kingdom"
[7] "United.States"
>
> # each model is actually an lm object
> class(gdpVar$varresult$Canada)
[1] "lm"
> class(gdpVar$varresult$Japan)
[1] "lm"
>
> # each model has its own coefficients
> head(coef(gdpVar$varresult$Canada))
  Canada.l1  China.l1  Israel.l1
-1.07854513 -7.28241774  1.06538174
  Japan.l1  Singapore.l1 United.Kingdom.l1
-0.45533608 -0.03827402  0.60149182
> head(coef(gdpVar$varresult$Japan))
  Canada.l1  China.l1  Israel.l1
  1.8045012 -19.7904918 -0.1507690
```

Japan.11 Singapore.11 United.Kingdom.11  
1.3344763 1.5738029 0.5707742

```
>  
> require(coefplot)  
> coefplot(gdpVar$varresult$Canada)  
> coefplot(gdpVar$varresult$Japan)
```



(a) Canada



(b) Japan

**Figure 21.9** Coefficient plots for VAR model of GDP data for Canada and Japan.

Predictions for this model are done just like with any other model, using the predict function.

```
> predict(gdpVar, n.ahead = 5)  
$Canada
```

	fcst	lower	upper	CI
[1,]	-12459.46	-13284.63	-11634.30	825.1656
[2,]	15067.05	14106.02	16028.08	961.0344

[3,]	20632.99	19176.30	22089.69	1456.6943
[4,]	-103830.42	-105902.11	-101758.73	2071.6904
[5,]	124483.19	119267.39	129699.00	5215.8046
\$China				
fcst	lower	upper	CI	
[1,]	-470.5917	-523.6101	-417.5733	53.01843
[2,]	899.5380	826.2362	972.8399	73.30188
[3,]	1730.8087	1596.4256	1865.1918	134.38308
[4,]	-3361.7713	-3530.6042	-3192.9384	168.83288
[5,]	2742.1265	2518.9867	2965.2662	223.13974
\$Israel				
fcst	lower	upper	CI	
[1,]	-6686.711	-7817.289	-5556.133	1130.578
[2,]	-39569.216	-40879.912	-38258.520	1310.696
[3,]	62192.139	60146.978	64237.300	2045.161
[4,]	-96325.105	-101259.427	-91390.783	4934.322
[5,]	-12922.005	-24003.839	-1840.171	11081.834
\$Japan				
fcst	lower	upper	CI	
[1,]	-14590.8574	-15826.761	-13354.954	1235.903
[2,]	-52051.5807	-53900.387	-50202.775	1848.806
[3,]	-248.4379	-3247.875	2750.999	2999.437
[4,]	-51465.6686	-55434.880	-47496.457	3969.212
[5,]	-111005.8032	-118885.682	-103125.924	7879.879
\$Singapore				
fcst	lower	upper	CI	
[1,]	-35923.80	-36071.93	-35775.67	148.1312
[2,]	54502.69	53055.85	55949.53	1446.8376
[3,]	-43551.08	-47987.48	-39114.68	4436.3991
[4,]	-99075.95	-107789.86	-90362.04	8713.9078

```
[5,] 145133.22 135155.64 155110.81 9977.5872
```

\$United.Kingdom

fcst	lower	upper	CI
------	-------	-------	----

```
[1,] -19224.96 -20259.35 -18190.56 1034.396
```

```
[2,] 31194.77 30136.87 32252.67 1057.903
```

```
[3,] 27813.08 24593.47 31032.68 3219.604
```

```
[4,] -66506.90 -70690.12 -62323.67 4183.226
```

```
[5,] 93857.98 88550.03 99165.94 5307.958
```

\$United.States

fcst	lower	upper	CI
------	-------	-------	----

```
[1,] -657.2679 -1033.322 -281.2137 376.0542
```

```
[2,] 11088.0517 10614.924 11561.1792 473.1275
```

```
[3,] 2340.6277 1426.120 3255.1350 914.5074
```

```
[4,] -5790.0143 -7013.843 -4566.1855 1223.8288
```

```
[5,] 24306.5309 23013.525 25599.5373 1293.0064
```

## 21.3. GARCH

A problem with ARMA models is that they do not handle extreme events or high volatility well. To overcome this a good tool to use is generalized autoregressive conditional heteroskedasticity or the GARCH family of models, which in addition to modeling the mean of the process also model the variance.

The model for the variance in a GARCH( $m, s$ ) is

$$\epsilon_t = \sigma_t \epsilon_t \quad (21.5)$$

where

$$\sigma_t^2 = \alpha_0 + \alpha_1 \epsilon_{t-1}^2 + \cdots + \alpha_m \epsilon_{t-m}^2 + \beta_1 \sigma_{t-1}^2 + \cdots + \beta_s \sigma_{t-s}^2 \quad (21.6)$$

and

$$\epsilon \sim \text{GWN}(0, 1) \quad (21.7)$$

is generalized white noise.

For this example we download AT&T ticker data using the quantmod package.

```
> require(quantmod)
> load("data/att.rdata")
> require(quantmod)
> att <- getSymbols("T", auto.assign = FALSE)
```

This loads the data into an xts object from the xts package, which is a more robust time series object that, among many other improvements, can handle irregularly spaced events. These objects even have improved plotting over ts, as seen in [Figure 21.10](#).

att



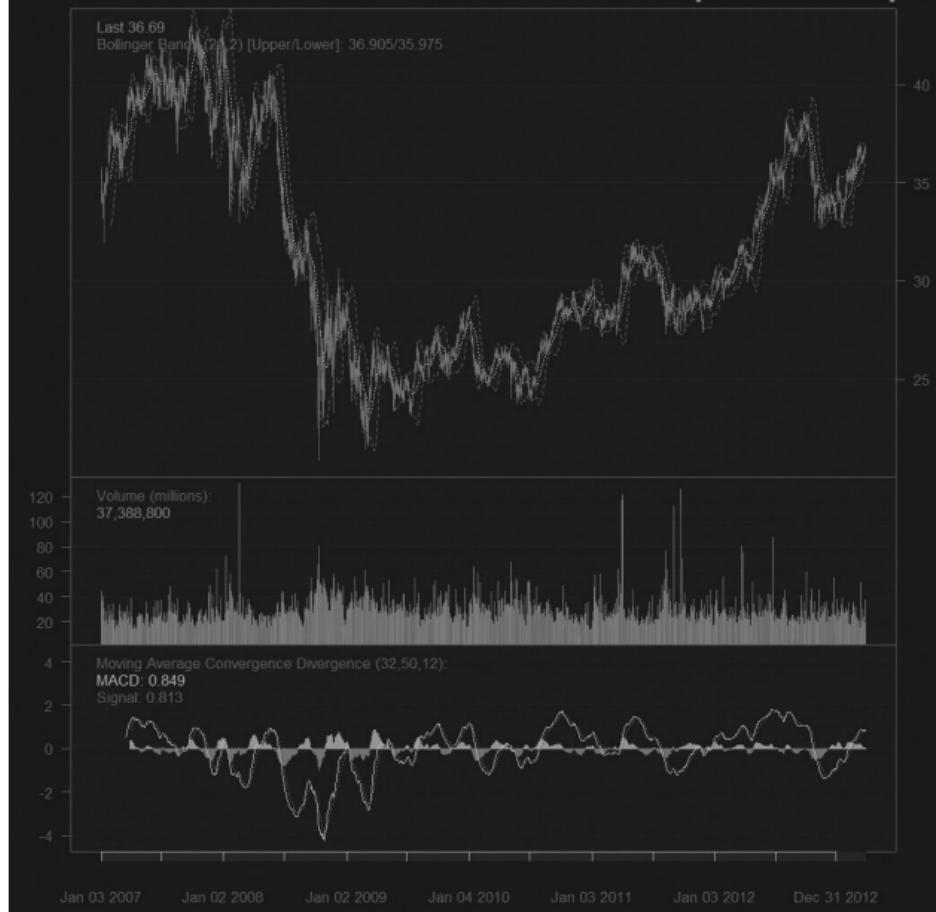
**Figure 21.10** Time series plot of AT&T ticker data.

```
> require(xts)
> # show data
> head(att)
T.Open T.High T.Low T.Close T.Volume T.Adjusted
```

```
2007-01-03 35.67 35.78 34.78 34.95 33694300 25.06
2007-01-04 34.95 35.24 34.07 34.50 44285400 24.74
2007-01-05 34.40 34.54 33.95 33.96 36561800 24.35
2007-01-08 33.40 34.01 33.21 33.81 40237400 24.50
2007-01-09 33.85 34.41 33.66 33.94 40082600 24.59
2007-01-10 34.20 35.00 31.94 34.03 29964300 24.66
> plot(att)
```

For those used to financial terminal charts, the `chartSeries` function should be comforting. It created the chart shown in [Figure 21.11](#).

```
> chartSeries(att)
> addBBands()
> addMACD(32, 50, 12)
```



**Figure 21.11** Series chart for AT&T.

We are only interested in the closing price, so we create a variable holding just that.

```
> attClose <- att$T.Close  
> class(attClose)
```

```
[1] "xts" "zoo"
> head(attClose)
  T.Close
 2007-01-03 34.95
 2007-01-04 34.50
 2007-01-05 33.96
 2007-01-08 33.81
 2007-01-09 33.94
 2007-01-10 34.03
```

The package most widely considered to be the best for fitting GARCH models is rugarch. There are other packages for fitting GARCH models, such as tseries, fGarch and bayesGARCH, but we will focus on rugarch.

Generally, a GARCH(1,1) will be sufficient so we will fit that model to the data. The first step is setting up the model specification using ugarchspec. We specify the volatility to be modeled as a GARCH(1, 1) and the mean to be modeled as an ARMA(1, 1). We also specify that the innovation distribution should be the t distribution.

```
> require(rugarch)
> attSpec <- ugarchspec(variance.model=list(mod-
el="sGARCH",
```

```
+                               garchOrder=c(1, 1)),  
+                               mean.model=list(armaOrder=c(1, 1)),  
+                               distribution.model="std")
```

The next step is to fit the model using ugarchfit.

```
> attGarch <- ugarchfit(spec = attSpec, data = attClose)
```

Printing the model spits out a lot of information, including the coefficients, standard errors, AIC and BIC. Most of this, such as the statistics on residuals, tests, AIC and BIC are diagnostic measures on the quality of the fit. The optimal parameters, seen near the top, are the crux of the model.

```
> attGarch  
*-----*  
*      GARCH Model Fit      *  
*-----*  
Conditional Variance Dynamics  
-----  
GARCH Model : sGARCH(1,1)  
Mean Model : ARFIMA(1,0,1)  
Distribution : std  
Optimal Parameters  
-----
```

	Estimate	Std. Error	t value	Pr(> t )
mu	35.159848	1.328210	26.47160	0.000000
ar1	0.997009	0.001302	765.82269	0.000000
ma1	-0.009937	0.026801	-0.37078	0.710800
omega	0.001335	0.000692	1.92969	0.053645
alpha1	0.069952	0.014968	4.67328	0.000003
beta1	0.925012	0.015400	60.06615	0.000000
shape	7.581676	1.404834	5.39685	0.000000

Robust Standard Errors:

	Estimate	Std. Error	t value	Pr(> t )
mu	35.159848	0.541745	64.9011	0.000000
ar1	0.997009	0.001155	862.8530	0.000000
ma1	-0.009937	0.028813	-0.3449	0.730171
omega	0.001335	0.000795	1.6781	0.093319
alpha1	0.069952	0.018096	3.8657	0.000111
beta1	0.925012	0.018992	48.7047	0.000000
shape	7.581676	1.332371	5.6904	0.000000

LogLikelihood : -776.0355

Information Criteria

Akaike 0.99750

Bayes 1.02139

Shibata 0.99746

Hannan-Quinn 1.00638

Q-Statistics on Standardized Residuals

statistic p-value

Lag[1] 0.5528 0.4572

Lag[p+q+1][3] 3.2738 0.0704

Lag[p+q+5][7] 6.8829 0.2295

d.o.f=2

H0 : No serial correlation

Q-Statistics on Standardized Squared Residuals

---

statistic p-value

Lag[1] 0.005088 0.94314

Lag[p+q+1][3] 3.989786 0.04578

Lag[p+q+5][7] 5.817106 0.32442

d.o.f=2

ARCH LM Tests

---

Statistic DoF P-Value

ARCH Lag[2] 2.229 2 0.3281

ARCH Lag[5] 4.597 5 0.4670

ARCH Lag[10] 9.457 10 0.4893

Nyblom stability test

---

Joint Statistic: 1.5032

Individual Statistics:

mu 0.18923

ar1 0.09786

ma1 0.24465

omega 0.13823

alpha1 0.62782

beta1 0.52974

shape 0.47109

Asymptotic Critical Values (10% 5% 1%)

Joint Statistic: 1.69 1.9 2.35

Individual Statistic: 0.35 0.47 0.75

Sign Bias Test

---

	t-value	prob	sig
Sign Bias	0.8259	0.4090	
Negative Sign Bias	0.8228	0.4108	
Positive Sign Bias	0.3965	0.6918	
Joint Effect	3.0136	0.3895	
Adjusted Pearson Goodness-of-Fit Test:			

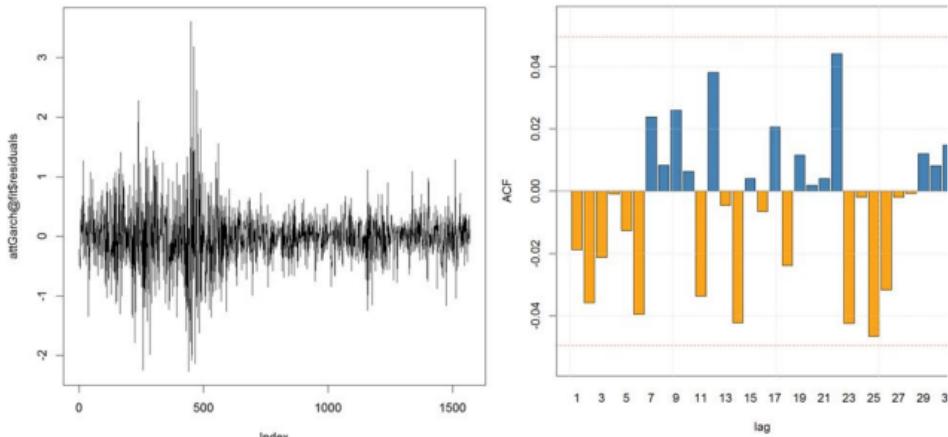
---

group	statistic	p-value(g-1)
1	20	28339 0
2	30	44012 0
3	40	59699 0
4	50	75391 0

Elapsed time : 0.8640492

Figure 21.12 shows a time series plot and the ACF of the residuals from the model.

```
> # attGarch is an S4 object so its slots are accessed by @  
> # the slot fit is a list, so its elements are accessed as usual  
with $  
> plot(attGarch@fit$residuals, type="l")  
> plot(attGarch, which=10)
```



**Figure 21.12** Residual plots from GARCH model on AT&T data.

To judge the quality of this model, we build a few models with different mean specifications—all GARCH(1, 1)—and compare their AICs.

```
> # ARMA(1,1)
> attSpec1 <- ugarchspec(variance.model=list(mod-
el="sGARCH",
+                                     garchOrder=c(1, 1)),
+                                     mean.model=list(armaOrder=c(1, 1)),
+                                     distribution.model="std")
> # ARMA(0,0)
> attSpec2 <- ugarchspec(variance.model=list(mod-
el="sGARCH",
```

```
+ garchOrder=c(1, 1)),  
+ mean.model=list(armaOrder=c(0, 0)),  
+ distribution.model="std")  
> # ARMA(0,2)  
> attSpec3 <- ugarchspec(variance.model=list(mod-  
el="sGARCH",  
+ garchOrder=c(1, 1)),  
+ mean.model=list(armaOrder=c(0, 2)),  
+ distribution.model="std")  
> # ARMA(1,2)  
> attSpec4 <- ugarchspec(variance.model=list(mod-  
el="sGARCH",  
+ garchOrder=c(1, 1)),  
+ mean.model=list(armaOrder=c(1, 2)),  
+ distribution.model="std")  
>  
> attGarch1 <- ugarchfit(spec=attSpec1, data=attClose)  
> attGarch2 <- ugarchfit(spec=attSpec2, data=attClose)  
> attGarch3 <- ugarchfit(spec=attSpec3, data=attClose)  
> attGarch4 <- ugarchfit(spec=attSpec4, data=attClose)  
>  
> infocriteria(attGarch1)  
Akaike    0.9974974  
Bayes     1.0213903  
Shibata   0.9974579  
Hannan-Quinn 1.0063781  
> infocriteria(attGarch2)  
Akaike    5.108533  
Bayes     5.125600  
Shibata   5.108513
```

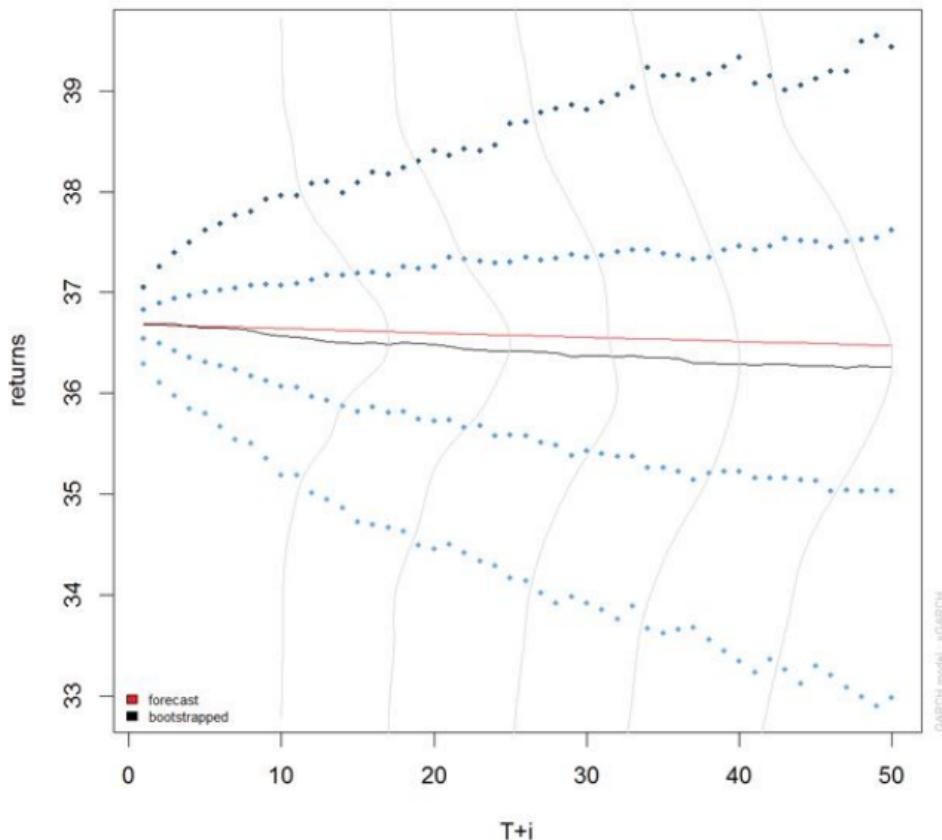
```
Hannan-Quinn 5.114877
> infocriteria(attGarch3)
Akaike    3.406478
Bayes     3.430371
Shibata   3.406438
Hannan-Quinn 3.415359
> infocriteria(attGarch4)
Akaike    0.9963163
Bayes     1.0236224
Shibata   0.9962647
Hannan-Quinn 1.0064656
```

This shows that the first and fourth models were the best, according to AIC and BIC and the other criteria.

Predicting with objects from rugarch is done through the ugarchboot function, which can then be plotted as seen in [Figure 21.13](#).

```
> attPred <- ugarchboot(attGarch, n.ahead=50,
+                         method = c("Partial", "Full")[1])
> plot(attPred, which=2)
```

Series Forecast  
with Bootstrap Error Bands  
(q: 5%, 25%, 75%, 95%)



**Figure 21.13** Predictions for GARCH model on AT&T data.

Because this is stock data, it is worth computing the model on the log returns instead of the actual closing prices.

```
> # diff the logs, drop the first one which is now NA
> attLog <- diff(log(attClose))[-1]
> # build the specification
> attLogSpec <- ugarchspec(variance.model=list(mod-
el="sGARCH",
+ garchOrder=c(1, 1)),
+ mean.model=list(armaOrder=c(1, 1)),
+ distribution.model="std")
> # fit the model
> attLogGarch <- ugarchfit(spec=attLogSpec, data=at-
tLog)
> infocriteria(attLogGarch)
Akaike    -5.870043
Bayes     -5.846138
Shibata   -5.870083
Hannan-Quinn -5.861158
```

This led to a significant drop in AIC.

It is important to remember that the purpose of GARCH models is not to fit the signal better but to capture the volatility better.

## 21.4. Conclusion

Time series play a crucial role in many fields, particularly finance and some physical sciences. The basic building block in R for time series is the `ts` object, which has been greatly extended by the `xts` object. The most common types of models are ARMA, VAR and GARCH, which are fitted by the `arima`, `VAR` and `ugarchfit` functions, respectively.

# Chapter 22. Clustering

Clustering, which plays a big role in modern machine learning, is the partitioning of data into groups. This can be done in a number of ways, the two most popular being K-means and hierarchical clustering. In terms of a `data.frame`, a clustering algorithm finds out which rows are similar to each other. Rows that are grouped together are supposed to have high similarity to each other and low similarity with rows outside the grouping.

## 22.1. K-means

One of the more popular algorithms for clustering is K-means. It divides the observations into discrete groups based on some distance metric. For this example, we use the wine dataset from the University of California–Irvine Machine Learning Repository, available at <http://archive.ics.uci.edu/ml/datasets/Wine>.

```
> wine <- read.table("data/wine.csv", header = TRUE, sep  
= ",")  
> head(wine)  
 Cultivar Alcohol Malic.acid Ash Alcalinity.of.ash Mag-  
nesium  
 1   1 14.23    1.71 2.43      15.6    127  
 2   1 13.20    1.78 2.14      11.2    100  
 3   1 13.16    2.36 2.67      18.6    101  
 4   1 14.37    1.95 2.50      16.8    113  
 5   1 13.24    2.59 2.87      21.0    118  
 6   1 14.20    1.76 2.45      15.2    112  
 Total.phenols Flavanoids Nonflavanoid.phenols Proantho-  
cyanins  
 1     2.80    3.06      0.28    2.29  
 2     2.65    2.76      0.26    1.28  
 3     2.80    3.24      0.30    2.81  
 4     3.85    3.49      0.24    2.18  
 5     2.80    2.69      0.39    1.82  
 6     3.27    3.39      0.34    1.97  
 Color.intensity Hue OD280.OD315.of.diluted.wines  
Proline  
 1     5.64 1.04      3.92    1065  
 2     4.38 1.05      3.40    1050  
 3     5.68 1.03      3.17    1185  
 4     7.80 0.86      3.45    1480  
 5     4.32 1.04      2.93    735  
 6     6.75 1.05      2.85    1450
```

Because the first column is the cultivar, and that might be too correlated with group membership, we exclude that from the analysis.

```
> wineTrain <- wine[, which(names(wine) != "Cultivar")]
```

For K-means we need to specify the number of clusters, and then the algorithm assigns observations into that many clusters. There are heuristic rules for determining the number of clusters, which we will get to later. In R, K-means is done with the aptly named kmeans function. Its first two arguments are the data to be clustered, which must be all numeric (K-means does not work with categorical data), and the number of centers (clusters). Because there is a random component to the clustering, we set the seed to generate reproducible results.

```
> set.seed(278613)  
> wineK3 <- kmeans(x = wineTrain, centers = 3)
```

Printing the K-means objects displays the size of the clusters, the cluster mean for each column,

the cluster membership for each row and similarity measures.

> wineK3

K-means clustering with 3 clusters of sizes 62, 47, 69

## Cluster means:

Alcohol Malic.acid Ash Alcalinity.of.ash Magnesi-  
um

1 12.92984 2.504032 2.408065 19.89032  
103.59677

2 13.80447 1.883404 2.426170 17.02340  
105.51064

3 12.51667 2.494203  
2.288551 20.82319 92.34783

## Total phenols Flavanoids Nonflavanoid phenols Proanthocyanins

1 2.111129 1.584032 0.3883871 1.503387

2	2.867234	3.014255	0.2853191	1.910426
3	2.070725	1.758406	0.3901449	1.451884

### Color.intensity      Hue

OD280, OD315 of diluted wines Proline

1 565032308839677 23654847283387

2 5.702553 1.0782979 3.114043 1195.148

3 4 086957 0 9411594 2 490725 458 2319

### Clustering vector:

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

[33] 2 2 2 1 1 2 2 1 1 2 2 1 1 2 2 2 2 2 2 2 2 2 2 2 2 3 1  
3 1 3

```
[65] 3 1 3 3 1 1 1 3 3 2 1 3 3 3 1 3 3 1 1 3 3 3 1 1 3 3 3
```

```
3 3 1
```

```
[97] 1 3 1 3 1 3 3 3 1 3 3 3 3 1 3 3 1 3 3 3 3 3 1 3 3 3 3
```

```
3 3 3
```

```
[129] 3 3 1 3 3 1 1 1 1 3 3 3 1 1 3 3 1 1 3 1 1 3 3 3 3 1 1 1 3
```

```
1 1 1
```

```
[161] 3 1 3 1 1 3 1 1 1 1 3 3 1 1 1 1 1 1 3
```

Within cluster sum of squares by cluster:

```
[1] 566572.5 1360950.5 443166.7
```

(between\_SS / total\_SS = 86.5 %)

Available components:

```
[1] "cluster"    "centers"    "totss"      "withinss"
```

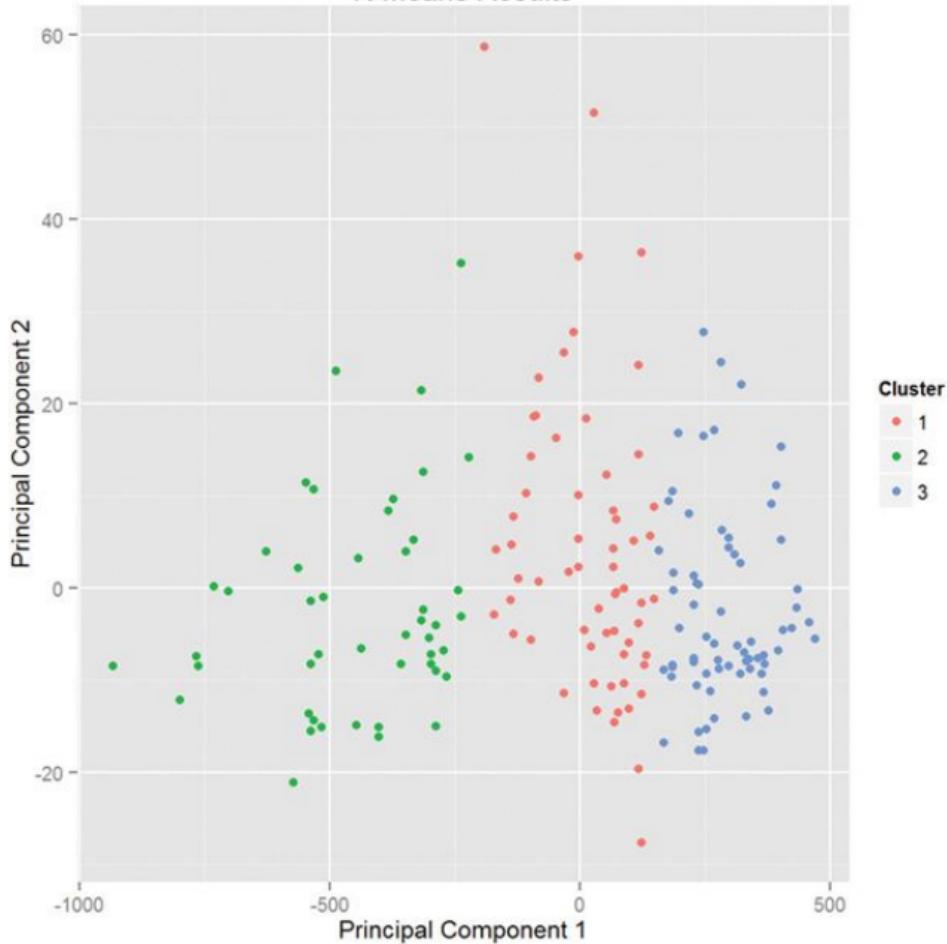
```
[5] "tot.withinss" "betweenss"  "size"
```

Plotting the result of K-means clustering can be difficult because of the high dimensional nature of the data. To overcome this, the `plot.kmeans` function in `useful` performs multidimensional scaling to project the data into two dimensions, and then color codes the points according to cluster membership. This is seen in [Figure 22.1](#).

```
> require(useful)
```

```
> plot(wineK3, data = wineTrain)
```

### K-Means Results



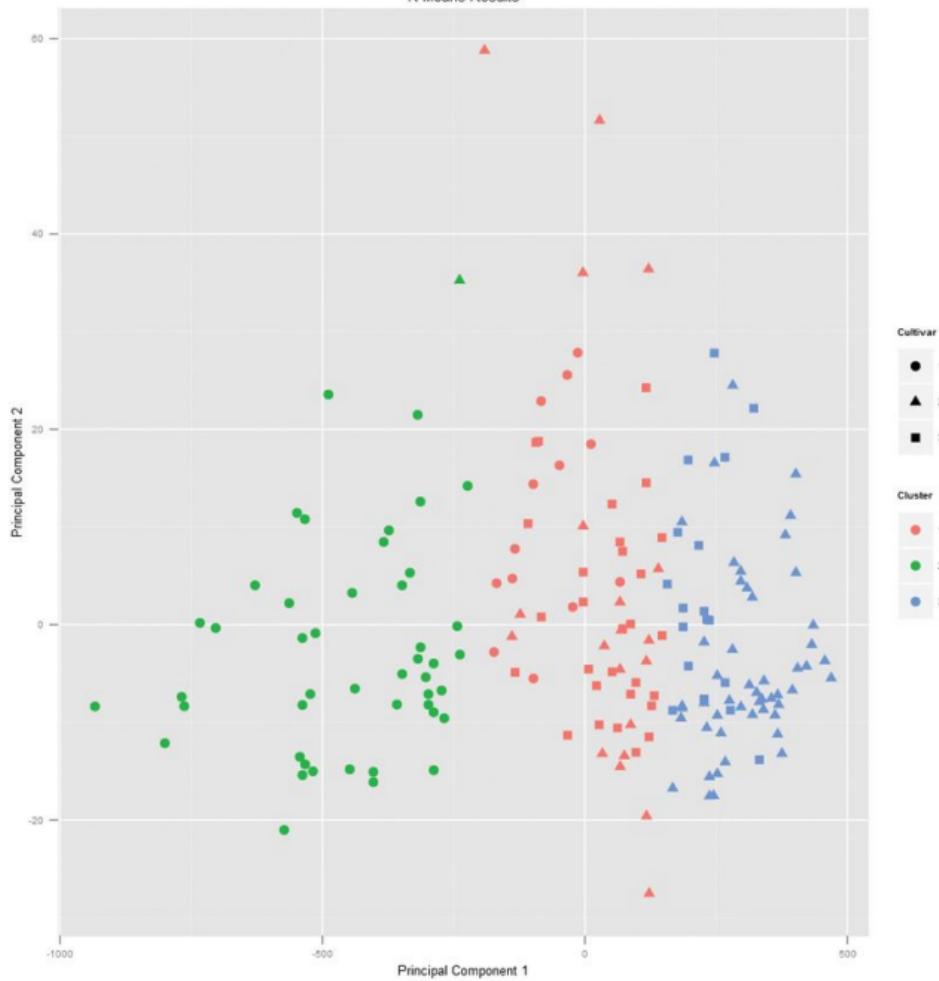
**Figure 22.1** Plot of wine data scaled into two dimensions and color coded by results of K-means clustering.

If we pass the original wine data and specify that Cultivar is the true membership column, the

shape of the points will be coded by Cultivar, so we can see how that compares to the colors in [Figure 22.2](#). A strong correlation between the color and shape would indicate a good clustering.

```
> plot(wineK3, data = wine, class = "Cultivar")
```

K-Means Results



**Figure 22.2** Plot of wine data scaled into two dimensions and color coded by results of K-means clustering. The shapes indicate the cultivar. A strong correlation between the color and shape would indicate a good clustering.

K-means can be subject to random starting conditions, so it is considered good practice to run it with a number of random starts. This is accomplished with the nstart argument.

```
> set.seed(278613)
> wineK3N25 <- kmeans(wineTrain, centers = 3, nstart =
25)
> # see the cluster sizes with 1 start
> wineK3$size
[1] 62 47 69
> # see the cluster sizes with 25 starts
> wineK3N25$size
[1] 62 47 69
```

For our data the results did not change. For other datasets the number of starts can have a significant impact.

Choosing the right number of clusters is important in getting a good partitioning of the data. According to David Madigan, the chair of the Department of Statistics, Columbia University, a good metric for determining the optimal number of clusters is Hartigan's Rule ( J. A. Hartigan is one of the authors of the most popular K-means algorithm). It essentially compares the ratio of the within-cluster sum of squares for a clustering with  $k$  clusters and one with  $k + 1$  clusters, accounting for the number of rows and clusters.

If that number is greater than 10, then it is worth using  $k + 1$  clusters. Fitting this repeatedly can be a chore and computationally inefficient if not done right. The useful package has the FitKMeans function for doing just that. The results are plotted in [Figure 22.3](#).

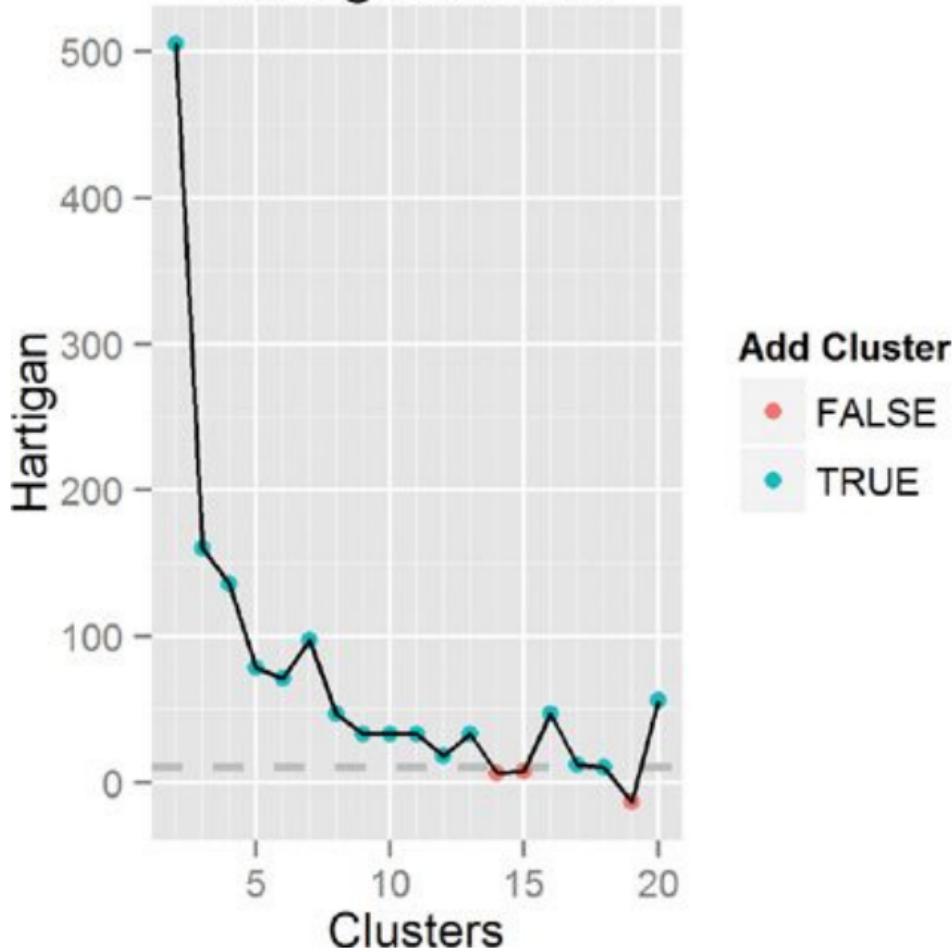
```
> wineBest <- FitKMeans(wineTrain, max.clusters=20,  
nstart=25,  
+ seed=278613)  
> wineBest
```

Clusters Hartigan AddCluster

1	2	505.429310	TRUE
2	3	160.411331	TRUE
3	4	135.707228	TRUE
4	5	78.445289	TRUE
5	6	71.489710	TRUE
6	7	97.582072	TRUE
7	8	46.772501	TRUE
8	9	33.198650	TRUE
9	10	33.277952	TRUE
10	11	33.465424	TRUE
11	12	17.940296	TRUE
12	13	33.268151	TRUE
13	14	6.434996	FALSE
14	15	7.833562	FALSE
15	16	46.783444	TRUE
16	17	12.229408	TRUE
17	18	10.261821	TRUE
18	19	-13.576343	FALSE
19	20	56.373939	TRUE

> **PlotHartigan**(wineBest)

## Hartigan's Rule

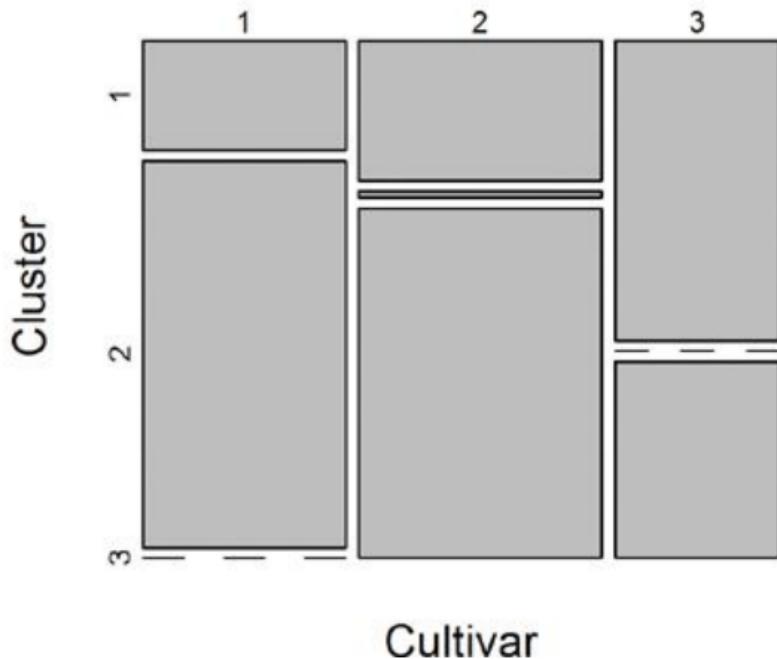


**Figure 22.3** Plot of Hartigan's Rule for a series of different cluster sizes.

According to this metric we should use 13 clusters. Again, this is just a rule of thumb and

should not be strictly adhered to. Because we know there are three cultivars it would seem natural to choose three clusters. Then again, the results of the clustering with three clusters did only a fairly good job of aligning the clusters with the cultivars, so it might not be that good of a fit. [Figure 22.4](#) shows the cluster assignment going down the left side and the cultivar across the top. Cultivar 1 is mostly alone in its own cluster, and cultivar 2 is just a little worse, while cultivar 3 is not clustered well at all. If this were truly a good fit, the diagonals would be the largest segments.

# Confusion Matrix for Wine Clustering



**Figure 22.4** Confusion matrix for clustering of wine data by cultivars.

```
> table(wine$Cultivar, wineK3N25$cluster)
  1 2 3
1 13 46 0
2 20 1 50
3 29 0 19
> plot(table(wine$Cultivar, wineK3N25$cluster),
+      main="Confusion Matrix for Wine Clustering",
+      xlab="Cultivar", ylab="Cluster")
```

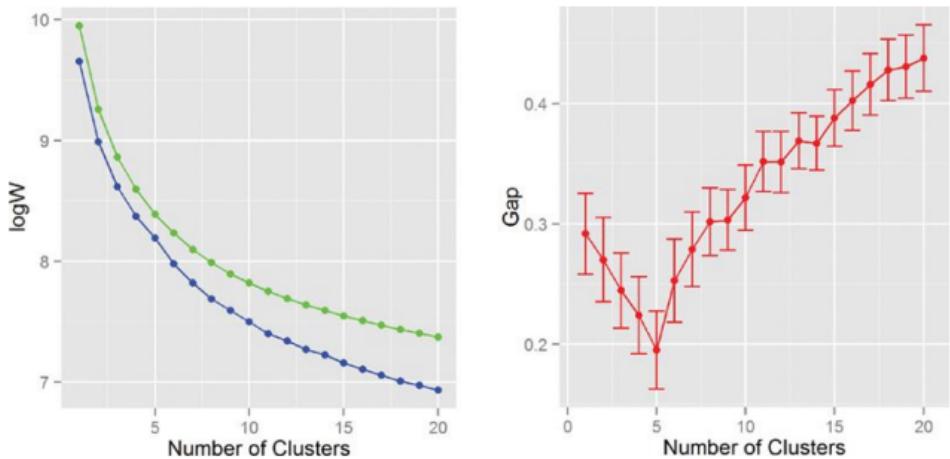
An alternative to Hartigan's Rule is the Gap statistic, which compares the within-cluster dissimilarity for a clustering of the data with that of a bootstrapped sample of data. It is measuring the gap between reality and expectation. This can be calculated (for numeric data only) using clusGap in cluster. It takes a bit of time to run because it is doing a lot of simulations.

```
> require(cluster)
> theGap <- clusGap(wineTrain, FUNcluster = pam,
K.max = 20)
> gapDF <- as.data.frame(theGap$Tab)
> gapDF
```

	logW	E.logW	gap	SE.sim
1	9.655294	9.947093	0.2917988	0.03367473
2	8.987942	9.258169	0.2702262	0.03498740
3	8.617563	8.862178	0.2446152	0.03117947
4	8.370194	8.594228	0.2240346	0.03193258
5	8.193144	8.388382	0.1952376	0.03243527
6	7.979259	8.232036	0.2527773	0.03456908
7	7.819287	8.098214	0.2789276	0.03089973
8	7.685612	7.987350	0.3017378	0.02825189
9	7.591487	7.894791	0.3033035	0.02505585
10	7.496676	7.818529	0.3218525	0.02707628
11	7.398811	7.750513	0.3517019	0.02492806
12	7.340516	7.691724	0.3512081	0.02529801

13	7.269456	7.638362	0.3689066	0.02329920
14	7.224292	7.591250	0.3669578	0.02248816
15	7.157981	7.545987	0.3880061	0.02352986
16	7.104300	7.506623	0.4023225	0.02451914
17	7.054116	7.469984	0.4158683	0.02541277
18	7.006179	7.433963	0.4277835	0.02542758
19	6.971455	7.401962	0.4305071	0.02616872
20	6.932463	7.369970	0.4375070	0.02761156

Figure 22.5 shows the Gap statistic for a number of different clusters. The optimal number of clusters is the smallest number producing a gap within one standard deviation of the number of clusters that minimizes the gap.



**Figure 22.5** Gap curves for wine data. The blue curve is the observed within-cluster dissimilarity, and the green curve is the expected within-cluster dissimilarity. The red curve represents the Gap statistic (expected-observed) and the error bars are the standard deviation of the gap.

```

> # logW curves
> ggplot(gapDF, aes(x=1:nrow(gapDF))) +
+   geom_line(aes(y=logW), color="blue") +
+   geom_point(aes(y=logW), color="blue") +
+   geom_line(aes(y=E.logW), color="green") +
+   geom_point(aes(y=E.logW), color="green") +
+   labs(x="Number of Clusters")
>
> # gap curve

```

```
> ggplot(gapDF, aes(x=1:nrow(gapDF))) +  
+   geom_line(aes(y=gap), color="red") +  
+   geom_point(aes(y=gap), color="red") +  
+   geom_errorbar(aes(ymin=gap-SE.sim,  
+                      ymax=gap+SE.sim), color="red") +  
+   labs(x="Number of Clusters", y="Gap")
```

## 22.2. PAM

Two problems with K-means clustering are that it does not work with categorical data and it is susceptible to outliers. An alternative is K-medoids. Instead of the center of a cluster being the mean of the cluster, the center is one of the actual observations in the cluster. This is akin to the median, which is likewise robust against outliers.

The most common K-medoids algorithm is Partitioning Around Medoids (PAM). The cluster package contains the pam function. For this example, we look at some data from the World Bank, including both numerical measures such as GDP and categorical information such as region and income level.

Now we use the country codes to download a number of indicators from the World Bank using WDI.

```
> indicators <- c("BX.KLT.DINV.WD.GD.ZS",
+ "NY.GDP.DEFL.KD.ZG",
+ "NY.GDP.MKTP.CD",
+ "NY.GDP.MKTP.KD.ZG",
+ "NY.GDP.PCAP.CD",
+ "NY.GDP.PCAP.KD.ZG",
+ "TG.VAL.TOTL.GD.ZS")
> require(WDI)
>
> # pull info on these indicators for all countries in our list
> # not all countries have information for every indicator
> # some countries do not have any data
> wbInfo <- WDI(country="all", indicator=indicators,
+ start=2011,
+ end=2011, extra=TRUE)
> # get rid of aggregated info
> wbInfo <- wbInfo[wbInfo$region != "Aggregates", ]
> # get rid of countries where all the indicators are NA
> wbInfo <- wbInfo[which(rowSums(!is.na(wbInfo[, indicators])) > 0), ]
> # get rid of any rows where the iso is missing
> wbInfo <- wbInfo[!is.na(wbInfo$iso2c), ]
```

The data have a few missing values, but fortunately pam handles missing values well. Before

we run the clustering algorithm we clean up the data some more, using the country names as the row names of the data.frame and ensuring the categorical variables are factors with the proper levels.

```
> # set rownames so we can know the country without us-  
  ing that for  
> # clustering  
> rownames(wbInfo) <- wbInfo$iso2c  
> # refactorize region, income and lending to account for  
  any changes  
> # in the levels  
> wbInfo$region <- factor(wbInfo$region)  
> wbInfo$income <- factor(wbInfo$income)  
> wbInfo$lending <- factor(wbInfo$lending)
```

Now we fit the clustering using pam from the cluster package. [Figure 22.6](#) shows a silhouette plot of the results. Each line represents an observation, and each grouping of lines is a cluster. Observations that fit the cluster well have large positive lines and observations that do not fit well have small or negative lines. A bigger average width for a cluster means a better clustering.

```

> # find which columns to keep
> # not those in this vector
> keep.cols <- which(!names(wbInfo) %in% c("iso2c",
"country", "year",
+
"capital", "iso3c")))
> # fit the clustering
> wbPam <- pam(x=wbInfo[, keep.cols], k=12,
keep.diss=TRUE,
+
keep.data=TRUE)
>
> # show the medoid observations
> wbPam$medoids
 BX.KLT.DINV.WD.GD.ZS NY.GDP.DEFL.KD.ZG
NY.GDP.MKTP.CD
PT      5.507851973    0.6601427  2.373736e+11
HT      2.463873387    6.7745103  7.346157e+09
BY      7.259657119    58.3675854  5.513208e+10
BE      19.857364384   2.0299163  5.136611e+11
MX      1.765034004    5.5580395  1.153343e+12
GB      1.157530889    2.6028860  2.445408e+12
IN      1.741905033    7.9938177  1.847977e+12
CN      3.008038634    7.7539567  7.318499e+12
DE      1.084936891    0.8084950  3.600833e+12
NL      1.660830419    1.2428287  8.360736e+11
JP      0.001347863   -2.1202280  5.867154e+12
US      1.717849686    2.2283033  1.499130e+13
NY.GDP.MKTP.KD.ZG NY.GDP.PCAP.CD
NY.GDP.PCAP.KD.ZG
PT      -1.6688187    22315.8420   -1.66562016
HT      5.5903433     725.6333    4.22882080

```

BY	5.3000000	5819.9177	5.48896865
BE	1.7839242	46662.5283	0.74634396
MX	3.9106137	10047.1252	2.67022734
GB	0.7583280	39038.4583	0.09938161
IN	6.8559233	1488.5129	5.40325582
CN	9.3000000	5444.7853	8.78729922
DE	3.0288866	44059.8259	3.09309213
NL	0.9925175	50076.2824	0.50493944
JP	-0.7000000	45902.6716	-0.98497734
US	1.7000000	48111.9669	0.96816270

TG.VAL.TOTL.GD.ZS region longitude latitude income  
lending

PT	58.63188	2	-9.135520	38.7072	2	4
HT	49.82197	3	-72.328800	18.5392	3	3
BY	156.27254	2	27.576600	53.9678	6	2
BE	182.42266	2	4.367610	50.8371	2	4
MX	61.62462	3	-99.127600	19.4270	6	2
GB	45.37562	2	-0.126236	51.5002	2	4
IN	40.45037	6	77.225000	28.6353	4	1
CN	49.76509	1	116.286000	40.0495	6	2
DE	75.75581	2	13.411500	52.5235	2	4
NL	150.41895	2	4.890950	52.3738	2	4
JP	28.58185	1	139.770000	35.6700	2	4
US	24.98827	5	-77.032000	38.8895	2	4

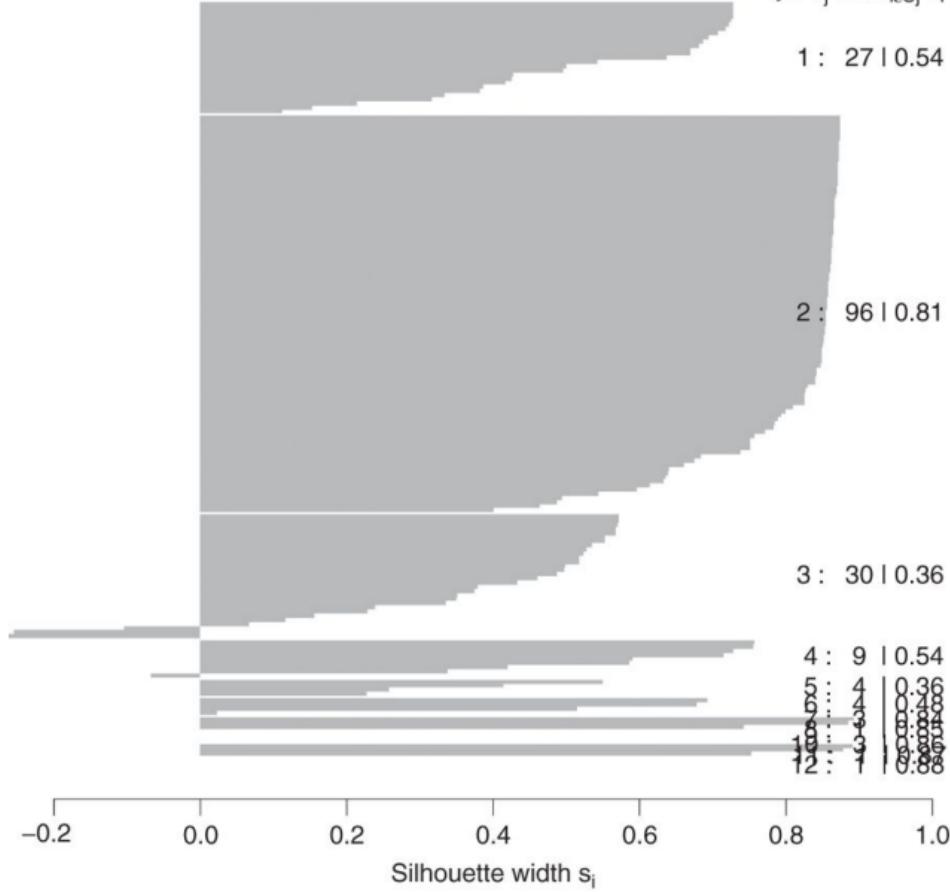
>

> # make a silhouette plot

> **plot**(wbPam, which.plots=2, main="")

$n=180$

12 clusters  $C_j$   
 $j : n_j | \text{ave}_{i \in C_j} s_i$



Average silhouette width : 0.65

**Figure 22.6** Silhouette plot for country clustering. Each line represents an observation, and each grouping of lines is a cluster.

Observations that fit the cluster well have large positive lines and observations that do not fit well have small or negative lines. A bigger average width for a cluster means a better clustering.

Because we are dealing with country level information, it would be informative to view the clustering on a world map. As we are working with World Bank data, we will use the World Bank shapefile of the world available at <http://maps.worldbank.org/overlays/2712>. It can be downloaded in a browser as any other file or using R. While this is slower than using a browser, it can be nice if we have to programmatically download many files.

```
> download.file(url="http://maps.worldbank.org/overlays/  
2712.zip",  
+ destfile="data/worldmap.zip", method="curl")
```

The file needs to be unzipped, which can be done through the operating system or in R.

```
> unzip(zipfile = "data/worldmap.zip", exdir = "data")
```

Of the four files, we only need to worry about the one ending in .shp because R will handle the rest. We read it in using `readShapeSpatial` from `maptools`.

	name	CntryName	FipsCntry
0	Fips Cntry:	Aruba	AA
1	Fips Cntry:	Antigua & Barbuda	AC
2	Fips Cntry:	United Arab Emirates	AE
3	Fips Cntry:	Afghanistan	AF
4	Fips Cntry:	Algeria	AG
5	Fips Cntry:	Azerbaijan	AJ

```
> require(maptools)
> world <- readShapeSpatial(
+   "data/
world_country_admin_boundary_shapefile_with_fips_codes.shp"
+ )
> head(world@data)
```

There are some blatant discrepancies between the two-digit code in the World Bank shapefile and the two-digit code in the World Bank data

pulled using WDI. Notably, Austria should be “AT,” Australia “AU,” Myanmar (Burma) “MM,” Vietnam “VN” and so on.

```
> require(plyr)
> world@data$FipsCntry <- as.character(
+   revalue(world@data$FipsCntry,
+         replace=c(AU="AT", AS="AU", VM="VN",
+ BM="MM", SP="ES",
+         PO="PT", IC="IL", SF="ZA", TU="TR",
+ IZ="IQ",
+         UK="GB", EI="IE", SU="SD",
+ MA="MG", MO="MA",
+         JA="JP", SW="SE", SN="SG"))
+   )
```

In order to use ggplot2 we need to convert this shapefile object into a data.frame, which requires a few steps.

```
> # make an id column using the rownames
> world@data$id <- rownames(world@data)
> # fortify it, this is a special ggplot2 function that converts
> # shapefiles to data.frames
> require(ggplot2)
> require(rgeos)
> world.df <- fortify(world, region = "id")
> head(world.df)
  long    lat order hole piece group id
1  10.4 52.3     1 FALSE    1    1  1
2  10.4 52.3     2 FALSE    1    1  1
3  10.4 52.3     3 FALSE    1    1  1
4  10.4 52.3     4 FALSE    1    1  1
5  10.4 52.3     5 FALSE    1    1  1
```

1	-69.88223	12.41111	1	FALSE	1	0.1	0
2	-69.94695	12.43667	2	FALSE	1	0.1	0
3	-70.05904	12.54021	3	FALSE	1	0.1	0
4	-70.05966	12.62778	4	FALSE	1	0.1	0
5	-70.03320	12.61833	5	FALSE	1	0.1	0
6	-69.93224	12.52806	6	FALSE	1	0.1	0

Before we can join this to the clustering, we need to join FipsCntry back into world.df.

```
> world.df <- join(world.df,
+                     world@data[, c("id", "CntryName",
+ "FipsCntry")],
+                     by="id")
> head(world.df)
  long    lat order hole piece group id CntryName
FipsCntry
1 -69.88223 12.41111   1
FALSE  1 0.1 0 Aruba     AA
2 -69.94695 12.43667   2
FALSE  1 0.1 0 Aruba     AA
3 -70.05904 12.54021   3
FALSE  1 0.1 0 Aruba     AA
4 -70.05966 12.62778   4
FALSE  1 0.1 0 Aruba     AA
5 -70.03320 12.61833   5
FALSE  1 0.1 0 Aruba     AA
6 -69.93224 12.52806   6
FALSE  1 0.1 0 Aruba     AA
```

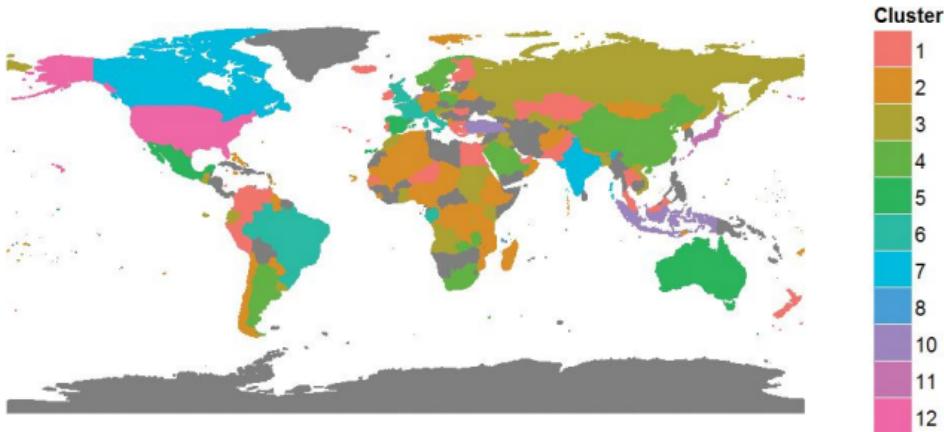
Now we can take the steps of joining in data from the clustering and the original World Bank data.

```
> clusterMembership <-  
  data.frame(FipsCntry=names(wbPam$clustering),  
  +             Cluster=wbPam$clustering,  
  +             stringsAsFactors=FALSE)  
> head(clusterMembership)  
   FipsCntry Cluster  
1 AE          AE      1  
2 AF          AF      2  
3 AG          AG      2  
4 AL          AL      2  
5 AM          AM      2  
6 AO          AO      3  
> world.df <- join(world.df, clusterMembership,  
+ by="FipsCntry")  
> world.df$Cluster <- as.character(world.df$Cluster)  
> world.df$Cluster <- factor(world.df$Cluster,  
+ levels=1:12)  
> 1  
[1] 1
```

Building the plot itself requires a number of ggplot2 commands to format it correctly. [Figure 22.7](#) shows the map, color coded by cluster membership; the gray countries either do not have

World Bank information or were not properly matched up between the two datasets.

```
> ggplot() +  
+   geom_polygon(data=world.df, aes(x=long, y=lat,  
group=group,  
+           fill=Cluster, color=Cluster)) +  
+   labs(x=NULL, y=NULL) + coord_equal() +  
+   theme(panel.grid.major=element_blank(),  
+         panel.grid.minor=element_blank(),  
+         axis.text.x=element_blank(), axis.text.y=ele-  
ment_blank(),  
+         axis.ticks=element_blank(), pan-  
el.background=element_blank())
```



**Figure 22.7** Map of PAM clustering of World Bank data. Gray countries either do not have World Bank information or were not properly matched up between the two datasets.

Much like with K-means, the number of clusters in a K-medoids clustering must be specified. Something similar to Hartigan's Rule can be built using the dissimilarity information returned by pam.

```
> wbPam$clusinfo  
    size   max_diss   av_diss   diameter separation  
[1,] 27 122871463849 46185193372 200539326122  
1.967640e+10
```

[2,] 96 22901202940 7270137217 31951289020  
3.373324e+09

[3,] 30 84897264072 21252371506 106408660458  
3.373324e+09

[4,] 9 145646809734 59174398936 251071168505  
4.799168e+10

[5,] 4 323538875043 146668424920 360634547126  
2.591686e+11

[6,] 4 327624060484 152576296819 579061061914  
3.362014e+11

[7,] 3 111926243631 40573057031 121719171093  
2.591686e+11

[8,] 1 0 0 1.451345e+12

[9,] 1 0 0 8.278012e+11

[10,] 3 61090193130 23949621648 71848864944  
1.156755e+11

[11,] 1 0 0 1.451345e+12

[12,] 1 0 0 7.672801e+12

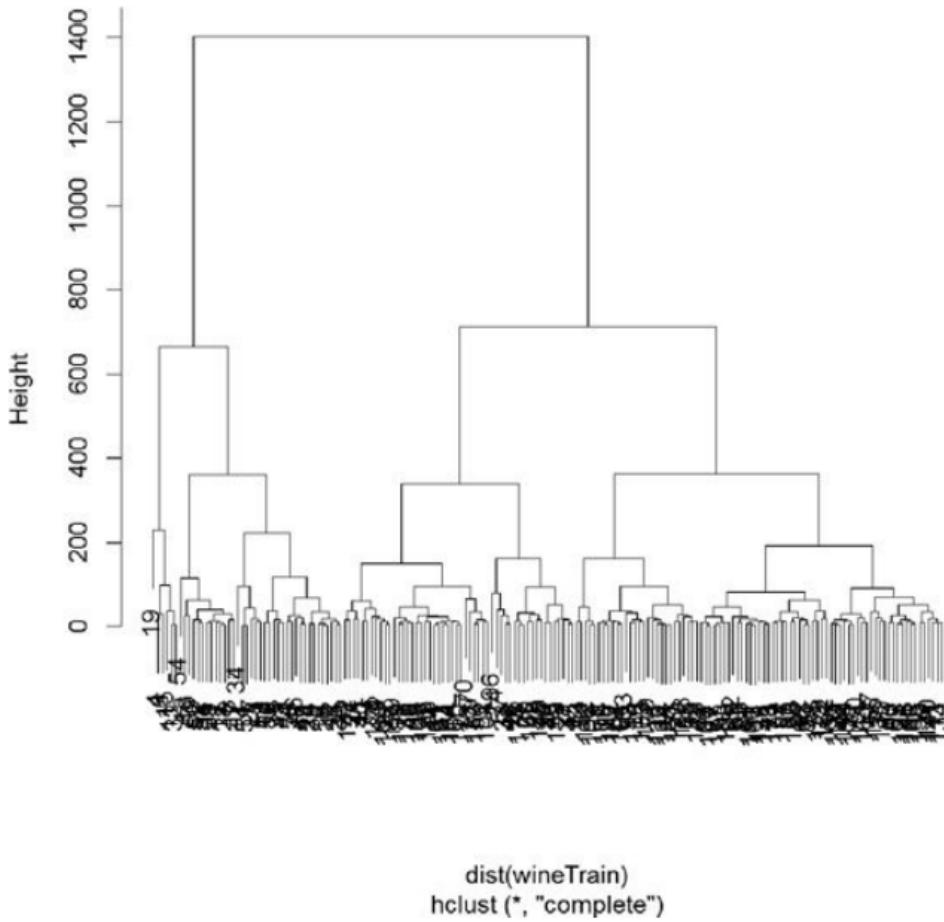
## 22.3. Hierarchical Clustering

Hierarchical clustering builds clusters within clusters, and does not require a prespecified number of clusters like K-means and K-medoids do. A hierarchical clustering can be thought of as a tree and displayed as a dendrogram; at the top there is just one cluster consisting of all the observations, and at the bottom each observation is an entire cluster. In between are varying levels of clustering.

Using the wine data, we can build the clustering with `hclust`. The result is visualized as a dendrogram in [Figure 22.8](#). While the text is hard to see, it labels the observations at the end nodes.

```
> wineH <- hclust(d = dist(wineTrain))  
> plot(wineH)
```

### Cluster Dendrogram



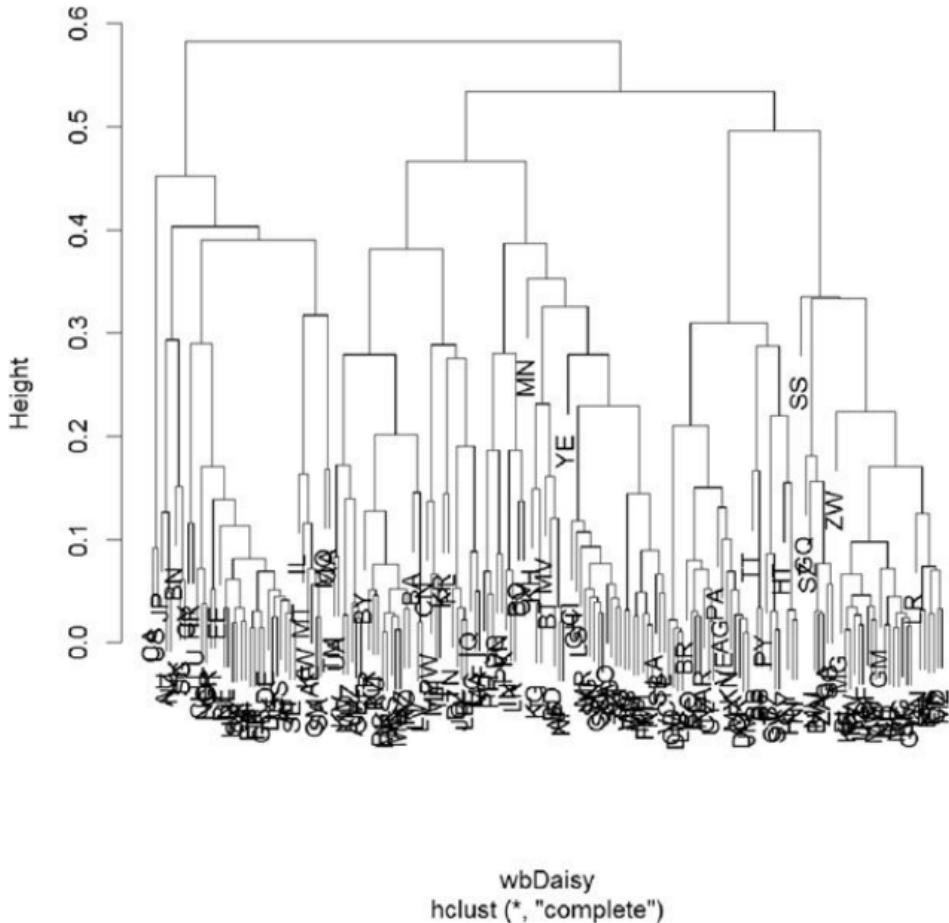
**Figure 22.8** Hierarchical clustering of wine data.

Hierarchical clustering also works on categorical data like the country information data. However, its dissimilarity matrix must be cal-

culated differently. The dendrogram is shown in [Figure 22.9](#).

```
> # calculate distance  
> keep.cols <- which(!names(wbInfo) %in% c("iso2c",  
  "country", "year",  
  +                               "capital", "iso3c"))  
> wbDaisy <- daisy(x=wbInfo[, keep.cols])  
>  
> wbH <- hclust(wbDaisy)  
> plot(wbH)
```

### Cluster Dendrogram



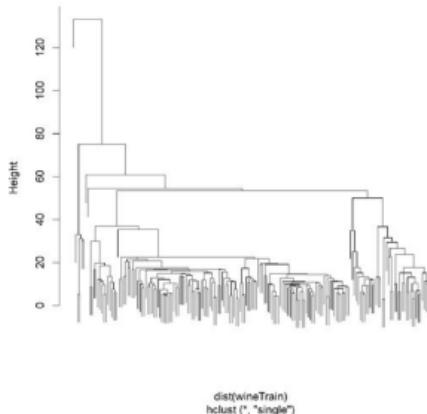
**Figure 22.9** Hierarchical clustering of country information data.

There are a number of different ways to compute the distance between clusters and they can have a significant impact on the results of a hier-

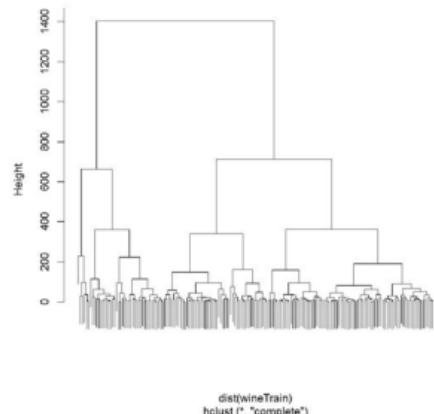
archical clustering. [Figure 22.10](#) shows the resulting tree from four different linkage methods: single, complete, average and centroid. Average linkage is generally considered the most appropriate.

```
> wineH1 <- hclust(dist(wineTrain), method = "single")
> wineH2 <- hclust(dist(wineTrain), method = "complete")
> wineH3 <- hclust(dist(wineTrain), method = "average")
> wineH4 <- hclust(dist(wineTrain), method = "centroid")
>
> plot(wineH1, labels = FALSE, main = "Single")
> plot(wineH2, labels = FALSE, main = "Complete")
> plot(wineH3, labels = FALSE, main = "Average")
> plot(wineH4, labels = FALSE, main = "Centroid")
```

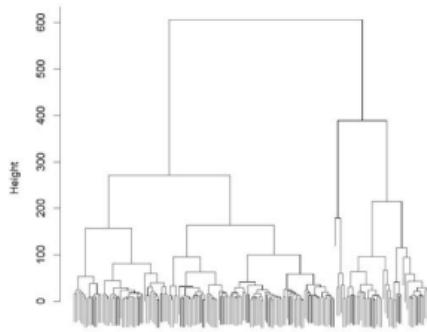
Single



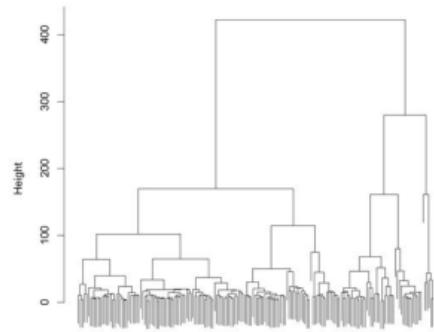
Complete



Average



Centroid



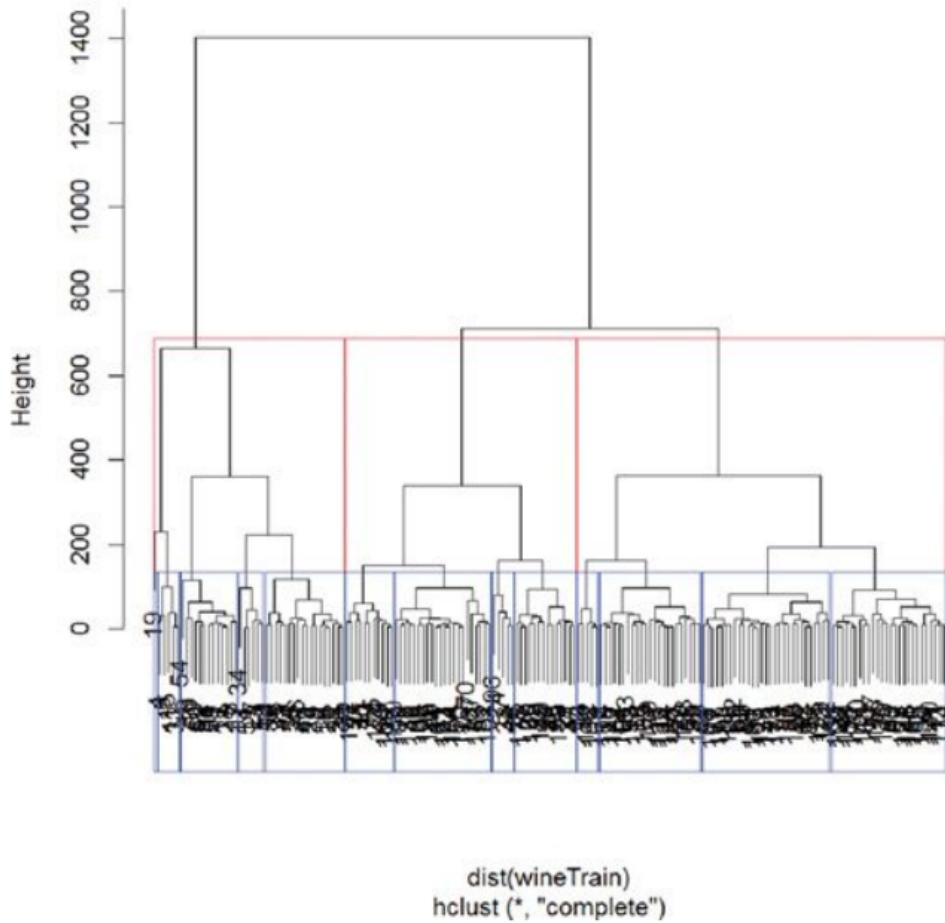
**Figure 22.10** Wine hierarchical clusters with different linkage methods. Clockwise from top left: single, complete, centroid, average.

Cutting the resulting tree produced by hierarchical clustering splits the observations into

defined groups. There are two ways to cut it, either specifying the number of clusters, which determines where the cuts take place, or specifying where to make the cut, which determines the number of clusters. [Figure 22.11](#) demonstrates cutting the tree by specifying the number of clusters.

```
> # plot the tree  
> plot(wineH)  
> # split into 3 clusters  
  
> rect.hclust(wineH, k = 3, border = "red")  
> # split into 13 clusters  
> rect.hclust(wineH, k = 13, border = "blue")
```

### Cluster Dendrogram

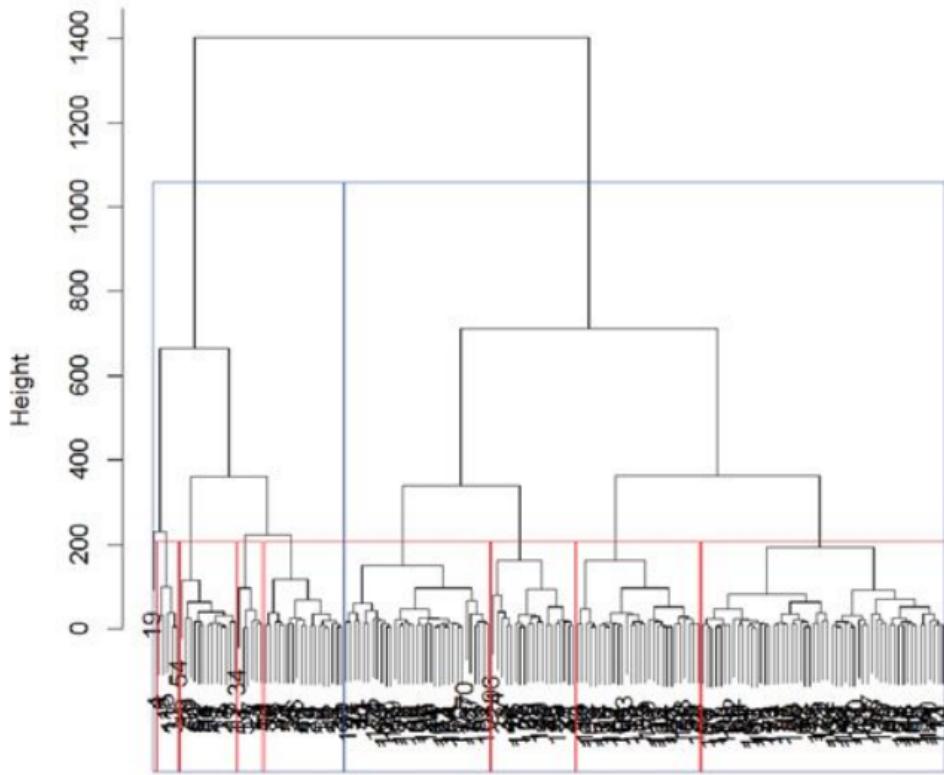


**Figure 22.11** Hierarchical clustering of wine data split into three groups (red) and 13 groups (blue).

[Figure 22.12](#) demonstrates cutting the tree by specifying the height of the cuts.

```
> # plot the tree  
> plot(wineH)  
> # split into 3 clusters  
> rect.hclust(wineH, h = 200, border = "red")  
> # split into 13 clusters  
> rect.hclust(wineH, h = 800, border = "blue")
```

### Cluster Dendrogram



dist(wineTrain)  
hclust (\*, "complete")

**Figure 22.12** Hierarchical clustering of wine data split by the height of cuts.

## 22.4. Conclusion

Clustering is a popular technique for segmenting data. The primary options for clustering in R are kmeans for K-means, pam in cluster for K-medoids and hclust for hierarchical clustering. Speed can sometimes be a problem with clustering, especially hierarchical clustering, so it is worth considering replacement packages like fastcluster, which has a drop-in replacement function, hclust, which operates just like the standard hclust, only faster.

# Chapter 23. Reproducibility, Reports and Slide Shows with knitr

Successfully delivering the results of an analysis can be just as important as the analysis itself, so it is vital to communicate them in an effective way. This can be a written report, a Web site of results, a slide show or a dashboard. In this chapter we focus on the first three, which are made remarkably easy using knitr, a package written by Yihui Xie.

knitr was initially created as a replacement for Sweave for the creation of PDF documents using LATEX interweaved with R code and the generated results. It has since added the capability to work with Markdown for generating HTML documents. While interweaving R code in LATEX and Markdown requires using a somewhat different syntax for each, the programs are similar enough to make them both easy to work with. First we dis-

cuss working with LATEX documents, and then Markdown.

The combination of knitr and RStudio is so powerful that it was possible to write this entire book inside the RStudio IDE using knitr to insert and run R code and graphics.

## 23.1. Installing a LATEX Program

LATEX (pronounced “lay-tech”) is a markup language based on the TEX typesetting system created by Donald Knuth. It is regularly used for writing scientific papers and books, including this one. Like any other program, LATEX must be installed before it can be used.

Each of the operating systems uses a different LATEX distribution. [Table 23.1](#) lists OS-specific distributions and download locations.

---

OS	Distribution	URL
Windows	MiKTeX	<a href="http://miktex.org/">http://miktex.org/</a>
Mac	MacTeX	<a href="http://www.tug.org/mactex/">http://www.tug.org/mactex/</a>
Linux	TeX Live	<a href="http://www.tug.org/texlive/">http://www.tug.org/texlive/</a>

---

**Table 23.1** LATEX Distributions and their Locations

## 23.2. LATEX Primer

This is not intended to be anywhere near a comprehensive lesson in LATEX, but it should be enough to get started with making documents. LATEX documents should be saved with a .tex extension to identify them as such. While RStudio is intended for working with R, it is a suitable text editor for LATEX and is the environment we will be using.

The very first line in a LATEX file declares the type of document, the most common being “article” and “book.” This is done with `\documentclass{...}`, replacing ... with the desired document class.

Immediately following the declaration of the `\documentclass` is the preamble. This is where

commands that affect the document go, such as what packages to load (LATEX packages) using \usepackage{...} and making an index with \makeindex.

In order to include images, it is advisable to use the graphicx package. This allows us to specify the type of image file that will be used by entering \DeclareGraphicsExtensions{.png,.jpg}, which means LATEX will first search for files ending in .png and then search for files ending in .jpg. This will be explained more when dealing with images later.

This is also where the title, author and date are declared with \title, \author and \date, respectively. New shortcuts can be created here such as \newcommand{\dataframe}{\texttt{data.frame}}, so that every time \dataframe{} is typed it will be printed as data.frame, which appears in a typewriter font because of the \texttt{...} .

The actual document starts with \begin{document} and ends with \end{document}. That is

where all the content goes. So far our LATEX document looks like the following example.

---

```
\documentclass{article}
% this is a comment
% all content following a % on a line will be commented
out as if it
never existed to latex
\usepackage{graphicx} % use graphics
\DeclareGraphicsExtensions{.png,.jpg} % search for png
then jpg
% define shortcut for dataframe
\newcommand{\dataframe}{\texttt{data.frame}}
\title{A Simple Article}
\author{Jared P. Lander\\ Lander Analytics}
% the \\ puts what follows on the next line
\date{April 14th, 2013}
\begin{document}
\maketitle
Some Content
\end{document}
```

---

Content can be split into sections using `\section{Section Name}`. All text following this command will be part of that section until another `\section{...}` is reached. Sections (and subsections

and chapters) are automatically numbered by LATEX. If given a label using \label{...} they can be referred to using \ref{...}. The table of contents is automatically numbered and is created using \tableofcontents. We can now further build out our document with some sections and a table of contents. Normally, LATEX must be run twice for cross references and the table of contents but RStudio, and most other LATEX editors, will do that automatically.

---

```
\documentclass{article}
% this is a comment
% all content following a % on a line will be commented
out as if it
never existed to latex
\usepackage{graphicx} % use graphics
\DeclareGraphicsExtensions{.png,.jpg} % search for png
then jpg
% define shortcut for dataframe
\newcommand{\dataframe}{\texttt{data.frame}}
\title{A Simple Article}
\author{Jared P. Lander\\ Lander Analytics}
% the \\ puts what follows on the next line
\date{April 14th, 2013}
\begin{document}
```

```
\maketitle % create the title page
\tableofcontents % build table of contents
\section{Getting Started}
\label{sec:GettingStarted}
This is the first section of our article. The only thing it will
talk
about is building \dataframe{}s and not much else.
A new paragraph is started simply by leaving a blank line.
That is all
that is required. Indenting will happen automatically.
\section{More Information}
\label{sec:MoreInfo}
Here is another section. In \ref{sec:GettingStarted} we
learned some
basics and now we will see just a little more. Suppose this
section is
getting too long so it should be broken up into subsections.
\subsection{First Subsection}
\label{FirstSub}
Content for a subsection.
\subsection{Second Subsection}
\label{SecondSub}
More content that is nested in \ref{sec:MoreInfo}
\section{Last Section}
\label{sec:LastBit}
This section was just created to show how to stop a preceding
sub-
section, section or chapter. Note that chapters are only
available in
books, not articles.
```

```
\makeindex % create the index  
\end{document}
```

---

While there is certainly a lot more to be learned about LATEX, this should provide enough of a start for using it with knitr. A great reference is the “Not So Short Introduction to LATEX,” which can be found at [ht-  
tp://tobi.oetiker.ch/lshort/lshort.pdf](http://tobi.oetiker.ch/lshort/lshort.pdf).

### 23.3. Using knitr with LATEX

Writing a LATEX document with R code is fairly straightforward. Regular text is written using normal LATEX conventions and the R code is delineated by special commands. All R code is preceded by <<label-name,option1='value1',option2='value2'>>= and is followed by @. While editing, RStudio nicely colors the background of the editor according to what is being written, LATEX or R code. This is seen in [Figure 23.1](#), and is called a “chunk.”

```
master.Rnw  knitr.Rnw  LinearModels.Rnw  Loops.Rnw  Run  Chunks
13 \section{\texttt{For} Loops}
14 \label{sec:forloops}
15 The most commonly used loop\texttt{general}(\texttt{loop}) is the \texttt{function(for)} loop\texttt{general}(loop). It iterates over an index--provided as a \texttt{Vector()}. It performs some operations. For a first simple example we will print out the first ten numbers.
16
17 The \texttt{loop\texttt{general}(\texttt{loop})} is declared using \texttt{function(for)} which takes one English seeming argument in three parts. The third part is any \texttt{Vector()} of values of any kind, most commonly \texttt{concept(numeric)} or \texttt{concept(character)}. The first part is the variable that is iteratively assigned the values in the \texttt{Vector()} from the third part. The middle part is simply the word ``in'' indicating that the variable (the first part) is in the \texttt{Vector()} (the third part).
18
19 <--simple-forloop>=
20 for(i in 1:10)
21 {
22   print(i)
23 }
24 @
25 \func{for}{func}{print}\colon()
26
27 Here we generated a \texttt{Vector()} holding the numbers \$1\$ through \$10\$ then printed each. Notice this could have been performed simply using
18 RStudio 1
```

## Figure 23.1 Screenshot of LATEX and R code in RStudio text editor. Notice that the code section is gray.

These documents are saved as .Rnw files. During the knitting process an .Rnw file is converted to a .tex file, which is then compiled to a PDF. If using the console, this is accomplished by calling the knit function, passing the .Rnw file as the first argument. In RStudio this is done by clicking the  **Compile PDF** button in the toolbar or pressing Ctrl+Shift+I on the keyboard.

Chunks are the workforce of knitr and are essential to understand. A typical use is to show both the code and results. It is possible to do one or the other, or neither as well, but for now we will focus on getting code printed and evaluated.

Suppose we want to illustrate loading ggplot2, viewing the head of the diamonds data, and then fitting a regression. The first step is to build a chunk.

```
<<diamonds-model>>=
# load ggplot
require(ggplot2)
# load and view the diamonds data
data(diamonds)
head(diamonds)
# fit the model

mod1 <- lm(price ~ carat + cut, data=diamonds)
# view a summary
summary(mod1)
@
```

This will then print both the code and the result in the final document as shown next.

```
> # load ggplot
> require(ggplot2)
>
> # load and view the diamonds data
> data(diamonds)
> head(diamonds)
  carat    cut color clarity depth table price   x   y   z
1  0.23  Ideal    E     SI2    61.5   55  326 3.95 3.98 2.43
```

2	0.21	Premium	E	SI1	59.8	61	326	3.89	3.84
2.31									
3	0.23	Good	E	VS1	56.9	65	327	4.05	4.07
4	0.29	Premi-							
um	I	VS2	62.4	58	334	4.20	4.23	2.63	
5	0.31	Good	J	SI2	63.3	58	335	4.34	4.35
6	0.24	Very							
Good	J	VVS2	62.8	57	336	3.94	3.96	2.48	
>									

> # fit the model

> mod1 <- lm(price ~ carat + cut, data = diamonds)

> # view a summary

> summary(mod1)

Call:

lm(formula = price ~ carat + cut, data = diamonds)

Residuals:

Min	1Q	Median	3Q	Max
-17540.7	-791.6	-37.6	522.1	12721.4

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	-2701.38	15.43	-175.061	< 2e-16 ***
carat	7871.08	13.98	563.040	< 2e-16 ***
cut.L	1239.80	26.10	47.502	< 2e-16 ***
cut.Q	-528.60	23.13	-22.851	< 2e-16 ***
cut.C	367.91	20.21	18.201	< 2e-16 ***
cut^4	74.59	16.24	4.593	4.37e-06 ***

---

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

Residual standard error: 1511 on 53934 degrees of freedom

Multiple R-squared: 0.8565, Adjusted R-squared: 0.8565  
F-statistic: 6.437e+04 on 5 and 53934 DF, p-value: < 2.2e-16

So far, the only thing supplied to the chunk was the label, in this case “diamonds-model.” It is best to avoid periods and spaces in chunk labels. Options can be passed to the chunk to control display and evaluation and are entered after the label, separated by commas. Some common knitr chunk options are listed in [Table 23.2](#). These options can be strings, numbers, TRUE/FALSE or any R object that evaluates to one of these.

Option	Effect
eval	Results printed when TRUE
echo	Code printed when TRUE
include	When FALSE, code is evaluated but neither the code nor results are printed.
cache	If the code has not changed, the results will be available but not evaluated again in order to save compilation time.
fig.cap	Caption text for images. Images will automatically be put into a special figure environment and be given a label based on the chunk label.
fig.scap	The short version of the image caption to be used in the list of captions
out.width	Width of displayed image
fig.show	Controls when images are shown. 'as.is' prints them when they appear in code and 'hold' prints them all at the end.
dev	Type of image to be printed, such as .png, .jpg, etc.
engine	knitr can handle code in other languages like Python, BASH, Perl, C++ and SAS.
prompt	Specifies the prompt character put before lines of code. If FALSE, there will be no prompt.
comment	For easier reproducibility, result lines can be commented out.

**Table 23.2 Common knitr Chunk Options**

Displaying images is made incredibly easy with knitr. Simply running a command that generates a plot inserts the image immediately following that line of code, with further code and results printed after that.

The following chunk will print  $1 + 1$  followed by the result, `plot(1:10)` followed by an image, and  $2 + 2$  followed by the result.

```
<<inline-plot>>=
1 + 1
```

```
plot(1:10)
```

```
2 + 2
```

```
@
```

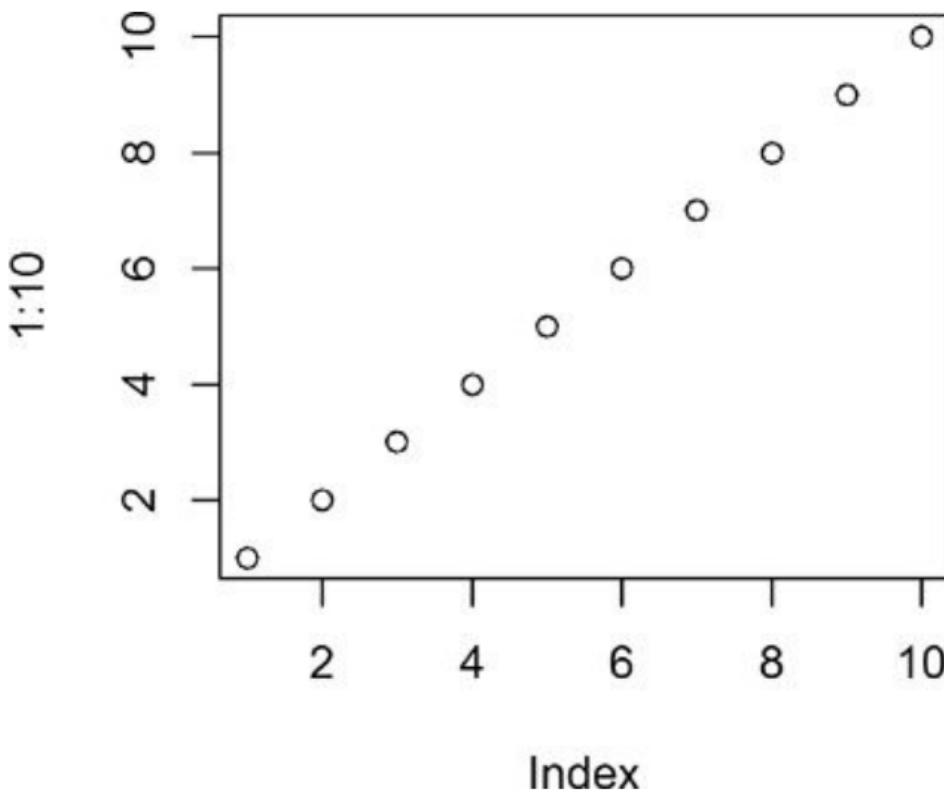
```
> 1 + 1
```

```
[1] 2
```

```
> plot(1:10)
```

```
> 2 + 2
```

```
[1] 4
```

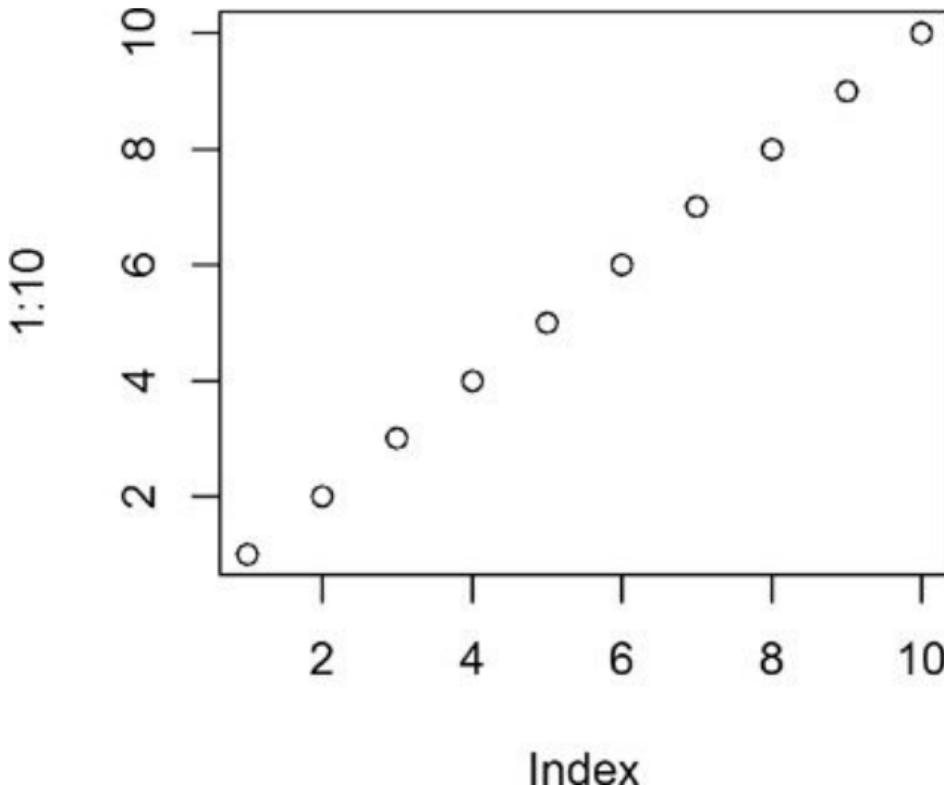


Adding the `fig.cap` option will put the image in a figure environment, which gets placed in a

convenient spot with a caption. Running the same chunk with `fig.cap` set to "Simple plot of the numbers 1 through 10." will display  $1 + 1$  followed by the result, `plot(1:10)`, and then  $2 + 2$  followed by the result. The image, along with the caption, will be placed where there is room, which very well could be in between lines of code. Setting `out.width` to '`.75\\linewidth`' (including the quote marks) will make the image's width 75% of the width of the line. While `\linewidth` is a LATEX command, because it is in an R string the backslash (`\`) needs to be escaped with another backslash. The resulting plot is shown in [Figure 23.2](#).

```
<<figure-plot,fig.cap="Simple plot of the numbers 1  
through 10.",  
fig.scap="Simple plot of the numbers 1 through 10",  
out.width='75\\linewidth'>>=  
1 + 1  
plot(1:10)  
2 + 2  
@  
> 1 + 1  
[1] 2  
> plot(1:10)  
> 2 + 2
```

```
[1] 4
```



**Figure 23.2** Simple plot of the numbers 1 through 10.

This just scratches the surface of what is possible with LATEX and knitr. More information can be found on Yihui's site at <http://yihui.name/knitr/>. When using knitr it is considered good form to use a formal citation of the form Yihui

Xie (2013). knitr: A general-purpose package for dynamic report generation in R. R package version 1.2. Proper citations can be found, for some packages, using the citation function.

```
> citation(package = "knitr")
```

To cite the 'knitr' package in publications use:

Yihui Xie (2013). knitr: A general-purpose package for dynamic report generation in R. R package version 1.4.1.

Yihui Xie (2013) Dynamic Documents with R and knitr.

Chapman

and Hall/CRC. ISBN 978-1482203530

Yihui Xie (2013) knitr: A Comprehensive Tool for Reproducible Research in R. In Victoria Stodden, Friedrich

Leisch and Roger D. Peng, editors, Implementing Reproducible

Computational Research. Chapman and Hall/CRC. ISBN 978-1466561595

## 23.4. Markdown Tips

While LATEX is a great tool for composing a book or an article, an easier tool is Markdown, which is ideal for Web sites and presentations.<sup>1</sup> It is a simplified version of HTML that does away with the tedium typically involved in writing a Web page. There is also much less structure in Markdown than in LATEX, meaning less control but easier writing.

1. LATEX can produce presentations using Beamer but Markdown slide shows, as seen in [Section 23.6](#), are quicker to build and allow for more interactivity.

Line breaks are created by leaving a blank line between blocks of text. Italics can be generated by putting an underscore (\_) on both sides of a word, and bold is generated by putting two underscores on each side. Lists are created by putting each element on its own line starting with an asterisk (\*). Text is made a header by starting a line with a pound symbol (#), the number of pounds indicating the header level.

Links are created by putting the text to be displayed in square brackets ([ ]) and the linked URL in parentheses. Inserting images is also done with square brackets and parentheses and preceded by an exclamation mark (!). A sample Markdown document is shown next.

---

```
# Title - Also a Header 1
this will be italicized
this will be bolded
## Header 2
Build a list
* Item 1
* Item 2
* Item 3
This is a link
[My Website](http://www.jaredlander.com)
## Another Header 2
This inserts an image
![Alt text goes in here](location-of-image.png)
#### Header 4
```

---

RStudio provides a handy quick reference guide to Markdown, accessed by clicking the  button in the toolbar.

## 23.5. Using knitr and Markdown

The work flow for writing Markdown documents is similar to that for LATEX documents: Normal text (flavored with Markdown) is written and R code is put in chunks. The style of the chunks is different but the idea is the same. A file that contains both Markdown and R code is saved as an .Rmd file, and then knitted to a Markdown file (.md), which is compiled to an HTML file. In the console this is done with the `knit` function, and in RStudio with the  Knit HTML button or `Ctrl+Shift+H`.

Chunks for Markdown documents start with ````{r label-name, option1='value1',option2='value2'}` and end with `````. Otherwise, everything else is the same with exceptions for HTML conventions such as `out.width='75%'` as opposed to `out.width='75\linewidth'`. Following is the same chunk from earlier, but modified to meet the conventions needed for a Markdown document.

```
```{r figure-plot,fig.cap="Simple plot of the numbers 1  
through 10.",  
fig.scap="Simple plot of the numbers 1 through 10",  
out.width='!.75\\linewidth'}  
1 + 1  
plot(1:10)  
2 + 2  
...``
```

## 23.6. pandoc

Creating reproducible presentations without leaving the friendly confines of the R environment has long been possible using LATEX's Beamer mode, which creates a PDF where each page is a slide. However, writing all that LATEX code can be unnecessarily time consuming. A simpler option is to write a Markdown document and compile it into an HTML5 slide show using pandoc, a great conversion utility written by John MacFarlane that is used from the command line.

Before it can be used, pandoc must be downloaded and installed from <http://johnmacfarlane.net/pandoc/installing.html>.

Pandoc can be used to convert files from one type to another. In our example we convert from Markdown to HTML5, in particular the slidy slide show format. (Other slide formats, such as s5, dzslides and slideous, are available.)

Slides are indicated by the header command (#), which also provides the slide title. While there are varying levels of headers, the highest level header in the deck that is immediately followed by content is used for slide titles. This can be overwritten by setting the --slide-level option when calling pandoc, which will be seen later. An example scenario would be using header 1 (#) to create sections, header 2 (##) to create subsections and header 3 (###) to create slides.

The first three lines of the Markdown file should each start with a percent symbol (%). The first is the title of the talk, the second is the author's name and the third is the date. These are used to create the title slide.

Aside from these caveats, and a few others, regular Markdown should be used. An example slide show code follows.

---

```
% Example Slideshow
```

```
% Jared P. Lander
```

```
% April 14th, 2013
```

## # First Section

### ### First Slide in First Section

A list of things to cover

- \* First Item

- \* Second Item

- \* Third Item

### ### Some R Code

The code below will generate some results and a plot.

```
```{r figure-plot,fig.cap="Simple plot of the numbers 1  
through 10.",  
fig.scap="Simple plot of the numbers 1 through  
10",out.width='50%',  
fig.show='hold'}
```

```
1 + 1
```

```
plot(1:10)
```

```
2 + 2  
...  
````
```

## # Second Section

### ## First Subsection

#### ### Another Slide

Some more information goes here

### ## Second Subsection

### ### Some Links

[My Website](<http://www.jaredlander.com>)

[R Bloggers](<http://www.r-bloggers.com>)

---

Running knit on this file, or pressing the  Knit HTML button or Ctrl+Shift+H creates both an .md file and an .html file. Pandoc should be used on the .md file, which we will call example.md, with the following line of code from the command line.

```
pandoc -s -S --toc -t slidify --self-contained  
--slide-level 3 example.md -o output.html
```

This calls pandoc on example.md and creates output.html with a number of options. -s builds a stand-alone file, -S runs it in smart mode, --toc creates a table of contents, -t slidify makes the final product a slidify slide show, --self-contained puts all of the content into a single HTML file with no other files needed (even images are encoded directly into the file), --slide-level 3 means header 3 creates new slides, example.md specifies the in-

put file and -o output.html provides the name for the output file.

This two-step process of generating the knitted Markdown file using knit (or the button or keyboard shortcut) and then going to the command line to run the preceding pandoc command can be tedious and error prone. Fortunately, at least for RStudio users, an option can be set to make this a one-step process. The following change to the R options makes the Knit button use pandoc for the conversion from Markdown to HTML.

```
> options(rstudio.markdownToHTML = function(in-  
putFile, outputFile)  
+ {  
+   system(paste(  
+ "pandoc -s -S --webtex --toc -t slidy --self-contained --  
slide-level 3",  
+ shQuote(inputFile), "-o", shQuote(outputFile))  
+ )  
+ }  
+ )
```

Now using the Knit button goes straight to the slide show format, which will even show up in the RStudio preview window.

Another alternative to using pandoc is the slidify package, written by Ramnath Vaidyanathan from McGill University. It uses a somewhat different syntax than pandoc but has a lot more power, and it even automatically changes the functionality of the Knit button in RStudio. Chunks of R code are still written as usual.

## 23.7. Conclusion

Writing reproducible, and maintainable, documents and slide shows from within R has never been easier, thanks to Yihui's knitr package. It allows seamless integration of R code, with results including images and either LATEX or Markdown text.

On top of that, the RStudio IDE is a fantastic text editor. This entire book was written using knitr from within RStudio, without ever having to use Microsoft Word or a LATEX editor.

# Chapter 24. Building R Packages

As of late-July 2013, there were 4,714 packages on CRAN and another 671 on Bioconductor, with more being added daily. In the past, building a package had the potential to be mystifying and complicated but that is no longer the case, especially when using Hadley Wickham's `devtools` package.

All packages submitted to CRAN (or Bioconductor) must follow specific guidelines, including the folder structure of the package, inclusion of `DESCRIPTION` and `NAMESPACE` files and proper help files.

## 24.1. Folder Structure

An R package is essentially a folder of folders, each containing specific files. At the very minimum there must be two folders, one called R where the included functions go, and the other called man where the documentation files are placed. It used to be that the documentation had to be written manually, but thanks to roxygen2 that is no longer necessary, as is seen in [Section 24.3](#). Starting with R 3.0.0, CRAN is very strict in requiring that all files must end with a blank line and that code examples must be shorter than 105 characters.

In addition to the R and man folders, other common folders are src for compiled code such as C++ and FORTRAN, data for data that is included in the package and inst for files that should be available to the end user. No files from the other folders are available in a human-readable form (except the INDEX, LICENSE and NEWS files in the root folder) when a package

is installed. [Table 24.1](#) lists the most common folders used in an R package.

| Folder | Explanation                                                                                                                    |
|--------|--------------------------------------------------------------------------------------------------------------------------------|
| R      | Files containing R code. Filenames must end in .R, .S, .q, .r, or .s as an extension, with .r being the most common.           |
| man    | Documentation files ending in .Rd, one for each function in the R folder. These can be generated automatically using roxygen2. |
| src    | Compiled code such as C/C++/FORTRAN                                                                                            |
| data   | Data included in the package                                                                                                   |
| inst   | Files to be included in the installed package for the end user                                                                 |
| test   | Code that tests the functions in the R folder                                                                                  |

**Table 24.1 Folders Used in R Packages  
(While there are other possible folders,  
these are the most common)**

## 24.2. Package Files

The root folder of the package must contain at least a DESCRIPTION file and a NAMESPACE file, which are described in [Sections 24.2.1](#) and [24.2.2](#). Other files like NEWS, LICENSE and README are recommended but not necessary. [Table 24.2](#) lists commonly used files.

| File        | Explanation                                                                      |
|-------------|----------------------------------------------------------------------------------|
| DESCRIPTION | Package information including dependencies                                       |
| NAMESPACE   | List of functions exposed to end user and functions imported from other packages |
| NEWS        | What has been updated in each version                                            |
| LICENSE     | Copyright information                                                            |
| README      | Basic description of package                                                     |

**Table 24.2 Files Used in R Packages  
(While there are other possible files,  
these are the most common)**

### 24.2.1. DESCRIPTION File

The DESCRIPTION file contains information about the package, such as its name, version, author and other packages it depends on. The information is entered, each on one line, as Item1: Value1. [Table 24.3](#) lists a number of fields that are used in DESCRIPTION files.

| Field       | Required | Explanation                                                        |
|-------------|----------|--------------------------------------------------------------------|
| Package     | Yes      | Name of package                                                    |
| Type        | No       | Just use Package                                                   |
| Title       | Yes      | Short description of package                                       |
| Version     | Yes      | Current version: v.s.ss                                            |
| Date        | No       | Latest build date                                                  |
| Author      | Yes      | Name of author                                                     |
| Maintainer  | Yes      | Author name and email address                                      |
| Description | Yes      | Complete description of package                                    |
| License     | Yes      | License type                                                       |
| Depends     | No       | Comma separated list of packages to be loaded                      |
| Imports     | No       | Comma separated list of packages to use but not load               |
| Suggests    | No       | Comma separated list of packages that are nice to have             |
| Collate     | No       | List (no commas) of R files in the R directory in processing order |
| ByteCompile | No       | If the package should be byte-compiled on installation             |

**Table 24.3 Fields in the DESCRIPTION File**

The Package field specifies the name of the package. This is the name that appears on CRAN and how users access the package.

Type is a bit archaic; it can be either Package or one other type, Frontend, which is used for building a graphical front end to R and will not be helpful for building an R package of functions.

Title is a short description of the package. It should be relatively brief and cannot end in a period. Description is a complete description of

the package, which can be several sentences long but no longer than a paragraph.

Version is the package version and usually consists of three period-separated integers; for example, 1.15.2. Date is the release date of the current version.

The Author and Maintainer fields are similar but both are necessary. Author can be multiple people, separated by commas, and Maintainer is the person in charge, or rather the person who gets complained to, and should be a name followed by an email address inside angle brackets (<>). An example is Maintainer: Jared P. Lander <[packages@jaredlander.com](mailto:packages@jaredlander.com)>. CRAN is actually very strict about the Maintainer field and can reject a package for not having the proper format.

License information goes in the appropriately named License field. It should be either an abbreviation of one of the standard specifications such as GPL-2 or BSD or the string 'file LICENSE' referring to the LICENSE file in the package's root folder.

Things get tricky with the Depends, Imports and Suggests fields. Often a package requires functions from other packages. In that case the other package, for example, ggplot2, should be listed in either the Depends or Imports field as a comma-separated list. If ggplot2 is listed in Depends, then when the package is loaded so will ggplot2, and its functions will be available to functions in the package and to the end user. If ggplot2 is listed in Imports, then when the package is loaded ggplot2 will not be loaded, and its functions will be available to functions in the package but not the end user. Packages should be listed in one or the other, not both. Packages listed in either of these fields will be automatically installed from CRAN when the package is installed. If the package depends on a specific version of another package, then that package name should be followed by the version number in parentheses; for example, Depends: ggplot2 (>= 0.9.1). Packages that are needed for the examples in the documentation, vignettes or testing

but are not necessary for the package's functionality should be listed in Suggests.

The Collate field specifies the R code files contained in the R folder. This will be populated automatically if the package is documented using roxygen2 and devtools.

A relatively new feature is byte-compilation, which can significantly speed up R code. Setting ByteCompile to TRUE will ensure the package is byte-compiled when installed by the end user.

The DESCRIPTION file from coefplot is shown next.

---

Package: coefplot

Type: Package

Title: Plots Coefficients from Fitted Models

Version: 1.1.9

Date: 2013-01-23

Author: Jared P. Lander

Maintainer: Jared P. Lander <[packages@jaredlander.com](mailto:packages@jaredlander.com)>

Description: Plots the coefficients from a model object

License: BSD

LazyLoad: yes

Depends:

ggplot2

Imports:

plyr,  
stringr,  
reshape2,  
useful,  
scales,  
proto

Collate:

'coefplot.r'  
'coefplot-package.r'  
'multiplot.r'  
'extractCoef.r'  
'buildPlottingFrame.r'  
'buildPlot.r'  
'dodging.r'

ByteCompile: TRUE

---

## 24.2.2. NAMESPACE File

The NAMESPACE file specifies which functions are exposed to the end user (not all functions in a package should be) and which other packages are imported into the NAMESPACE. Functions that are exported are listed as `export(multiplot)` and imported packages are listed as `import(plyr)`. Building this file by hand can be quite tedious, so fortunately `roxygen2` and `devtools` can, and should, build this file automatically.

R has three object-oriented systems: S3, S4 and Reference Classes. S3 is the oldest and simplest of the systems and is what we will focus on in this book. It consists of a number of generic functions such as `print`, `summary`, `coef` and `coefplot`. The generic functions exist only to dispatch object-specific functions. Typing `print` into the console shows this.

```
> print
standardGeneric for "print" defined from package "base"
function (x, ...)
standardGeneric("print")
```

```
<environment: 0x000000001e1aecc0>
```

```
Methods may be defined for arguments: x
```

```
Use showMethods("print") for currently available ones.
```

It is a single-line function containing the command `UseMethod("print")`, which tells R to call another function depending on the class of the object passed. These can be seen with `methods(print)`. To save space we show only 20 of the results. Functions not exposed to the end user are marked with an asterisk (\*). All of the names are `print` and the object class separated by a period.

```
> methods(print)
[1] print.aareg*          print.abbrev*
[3] print.acf*           print.AES*
[5] print.agnes*          print.anova
[7] print.Anova*          print.anova.gam
[9] print.anova.lme*       print.anova.loglm*
[11] print.aov*           print.aovlist*
[13] print.ar*            print.Arima*
[15] print.arima0*         print.arma*
[17] print.AsIs            print.aspell*
[19] print.aspell_inspect_context* print.balance*
[ reached getOption("max.print") -- omitted 385 entries ]
Non-visible functions are asterisked
```

When print is called on an object, it then calls one of these functions depending on the type of object. For instance, a data.frame is sent to print.data.frame and an lm object is sent to print.lm.

These different object-specific functions that get called by generic S3 functions must be declared in the NAMESPACE in addition to the functions that are exported. This is indicated as S3Method(coefplot, lm) to say that coefplot.lm is registered with the coefplot generic function.

The NAMESPACE file from coefplot is shown next.

---

```
S3method(coefplot,default)
S3method(coefplot,glm)
S3method(coefplot,lm)
S3method(coefplot,rxGlm)
S3method(coefplot,rxLinMod)
S3method(coefplot,rxLogit)
S3method(extract.coef,default)
S3method(extract.coef,glm)
S3method(extract.coef,lm)
S3method(extract.coef,rxGlm)
```

```
S3method(extract.coef,rxLinMod)
S3method(extract.coef,rxLogit)
export(buildModelCI)
export(coefplot)
export(coefplot.default)
export(coefplot.glm)
export(coefplot.lm)
export(coefplot.rxGlm)
export(coefplot.rxLinMod)
export(coefplot.rxLogit)
export(collidev)
export(extract.coef)
export(multiplot)
export(plotcoef)
export(pos dodgev)
import(ggplot2)
import(plyr)
import(proto)
import(reshape2)
import(scales)
import(stringr)
import(useful)
```

---

Even with a small package like `coefplot`, building the NAMESPACE file by hand can be tedious and error prone, so it is best to let `devtools` and `roxygen2` build it.

### 24.2.3. Other Package Files

The NEWS file is for detailing what is new or changed in each version. The three most recent entries in the coefplot NEWS file are shown next. Notice how it is good practice to thank people who helped with or inspired the update. This file will be available to the end user's installation.

---

## Version 1.1.9

Refactoring of code to make new models easier to add.

For now this means certain functionality will be lost, such as the shortening of coefficient names, plot a factor variable numerically.

## Version 1.1.8

Minor changes to plotting to reflect change in `ggplot2 0.9.2`.

## Version 1.1.7

Thanks to Felipe Carrillo I have fixed a bug in `multiplot`. Previously, if multiple models with the same formula but different `data.frames` were inputed then they would all have the same name (even if specified with the “`names`” argument) and only one model would be plotted. This now works as expected,

plotting all the models regardless of identical formulas.

---

The LICENSE file is for specifying more detailed information about the package's license and will be available to the end user's installation. The LICENSE file from coefplot is shown here.

---

Copyright (c) 2013, under the Simplified BSD License.

For more information on FreeBSD see:  
<http://www.opensource.org/licenses/bsd-license.php>

All rights reserved.

---

The README file is purely informational and is not included in the end user's installation. Its biggest benefit may be for packages hosted on GitHub, where the README will be the information displayed on the project's home page.

## 24.3. Package Documentation

A very strict requirement for R packages to be accepted by CRAN is proper documentation. Each exported function in a package needs its own .Rd file that is written in a LATEX-like syntax. This can be difficult to write for even simple functions like the following one.

```
> simple.ex <- function(x, y)
+ {
+   return(x * y)
+ }
```

Even though it has only two arguments and simply returns the product of the two, it has a lot of necessary documentation, shown here.

---

```
\name{simple.ex}
\alias{simple.ex}
\title{within.distance}
\usage{\code{simple.ex(x, y)}}
\arguments{
  \item{x}{A numeric}
  \item{y}{A second numeric}
}
```

```
\value{x times y}
\description{Compute distance threshold}
\details{This is a simple example of a function}
\author{Jared P. Lander}
\examples{
  simple.ex(3, 5)
}
```

---

Rather than taking this two-step approach, it is better to write function documentation along with the function. That is, the documentation is written in a specially commented out block right above the function, as shown here.

```
> #' @title simple.ex
> #' @description Simple Example
> #' @details This is a simple example of a function
> #' @aliases simple.ex
> #' @author Jared P. Lander
> #' @export simple.ex
> #' @param x A numeric
> #' @param y A second numeric
> #' @return x times y
> #' @examples
> #' simple.ex(5, 3)
> simple.ex <- function(x, y)
+ {
+   return(x * y)
```

+ }

Running document from devtools will automatically generate the appropriate .Rd file based on the block of code above the function. The code is indicated by #' at the beginning of the line. [Table 24.4](#) lists a number of commonly used roxygen2 tags.

| Tag            | Explanation                                                                           |
|----------------|---------------------------------------------------------------------------------------|
| @param         | The name of an argument and a short description                                       |
| @inheritParams | Copies the @param tags from another function so that they do not need be to rewritten |
| @examples      | Examples of the function being used                                                   |
| @return        | Description of the object that is returned by the function                            |
| @author        | Name of the author of the function                                                    |
| @aliases       | Names by which a user can search for the function                                     |
| @export        | Lists the function as an export in the NAMESPACE file                                 |
| @import        | Lists a package as an import in the NAMESPACE file                                    |
| @seealso       | A list of other functions to see                                                      |
| @title         | Title of help file                                                                    |
| @description   | Short description of the function                                                     |
| @details       | Detailed information about the function                                               |
| @useDynLib     | Indicates that compiled source code will be used for the package                      |
| @S3Method      | Declares functions that go with s3 generic functions                                  |

**Table 24.4 Tags Used in roxygen2 Documentation of Functions**

Every argument must be documented with a @param tag, including the dots (...), which are

written as \dots. There must be an exact correspondence between @param tags and arguments; one more or less will cause an error.

It is considered good form to show examples of a function's usage. This is done on the lines following the @examples tag. In order to be accepted by CRAN all of the examples must work without error. In order to show, but not run, the examples wrap them in \dontrun{...}.

Knowing the type of object is important when using a function, so @return should be used to describe the returned object. If the object is a list, the @return tag should be an itemized list of the form \item{name a} {description a}\item{name b} {description b}.

Help pages are typically arrived at by typing ?FunctionName into the console. The @aliases tag uses a space-separated list to specify the names that will lead to a particular help file. For instance, using @aliases coefplot plotcoef will result in both ?coefplot and ?plotcoef leading to the same help file.

In order for a function to be exposed to the end user, it must be listed as an export in the NAMESPACE file. Using @export `FunctionName` automatically adds `export(FunctionName)` to the NAMESPACE file. Similarly, to use a function from another package, that package must be imported and @import `PackageName` adds `import(PackageName)` to the NAMESPACE file.

When building functions that get called by generic functions, such as `coefplot.lm` or `print.anova`, the @S3method tag should be used. @S3method GenericFunction Class adds `S3-method(GenericFunction, class)` to the NAMESPACE file. When using @S3method it is a good idea to also use @method with the same arguments. This is shown in the following function.

```
> #' @title print.myClass  
> #' @aliases print.myClass  
> #' @method print myClass  
> #' @S3method print myClass  
> #' @export print.myClass
```

```
> #' @param x Simple object
> #' @param ... Further arguments to be passed on
> #' @return The top 5 rows of x
> print.myClass <- function(x, ...)
+ {
+   class(x) <- "list"
+   x <- as.data.frame(x)
+   print.data.frame(head(x, 5))
+ }
```

## 24.4. Checking, Building and Installing

Building a package used to require going to the command prompt and using commands like R CMD check, R CMD build and R CMD INSTALL (in Windows it is Rcmd instead of R CMD), which required being in the proper directory, knowing the correct options and other bothersome time wasters. Thanks to Hadley Wickham, this has all been made much easier and can be done from within the R console.

The first step is to make sure a package is properly documented by calling document. The first argument is the path to the root folder of the package as a string. (If the current working dir-

ecitory is the same as the root folder, then no arguments are even needed. This is true of all the devtools functions.) This builds all the necessary .Rd files, the NAMESPACE file and the Collate field of the DESCRIPTION file.

```
> require(devtools)  
> document()
```

After the package is properly documented, it is time to check it. This is done using check with the path to the package as the first argument. This will make note of any errors or warnings that would prevent CRAN from accepting the package. CRAN can be very strict, so it is essential to address all the issues.

```
> check()
```

Building the package is equally simple using the build function, which also takes the path to the package as the first argument. By default it builds a .tar.gz—a collection of all the files in the package—that still needs to be built into a binary that can be installed in R. It is portable in that

it can be built on any operating system. The binary argument, if set to TRUE, will build a binary that is operating system specific. This can be problematic if compiled source code is involved.

> **build()**

> **build(binary = TRUE)**

Other functions to help with the development process are `install`, which rebuilds and loads the package, and `load all`, which simulates the loading of the package and NAMESPACE.

Another great function, not necessarily for the development process so much as for getting other people's latest work, is `install github`, which can install an R package directly from a GitHub repository. There are analogous functions for installing from BitBucket (`install bitbucket`) and Git (`install git`) in general.

For instance, to get the latest version of `coefplot` the following code should be run. By the time of publication this might no longer be the the latest version.

```
> install_github(repo = "coefplot", username = "jared-  
lander",  
+                 ref = "survival")
```

Sometimes an older version of a package on CRAN is needed, which under normal circumstances is hard to do without downloading source packages manually and building them. However, `install` version was recently added to `devtools`, allowing a specific version of a package to be downloaded from CRAN, built and installed.

## 24.5. Submitting to CRAN

The best way to get a package out to the R masses is to have it on CRAN. Assuming the package passed the check using check from devtools, it is ready to be uploaded to CRAN using the new Web uploader (as opposed to using FTP) at <http://xmpalantir.wu.ac.at/cransubmit/>. The .tar.gz file is the one to upload. After submission, CRAN will send an email requiring confirmation that the package was indeed uploaded by the maintainer. Alternatively, the package can be uploaded by anonymous FTP to <ftp://CRAN.R-project.org/incoming/> with an email sent to Uwe Ligges at [ligges@statistik.tu-dortmund.de](mailto:ligges@statistik.tu-dortmund.de) and to [cran@r-project.org](mailto:cran@r-project.org). The subject line *must* be of the format CRAN Upload: PackageName PackageVersion. The name of the package is case sensitive and must match the name of the package in the DESCRIPTION file. The body of the message does not have to follow any guidelines, but should be polite and include the words “thank you” somewhere, because the CRAN team puts

in an incredible amount of effort despite not getting paid.

## 24.6. C++ Code

Sometimes R code is just not fast enough (even when byte-compiled) for a given problem and a compiled language must be used. R's foundation in C and links to FORTRAN libraries (digging deep enough into certain functions, such as `lm`, reveals that the underpinnings are written in FORTRAN) makes incorporating those languages fairly natural. `.Fortran` is used for calling a function written in FORTRAN and `.Call` is used for calling C and C++ functions.<sup>1</sup> Even with those convenient functions, knowledge of either FORTRAN or C/C++ is still necessary, as is knowledge of how R objects are represented in the underlying language.

<sup>1</sup> There is also a `.C` function, although despite much debate it is generally frowned upon.

Thanks to Dirk Eddelbuettel and Romain François, integrating C++ code has become much

easier using the Rcpp package. It handles a lot of the scaffolding necessary to make C++ functions callable from R. Not only did they make developing R packages with C++ easier, but they also made running ad hoc C++ possible.

A number of tools are necessary for working with C++ code. First, a proper C++ compiler must be available. To maintain compatibility it is best to use gcc.

Linux users should already have gcc installed and should not have a problem, but they might need to install g++.

Mac users need to install Xcode and might have to manually select g++. The compiler offered on Mac generally lags behind the most recent version available, which has been known to cause some issues.

Windows users should actually have an easy time getting started, thanks to RTools developed by Brian Ripley and Duncan Murdoch. It provides all necessary development tools, including gcc and make. The proper version, depending

on the installed version of R, can be downloaded from <http://cran.r-project.org/bin/windows/Rtools/> and installed like any other program. It installs gcc and makes the Windows command prompt act more like a BASH terminal. If building packages from within R using devtools and RStudio (which is the best way now), then the location of gcc will be determined from the operating system's registry. If building packages from the command prompt, then the location of gcc must be put at the very beginning of the system PATH

like

c:\Rtools\bin;c:\Rtools\gcc-4.6.3\bin;C:\Users\Jared  
Documents\R\R-3.0.0\bin\x64.

A LATEX distribution is needed for building package help documents and vignettes. [Table 23.1](#) lists the primary distributions for the different operating systems.

## 24.6.1. sourceCpp

To start, we build a simple C++ function for adding two vectors. Doing so does not make sense from a practical point of view because R already does this natively and quickly, but it will be good for illustrative purposes. The function will have arguments for two vectors and return the element-wise sum. The `// [[Rcpp::export]]` tag tells Rcpp that the function should be exported for use in R.

```
#include <Rcpp.h>
using namespace Rcpp;
// [[Rcpp::export]]
NumericVector vector_add(NumericVector x, NumericVector y)
{
    // declare the result vector
    NumericVector result(x.size());
    // loop through the vectors and add them element by element
    for(int i=0; i<x.size(); ++i)
    {
        result[i] = x[i] + y[i];
    }
    return(result);
}
```

This function should be saved in a .cpp file (for example, vector add.cpp) or as a character variable so it can be sourced using sourceCpp, which will automatically compile the code and create a new R function with the same name that, when called, executes the C++ function.

```
> require(Rcpp)  
> sourceCpp("vector_add.cpp")
```

Printing the function shows that it points to a temporary location where the compiled function is currently stored.

```
> vector_add  
function (x, y)  
.Primitive(".Call")(<pointer: 0x0000000066e81710>, x, y)
```

The function can now be called just like any other R function.

```
> vector_add(x = 1:10, y = 21:30)  
[1] 22 24 26 28 30 32 34 36 38 40  
> vector_add(1, 2)  
[1] 3  
> vector_add(c(1, 5, 3, 1), 2:5)  
[1] 3 8 7 6
```

JJ Allaire (the founder of RStudio) is responsible for sourceCpp, the `// [[Rcpp::export]]` shortcut and a lot of the magic that simplifies using C++ with R in general. Rcpp maintainer Dirk Eddelbuettel cannot stress enough how helpful Allaire's contributions have been.

Another nice feature of Rcpp is the syntactic sugar that allows C++ code to be written like R. Using sugar we can rewrite vector add with just one line of code.

```
#include <Rcpp.h>
using namespace Rcpp;
// [[Rcpp::export]]
NumericVector vector_add(NumericVector x, NumericVector y)
{
    return(x + y);
}
```

The syntactic sugar allowed two vectors to be added just as if they were being added in R.

Because C++ is a strongly typed language, it is important that function arguments and return types be explicitly declared using the correct

type. Typical types are NumericVector, IntegerVector, LogicalVector, CharacterVector, DataFrame and List.

## 24.6.2. Compiling Packages

While sourceCpp makes ad hoc C++ compilation easy, a different tactic is needed for building R packages using C++ code. The C++ code is put in a .cpp file inside the src folder. Any functions preceded by `// [[Rcpp::export]]` will be converted into end user facing R functions when the package is built using build from devtools. Any roxygen2 documentation written above an exported C++ function will be used to document the resulting R function.

The vector add function should be rewritten using roxygen2 and saved in the appropriate file.

```
# include <Rcpp.h>
using namespace Rcpp;
// @title vector_add
// @description Add two vectors
// @details Adding two vectors with a for loop
// @author Jared P. Lander
```

```
//' @export vector_add
//' @aliases vector_add
//' @param x Numeric Vector
//' @param y Numeric Vector
//' @return a numeric vector resulting from adding x and y
//' @useDynLib ThisPackage
// [[Rcpp::export]]
NumericVector vector_add(NumericVector x, NumericVector y)
{
    NumericVector result(x.size());
    for(int i=0; i<x.size(); ++i)
    {
        result[i] = x[i] + y[i];
    }
    return(result);
}
```

The magic is that Rcpp compiles the code, and then creates a new .R file in the R folder with the corresponding R code. In this case it builds the following.

```
> # This file was generated
> # by Rcpp::compileAttributes Generator token:
> # 10BE3573-1514-4C36-9D1C-5A225CD40393
>
> #' @title vector_add
> #' @description Add two vectors
```

```
> #' @details Adding two vectors with a for loop
> #' @author Jared P. Lander
> #' @export vector_add
> #' @aliases vector_add
> #' @param x Numeric Vector
> #' @param y Numeric Vector
> #' @useDynLib RcppTest
> #' @return a numeric vector resulting from adding x and
y
> vector_add <- function(x, y)
+ {
+   .Call("RcppTest_vector_add", PACKAGE = "Rcp-
pTest", x, y)
+ }
```

It is simply a wrapper function that uses `.Call` to call the compiled C++ function.

Any functions that are not preceded by `// [[Rcpp::export]]` are available to be called from within other C++ functions, but not from R, using `.Call`. Specifying a name attribute in the export statement—like

`// [[Rcpp::export(name="NewName")]]`—causes the resulting R function to be called that name. Functions that do not need an R wrapper function automatically built, but need to be callable using

.Call, should be placed in a separate .cpp file where `// [[Rcpp::interfaces(cpp)]]` is declared and each function that is to be user accessible is preceded by `// [[Rcpp::export]]`.

In order to expose its C++ functions, a package's NAMESPACE must contain `useDynLib(PackageName)`. This can be accomplished by putting the `@useDynLibPackageName` tag in any of the roxygen2 blocks. Further, if a package uses Rcpp the DESCRIPTION file must list Rcpp in both the LinkingTo and Depends fields. The LinkingTo field also allows easy linking to other C++ libraries such as RcppArmadillo, bigmemory and BH (Boost).

The src folder of the package must also contain Makevars and Makevars.win files to help with compilation. The following examples were automatically generated using `Rcpp.package.skeleton` and should be sufficient for most packages.

First the Makevars file:

---

```
## Use the R_HOME indirection to support installations of
## multiple
## R version
PKG_LIBS = `$(R_HOME)/bin/Rscript -e
"Rcpp:::LdFlags()"`
## As an alternative, one can also add this code in a file
'configure'
##
## PKG_LIBS=`${R_HOME}/bin/Rscript -e
"Rcpp:::LdFlags()"`
##
## sed -e "s|@PKG_LIBS@|${PKG_LIBS}|" \
##       src/Makevars.in > src/Makevars
##
## which together with the following file 'src/Makevars.in'
##
## PKG_LIBS = @PKG_LIBS@
## can be used to create src/Makevars dynamically. This
## scheme is more
## powerful and can be expanded to also check for and link
## with other
## libraries. It should be complemented by a file 'cleanup'
##
## rm src/Makevars
##
## which removes the autogenerated file src/Makevars.
##
## Of course, autoconf can also be used to write configure
## files. This is
```

```
## done by a number of packages, but recommended only  
for more advanced  
## users comfortable with autoconf and its related tools.
```

---

## Now the Makevars.win file:

---

```
## Use the R_HOME indirection to support installations of  
multiple  
## R version  
PKG_LIBS = $(shell "${R_HOME}/  
bin${R_ARCH_BIN}/Rscript.exe" -e  
"Rcpp:::LdFlags()")
```

---

This just barely scratches the surface of Rcpp, but should be enough to start a basic package that relies on C++ code. Packages containing C++ code are built the same as any other package, preferably using build in devtools.

## 24.7. Conclusion

Package building is a great way to make code portable between projects and to share it with other people. A package purely built with R code only requires working functions that can pass the CRAN check using `check` and proper help files that can be easily built by including `roxygen2` documentation above functions and calling document. Building the package is as simple as using `build`. Packages with C++ should use `Rcpp`.

# Appendix A. Real-Life Resources

One of the greatest aspects of R is the surrounding community, both online and in person. This includes Web resources like Twitter and Stack Overflow, meetups and textbooks.

## A.1. Meetups

[Meetup.com](http://Meetup.com) is a fantastic resource for finding like-minded people and learning experiences for just about anything including programming, statistics, video games, cupcakes and beer. They are so pervasive that as of late-July 2013, there were over 126,000 meetup groups in nearly 200 countries. Data meetups draw particularly large crowds and usually take the format of socializing, a talk for 45 to 90 minutes, and then more socializing. Meetups are not only great for learning, but also for hiring or getting hired.

R meetups are very common, although some are starting to rebrand from R meetups to statistic-

al programming meetups. Some popular meetups take place in New York, Chicago, Boston, Amsterdam, Washington D.C., San Francisco, London, Cleveland, Singapore and Melbourne. The talks generally show cool features in R, new packages or software or just an interesting analysis performed in R. The focus is usually on programming more than statistics. [Table A.1](#) lists a number of popular meetups but it is an incredibly short list compared to how many meetups exist for R.

| City           | Group Name                                             | URL                                                                                                                                   |
|----------------|--------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| New York       | New York Open Statistical Programming Meetup           | <a href="http://www.meetup.com/nyhackr/">http://www.meetup.com/nyhackr/</a>                                                           |
| New York       | NYC Stats Programming Master Classes                   | <a href="http://www.meetup.com/datasciencelclasses/">http://www.meetup.com/datasciencelclasses/</a>                                   |
| Washington, DC | Statistical Programming DC                             | <a href="http://www.meetup.com/stats-prog-dc/">http://www.meetup.com/stats-prog-dc/</a>                                               |
| Amsterdam      | amst-R-dam                                             | <a href="http://www.meetup.com/amst-R-dam/">http://www.meetup.com/amst-R-dam/</a>                                                     |
| Boston         | Greater Boston useR Group (R Programming Language)     | <a href="http://www.meetup.com/Boston-useR/">http://www.meetup.com/Boston-useR/</a>                                                   |
| San Francisco  | Bay Area useR Group (R Programming Language)           | <a href="http://www.meetup.com/R-Users/">http://www.meetup.com/R-Users/</a>                                                           |
| Chicago        | Chicago R User Group (Chicago RUG) Data and Statistics | <a href="http://www.meetup.com/ChicagoRUG/">http://www.meetup.com/ChicagoRUG/</a>                                                     |
| London         | LondonR                                                | <a href="http://www.meetup.com/LondonR/">http://www.meetup.com/LondonR/</a>                                                           |
| Singapore      | R User Group Singapore (RUGS)                          | <a href="http://www.meetup.com/R-User-Group-SG/">http://www.meetup.com/R-User-Group-SG/</a>                                           |
| Cleveland      | Greater Cleveland R Group                              | <a href="http://www.meetup.com/Cleveland-useR-Group/">http://www.meetup.com/Cleveland-useR-Group/</a>                                 |
| Melbourne      | Melbourne Users of R Network (MelbURN)                 | <a href="http://www.meetup.com/MelbURN-Melbourne-Users-of-R-Network/">http://www.meetup.com/MelbURN-Melbourne-Users-of-R-Network/</a> |
| Connecticut    | Connecticut R Users Group                              | <a href="http://www.meetup.com/Conncticut-R-Users-Group/">http://www.meetup.com/Conncticut-R-Users-Group/</a>                         |
| New York       | NYC Machine Learning Meetup                            | <a href="http://www.meetup.com/NYC-Machine-Learning/">http://www.meetup.com/NYC-Machine-Learning/</a>                                 |
| Tel Aviv       | Big Data & Data Science Israel                         | <a href="http://www.meetup.com/Big-Data-Israel/">http://www.meetup.com/Big-Data-Israel/</a>                                           |

**Table A.1 R and Related Meetups**

Machine Learning meetups are also good for finding presentations on R, although they will not necessarily be as focused on R. They are located in many of the same cities as R meetups and draw

similar speakers and audiences. These meetups tend more toward the academic than focusing on programming.

The third core meetup type is Predictive Analytics. While they may seem similar to Machine Learning meetups, they cover different material. The focus is somewhere in between that of R and Machine Learning meetups. And yes, there is significant overlap in the audiences for these meetups.

Other meetup groups that might be of interest are data science, big data and data visualization.

## A.2. Stack Overflow

Sometimes when confronted with a burning question that cannot be solved alone, a good place to turn for help is Stack Overflow (<http://stackoverflow.com/>). Previously the R mailing list was the best, or only, online resource for help, but that has since been superseded by Stack Overflow.

The site is a forum for asking programming questions where both questions and answers are voted on by users and people can build reputations as experts. This is a very quick way to get answers for even difficult questions.

Common search tags related to R are r, statistics, rcpp, ggplot2, shiny and other statistics-related terms.

Many R packages these days are hosted on GitHub, so if a bug is found and confirmed, the best way to address it is not on Stack Overflow but on the GitHub issues list for the package.

### A.3. Twitter

Sometimes just a quick answer is needed that would fit in 140 characters. In this case, Twitter is a terrific resource for R questions ranging from simple package recommendations to code snippets.

To reach the widest audience, it is important to use hash tags such as #rstats, #ggplot2, #knitr, #rcpp, #nycdatamafia and #statistics.

Great people to follow are @drewconway, @mikedewar, @harlanharris, @xieyihui, @hadleywickham, @jeffreyhorner, @revodavid, @eddelbuettel, @johnmyleswhite, @Rbloggers, @statalgo, @ProbablePattern, @CJBayesian, @RLangTip, @cmastication, @nyhackr and this book's author, @jaredlander.

## A.4. Conferences

There are a number of conferences where R is either the focus or receives a lot of attention. There are usually presentations about or involving R, and sometimes classes that teach something specific about R.

The main one is the appropriately named useR! conference, which is a yearly event at rotating locations around the world. The Web site is at <http://www.r-project.org/conferences.html>.

R in Finance is a yearly conference that takes place in Chicago and is coorganized by Dirk Edelbuettel. It is quantitatively focused and heavy in advanced math. The Web site is at <http://www.rinfinance.com/>.

Other statistics conferences that are worth attending are the Joint Statistical Meetings organized by the American Statistical Association (<http://www.amstat.org/meetings/jsm.cfm>) and Strata New York (<http://strataconf.com/strata2013/public/content/home>).

Data Gotham is a very new data science conference organized by some of the leaders of the data science community like Drew Conway and Mike Dewar. The Web site is at <http://www.datagotham.com/>.

## A.5. Web Sites

Being that R is an open-source project with a strong community, it is only appropriate that there is a large ecosystem of Web sites devoted to it. Most of them are maintained by people who love R and want to share their knowledge. Some are exclusively focused on R and some only partially.

Besides <http://www.jaredlander.com/>, some of our favorites are R-Bloggers (<http://www.r-bloggers.com/>), Zero Intelligence Agents (<http://drewconway.com/zia/>), R Enthusiasts (<http://gallery.r-enthusiasts.com/>), Rcpp Gallery (<http://gallery.rcpp.org/>), Revolution Analytics (<http://blog.revolutionanalytics.com/>), Andrew Gelman's site (<http://andrewgelman.com/>), John Myles White's site (<http://www.johnmyleswhite.com/>) and chartsnthings from *The New York Times* graphics department (<http://chartsnthings.tumblr.com/>).

## A.6. Documents

Over the years, a number of very good documents have been written about R and made freely available.

*An Introduction to R*, by William N. Venables, David M. Smith and The R Development Core Team, has been around since S, the precursor of R, and can be found at <http://cran.r-project.org/doc/manuals/R-intro.pdf>.

*The R Inferno* is a legendary document by Patrick Burns that delves into the nuances and idiosyncrasies of the language. It is available as both a printed book and a free PDF. Its Web site is <http://www.burns-stat.com/documents/books/the-r-inferno/>.

*Writing R Extensions* is a comprehensive treatise on building R packages that expands greatly on [Chapter 24](#). It is available at <http://cran.r-project.org/doc/manuals/R-exts.html>.

## A.7. Books

For a serious dose of statistics knowledge, textbooks offer a huge amount of material. Some are old fashioned and obtuse, while others are modern and packed with great techniques and tricks.

Our favorite statistics book—which happens to include a good dose of R code—is *Data Analysis Using Regression and Multilevel/Hierarchical Models* by Andrew Gelman and Jennifer Hill. The first half of the book is a good general text on statistics with R used for examples. The second half of the book focuses on Bayesian models using BUGS; the next edition is rumored to use STAN.

For advanced machine learning techniques, but not R code, Hastie, Tibshirani and Hastie's landmark *The Elements of Statistical Learning: Data Mining, Inference, and Prediction* details a number of modern algorithms and models. It delves deep into the underlying math and ex-

plains how the algorithms, including the Elastic Net, work.

Other books, not necessarily textbooks, have recently came out that are focused primarily on R. *Machine Learning for Hackers* by Drew Conway and John Myles White uses R as a tool in learning some basic machine learning algorithms. *Dynamic Documents with R and knitr* by Yihui Xie is an in-depth look at knitr and expands greatly on [Chapter 23](#). Integrating C++ into R, discussed in [Section 24.6](#), receives full treatment in *Seamless R and C++ Integration with Rcpp* by Dirk Eddelbuettel.

## A.8. Conclusion

Making use of R's fantastic community is an integral part of learning R. Person-to-person opportunities exist in the form of meetups and conferences. The best online resources are Stack Overflow and Twitter. And naturally there are a number of books and documents available both online and in bookstores.

# Appendix B. Glossary

ACF

See [autocovariance function](#)

AIC

See [Akaike Information Criterion](#)

AICC

See [Akaike Information Criterion Corrected](#)

Akaike Information Criterion

Measure of model fit quality that penalizes model complexity

Akaike Information Criterion Corrected

Version of AIC with greater penalty for model complexity

Analysis of variance

See [ANOVA](#)

Andersen-Gill

Survival analysis for modeling time to multiple events

## ANOVA

Test for comparing the means of multiple groups; the test can only detect if there is a difference between any two groups, it cannot tell which ones are different from which others

## Ansari-Bradley test

Nonparametric test for the equality of variances between two groups

## AR

See [autoregressive](#)

## ARIMA

Like an ARMA model but it includes a parameter for the number of differences of the time series data

## ARMA

See [Autoregressive Moving Average](#)

## array

Object that holds data in multiple dimensions

autocorrelation

When observations in a single variable are correlated with previous observations

Autocovariance function

The correlation of a time series with lags of itself

Autoregressive

Time series model that is a linear regression of the current value of a time series against previous values

Autoregressive Moving Average

Combination of AR and MA models

average

While generally held to be the arithmetic mean, average is actually a generic term that can mean any number of measures of centrality such as the mean, median or mode

Bartlett test

Parametric test for the equality of variances between two groups

BASH

A command line processor in the same vein as DOS; mainly used on Linux and MAC OS X though there is an emulator for Windows

basis functions

Functions whose linear combination make up other functions

basis splines

Basis functions used to compose splines

Bayesian

Type of statistics where prior information is used to inform the model

Bayesian Information Criterion

Similar to AIC but with an even greater penalty for model complexity

## Beamer

LATEX document class for producing slide shows

## Bernoulli Distribution

Probability distribution for modeling the success or failure of an event

## Beta Distribution

Probability distribution for modeling a set of possible values on a finite interval

## BIC

See [Bayesian Information Criterion](#)

## Binomial Distribution

Probability distribution for modeling the number of successful independent trials with identical probabilities of success

## Bioconductor

Repository of R packages for the analysis of genomic data

## BitBucket

Online Git repository

Boost

Fast C++ library

Bootstrap

A process in which data are resampled repeatedly, and a statistic is calculated for each resampling to form an empirical distribution for that statistic

Boxplot

A graphical display of one variable where the middle 50% of the data are in a box, and there are lines reaching out to 1.5 times the Interquartile Range and dots representing outliers

BUGS

Probabilistic programming language specializing in Bayesian computations

byte-compilation

The process of turning human readable code into machine code that runs faster

C

A fast, low-level programming language; R is written primarily in C

C++

A fast, low-level programming language that is similar to C

Cauchy Distribution

Probability distribution for the ratio of two Normal random variables

censored data

Data with unknown information, such as the occurrence of an event after a cutoff time

character

Data type for storing text

Chi-squared Distribution

The sum of  $k$  squared standard normal distributions

chunk

Piece of R code inside a LATEX or Mark-down document

class

Type of an R object

Classification

Determining the class membership of data

Clustering

Partitioning data into groups

Coefficient

A multiplier associated with a variable in an equation; in statistics this is typically what is being estimated by a regression

Coefficient plot

A visual display of the coefficients and standard errors from a regression

Comprehensive R Archive Network

See [CRAN](#)

Confidence Interval

A range within which an estimate should fall a certain percent of time

correlation

The strength of the association between two variables

covariance

A measure of the association between two variables; the strength of the relationship is not necessarily indicated

Cox proportional hazards

Model for survival analysis where predictors have a multiplicative effect on the survival rate

CRAN

The central repository for all things R

cross-validation

A modern form of model assessment where the data are split into  $k$  discrete folds, and a model is repeatedly fitted on all but one and

used to make predictions on the holdout fold

## Data Gotham

Data science conference in New York

## data munging

The process of cleaning, correcting, aggregating, joining and manipulating data to prepare it for analysis

## Data Science

The confluence of statistics, machine learning, computer engineering, visualization and social skills

## data.frame

The main data type in R, similar to a spreadsheet with tabular rows and columns

## data.table

A high speed extension of data.frames

## database

Store of data, usually in relational tables

Date

Data type for storing dates

DB2

Enterprise level database from IBM

Debian

Linux Distribution

decision tree

Modern technique for performing nonlinear regression or classification by iteratively splitting predictors

Degrees of freedom

For some statistic or distribution, this is the number of observations minus the number of parameters being estimated

density plot

Display showing the probability of observations falling within a sliding window along a variable of interest

deviance

A measure of error for generalized linear models

drop-in deviance

The amount by which deviance drops when adding a variable to a model; a general rule of thumb is that deviance should drop by two for each term added

DSN

Data source connection used to describe communication to a data source, often a database

dzslides

HTML5 slide show format

EDA

See [Exploratory Data Analysis](#)

Elastic Net

New algorithm that is a dynamic blending of lasso and ridge regressions, which is great for predictions and dealing with high dimensional datasets

Emacs

Text editor popular among programmers  
ensemble

Method of combining multiple models to  
get an average prediction

Excel

The most commonly used data analysis tool  
in the world

expected value

Weighted mean

Exploratory Data Analysis

Visually and numerically exploring data to  
get a sense of it before performing rigorous  
analysis

Exponential Distribution

Probability distribution often used to model  
the amount of time until an event occurs

F-test

Statistical test often used for comparing models, as with the ANOVA

## F Distribution

The ratio of two Chi-Squared Distributions, often used as the null distribution in analysis of variance

## factor

Special data type for handling character data as an integer value with character labels; important for including categorical data in models

## fitted values

Values predicted by a model, mostly used to denote predictions made on the same data used to fit the model

## formula

Novel interface in R that allows specification of a model using convenient mathematical notation

## FORTRAN

High-speed, low-level language; much of R is written in FORTRAN

FRED

Federal Reserve Economic Data

FTP

file transfer protocol

g++

Open source compiler for C++

GAM

See [Generalized Additive Models](#)

Gamma Distribution

Probability distribution for the time one has to wait for  $n$  events to occur

gamma regression

GLM for response data that are continuous, positive and skewed, such as auto insurance claims

Gap statistic

Measure of clustering quality, which compares the within-cluster dissimilarity for a clustering of the data with that of a bootstrapped sample of data

GARCH

See [Generalized Autoregressive Conditional Heteroskedasticity](#)

Gaussian Distribution

See [Normal Distribution](#)

gcc

Family of open-source compilers

Generalized Additive Models

Models that are formed by adding a series of smoother functions fitted on individual variables

Generalized Autoregressive Conditional Heteroskedasticity

Time series method that is more robust to extreme values of data

Generalized Linear Models

Family of regression models that model non-normal response data such as binary and count data

## Geometric Distribution

Probability distribution for the number of Bernoulli trials required before the first success occurs

## Git

Popular version control standard

## GitHub

Online Git repository

## GLM

See [Generalized Linear Models](#)

## Hadoop

Framework for distributing data and computations across a grid of computers

## Hartigan's Rule

Measure of clustering quality, which compares the within-cluster sum of squares for

a clustering of  $k$  clusters and one with  $k + 1$  clusters

heatmap

Visual display where the relationship between two variables is visualized as a mix of colors

Hierarchical Clustering

Form of clustering where each observation belongs to a cluster, which in turn belongs to a larger cluster and so on until the whole dataset is represented

histogram

Display of the counts of observations falling in discrete buckets of a variable of interest

HTML

Hypertext Markup Language; used for creating Web pages

Hypergeometric Distribution

Probability distribution for drawing  $k$  successes out of a possible  $N$  items, of which  $K$  are considered successes

hypothesis test

Test for the significance of a statistic that is being estimated

IDE

See [Integrated Development Environment](#)

indicator variables

Binary variables representing one level of a categorical variable; also called dummy variables

inference

Drawing conclusions on how predictors affect a response

integer

Data type that is only whole numbers, either positive, negative or zero

Integrated Development Environment

Software with features to make programming easier

Intel Matrix Kernel Library

Optimized matrix algebra library

interaction

The combined effect of two or more variables in a regression

intercept

Constant term in a regression; literally, the point where the best fit line passes through the  $y$ -axis; it is generalized for higher dimensions

Interquartile Range

The third quartile minus the first quartile

inverse link function

Function that transforms linear predictors to the original scale of the response data

inverse logit

Transformation needed to interpret logistic regression on the 0/1 scale; scales any number to be between 0 and 1

IQR

See [Interquartile Range](#)

Java

Low-level programming language

Joint Statistical Meetings

Conference for statisticians

JSM

See [Joint Statistical Meetings](#)

K-means

Clustering that divides the data into  $k$  discrete groups as defined by some distance measurement

K-medoids

Similar to K-means except it handles categorical data and is more robust to outliers

knitr

Modern package for interweaving R code  
with LATEX or Markdown

## Lasso Regression

Modern regression using an L1 penalty to  
perform variable selection and dimension  
reduction

## LATEX

High-quality typesetting program especially  
well suited for mathematical and scientific  
documents and books

## level

A unique value in a factor variable

## linear model

Model that is linear in the coefficients

## link function

Function that transforms response data so it  
can be modeled with a GLM

## Linux

Open source operating system

list

Robust data type that can hold any arbitrary data types

log

The inverse of an exponent; typically the natural log in statistics

Log-normal Distribution

Probability distribution whose log is Normally distributed

logical

Data type that takes on the values TRUE or FALSE

Logistic Distribution

Probability distribution used primarily for logistic regression

Logistic Regression

Regression for modeling a binary response

logit

The opposite of the inverse logit; transforms numbers between 0 and 1 to the real numbers

loop

Code that iterates through some index

MA

See [Moving Average](#)

Mac OS X

Apple's proprietary operating system

Machine Learning

Modern, computationally heavy statistics

MapReduce

Paradigm where data are split into discrete sets, computed on, and then recombined in some fashion

Markdown

Simplified formatting syntax used to produce elegant HTML documents in a simple fashion

Matlab

Expensive commercial software for mathematical programming

matrix

Two-dimensional data type

matrix algebra

Algebra performed on matrices, which greatly simplifies the math

maximum

Largest value in a set of data

mean

Mathematical average; typically either arithmetic (traditional average) or weighted

mean squared error

Quality measure for an estimator; the average of the squares of the differences between an estimator and the true value

median

Middle number of an ordered set of numbers; when there are an even number of numbers, the median is the mean of the middle two numbers

## Meetup

A Web site that facilitates real-life social interaction for any number of interests; particularly popular in the data field

## memory

Also referred to as RAM, this is where the data that R analyzes is stored while being processed; this is typically the limiting factor on the size of data that R can handle

## Microsoft Access

Lightweight database from Microsoft

## Microsoft SQL Server

Enterprise-level database from Microsoft

## minimum

Smallest value in a set of data

## Minitab

GUI based statistical package

missing data

A big problem in statistics, this is data that is not available to compute for any one of a number of reasons

MKL

See [Intel Matrix Kernel Library](#)

model complexity

Primarily how many variables are included in the model; overly complex models can be problematic

model selection

Process of fitting the optimal model

Moving Average

Time series model that is a linear regression of the current value of a time series against current and previous residuals

multicollinearity

When one column in a matrix is a linear combination of any other columns

multidimensional scaling

Projecting multiple dimensions into a smaller dimensionality

Multinomial Distribution

Probability distribution for discrete data that can take on any of  $k$  classes

Multinomial Regression

Regression for discrete response that can take on any of  $k$  classes

multiple comparisons

Doing repeated tests on multiple groups

multiple imputation

Advanced process to fill in missing data using repeated regressions

Multiple Regression

Regression with more than one predictor

MySQL

Open source database

NA

Value that indicates missing data

namespace

Convention where functions belong to specific packages; helps solve conflicts when multiple functions have the same name

natural cubic spline

Smoothing function with smooth transitions at interior breakpoints and linear behavior beyond the endpoints of the input data

Negative Binomial Distribution

Probability distribution for the number of trials required to obtain  $r$  successes; this is often used as the approximate distribution for pseudopoission regression

nonlinear least squares

Least squares regression (squared error loss) with nonlinear parameters

nonlinear model

Model where the variables do not necessarily have a linear relationship, such as decision trees and GAMs

nonparametric model

Model where the response does not necessarily follow the regular GLM distributions such as Normal, Logistic or Poisson

Normal Distribution

The most common probability distribution that is used for a wide array of phenomenon; the familiar bell curve

NULL

A data concept that represents nothingness  
null hypothesis

The assumed true value in hypothesis tests  
numeric

Data type for storing numeric values

NYC Data Mafia

Informal term for the growing prevalence of data scientists in New York City

## NYC Open Data

Initiative to make New York City government data transparent and available

## Octave

Open-source version of Matlab

## ODBC

See [Open Database Connectivity](#)

## Open Database Connectivity

Industry standard for communicating data to and from a database

## ordered factor

Character data where one level can be said to be greater or less than another level

## overdispersion

When data show more variability than indicated by the theoretical probability distribution

## p-value

The probability, if the null hypothesis were correct, of getting as extreme, or more extreme, a result

## PACF

See [partial autocovariance function](#)

## paired t-test

Two-sample t-test where every member of one sample is paired with a member of a second sample

## PAM

See Partitioning Around Medoids

## pandoc

Software for easy conversion of documents among various formats such as Markdown, HTML, LATEX and Microsoft Word

## parallel

In computational context, the running of multiple instructions simultaneously to speed computation

parallelization

The process of writing code to run in parallel

partial autocovariance function

The amount of correlation between a time series and lags of itself that is not explained by previous lags

Partitioning Around Medoids

Most common algorithm for K-medoids clustering

PDF

Common document format most often opened with Adobe Acrobat Reader

Penalized Regression

Form of regression where a penalty term prevents the coefficients from growing too large

Perl

Scripting language commonly used for text parsing

## Poisson Distribution

Probability Distribution for count data

## Poisson Regression

GLM for response data that are counts, such as number of accidents, number of touchdowns or number of ratings for a pizzeria

## POSIXct

Date-time data type

## prediction

Finding the expected value of response data for given values of predictors

## predictor

Data that are used as inputs into a model and explain and/or predict the response

## prior

Bayesian statistics use prior information, in the form of distributions for the coefficients of predictors, to improve the model fit

## Python

Scripted language that is popular for data munging

## Q-Q plot

Visual means of comparing two distributions by seeing if the quantiles of the two fall on a diagonal line

## quantile

Value, corresponding to a specified percentage, for a set of numbers, below which that percent of numbers falls

## quartile

The 25th quantile

## Quasipoisson Distribution

Distribution (actually the Negative Binomial) used for estimating count data that are overdispersed

## R-Bloggers

Popular site from Tal Galili that aggregates blogs about R

## R Console

Where R commands are entered and results are shown

## R Core Team

Group of 20 prime contributors to R who are responsible for its maintenance and direction

## R Enthusiasts

Popular R blog by Romain François

## R in Finance

Conference in Chicago about using R for finance

## RAM

See [memory](#)

## Random Forest

Ensemble method that builds multiple decision trees, each with a random subset of predictors, and combines the results to make predictions

Rcmdr

GUI interface to R

Rcpp Gallery

Online collection of Rcpp examples

Rdata

File format for storing R objects on disk

regression

Method that analyzes the relationship between predictors and a response; the bedrock of statistics

regression tree

See [decision tree](#)

Regular Expressions

String pattern matching paradigm

regularization

Method to prevent overfitting of a model, usually by introducing a penalty term

residual sum of squares

Summation of the squared residuals

Difference between fitted values from a model and the actual response values

Data that are the outcome of a model and are predicted and/or explained by the predictors

Revolution R

Commercial distribution of R developed by Revolution Analytics designed to be faster and more stable and scale better

Ridge Regression

Modern regression using an L2 penalty to shrink coefficients for more stable predictions

RSS

See [residual sum of squares](#)

RStudio

Powerful and popular open-source IDE for R

## RTools

Set of tools needed in Windows for integrating C++, and other compiled code, into R

## S

Statistical language developed at Bell Labs that was the precursor to R

## S3

Basic object type in R

## S4

Advanced object type in R

## s5

HTML5 slide show format

## SAS

Expensive commercial scripting software for statistical analysis

## scatterplot

Two-dimensional display of data where each point represents a unique combination of two variables

shapefile

Common file format for map data

shrinkage

Reducing the size of coefficients to prevent overfitting

Simple Regression

Regression with one predictor, not including the intercept

slideous

HTML5 slide show format

slidy

HTML5 slide show format

slope

Ratio of a line's rise and run; in regression this is represented by the coefficients

smoothing spline

Spline used for fitting a smooth trend to data

## spline

Function  $f$  that is a linear combination of  $N$  functions (one for each unique data point) that are transformations of the variable  $x$

## SPSS

Expensive point-and-click commercial software for statistical analysis

## SQL

Database language for accessing or inserting data

## Stack Overflow

Online resource for programming questions

## STAN

Next generation probabilistic programming language specializing in Bayesian computations

## standard deviation

How far, on average, each point is from the mean

standard error

Measure of the uncertainty for a parameter estimate

Stata

Commercial scripting language for statistical analysis

stationarity

When the mean and variance of a time series are constant for the whole series

stepwise selection

Process of choosing model variables by systematically fitting different models and adding or eliminating variables at each step

Strata

Large data conference

survival analysis

Analysis of time to event, such as death or failure

SUSE

Linux Distribution

SVN

Older version control standard

Sweave

Framework for interweaving R code with LATEX; has been superceded by knitr

Systat

Commercial statistical package

t-statistic

Ratio where the numerator is the difference between the estimated mean and the hypothesized mean, and the denominator is the standard error of the estimated mean

t-test

Test for the value of the mean of a group or the difference between the means of two groups

t Distribution

Probability distribution used for testing a mean with a student t-test

tensor product

A way of representing transformation functions of predictors, possibly measured on different units

text editor

Program for editing code that preserves the structure of the text

TextPad

Popular text editor

time series

Data where the order and time of the data are important to its analysis

ts

Data type for storing time series data

Two Sample t-test

Test for the difference of means between two samples

Ubuntu

Linux Distribution

UltraEdit

Popular text editor

Uniform Distribution

Probability distribution where every value is equally likely to be drawn

USAID Open Government

Initiative to make U.S. Aid data transparent and available

useR!

Conference for R users

VAR

See [Vector Autoregressive Model](#)

variable

R object; can be data, functions, any object  
variance

Measure of the variability, or spread, of the  
data

vector

A collection of data elements, all of the  
same type

Vector Autoregressive Model

Multivariate times series model

version control

Means of saving snapshots of code at dif-  
ferent time periods for easy maintenance  
and collaboration

vim

Text editor popular among programmers

violin plot

Similar to a boxplot except that the box is curved, giving a sense of the density of the data

Visual Basic

Programming language for building macros, mostly associated with Excel

Visual Studio

IDE produced by Microsoft

Wald test

Test for comparing models

Weibull Distribution

Probability distribution for the lifetime of an object

weighted mean

Mean where each value carries a weight, allowing the numbers to have different effects on the mean

weights

Importance given to observations in data so that one observation can be valued more or less than another

Welch t-test

Test for the difference in means between two samples where the variances of each sample can be different

white noise

Essentially random data

Windows Live Writer

Desktop blog publishing application from Microsoft

Xcode

Apple's IDE

xkcd

Web comic by Randall Munroe, beloved by statisticians, physicists and mathematicians

XML

Extensible Markup Language; often used to descriptively store and transport data

xts

Advanced data type for storing time series data

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```
> install.packages("coefplot")
```

```
> require(devtools)
> install_github(repo = "coefplot", username = "jaredlander")
```

```
> install.packages("coefplot_1.1.7.zip")
```

```
> require(coefplot)
```

*Loading required package: coefplot*

*Loading required package: ggplot2*

```
> require(coefplot, quietly = TRUE)
```

```
> detach( "package:coefplot" )
```

```
> arm::coefplot(object)
> coefplot::coefplot(object)
```



```
> j
```

```
[1] 4
```

```
> rm(j)
```

```
> # now it is gone
```

```
> j
```

Error: object 'j' not found

```
> theVariable <- 17  
> theVariable  
[1] 17
```

```
> THEVARIABLE
```

Error: object 'THEVARIABLE' not found

```
> nchar(y)  
Error: 'nchar()' requires a character vector
```

```
> date1 <- as.Date("2012-06-28")
> date1
[1] "2012-06-28"

> class(date1)
[1] "Date"

> as.numeric(date1)
[1] 15519

>
> date2 <- as.POSIXct("2012-06-28 17:42")
> date2
[1] "2012-06-28 17:42:00 EDT"

> class(date2)
[1] "POSIXct" "POSIXt"

> as.numeric(date2)
[1] 1340919720
```

```
> class(date1)
```

```
[1] "Date"
```

```
> class(as.numeric(date1))
```

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

```
> # does 2 equal 3?  
> 2 == 3  
  
[1] FALSE  
  
> # does 2 not equal three?  
> 2 != 3  
  
[1] TRUE  
  
> # is two less than three?  
> 2 < 3  
  
[1] TRUE  
  
> # is two less than or equal to three?  
> 2 <= 3  
  
[1] TRUE  
  
> # is two greater than three?  
> 2 > 3
```

```
[1] FALSE
```

```
> # is two greater than or equal to three?  
> 2 >= 3
```

```
[1] FALSE
```

```
> # is 'data' equal to 'stats'?  
> "data" == "stats"
```

```
[1] FALSE
```

```
> # is 'data' less than 'stats'?  
> "data" < "stats"
```

```
[1] TRUE
```

```
> x <- c(1, 2, 3, 4, 5, 6, 7, 8, 9, 10)
> x
[1] 1 2 3 4 5 6 7 8 9 10
```

```
> x * 3
```

```
[1] 3 6 9 12 15 18 21 24 27 30
```

```
> x + 2  
[1] 3 4 5 6 7 8 9 10 11 12  
  
> x - 3  
[1] -2 -1 0 1 2 3 4 5 6 7  
  
> x/4  
[1] 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50  
  
> x^2  
[1] 1 4 9 16 25 36 49 64 81 100  
  
> sqrt(x)  
[1] 1.000 1.414 1.732 2.000 2.236 2.449 2.646 2.828 3.000 3.162
```

```
> 1:10
```

```
[1] 1 2 3 4 5 6 7 8 9 10
```

```
> 10:1
```

```
[1] 10 9 8 7 6 5 4 3 2 1
```

```
> -2:3
```

```
[1] -2 -1 0 1 2 3
```

```
> 5:-7
```

```
[1] 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7
```

```
> # create two vectors of equal length
> x <- 1:10
> y <- -5:4
> # add them
> x + y

[1] -4 -2  0  2  4  6  8 10 12 14

> # subtract them
> x - y

[1] 6 6 6 6 6 6 6 6 6 6

> # multiply them
> x * y

[1] -5 -8 -9 -8 -5  0  7 16 27 40

> # divide them--notice division by 0 results in Inf
> x/y

[1] -0.2 -0.5 -1.0 -2.0 -5.0  Inf  7.0  4.0  3.0  2.5

> # raise one to the power of the other
> x^y

[1] 1.000e+00 6.250e-02 3.704e-02 6.250e-02 2.000e-01 1.000e+00
[7] 7.000e+00 6.400e+01 7.290e+02 1.000e+04

> # check the length of each
> length(x)

[1] 10

> length(y)

[1] 10

> # the length of them added together should be the same
> length(x + y)

[1] 10
```

```
> x + c(1, 2)
```

```
[1] 2 4 4 6 6 8 8 10 10 12
```

```
> x + c(1, 2, 3)
```

```
Warning: longer object length is not a multiple of shorter object  
length
```

```
[1] 2 4 6 5 7 9 8 10 12 11
```

```
> x <= 5
```

```
[1] TRUE TRUE TRUE TRUE TRUE FALSE FALSE FALSE FALSE FALSE
```

```
> x > y
```

```
[1] TRUE TRUE TRUE TRUE TRUE TRUE TRUE TRUE TRUE TRUE
```

```
> x < y
```

```
[1] FALSE FALSE FALSE FALSE FALSE FALSE FALSE FALSE FALSE FALSE
```

```
> q <- c("Hockey", "Football", "Baseball", "Curling", "Rugby",
+       "Lacrosse", "Basketball", "Tennis", "Cricket", "Soccer")
> nchar(q)
[1] 6 8 8 7 5 8 10 6 7 6
> nchar(y)
[1] 2 2 2 2 1 1 1 1 1 1
```

```
> # provide a name for each element of an array using a name-value pair
> c(One = "a", Two = "y", Last = "r")
One   Two  Last
"a"   "y"   "r"

>
> # create a vector
> w <- 1:3
> # name the elements
> names(w) <- c("a", "b", "c")
> w
a b c
1 2 3
```

```
> q2 <- c(q, "Hockey", "Lacrosse", "Hockey", "Water Polo",
+           "Hockey", "Lacrosse")
```

```
> q2Factor <- as.factor(q2)
> q2Factor
[1] Hockey      Football    Baseball   Curling     Rugby      Lacrosse
[7] Basketball Tennis     Cricket    Soccer      Hockey     Lacrosse
[13] Hockey     Water Polo Hockey    Lacrosse
11 Levels: Baseball Basketball Cricket Curling Football ... Water Polo
```

```
> as.numeric(q2Factor)
```

```
[1] 6 5 1 4 8 7 2 10 3 9 6 7 6 11 6 7
```

```
> factor(x=c("High School", "College", "Masters", "Doctorate"),
+         levels=c("High School", "College", "Masters", "Doctorate"),
+         ordered=TRUE)

[1] High School College      Masters      Doctorate
Levels: High School < College < Masters < Doctorate
```

```
> apropos ("mea")
```

```
[1] ".cache/mean-simple_ce29515dafe58a90a771568646d73aae"  
[2] ".colMeans"  
[3] ".rowMeans"  
[4] "colMeans"  
[5] "influence.measures"  
[6] "kmeans"  
[7] "mean"  
[8] "mean.Date"  
[9] "mean.default"  
[10] "mean.difftime"  
[11] "mean.POSIXct"  
[12] "mean.POSIXlt"  
[13] "mean_cl_boot"  
[14] "mean_cl_normal"  
[15] "mean_sdl"  
[16] "mean_se"  
[17] "rowMeans"  
[18] "weighted.mean"
```

```
> z <- c(1, 2, NA, 8, 3, NA, 3)
```

```
> z
```

```
[1] 1 2 NA 8 3 NA 3
```

```
> is.na(z)
```

```
[1] FALSE FALSE TRUE FALSE FALSE TRUE FALSE
```

```
> zChar <- c("Hockey", NA, "Lacrosse")
> zChar
[1] "Hockey"      NA           "Lacrosse"
> is.na(zChar)
[1] FALSE  TRUE FALSE
```



```
> x <- 10:1
> y <- -4:5
> q <- c("Hockey", "Football", "Baseball", "Curling", "Rugby",
+       "Lacrosse", "Basketball", "Tennis", "Cricket", "Soccer")
> theDF <- data.frame(x, y, q)
> theDF
```

|    | x  | y  | q          |
|----|----|----|------------|
| 1  | 10 | -4 | Hockey     |
| 2  | 9  | -3 | Football   |
| 3  | 8  | -2 | Baseball   |
| 4  | 7  | -1 | Curling    |
| 5  | 6  | 0  | Rugby      |
| 6  | 5  | 1  | Lacrosse   |
| 7  | 4  | 2  | Basketball |
| 8  | 3  | 3  | Tennis     |
| 9  | 2  | 4  | Cricket    |
| 10 | 1  | 5  | Soccer     |

```
> theDF <- data.frame(First = x, Second = y, Sport = q)
> theDF
```

|    | First | Second | Sport      |
|----|-------|--------|------------|
| 1  | 10    | -4     | Hockey     |
| 2  | 9     | -3     | Football   |
| 3  | 8     | -2     | Baseball   |
| 4  | 7     | -1     | Curling    |
| 5  | 6     | 0      | Rugby      |
| 6  | 5     | 1      | Lacrosse   |
| 7  | 4     | 2      | Basketball |
| 8  | 3     | 3      | Tennis     |
| 9  | 2     | 4      | Cricket    |
| 10 | 1     | 5      | Soccer     |

```
> names(theDF)
```

```
[1] "First"   "Second"  "Sport"
```

```
> names(theDF)[3]
```

```
[1] "Sport"
```

```
> rownames(theDF)
[1] "1"  "2"  "3"  "4"  "5"  "6"  "7"  "8"  "9"  "10"
> rownames(theDF) <- c("One", "Two", "Three", "Four", "Five", "Six",
+                         "Seven", "Eight", "Nine", "Ten")
> rownames(theDF)
[1] "One"   "Two"   "Three" "Four"  "Five"  "Six"   "Seven" "Eight"
[9] "Nine"  "Ten"
> # set them back to the generic index
> rownames(theDF) <- NULL
> rownames(theDF)
[1] "1"  "2"  "3"  "4"  "5"  "6"  "7"  "8"  "9"  "10"
```

```
> head(theDF)
```

|   | First | Second | Sport    |
|---|-------|--------|----------|
| 1 | 10    | -4     | Hockey   |
| 2 | 9     | -3     | Football |
| 3 | 8     | -2     | Baseball |
| 4 | 7     | -1     | Curling  |
| 5 | 6     | 0      | Rugby    |
| 6 | 5     | 1      | Lacrosse |

```
> head(theDF, n = 7)
```

|   | First | Second | Sport      |
|---|-------|--------|------------|
| 1 | 10    | -4     | Hockey     |
| 2 | 9     | -3     | Football   |
| 3 | 8     | -2     | Baseball   |
| 4 | 7     | -1     | Curling    |
| 5 | 6     | 0      | Rugby      |
| 6 | 5     | 1      | Lacrosse   |
| 7 | 4     | 2      | Basketball |



```
> theDF$Sport  
[1] Hockey      Football    Baseball   Curling     Rugby       Lacrosse  
[7] Basketball Tennis     Cricket     Soccer  
10 Levels: Baseball Basketball Cricket Curling Football ... Tennis
```

```
> # row 3, columns 2 through 3
> theDF[3, 2:3]
   Second      Sport
3       -2 Baseball

>
> # rows 3 and 5, column 2
> # since only one column was selected it was returned as a vector
> # hence the column names will not be printed
> theDF[c(3, 5), 2]

[1] -2  0

>
> # rows 3 and 5, columns 2 through 3
> theDF[c(3, 5), 2:3]
   Second      Sport
3       -2 Baseball
5        0    Rugby
```

```
> # all of column 3
> # since it is only one column a vector is returned
> theDF[, 3]
[1] Hockey      Football    Baseball   Curling      Rugby       Lacrosse
[7] Basketball  Tennis      Cricket     Soccer
10 Levels: Baseball Basketball Cricket Curling Football ... Tennis

>
> # all of columns 2 through 3
> theDF[, 2:3]

  Second      Sport
1      -4      Hockey
2      -3      Football
3      -2      Baseball
4      -1      Curling
5       0      Rugby
6       1      Lacrosse
7       2 Basketball
8       3      Tennis
9       4      Cricket
10      5      Soccer

>
> # all of row 2
> theDF[2, ]

  First Second      Sport
2      9      -3 Football

>
> # all of rows 2 through 4
> theDF[2:4, ]

  First Second      Sport
2      9      -3 Football
3      8      -2 Baseball
4      7      -1 Curling
```

```
> theDF[, c("First", "Sport")]
```

|    | First | Sport      |
|----|-------|------------|
| 1  | 10    | Hockey     |
| 2  | 9     | Football   |
| 3  | 8     | Baseball   |
| 4  | 7     | Curling    |
| 5  | 6     | Rugby      |
| 6  | 5     | Lacrosse   |
| 7  | 4     | Basketball |
| 8  | 3     | Tennis     |
| 9  | 2     | Cricket    |
| 10 | 1     | Soccer     |

```
> # just the "Sport" column
> # since it is one column it returns as a (factor) vector
> theDF[, "Sport"]
[1] Hockey      Football    Baseball   Curling      Rugby       Lacrosse
[7] Basketball Tennis     Cricket     Soccer
10 Levels: Baseball Basketball Cricket Curling Football ... Tennis

> class(theDF[, "Sport"])
[1] "factor"

>
> # just the "Sport" column
> # this returns a one column data.frame
> theDF[["Sport"]]

      Sport
1      Hockey
2      Football
3      Baseball
4      Curling
5      Rugby
6      Lacrosse
7  Basketball
8      Tennis
9      Cricket
10     Soccer

> class(theDF[["Sport"]])
[1] "data.frame"

>
> # just the "Sport" column
> # this also returns a (factor) vector
> theDF[["Sport"]]
[1] Hockey      Football    Baseball   Curling      Rugby       Lacrosse
[7] Basketball Tennis     Cricket     Soccer
10 Levels: Baseball Basketball Cricket Curling Football ... Tennis

> class(theDF[["Sport"]])
[1] "factor"
```

```
> theDF[, "Sport", drop = FALSE]  
      Sport  
1    Hockey  
2   Football  
3  Baseball  
4   Curling  
5    Rugby  
6  Lacrosse  
7 Basketball  
8    Tennis  
9   Cricket  
10   Soccer
```

```
> class(theDF[, "Sport", drop = FALSE])
```

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

```
>
```

```
> theDF[, 3, drop = FALSE]  
      Sport  
1    Hockey  
2  Football  
3 Baseball  
4   Curling  
5    Rugby  
6 Lacrosse  
7 Basketball  
8    Tennis  
9   Cricket  
10   Soccer  
  
> class(theDF[, 3, drop = FALSE])  
[1] "data.frame"
```

```
> newFactor <- factor(c("Pennsylvania", "New York", "New Jersey", "New York",
+ "Tennessee", "Massachusetts", "Pennsylvania", "New York"))
> model.matrix(~newFactor - 1)

   newFactorMassachusetts newFactorNew Jersey newFactorNew York
1                      0                      0                      0
2                      0                      0                      1
3                      0                      1                      0
4                      0                      0                      1
5                      0                      0                      0
6                      1                      0                      0
7                      0                      0                      0
8                      0                      0                      1

   newFactorPennsylvania newFactorTennessee
1                     1                      0
2                     0                      0
3                     0                      0
4                     0                      0
5                     0                      1
6                     0                      0
7                     1                      0
8                     0                      0

attr(,"assign")
[1] 1 1 1 1 1
attr(,"contrasts")
attr(,"contrasts")$newFactor
[1] "contr.treatment"
```

```
> # creates a three element list
> list(1, 2, 3)

[[1]]
[1] 1

[[2]]
[1] 2

[[3]]
[1] 3

>
> # creates a single element list where the only element is a vector
> # that has three elements
> list(c(1, 2, 3))

[[1]]
[1] 1 2 3

>
> # creates a two element list
> # the first element is a three element vector
> # the second element is a five element vector
> (list3 <- list(c(1, 2, 3), 3:7))
```

```
[[1]]  
[1] 1 2 3  
  
[[2]]  
[1] 3 4 5 6 7  
  
>  
> # two element list  
> # first element is a data.frame  
> # second element is a 10 element vector  
> list(theDF, 1:10)  
  
[[1]]  
First Second     Sport  
1      10      -4    Hockey  
2       9      -3   Football  
3       8      -2  Baseball  
4       7      -1  Curling  
5       6       0    Rugby  
6       5       1 Lacrosse  
7       4       2 Basketball  
8       3       3    Tennis  
9       2       4   Cricket  
10      1       5   Soccer  
  
[[2]]  
[1] 1 2 3 4 5 6 7 8 9 10
```

```
>
> # three element list
> # first is a data.frame
> # second is a vector
> # third is list3, which holds two vectors
> list5 <- list(theDF, 1:10, list3)
> list5
```

```
[1]
First Second      Sport
1     10      -4    Hockey
2      9      -3   Football
3      8      -2  Baseball
4      7      -1   Curling
5      6       0    Rugby
6      5       1 Lacrosse
7      4       2 Basketball
8      3       3    Tennis
9      2       4   Cricket
10     1       5   Soccer
```

```
[2]
[1] 1 2 3 4 5 6 7 8 9 10
```

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

```
[[3]][[2]]
[1] 3 4 5 6 7
```

```
> names(list5)
```

```
NULL
```

```
> names(list5) <- c("data.frame", "vector", "list")  
> names(list5)
```

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

```
> list5
```

```
$data.frame  
  First Second     Sport  
1     10     -4    Hockey  
2      9     -3   Football  
3      8     -2   Baseball  
4      7     -1   Curling  
5      6      0    Rugby  
6      5      1 Lacrosse
```

```
7      4      2 Basketball
8      3      3      Tennis
9      2      4      Cricket
10     1      5      Soccer
```

```
$vector
```

```
[1] 1 2 3 4 5 6 7 8 9 10
```

```
$list
```

```
$list[[1]]
```

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

```
$list[[2]]
```

```
[1] 3 4 5 6 7
```

```
> list6 <- list(TheDataFrame = theDF, TheVector = 1:10, TheList = list3)
> names(list6)

[1] "TheDataFrame" "TheVector"      "TheList"

> list6

$TheDataFrame
  First Second     Sport
1     10     -4    Hockey
2      9     -3   Football
3      8     -2  Baseball
4      7     -1   Curling
5      6      0    Rugby
6      5      1  Lacrosse
7      4      2 Basketball
8      3      3    Tennis
9      2      4   Cricket
10     1      5   Soccer

$TheVector
[1] 1 2 3 4 5 6 7 8 9 10

$TheList
$TheList[[1]]
[1] 1 2 3

$TheList[[2]]
[1] 3 4 5 6 7
```

```
> (emptyList <- vector(mode = "list", length = 4))  
[[1]]  
NULL  
  
[[2]]  
NULL  
  
[[3]]  
NULL  
  
[[4]]  
NULL
```

```
> list5[[1]]
```

|    | First | Second | Sport      |
|----|-------|--------|------------|
| 1  | 10    | -4     | Hockey     |
| 2  | 9     | -3     | Football   |
| 3  | 8     | -2     | Baseball   |
| 4  | 7     | -1     | Curling    |
| 5  | 6     | 0      | Rugby      |
| 6  | 5     | 1      | Lacrosse   |
| 7  | 4     | 2      | Basketball |
| 8  | 3     | 3      | Tennis     |
| 9  | 2     | 4      | Cricket    |
| 10 | 1     | 5      | Soccer     |

```
> list5[["data.frame"]]
```

|   | First | Second | Sport    |
|---|-------|--------|----------|
| 1 | 10    | -4     | Hockey   |
| 2 | 9     | -3     | Football |



```
> list5[[1]]$Sport
[1] Hockey      Football    Baseball   Curling     Rugby       Lacrosse
[7] Basketball Tennis      Cricket     Soccer
10 Levels: Baseball Basketball Cricket Curling Football ... Tennis

> list5[[1]][, "Second"]
[1] -4 -3 -2 -1  0  1  2  3  4  5

> list5[[1]][, "Second", drop = FALSE]
  Second
1      -4
2      -3
3      -2
4      -1
5       0
6       1
7       2
8       3
9       4
10      5
```

```
> # see how long it currently is
> length(list5)

[1] 3

>
> # add a fourth element, unnamed
> list5[[4]] <- 2
> length(list5)

[1] 4

>
> # add a fifth element, named
> list5[["NewElement"]] <- 3:6
> length(list5)

[1] 5

>
> names(list5)

[1] "data.frame" "vector"      "list"        ""
                               "NewElement"

> list5

$data.frame
  First Second      Sport
```

|    |    |    |            |
|----|----|----|------------|
| 1  | 10 | -4 | Hockey     |
| 2  | 9  | -3 | Football   |
| 3  | 8  | -2 | Baseball   |
| 4  | 7  | -1 | Curling    |
| 5  | 6  | 0  | Rugby      |
| 6  | 5  | 1  | Lacrosse   |
| 7  | 4  | 2  | Basketball |
| 8  | 3  | 3  | Tennis     |
| 9  | 2  | 4  | Cricket    |
| 10 | 1  | 5  | Soccer     |

```
$vector  
[1] 1 2 3 4 5 6 7 8 9 10
```

```
$list  
$list[[1]]  
[1] 1 2 3
```

```
$list[[2]]  
[1] 3 4 5 6 7
```

```
[[4]]  
[1] 2
```

```
$NewElement  
[1] 3 4 5 6
```

```
> # create a 5x2 matrix  
> A <- matrix(1:10, nrow = 5)  
> # create another 5x2 matrix  
> B <- matrix(21:30, nrow = 5)  
> # create another 5x2 matrix  
> C <- matrix(21:40, nrow = 2)  
> A
```

[,1] [,2]

```
[1,] 1 6  
[2,] 2 7  
[3,] 3 8  
[4,] 4 9  
[5,] 5 10
```

```
> B
```

[,1] [,2]

```
[1,] 21 26  
[2,] 22 27  
[3,] 23 28  
[4,] 24 29  
[5,] 25 30
```

```
> C
```

[,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]

```
[1,] 21 23 25 27 29 31 33 35 37 39  
[2,] 22 24 26 28 30 32 34 36 38 40
```

```
> nrow(A)
[1] 5

> ncol(A)
[1] 2

> dim(A)
[1] 5 2

> # add them
> A + B

[,1] [,2]
[1,]    22   32
[2,]    24   34
[3,]    26   36
[4,]    28   38
[5,]    30   40

> # multiply them
> A * B
```

```
[,1] [,2]
[1,]    21   156
[2,]    44   189
[3,]    69   224
[4,]    96   261
[5,]   125   300

> # see if the elements are equal
> A == B

[,1] [,2]
[1,] FALSE FALSE
[2,] FALSE FALSE
[3,] FALSE FALSE
[4,] FALSE FALSE
[5,] FALSE FALSE
```

```
> A %*% t(B)
```

|      | [,1] | [,2] | [,3] | [,4] | [,5] |
|------|------|------|------|------|------|
| [1,] | 177  | 184  | 191  | 198  | 205  |
| [2,] | 224  | 233  | 242  | 251  | 260  |
| [3,] | 271  | 282  | 293  | 304  | 315  |
| [4,] | 318  | 331  | 344  | 357  | 370  |
| [5,] | 365  | 380  | 395  | 410  | 425  |

```
> colnames(A)  
NULL  
  
> rownames(A)  
NULL  
  
> colnames(A) <- c("Left", "Right")  
> rownames(A) <- c("1st", "2nd", "3rd", "4th", "5th")  
>  
> colnames(B)  
  
NULL  
  
> rownames(B)  
NULL  
  
> colnames(B) <- c("First", "Second")  
> rownames(B) <- c("One", "Two", "Three", "Four", "Five")  
>  
> colnames(C)  
  
NULL  
  
> rownames(C)  
NULL  
  
> colnames(C) <- LETTERS[1:10]  
> rownames(C) <- c("Top", "Bottom")
```

```
> t(A)
```

|       | 1st | 2nd | 3rd | 4th | 5th |
|-------|-----|-----|-----|-----|-----|
| Left  | 1   | 2   | 3   | 4   | 5   |
| Right | 6   | 7   | 8   | 9   | 10  |

```
> A %*% C
```

|     | A   | B   | C   | D   | E   | F   | G   | H   | I   | J   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1st | 153 | 167 | 181 | 195 | 209 | 223 | 237 | 251 | 265 | 279 |
| 2nd | 196 | 214 | 232 | 250 | 268 | 286 | 304 | 322 | 340 | 358 |
| 3rd | 239 | 261 | 283 | 305 | 327 | 349 | 371 | 393 | 415 | 437 |
| 4th | 282 | 308 | 334 | 360 | 386 | 412 | 438 | 464 | 490 | 516 |
| 5th | 325 | 355 | 385 | 415 | 445 | 475 | 505 | 535 | 565 | 595 |

```
> theArray <- array(1:12, dim = c(2, 3, 2))
> theArray
, , 1

[,1] [,2] [,3]
[1,]    1    3    5
[2,]    2    4    6

, , 2

[,1] [,2] [,3]
[1,]    7    9   11
[2,]    8   10   12

> theArray[1, , ]
, , 1

[,1] [,2]
[1,]    1    7
[2,]    3    9
[3,]    5   11

> theArray[1, , 1]
[1] 1 3 5

> theArray[, , 1]

[,1] [,2] [,3]
[1,]    1    3    5
```



```
> theUrl <- "http://www.jaredlander.com/data/Tomato%20First.csv"
> tomato <- read.table (file = theUrl, header = TRUE, sep = ",")
```

```
> head(tomato)
```

| Round                              |     | Tomato             | Price | Source      | Sweet | Acid | Color | Texture |
|------------------------------------|-----|--------------------|-------|-------------|-------|------|-------|---------|
| 1                                  | 1   | Simpson SM         | 3.99  | Whole Foods | 2.8   | 2.8  | 3.7   | 3.4     |
| 2                                  | 1   | Tuttorosso (blue)  | 2.99  | Pioneer     | 3.3   | 2.8  | 3.4   | 3.0     |
| 3                                  | 1   | Tuttorosso (green) | 0.99  | Pioneer     | 2.8   | 2.6  | 3.3   | 2.8     |
| 4                                  | 1   | La Fede SM DOP     | 3.99  | Shop Rite   | 2.6   | 2.8  | 3.0   | 2.3     |
| 5                                  | 2   | Cento SM DOP       | 5.49  | D Agostino  | 3.3   | 3.1  | 2.9   | 2.8     |
| 6                                  | 2   | Cento Organic      | 4.99  | D Agostino  | 3.2   | 2.9  | 2.9   | 3.1     |
| Overall Avg.of.Totals Total.of.Avg |     |                    |       |             |       |      |       |         |
| 1                                  | 3.4 |                    | 16.1  |             | 16.1  |      |       |         |
| 2                                  | 2.9 |                    | 15.3  |             | 15.3  |      |       |         |
| 3                                  | 2.9 |                    | 14.3  |             | 14.3  |      |       |         |
| 4                                  | 2.8 |                    | 13.4  |             | 13.4  |      |       |         |
| 5                                  | 3.1 |                    | 14.4  |             | 15.2  |      |       |         |
| 6                                  | 2.9 |                    | 15.5  |             | 15.1  |      |       |         |

```
> x <- 10:1
> y <- -4:5
> q <- c("Hockey", "Football", "Baseball", "Curling", "Rugby",
+       "Lacrosse", "Basketball", "Tennis", "Cricket", "Soccer")
> theDF <- data.frame(First=x, Second=y, Sport=q, stringsAsFactors=FALSE)
> theDF$Sport

[1] "Hockey"      "Football"     "Baseball"     "Curling"      "Rugby"
[6] "Lacrosse"    "Basketball"   "Tennis"       "Cricket"      "Soccer"
```

```
> db <- odbcConnect("QV Training")
```

```
> # simple SELECT * query from one table
> ordersTable <- sqlQuery(db, "SELECT * FROM Orders",
+                           stringsAsFactors=FALSE)
> # simple SELECT * query from one table
> detailsTable <- sqlQuery(db, "SELECT * FROM [Order Details]",
+                            stringsAsFactors=FALSE)
> # do a join between the two tables
> longQuery <- "SELECT * FROM Orders, [Order Details]
+ WHERE Orders.OrderID = [Order Details].OrderID"
> detailsJoin <- sqlQuery(db, longQuery, stringsAsFactors=FALSE)
```

```
> head(ordersTable)
```

|   | OrderID | OrderDate  | CustomerID | EmployeeID | ShipperID | Freight |
|---|---------|------------|------------|------------|-----------|---------|
| 1 | 10248   | 2008-06-29 |            | 4          | 2         | 2 43.48 |
| 2 | 10249   | 2007-06-29 |            | 79         | 7         | 2 29.20 |
| 3 | 10250   | 2008-07-03 |            | 34         | 2         | 2 79.17 |
| 4 | 10251   | 2007-12-02 |            | 1          | 7         | 2 43.41 |
| 5 | 10252   | 2008-04-04 |            | 76         | 5         | 1 23.20 |
| 6 | 10253   | 2008-07-05 |            | 34         | 3         | 2 66.54 |

```
> head(detailsTable)
```

|   | OrderID | LineNo | ProductID | Quantity | UnitPrice | Discount |
|---|---------|--------|-----------|----------|-----------|----------|
| 1 | 10402   | 2      | 63        | 65       | 18.94     | 0.00     |
| 2 | 10403   | 1      | 48        | 70       | 31.83     | 0.15     |
| 3 | 10403   | 2      | 16        | 21       | 10.15     | 0.15     |
| 4 | 10404   | 1      | 42        | 40       | 13.37     | 0.05     |
| 5 | 10404   | 2      | 49        | 30       | 19.82     | 0.05     |
| 6 | 10404   | 3      | 26        | 30       | 33.93     | 0.05     |

```
> head(detailsJoin)
```

|   | OrderID | OrderDate  | CustomerID | EmployeeID | ShipperID | Freight |
|---|---------|------------|------------|------------|-----------|---------|
| 1 | 10402   | 2006-04-28 |            | 20         | 4         | 1 46.63 |
| 2 | 10403   | 2006-09-28 |            | 20         | 4         | 1 26.43 |
| 3 | 10403   | 2006-09-28 |            | 20         | 4         | 1 26.43 |
| 4 | 10404   | 2006-04-19 |            | 49         | 6         | 1 72.73 |
| 5 | 10404   | 2006-04-19 |            | 49         | 6         | 1 72.73 |
| 6 | 10404   | 2006-04-19 |            | 49         | 6         | 1 72.73 |

|   | OrderID.1 | LineNo | ProductID | Quantity | UnitPrice | Discount |
|---|-----------|--------|-----------|----------|-----------|----------|
| 1 | 10402     | 2      | 63        | 65       | 18.94     | 0.00     |
| 2 | 10403     | 1      | 48        | 70       | 31.83     | 0.15     |
| 3 | 10403     | 2      | 16        | 21       | 10.15     | 0.15     |
| 4 | 10404     | 1      | 42        | 40       | 13.37     | 0.05     |
| 5 | 10404     | 2      | 49        | 30       | 19.82     | 0.05     |
| 6 | 10404     | 3      | 26        | 30       | 33.93     | 0.05     |

```
> # save the tomato data.frame to disk  
> save(tomato, file = "data/tomato.rdata")  
> # remove tomato from memory  
> rm(tomato)  
> # check if it still exists  
> head(tomato)
```

Error: object 'tomato' not found

```
> # read it from the rdata file  
> load("data/tomato.rdata")  
> # check if it exists now  
> head(tomato)
```

|   | Round | Tomato                | Price        | Source      | Sweet | Acid | Color | Texture |
|---|-------|-----------------------|--------------|-------------|-------|------|-------|---------|
| 1 | 1     | Simpson SM            | 3.99         | Whole Foods | 2.8   | 2.8  | 3.7   | 3.4     |
| 2 | 1     | Tuttorosso (blue)     | 2.99         | Pioneer     | 3.3   | 2.8  | 3.4   | 3.0     |
| 3 | 1     | Tuttorosso (green)    | 0.99         | Pioneer     | 2.8   | 2.6  | 3.3   | 2.8     |
| 4 | 1     | La Fede SM DOP        | 3.99         | Shop Rite   | 2.6   | 2.8  | 3.0   | 2.3     |
| 5 | 2     | Cento SM DOP          | 5.49         | D Agostino  | 3.3   | 3.1  | 2.9   | 2.8     |
| 6 | 2     | Cento Organic         | 4.99         | D Agostino  | 3.2   | 2.9  | 2.9   | 3.1     |
|   |       | Overall Avg.of.Totals | Total.of.Avg |             |       |      |       |         |
| 1 |       | 3.4                   | 16.1         |             | 16.1  |      |       |         |
| 2 |       | 2.9                   | 15.3         |             | 15.3  |      |       |         |
| 3 |       | 2.9                   | 14.3         |             | 14.3  |      |       |         |
| 4 |       | 2.8                   | 13.4         |             | 13.4  |      |       |         |
| 5 |       | 3.1                   | 14.4         |             | 15.2  |      |       |         |
| 6 |       | 2.9                   | 15.5         |             | 15.1  |      |       |         |

```
> # create some objects  
> n <- 20  
> r <- 1:10  
> w <- data.frame(n, r)  
> # check them out  
> n
```

```
[1] 20
```

```
> r
```

```
[1] 1 2 3 4 5 6 7 8 9 10
```

```
> w
```

|    | n  | r  |
|----|----|----|
| 1  | 20 | 1  |
| 2  | 20 | 2  |
| 3  | 20 | 3  |
| 4  | 20 | 4  |
| 5  | 20 | 5  |
| 6  | 20 | 6  |
| 7  | 20 | 7  |
| 8  | 20 | 8  |
| 9  | 20 | 9  |
| 10 | 20 | 10 |

```
> # save them  
> save(n, r, w, file = "data/multiple.rdata")  
> # delete them
```

```
> rm(n, r, w)
> # are they gone?
> n

Error: object 'n' not found

> r

Error: object 'r' not found

> w

Error: object 'w' not found

> # load them back
> load("data/multiple.rdata")
> # check them out again
> n

[1] 20

> r
```

```
[1] 1 2 3 4 5 6 7 8 9 10
```

```
> w
```

|    | n  | r  |
|----|----|----|
| 1  | 20 | 1  |
| 2  | 20 | 2  |
| 3  | 20 | 3  |
| 4  | 20 | 4  |
| 5  | 20 | 5  |
| 6  | 20 | 6  |
| 7  | 20 | 7  |
| 8  | 20 | 8  |
| 9  | 20 | 9  |
| 10 | 20 | 10 |

```
> require(ggplot2)
> data(diamonds)
> head(diamonds)
```

|   | carat | cut       | color | clarity | depth | table | price | x    | y    | z    |
|---|-------|-----------|-------|---------|-------|-------|-------|------|------|------|
| 1 | 0.23  | Ideal     | E     | SI2     | 61.5  | 55    | 326   | 3.95 | 3.98 | 2.43 |
| 2 | 0.21  | Premium   | E     | SI1     | 59.8  | 61    | 326   | 3.89 | 3.84 | 2.31 |
| 3 | 0.23  | Good      | E     | VS1     | 56.9  | 65    | 327   | 4.05 | 4.07 | 2.31 |
| 4 | 0.29  | Premium   | I     | VS2     | 62.4  | 58    | 334   | 4.20 | 4.23 | 2.63 |
| 5 | 0.31  | Good      | J     | SI2     | 63.3  | 58    | 335   | 4.34 | 4.35 | 2.75 |
| 6 | 0.24  | Very Good | J     | VVS2    | 62.8  | 57    | 336   | 3.94 | 3.96 | 2.48 |

```
> require(XML)
> theURL <- "http://www.jaredlander.com/2012/02/another-kind-of-
+      super-bowl-pool/"
> bowlPool <- readHTMLTable(theURL, which = 1, header = FALSE,
+      stringsAsFactors = FALSE)
> bowlPool
```

|    | V1             | V2      | V3        |
|----|----------------|---------|-----------|
| 1  | Participant 1  | Giant A | Patriot Q |
| 2  | Participant 2  | Giant B | Patriot R |
| 3  | Participant 3  | Giant C | Patriot S |
| 4  | Participant 4  | Giant D | Patriot T |
| 5  | Participant 5  | Giant E | Patriot U |
| 6  | Participant 6  | Giant F | Patriot V |
| 7  | Participant 7  | Giant G | Patriot W |
| 8  | Participant 8  | Giant H | Patriot X |
| 9  | Participant 9  | Giant I | Patriot Y |
| 10 | Participant 10 | Giant J | Patriot Z |



```
> require(ggplot2)
> data(diamonds)
> head(diamonds)
```

|   | carat | cut       | color | clarity | depth | table | price | x    | y    | z    |
|---|-------|-----------|-------|---------|-------|-------|-------|------|------|------|
| 1 | 0.23  | Ideal     | E     | SI2     | 61.5  | 55    | 326   | 3.95 | 3.98 | 2.43 |
| 2 | 0.21  | Premium   | E     | SI1     | 59.8  | 61    | 326   | 3.89 | 3.84 | 2.31 |
| 3 | 0.23  | Good      | E     | VS1     | 56.9  | 65    | 327   | 4.05 | 4.07 | 2.31 |
| 4 | 0.29  | Premium   | I     | VS2     | 62.4  | 58    | 334   | 4.20 | 4.23 | 2.63 |
| 5 | 0.31  | Good      | J     | SI2     | 63.3  | 58    | 335   | 4.34 | 4.35 | 2.75 |
| 6 | 0.24  | Very Good | J     | VVS2    | 62.8  | 57    | 336   | 3.94 | 3.96 | 2.48 |

```
> hist(diamonds$carat, main = "Carat Histogram", xlab = "Carat")
```

```
> plot(price ~ carat, data = diamonds)
```

```
> plot(diamonds$carat, diamonds$price)
```

```
> boxplot(diamonds$carat)
```

```
> ggplot(data = diamonds) + geom_histogram(aes(x = carat))
```

```
> ggplot(data = diamonds) + geom_density(aes(x = carat), fill = "grey50")
```

```
> ggplot(diamonds, aes(x = carat, y = price)) + geom_point()
```

```
> # save basics of ggplot object to a variable  
> g <- ggplot(diamonds, aes(x = carat, y = price))
```

```
> g + geom_point(aes(color = color))
```

```
> g + geom_point(aes(color = color)) + facet_wrap(~color)

> g + geom_point(aes(color = color)) + facet_grid(cut ~ clarity)
```

```
> ggplot(diamonds, aes(x = carat)) + geom_histogram() + facet_wrap(~color)
```

```
> ggplot(diamonds, aes(y = carat, x = 1)) + geom_boxplot()
```

```
> ggplot(diamonds, aes(y = carat, x = cut)) + geom_boxplot()
```

```
> ggplot(diamonds, aes(y = carat, x = cut)) + geom_violin()
```

```
> ggplot(diamonds, aes(y = carat, x = cut)) + geom_point() + geom_violin()  
> ggplot(diamonds, aes(y = carat, x = cut)) + geom_violin() + geom_point()
```

```
> ggplot(economics, aes(x = date, y = pop)) + geom_line()
```

```
> # load the lubridate package
> require(lubridate)
>
> ## create year and month variables
> economics$year <- year(economics$date)
> # the label argument to month means that the result should be the
> # names of the month instead of the number
> economics$month <- month(economics$date, label=TRUE)
>
> # subset the data
> # the which function returns the indices of observations where the
> # tested condition was TRUE
> econ2000 <- economics[which(economics$year >= 2000), ]
>
> # load the scales package for better axis formatting
> require(scales)
>
> # build the foundation of the plot
> g <- ggplot(econ2000, aes(x=month, y=pop))
> # add lines color coded and grouped by year
> # the group aesthetic breaks the data into separate groups
> g <- g + geom_line(aes(color=factor(year), group=year))
> # name the legend "Year"
> g <- g + scale_color_discrete(name="Year")
> # format the y axis
> g <- g + scale_y_continuous(labels=comma)
> # add a title and axis labels
> g <- g + labs(title="Population Growth", x="Month", y="Population")
> # plot the graph
> g
```

```
> require(ggthemes)
> # build a plot and store it in g2
> g2 <- ggplot(diamonds, aes(x=carat, y=price)) +
+     geom_point(aes(color=color))
>
> # apply a few themes
> g2 + theme_economist() + scale_colour_economist()
> g2 + theme_excel() + scale_colour_excel()
> g2 + theme_tufte()
> g2 + theme_wsj()
```



```
> say.hello <- function()  
+ {  
+     print("Hello, World!")  
+ }
```

```
> # one substitution
> sprintf("Hello %s", "Jared")
[1] "Hello Jared"

> # two substitutions
> sprintf("Hello %s, today is %s", "Jared", "Sunday")
[1] "Hello Jared, today is Sunday"
```

```
> hello.person <- function(name)
+ {
+   print(sprintf("Hello %s", name))
+ }
> hello.person("Jared")

[1] "Hello Jared"

> hello.person("Bob")

[1] "Hello Bob"

> hello.person("Sarah")

[1] "Hello Sarah"
```

```
> hello.person <- function(first, last)
+ {
+   print(sprintf("Hello %s %s", first, last))
+ }
> # by position
> hello.person("Jared", "Lander")
[1] "Hello Jared Lander"

> # by name
> hello.person(first = "Jared", last = "Lander")
[1] "Hello Jared Lander"

> # the other order
> hello.person(last = "Lander", first = "Jared")
[1] "Hello Jared Lander"

> # just specify one name
> hello.person("Jared", last = "Lander")
[1] "Hello Jared Lander"

> # specify the other
> hello.person(first = "Jared", "Lander")
[1] "Hello Jared Lander"

> # specify the second argument first then provide the first argument
> # with no name
> hello.person(last = "Lander", "Jared")
[1] "Hello Jared Lander"
```

```
> hello.person(fir = "Jared", l = "Lander")  
[1] "Hello Jared Lander"
```

```
> hello.person <- function(first, last = "Doe")
+ {
+     print(sprintf("Hello %s %s", first, last))
+ }
>
> # call without specifying last
> hello.person("Jared")

[1] "Hello Jared Doe"

> # call with a different last
> hello.person("Jared", "Lander")

[1] "Hello Jared Lander"
```

```
> # call hello.person with an extra argument
> hello.person("Jared", extra = "Goodbye")

Error: unused argument (extra = "Goodbye")

> # call it with two valid arguments and a third
> hello.person("Jared", "Lander", "Goodbye")

Error: unused argument ("Goodbye")

>
> # now build hello.person with ... so that it absorbs extra arguments
> hello.person <- function(first, last = "Doe", ...)
+ {
+   print(sprintf("Hello %s %s", first, last))
+ }
> # call hello.person with an extra argument
> hello.person("Jared", extra = "Goodbye")

[1] "Hello Jared Doe"

> # call it with two valid arguments and a third
> hello.person("Jared", "Lander", "Goodbye")

[1] "Hello Jared Lander"
```

```
> # first build it without an explicit return
> double.num <- function(x)
+ {
+     x * 2
+ }
>
> double.num(5)

[1] 10

>
> # now build it with an explicit return
> double.num <- function(x)
+ {
+     return(x * 2)
+ }
>
> double.num(5)

[1] 10

>
> # build it again, this time with another argument after the explicit
> # return
> double.num <- function(x)
+ {
+     return(x * 2)
+
+     # below here is not executed because the function already exited
+     print("Hello!")
+     return(17)
+ }
>
> double.num(5)

[1] 10
```

```
> do.call("hello.person", args = list(first = "Jared", last = "Lander"))
[1] "Hello Jared Lander"

> do.call(hello.person, args = list(first = "Jared", last = "Lander"))
[1] "Hello Jared Lander"
```

```
> run.this <- function(x, func = mean)
+ {
+     do.call(func, args = list(x))
+ }
>
> # finds the mean by default
> run.this(1:10)

[1] 5.5

> # specify to calculate the mean
> run.this(1:10, mean)

[1] 5.5

> # calculate the sum
> run.this(1:10, sum)

[1] 55

> # calculate the standard deviation
> run.this(1:10, sd)

[1] 3.028
```



```
> # set up a variable to hold 1
> toCheck <- 1
>
> # if toCheck is equal to 1, print hello
> if (toCheck == 1)
+ {
+   print("hello")
+ }

[1] "hello"

>
> # now if toCheck is equal to 0, print hello
> if (toCheck == 0)
+ {
+   print("hello")
+ }

> # notice nothing was printed
```

```
> # first create the function
> check.bool <- function(x)
+ {
+   if (x == 1)
+   {
+     # if the input is equal to 1, print hello
+     print("hello")
+   } else
+   {
+     # otherwise print goodbye
+     print("goodbye")
+   }
+ }
```

```
> check.bool <- function(x)
+ {
+   if (x == 1)
+   {
+     # if the input is equal to 1, print hello
+     print("hello")
+   } else if (x == 0)
+   {
+     # if the input is equal to 0, print goodbye
+     print("goodbye")
+   } else
+   {
+     # otherwise print confused
+     print("confused")
+   }
+ }
>
> check.bool(1)

[1] "hello"

> check.bool(0)

[1] "goodbye"

> check.bool(2)

[1] "confused"

> check.bool("k")

[1] "confused"
```

```
> use.switch <- function(x)
+ {
+   switch(x,
+     "a"="first",
+     "b"="second",
+     "z"="last",
+     "c"="third",
+     "other")
+ }
```

```
>
```

```
> use.switch("a")
```

```
[1] "first"
```

```
> use.switch("b")
```

```
[1] "second"
```

```
> use.switch("c")
```

```
[1] "third"
```



```
> use.switch(1)

[1] "first"

> use.switch(2)

[1] "second"

> use.switch(3)

[1] "last"

> use.switch(4)

[1] "third"

> use.switch(5)

[1] "other"

> use.switch(6)  # nothing is returned
> is.null(use.switch(6))

[1] TRUE
```

```
> # see if 1 == 1
> ifelse(1 == 1, "Yes", "No")
[1] "Yes"

> # see if 1 == 0
> ifelse(1 == 0, "Yes", "No")
[1] "No"
```

```
> toTest <- c(1, 1, 0, 1, 0, 1)
> ifelse(toTest == 1, "Yes", "No")
```

```
[1] "Yes" "Yes" "No"   "Yes" "No"   "Yes"
```

```
> ifelse(toTest == 1, toTest * 3, toTest)
[1] 3 3 0 3 0 3

> # the FALSE argument is repeated as needed
> ifelse(toTest == 1, toTest * 3, "Zero")
[1] "3"      "3"      "Zero"   "3"      "Zero"   "3"
```

```
> toTest[2] <- NA  
> ifelse(toTest == 1, "Yes", "No")
```

```
[1] "Yes" NA      "No"   "Yes"  "No"   "Yes"
```

```
> ifelse(toTest == 1, toTest * 3, toTest)
[1]  3 NA  0  3  0  3

> ifelse(toTest == 1, toTest * 3, "Zero")
[1] "3"      NA      "Zero"  "3"      "Zero"  "3"
```

```
> a <- c(1, 1, 0, 1)
> b <- c(2, 1, 0, 1)
>
> # this checks each element of a and each element of b
> ifelse(a == 1 & b == 1, "Yes", "No")
[1] "No"  "Yes" "No"  "Yes"

>
> # this only checks the first element of a and the first element of b,
> # returning only one result
> ifelse(a == 1 && b == 1, "Yes", "No")
[1] "No"
```



```
> print(1:10)
```

```
[1] 1 2 3 4 5 6 7 8 9 10
```

```
> # build a vector holding fruit names
> fruit <- c("apple", "banana", "pomegranate")
> # make a variable to hold their lengths, with all NA to start
> fruitLength <- rep(NA, length(fruit))
> # show it, all NAs
> fruitLength
[1] NA NA NA

> # give it names
> names(fruitLength) <- fruit
> # show it again, still NAs
> fruitLength
apple      banana pomegranate
      NA          NA          NA

> # loop through the fruit assigning their lengths to the result vector
> for (a in fruit)
+ {
+   fruitLength[a] <- nchar(a)
+ }
> # show the lengths
> fruitLength
apple      banana pomegranate
      5          6          11
```

```
> # simply call nchar  
> fruitLength2 <- nchar(fruit)  
> # give it names  
> names(fruitLength2) <- fruit  
> # show it  
> fruitLength2  
apple      banana pomegranate  
      5          6          11
```

```
> identical(fruitLength, fruitLength2)
[1] TRUE
```



```
> # build the matrix
> theMatrix <- matrix(1:9, nrow = 3)
> # sum the rows
> apply(theMatrix, 1, sum)

[1] 12 15 18

> # sum the columns
> apply(theMatrix, 2, sum)

[1] 6 15 24
```

```
> theMatrix[2, 1] <- NA  
> apply(theMatrix, 1, sum)
```

```
[1] 12 NA 18
```

```
> apply(theMatrix, 1, sum, na.rm = TRUE)
```

```
[1] 12 13 18
```

```
> rowSums(theMatrix)
```

```
[1] 12 NA 18
```

```
> rowSums(theMatrix, na.rm = TRUE)
```

```
[1] 12 13 18
```

```
> theList <- list(A = matrix(1:9, 3), B = 1:5, C = matrix(1:4, 2), D = 2)
> lapply(theList, sum)

$A
[1] 45

$B
[1] 15

$C
[1] 10

$D
[1] 2
```

```
> theNames <- c("Jared", "Deb", "Paul")  
> lapply(theNames, nchar)
```

```
[[1]]
```

```
[1] 5
```

```
[[2]]
```

```
[1] 3
```

```
[[3]]
```

```
[1] 4
```

```
> ## build two lists
> firstList <- list(A = matrix(1:16, 4), B = matrix(1:16, 2), C = 1:5)
> secondList <- list(A = matrix(1:16, 4), B = matrix(1:16, 8), C = 15:1)
> # test element-by-element if they are identical
> mapply(identical, firstList, secondList)

      A      B      C
TRUE FALSE FALSE

> ## build a simple function that adds the number of rows (or length) of
> ## each corresponding element
> simpleFunc <- function(x, y)
+ {
+   NROW(x) + NROW(y)
+ }
> # apply the function to the two lists
> mapply(simpleFunc, firstList, secondList)

A  B  C
8 10 20
```

```
> require(ggplot2)
> data(diamonds)
> head(diamonds)
```

|   | carat | cut       | color | clarity | depth | table | price | x    | y    | z    |
|---|-------|-----------|-------|---------|-------|-------|-------|------|------|------|
| 1 | 0.23  | Ideal     | E     | SI2     | 61.5  | 55    | 326   | 3.95 | 3.98 | 2.43 |
| 2 | 0.21  | Premium   | E     | SI1     | 59.8  | 61    | 326   | 3.89 | 3.84 | 2.31 |
| 3 | 0.23  | Good      | E     | VS1     | 56.9  | 65    | 327   | 4.05 | 4.07 | 2.31 |
| 4 | 0.29  | Premium   | I     | VS2     | 62.4  | 58    | 334   | 4.20 | 4.23 | 2.63 |
| 5 | 0.31  | Good      | J     | SI2     | 63.3  | 58    | 335   | 4.34 | 4.35 | 2.75 |
| 6 | 0.24  | Very Good | J     | VVS2    | 62.8  | 57    | 336   | 3.94 | 3.96 | 2.48 |

```
> aggregate(price ~ cut, diamonds, mean)

      cut     price
1    Fair 4358.758
2   Good 3928.864
3 Very Good 3981.760
4  Premium 4584.258
5    Ideal 3457.542
```

```
> aggregate(price ~ cut + color, diamonds, mean)
```

|    | cut       | color | price    |
|----|-----------|-------|----------|
| 1  | Fair      | D     | 4291.061 |
| 2  | Good      | D     | 3405.382 |
| 3  | Very Good | D     | 3470.467 |
| 4  | Premium   | D     | 3631.293 |
| 5  | Ideal     | D     | 2629.095 |
| 6  | Fair      | E     | 3682.312 |
| 7  | Good      | E     | 3423.644 |
| 8  | Very Good | E     | 3214.652 |
| 9  | Premium   | E     | 3538.914 |
| 10 | Ideal     | E     | 2597.550 |
| 11 | Fair      | F     | 3827.003 |
| 12 | Good      | F     | 3495.750 |
| 13 | Very Good | F     | 3778.820 |
| 14 | Premium   | F     | 4324.890 |
| 15 | Ideal     | F     | 3374.939 |
| 16 | Fair      | G     | 4239.255 |
| 17 | Good      | G     | 4123.482 |
| 18 | Very Good | G     | 3872.754 |

|    |           |   |          |
|----|-----------|---|----------|
| 19 | Premium   | G | 4500.742 |
| 20 | Ideal     | G | 3720.706 |
| 21 | Fair      | H | 5135.683 |
| 22 | Good      | H | 4276.255 |
| 23 | Very Good | H | 4535.390 |
| 24 | Premium   | H | 5216.707 |
| 25 | Ideal     | H | 3889.335 |
| 26 | Fair      | I | 4685.446 |
| 27 | Good      | I | 5078.533 |
| 28 | Very Good | I | 5255.880 |
| 29 | Premium   | I | 5946.181 |
| 30 | Ideal     | I | 4451.970 |
| 31 | Fair      | J | 4975.655 |
| 32 | Good      | J | 4574.173 |
| 33 | Very Good | J | 5103.513 |
| 34 | Premium   | J | 6294.592 |
| 35 | Ideal     | J | 4918.186 |

```
> aggregate(cbind(price, carat) ~ cut, diamonds, mean)

      cut     price     carat
1    Fair 4358.758 1.0461366
2   Good 3928.864 0.8491847
3 Very Good 3981.760 0.8063814
4 Premium 4584.258 0.8919549
5   Ideal 3457.542 0.7028370
```

```
> aggregate(cbind(price, carat) ~ cut + color, diamonds, mean)
```

|    | cut       | color | price    | carat     |
|----|-----------|-------|----------|-----------|
| 1  | Fair      | D     | 4291.061 | 0.9201227 |
| 2  | Good      | D     | 3405.382 | 0.7445166 |
| 3  | Very Good | D     | 3470.467 | 0.6964243 |
| 4  | Premium   | D     | 3631.293 | 0.7215471 |
| 5  | Ideal     | D     | 2629.095 | 0.5657657 |
| 6  | Fair      | E     | 3682.312 | 0.8566071 |
| 7  | Good      | E     | 3423.644 | 0.7451340 |
| 8  | Very Good | E     | 3214.652 | 0.6763167 |
| 9  | Premium   | E     | 3538.914 | 0.7177450 |
| 10 | Ideal     | E     | 2597.550 | 0.5784012 |
| 11 | Fair      | F     | 3827.003 | 0.9047115 |
| 12 | Good      | F     | 3495.750 | 0.7759296 |
| 13 | Very Good | F     | 3778.820 | 0.7409612 |
| 14 | Premium   | F     | 4324.890 | 0.8270356 |
| 15 | Ideal     | F     | 3374.939 | 0.6558285 |
| 16 | Fair      | G     | 4239.255 | 1.0238217 |
| 17 | Good      | G     | 4123.482 | 0.8508955 |
| 18 | Very Good | G     | 3872.754 | 0.7667986 |
| 19 | Premium   | G     | 4500.742 | 0.8414877 |
| 20 | Ideal     | G     | 3720.706 | 0.7007146 |
| 21 | Fair      | H     | 5135.683 | 1.2191749 |
| 22 | Good      | H     | 4276.255 | 0.9147293 |
| 23 | Very Good | H     | 4535.390 | 0.9159485 |
| 24 | Premium   | H     | 5216.707 | 1.0164492 |
| 25 | Ideal     | H     | 3889.335 | 0.7995249 |
| 26 | Fair      | I     | 4685.446 | 1.1980571 |
| 27 | Good      | I     | 5078.533 | 1.0572222 |
| 28 | Very Good | I     | 5255.880 | 1.0469518 |
| 29 | Premium   | I     | 5946.181 | 1.1449370 |
| 30 | Ideal     | I     | 4451.970 | 0.9130291 |
| 31 | Fair      | J     | 4975.655 | 1.3411765 |
| 32 | Good      | J     | 4574.173 | 1.0995440 |
| 33 | Very Good | J     | 5103.513 | 1.1332153 |
| 34 | Premium   | J     | 6294.592 | 1.2930941 |
| 35 | Ideal     | J     | 4918.186 | 1.0635937 |

```
> require(plyr)  
> head(baseball)
```

```
> # subsetting with [ is faster than using ifelse
> baseball$sf[baseball$year < 1954] <- 0
> # check that it worked
> any(is.na(baseball$sf))

[1] FALSE

> # set NA hbp's to 0
> baseball$hbp[is.na(baseball$hbp)] <- 0
> # check that it worked
> any(is.na(baseball$hbp))

[1] FALSE

> # only keep players with at least 50 at bats in a season
> baseball <- baseball[baseball$ab >= 50, ]
```

```
> # calculate OBP
> baseball$OBP <- with(baseball, (h + bb + hbp)/(ab + bb + hbp + sf))
> tail(baseball)

      id year stint team lg   g  ab   r    h X2b X3b hr rbi sb
89499 claytro01 2007      1 TOR AL  69 189 23  48  14  0  1 12  2
89502 cirilje01 2007      1 MIN AL  50 153 18  40   9  2  2 21  2
89521 bondsba01 2007      1 SFN NL 126 340 75  94  14  0 28 66  5
89523 biggicr01 2007      1 HOU NL 141 517 68 130  31  3 10 50  4
89530 ausmubr01 2007      1 HOU NL 117 349 38  82  16  3  3 25  6
89533 aloumo01 2007      1 NYN NL  87 328 51 112  19  1 13 49  3

      cs   bb   so   ibb   hbp   sh   sf   gidp          OBP
89499  1   14   50    0    1   3   3     8 0.3043478
89502  0   15   13    0    1   3   2     9 0.3274854
89521  0  132   54   43    3   0   2    13 0.4800839
89523  3   23  112    0    3   7   5     5 0.2846715
89530  1   37   74    3    6   4   1    11 0.3180662
89533  0   27   30    5    2   0   3    13 0.3916667
```

```
> # this function assumes that the column names for the data are as
> # below
> obp <- function(data)
> {
+   c(OBP = with(data, sum(h + bb + hbp) / sum(ab + bb + hbp + sf)))
+ }
>
> # use ddply to calculate career OBP for each player
> careerOBP <- ddply(baseball, .variables = "id", .fun = obp)
> # sort the results by OBP
> careerOBP <- careerOBP[order(careerOBP$OBP, decreasing = TRUE), ]
> # see the results
> head(careerOBP, 10)
```

|      | id        | OBP       |
|------|-----------|-----------|
| 1089 | willite01 | 0.4816861 |
| 875  | ruthba01  | 0.4742209 |
| 658  | mcgrajo01 | 0.4657478 |
| 356  | gehrilo01 | 0.4477848 |
| 85   | bondsba01 | 0.4444622 |
| 476  | hornsro01 | 0.4339068 |
| 184  | cobbty01  | 0.4329655 |
| 327  | foxxji01  | 0.4290509 |
| 953  | speaktr01 | 0.4283386 |
| 191  | collied01 | 0.4251246 |

```
> theList <- list(A = matrix(1:9, 3), B = 1:5, C = matrix(1:4, 2), D = 2)
> lapply(theList, sum)

$A
[1] 45

$B
[1] 15

$C
[1] 10

$D
[1] 2
```

```
> l1lply(theList, sum)
```

```
$A
```

```
[1] 45
```

```
$B
```

```
[1] 15
```

```
$C
```

```
[1] 10
```

```
$D
```

```
[1] 2
```

```
> identical(lapply(theList, sum), l1lply(theList, sum))
```

```
[1] TRUE
```

```
> aggregate(price ~ cut, diamonds, each(mean, median))
```

|   | cut       | price.mean | price.median |
|---|-----------|------------|--------------|
| 1 | Fair      | 4358.758   | 3282.000     |
| 2 | Good      | 3928.864   | 3050.500     |
| 3 | Very Good | 3981.760   | 2648.000     |
| 4 | Premium   | 4584.258   | 3185.000     |
| 5 | Ideal     | 3457.542   | 1810.000     |

```
> system.time(dplyr::baseball, "id", nrow))  
  
    user  system elapsed  
0.29      0.00    0.33  
  
> iBaseball <- iData::idata.frame(baseball)  
> system.time(dplyr::baseball, "id", nrow))  
  
    user  system elapsed  
0.42      0.00    0.47
```

```
> require(data.table)
> # create a regular data.frame
> theDF <- data.frame(A=1:10,
+                         B=letters[1:10],
+                         C=LETTERS[11:20],
+                         D=rep(c("One", "Two", "Three"), length.out=10))
> # create a data.table
> theDT <- data.table(A=1:10,
+                         B=letters[1:10],
+                         C=LETTERS[11:20],
+                         D=rep(c("One", "Two", "Three"), length.out=10))
> # print them and compare
> theDF
```

|    | A  | B | C | D     |
|----|----|---|---|-------|
| 1  | 1  | a | K | One   |
| 2  | 2  | b | L | Two   |
| 3  | 3  | c | M | Three |
| 4  | 4  | d | N | One   |
| 5  | 5  | e | O | Two   |
| 6  | 6  | f | P | Three |
| 7  | 7  | g | Q | One   |
| 8  | 8  | h | R | Two   |
| 9  | 9  | i | S | Three |
| 10 | 10 | j | T | One   |

```
> theDT
```

|     | A  | B | C | D     |
|-----|----|---|---|-------|
| 1:  | 1  | a | K | One   |
| 2:  | 2  | b | L | Two   |
| 3:  | 3  | c | M | Three |
| 4:  | 4  | d | N | One   |
| 5:  | 5  | e | O | Two   |
| 6:  | 6  | f | P | Three |
| 7:  | 7  | g | Q | One   |
| 8:  | 8  | h | R | Two   |
| 9:  | 9  | i | S | Three |
| 10: | 10 | j | T | One   |

```
> # notice by default data.frame turns character data into factors
> # while data.table does not
> class(theDF$B)

[1] "factor"

> class(theDT$B)

[1] "character"
```

```
> diamondsDT <- data.table(diamonds)
> diamondsDT
```

|        | carat | cut       | color | clarity | depth | table | price | x    | y    | z    |
|--------|-------|-----------|-------|---------|-------|-------|-------|------|------|------|
| 1:     | 0.23  | Ideal     | E     | SI2     | 61.5  | 55    | 326   | 3.95 | 3.98 | 2.43 |
| 2:     | 0.21  | Premium   | E     | SI1     | 59.8  | 61    | 326   | 3.89 | 3.84 | 2.31 |
| 3:     | 0.23  | Good      | E     | VS1     | 56.9  | 65    | 327   | 4.05 | 4.07 | 2.31 |
| 4:     | 0.29  | Premium   | I     | VS2     | 62.4  | 58    | 334   | 4.20 | 4.23 | 2.63 |
| 5:     | 0.31  | Good      | J     | SI2     | 63.3  | 58    | 335   | 4.34 | 4.35 | 2.75 |
| ---    |       |           |       |         |       |       |       |      |      |      |
| 53936: | 0.72  | Ideal     | D     | SI1     | 60.8  | 57    | 2757  | 5.75 | 5.76 | 3.50 |
| 53937: | 0.72  | Good      | D     | SI1     | 63.1  | 55    | 2757  | 5.69 | 5.75 | 3.61 |
| 53938: | 0.70  | Very Good | D     | SI1     | 62.8  | 60    | 2757  | 5.66 | 5.68 | 3.56 |
| 53939: | 0.86  | Premium   | H     | SI2     | 61.0  | 58    | 2757  | 6.15 | 6.12 | 3.74 |
| 53940: | 0.75  | Ideal     | D     | SI2     | 62.2  | 55    | 2757  | 5.83 | 5.87 | 3.64 |

```
A C  
1: 1 K  
2: 2 L  
3: 3 M  
4: 4 N  
5: 5 O  
6: 6 P  
7: 7 Q  
8: 8 R  
9: 9 S  
10: 10 T
```

```
> # just one column
```

```
> theDT[, B]
```

```
[1] "a" "b" "c" "d" "e" "f" "g" "h" "i" "j"
```

```
> # one column while maintaining data.table structure
```

```
> theDT[, list(B)]
```

```
B  
1: a  
2: b  
3: c  
4: d  
5: e  
6: f  
7: g  
8: h  
9: i  
10: j
```

```
> theDT[, "B", with = FALSE]
```

```
      B  
1: a  
2: b  
3: c  
4: d  
5: e  
6: f  
7: g  
8: h  
9: i  
10: j
```

```
> theDT[, c("A", "C"), with = FALSE]
```

```
      A  C  
1: 1  K  
2: 2  L  
3: 3  M  
4: 4  N  
5: 5  O  
6: 6  P  
7: 7  Q
```



```
> # show tables
> tables()

      NAME          NROW MB
[1,] diamondsDT 53,940 4
[2,] theDT         10  1
      COLS          KEY
[1,] carat,cut,color,clarity,depth,table,price,x,y,z
[2,] A,B,C,D
Total: 5MB
```

```
> # set the key  
> setkey(theDT, D)  
> # show the data.table again  
> theDT
```

|     | A  | B | C | D     |
|-----|----|---|---|-------|
| 1:  | 1  | a | K | One   |
| 2:  | 4  | d | N | One   |
| 3:  | 7  | g | Q | One   |
| 4:  | 10 | j | T | One   |
| 5:  | 3  | c | M | Three |
| 6:  | 6  | f | P | Three |
| 7:  | 9  | i | S | Three |
| 8:  | 2  | b | L | Two   |
| 9:  | 5  | e | O | Two   |
| 10: | 8  | h | R | Two   |

```
> key(theDT)
```

```
[1] "D"
```

Or tables.

```
> tables()
```

|        | NAME                                            | NROW   | MB |     |
|--------|-------------------------------------------------|--------|----|-----|
| [1,]   | diamondsDT                                      | 53,940 | 4  |     |
| [2,]   | theDT                                           |        | 10 | 1   |
|        | COLS                                            |        |    | KEY |
| [1,]   | carat,cut,color,clarity,depth,table,price,x,y,z |        |    |     |
| [2,]   | A,B,C,D                                         |        |    | D   |
| Total: | 5MB                                             |        |    |     |

```
> # set the key  
> setkey(diamondsDT, cut, color)
```

```
> # access some rows  
> diamondsDT[J("Ideal", "E"), ]
```

|       |       | cut | color | carat | clarity | depth | table | price | x    | y    | z    |
|-------|-------|-----|-------|-------|---------|-------|-------|-------|------|------|------|
| 1:    | Ideal | E   | 0.23  |       | SI2     | 61.5  | 55    | 326   | 3.95 | 3.98 | 2.43 |
| 2:    | Ideal | E   | 0.26  |       | VVS2    | 62.9  | 58    | 554   | 4.02 | 4.06 | 2.54 |
| 3:    | Ideal | E   | 0.70  |       | SI1     | 62.5  | 57    | 2757  | 5.70 | 5.72 | 3.57 |
| 4:    | Ideal | E   | 0.59  |       | VVS2    | 62.0  | 55    | 2761  | 5.38 | 5.43 | 3.35 |
| 5:    | Ideal | E   | 0.74  |       | SI2     | 62.2  | 56    | 2761  | 5.80 | 5.84 | 3.62 |
| ---   |       |     |       |       |         |       |       |       |      |      |      |
| 3899: | Ideal | E   | 0.70  |       | SI1     | 61.7  | 55    | 2745  | 5.71 | 5.74 | 3.53 |
| 3900: | Ideal | E   | 0.51  |       | VVS1    | 61.9  | 54    | 2745  | 5.17 | 5.11 | 3.18 |
| 3901: | Ideal | E   | 0.56  |       | VVS1    | 62.1  | 56    | 2750  | 5.28 | 5.29 | 3.28 |
| 3902: | Ideal | E   | 0.77  |       | SI2     | 62.1  | 56    | 2753  | 5.84 | 5.86 | 3.63 |
| 3903: | Ideal | E   | 0.71  |       | SI1     | 61.9  | 56    | 2756  | 5.71 | 5.73 | 3.54 |

```
> diamondsDT[J("Ideal", c("E", "D")), ]
```

|       |       | cut | color | carat | clarity | depth | table | price | x    | y    | z    |
|-------|-------|-----|-------|-------|---------|-------|-------|-------|------|------|------|
| 1:    | Ideal | E   | 0.23  |       | SI2     | 61.5  | 55    | 326   | 3.95 | 3.98 | 2.43 |
| 2:    | Ideal | E   | 0.26  |       | VVS2    | 62.9  | 58    | 554   | 4.02 | 4.06 | 2.54 |
| 3:    | Ideal | E   | 0.70  |       | SI1     | 62.5  | 57    | 2757  | 5.70 | 5.72 | 3.57 |
| 4:    | Ideal | E   | 0.59  |       | VVS2    | 62.0  | 55    | 2761  | 5.38 | 5.43 | 3.35 |
| 5:    | Ideal | E   | 0.74  |       | SI2     | 62.2  | 56    | 2761  | 5.80 | 5.84 | 3.62 |
| ---   |       |     |       |       |         |       |       |       |      |      |      |
| 6733: | Ideal | D   | 0.51  |       | VVS2    | 61.7  | 56    | 2742  | 5.16 | 5.14 | 3.18 |
| 6734: | Ideal | D   | 0.51  |       | VVS2    | 61.3  | 57    | 2742  | 5.17 | 5.14 | 3.16 |
| 6735: | Ideal | D   | 0.81  |       | SI1     | 61.5  | 57    | 2748  | 6.00 | 6.03 | 3.70 |
| 6736: | Ideal | D   | 0.72  |       | SI1     | 60.8  | 57    | 2757  | 5.75 | 5.76 | 3.50 |
| 6737: | Ideal | D   | 0.75  |       | SI2     | 62.2  | 55    | 2757  | 5.83 | 5.87 | 3.64 |

```
> aggregate(price ~ cut, diamonds, mean)
```

|   | cut       | price    |
|---|-----------|----------|
| 1 | Fair      | 4358.758 |
| 2 | Good      | 3928.864 |
| 3 | Very Good | 3981.760 |
| 4 | Premium   | 4584.258 |
| 5 | Ideal     | 3457.542 |

```
> diamondsDT[, mean(price), by = cut]
```

|    | cut       | V1       |
|----|-----------|----------|
| 1: | Fair      | 4358.758 |
| 2: | Good      | 3928.864 |
| 3: | Very Good | 3981.760 |
| 4: | Premium   | 4584.258 |
| 5: | Ideal     | 3457.542 |

```
> diamondsDT[, list(price = mean(price)), by = cut]

      cut     price
1: Fair 4358.758
2: Good 3928.864
3: Very Good 3981.760
4: Premium 4584.258
5: Ideal 3457.542
```

```
> diamondsDT[, mean(price), by = list(cut, color)]
```

|     | cut       | color | V1       |
|-----|-----------|-------|----------|
| 1:  | Fair      | D     | 4291.061 |
| 2:  | Fair      | E     | 3682.312 |
| 3:  | Fair      | F     | 3827.003 |
| 4:  | Fair      | G     | 4239.255 |
| 5:  | Fair      | H     | 5135.683 |
| 6:  | Fair      | I     | 4685.446 |
| 7:  | Fair      | J     | 4975.655 |
| 8:  | Good      | D     | 3405.382 |
| 9:  | Good      | E     | 3423.644 |
| 10: | Good      | F     | 3495.750 |
| 11: | Good      | G     | 4123.482 |
| 12: | Good      | H     | 4276.255 |
| 13: | Good      | I     | 5078.533 |
| 14: | Good      | J     | 4574.173 |
| 15: | Very Good | D     | 3470.467 |
| 16: | Very Good | E     | 3214.652 |
| 17: | Very Good | F     | 3778.820 |
| 18: | Very Good | G     | 3872.754 |
| 19: | Very Good | H     | 4535.390 |
| 20: | Very Good | I     | 5255.880 |

|     |           |   |          |
|-----|-----------|---|----------|
| 21: | Very Good | J | 5103.513 |
| 22: | Premium   | D | 3631.293 |
| 23: | Premium   | E | 3538.914 |
| 24: | Premium   | F | 4324.890 |
| 25: | Premium   | G | 4500.742 |
| 26: | Premium   | H | 5216.707 |
| 27: | Premium   | I | 5946.181 |
| 28: | Premium   | J | 6294.592 |
| 29: | Ideal     | D | 2629.095 |
| 30: | Ideal     | E | 2597.550 |
| 31: | Ideal     | F | 3374.939 |
| 32: | Ideal     | G | 3720.706 |
| 33: | Ideal     | H | 3889.335 |
| 34: | Ideal     | I | 4451.970 |
| 35: | Ideal     | J | 4918.186 |

cut color              v1

```
> diamondsDT[, list(price = mean(price), carat = mean(carat)), by = cut]

      cut     price     carat
1: Ideal 3457.542 0.7028370
2: Premium 4584.258 0.8919549
3: Good 3928.864 0.8491847
4: Very Good 3981.760 0.8063814
5: Fair 4358.758 1.0461366

> diamondsDT[, list(price = mean(price), carat = mean(carat),
+   caratSum = sum(carat)), by = cut]

      cut     price     carat caratSum
1: Ideal 3457.542 0.7028370 15146.84
2: Premium 4584.258 0.8919549 12300.95
3: Good 3928.864 0.8491847 4166.10
4: Very Good 3981.760 0.8063814 9742.70
5: Fair 4358.758 1.0461366 1684.28
```

```
> diamondsDT[, list(price = mean(price), carat = mean(carat)),
+   by = list(cut, color)]
```

|     | cut       | color | price    | carat     |
|-----|-----------|-------|----------|-----------|
| 1:  | Ideal     | E     | 2597.550 | 0.5784012 |
| 2:  | Premium   | E     | 3538.914 | 0.7177450 |
| 3:  | Good      | E     | 3423.644 | 0.7451340 |
| 4:  | Premium   | I     | 5946.181 | 1.1449370 |
| 5:  | Good      | J     | 4574.173 | 1.0995440 |
| 6:  | Very Good | J     | 5103.513 | 1.1332153 |
| 7:  | Very Good | I     | 5255.880 | 1.0469518 |
| 8:  | Very Good | H     | 4535.390 | 0.9159485 |
| 9:  | Fair      | E     | 3682.312 | 0.8566071 |
| 10: | Ideal     | J     | 4918.186 | 1.0635937 |
| 11: | Premium   | F     | 4324.890 | 0.8270356 |
| 12: | Ideal     | I     | 4451.970 | 0.9130291 |
| 13: | Good      | I     | 5078.533 | 1.0572222 |
| 14: | Very Good | E     | 3214.652 | 0.6763167 |
| 15: | Very Good | G     | 3872.754 | 0.7667986 |

|     |           |   |          |           |
|-----|-----------|---|----------|-----------|
| 16: | Very Good | D | 3470.467 | 0.6964243 |
| 17: | Very Good | F | 3778.820 | 0.7409612 |
| 18: | Good      | F | 3495.750 | 0.7759296 |
| 19: | Good      | H | 4276.255 | 0.9147293 |
| 20: | Good      | D | 3405.382 | 0.7445166 |
| 21: | Ideal     | G | 3720.706 | 0.7007146 |
| 22: | Premium   | D | 3631.293 | 0.7215471 |
| 23: | Premium   | J | 6294.592 | 1.2930941 |
| 24: | Ideal     | D | 2629.095 | 0.5657657 |
| 25: | Premium   | G | 4500.742 | 0.8414877 |
| 26: | Premium   | H | 5216.707 | 1.0164492 |
| 27: | Fair      | F | 3827.003 | 0.9047115 |
| 28: | Ideal     | F | 3374.939 | 0.6558285 |
| 29: | Ideal     | H | 3889.335 | 0.7995249 |
| 30: | Fair      | H | 5135.683 | 1.2191749 |
| 31: | Good      | G | 4123.482 | 0.8508955 |
| 32: | Fair      | G | 4239.255 | 1.0238217 |
| 33: | Fair      | J | 4975.655 | 1.3411765 |
| 34: | Fair      | I | 4685.446 | 1.1980571 |
| 35: | Fair      | D | 4291.061 | 0.9201227 |

cut color price carat



```
> # make two vectors and combine them as columns in a data.frame
> sport <- c("Hockey", "Baseball", "Football")
> league <- c("NHL", "MLB", "NFL")
> trophy <- c("Stanley Cup", "Commissioner's Trophy",
+              "Vince Lombardi Trophy")
> trophies1 <- cbind(sport, league, trophy)
> # make another data.frame using data.frame()
> trophies2 <- data.frame(sport=c("Basketball", "Golf"),
+                           league=c("NBA", "PGA"),
+                           trophy=c("Larry O'Brien Championship Trophy",
+                                   "Wanamaker Trophy"),
+                           stringsAsFactors=FALSE)
> # combine them into one data.frame with rbind
> trophies <- rbind(trophies1, trophies2)
```

```
> cbind(Sport = sport, Association = league, Prize = trophy)
```

|      | Sport      | Association | Prize                   |
|------|------------|-------------|-------------------------|
| [1,] | "Hockey"   | "NHL"       | "Stanley Cup"           |
| [2,] | "Baseball" | "MLB"       | "Commissioner's Trophy" |
| [3,] | "Football" | "NFL"       | "Vince Lombardi Trophy" |

```
> download.file(url="http://jaredlander.com/data/US_Foreign_Aid.zip",
+                  destfile="data/ForeignAid.zip")
> unzip("data/ForeignAid.zip", exdir="data")
```

```
> require(stringr)
> # first get a list of the files
> theFiles <- dir("data/", pattern="\\.csv")
> ## loop through those files
> for(a in theFiles)
+ {
+   # build a good name to assign to the data
+   nameToUse <- str_sub(string=a, start=12, end=18)
+   # read in the csv using read.table
+   # file.path is a convenient way to specify a folder and file name
+   temp <- read.table(file=file.path("data", a),
+                      header=TRUE, sep=",", stringsAsFactors=FALSE)
+   # assign them into the workspace
+   assign(x=nameToUse, value=temp)
+ }
```

```
> Aid90s00s <- merge(x=Aid_90s, y=Aid_00s,  
+                      by.x=c("Country.Name", "Program.Name"),  
+                      by.y=c("Country.Name", "Program.Name"))  
> head(Aid90s00s)
```

|   | Country.Name |                                                   | Program.Name                              |            |           |        |        |            |            |
|---|--------------|---------------------------------------------------|-------------------------------------------|------------|-----------|--------|--------|------------|------------|
| 1 | Afghanistan  |                                                   | Child Survival and Health                 |            |           |        |        |            |            |
| 2 | Afghanistan  |                                                   | Department of Defense Security Assistance |            |           |        |        |            |            |
| 3 | Afghanistan  |                                                   | Development Assistance                    |            |           |        |        |            |            |
| 4 | Afghanistan  | Economic Support Fund/Security Support Assistance |                                           |            |           |        |        |            |            |
| 5 | Afghanistan  |                                                   | Food For Education                        |            |           |        |        |            |            |
| 6 | Afghanistan  |                                                   | Global Health and Child Survival          |            |           |        |        |            |            |
|   | FY1990       | FY1991                                            | FY1992                                    | FY1993     | FY1994    | FY1995 | FY1996 | FY1997     | FY1998     |
| 1 | NA           | NA                                                | NA                                        | NA         | NA        | NA     | NA     | NA         | NA         |
| 2 | NA           | NA                                                | NA                                        | NA         | NA        | NA     | NA     | NA         | NA         |
| 3 | NA           | NA                                                | NA                                        | NA         | NA        | NA     | NA     | NA         | NA         |
| 4 | NA           | NA                                                | NA                                        | 14178135   | 2769948   | NA     | NA     | NA         | NA         |
| 5 | NA           | NA                                                | NA                                        | NA         | NA        | NA     | NA     | NA         | NA         |
| 6 | NA           | NA                                                | NA                                        | NA         | NA        | NA     | NA     | NA         | NA         |
|   | FY1999       | FY2000                                            | FY2001                                    | FY2002     | FY2003    |        |        | FY2004     | FY2005     |
| 1 | NA           | NA                                                | NA                                        | 2586555    | 56501189  |        |        | 40215304   | 39817970   |
| 2 | NA           | NA                                                | NA                                        | 2964313    | NA        |        |        | 45635526   | 151334908  |
| 3 | NA           | NA                                                | 4110478                                   | 8762080    | 54538965  |        |        | 180539337  | 193598227  |
| 4 | NA           | NA                                                | 61144                                     | 31827014   | 341306822 |        |        | 1025522037 | 1157530168 |
| 5 | NA           | NA                                                | NA                                        | NA         | 3957312   |        |        | 2610006    | 3254408    |
| 6 | NA           | NA                                                | NA                                        | NA         | NA        |        |        | NA         | NA         |
|   | FY2006       | FY2007                                            | FY2008                                    | FY2009     |           |        |        |            |            |
| 1 | 40856382     | 72527069                                          | 28397435                                  | NA         |           |        |        |            |            |
| 2 | 230501318    | 214505892                                         | 495539084                                 | 552524990  |           |        |        |            |            |
| 3 | 212648440    | 173134034                                         | 150529862                                 | 3675202    |           |        |        |            |            |
| 4 | 1357750249   | 1266653993                                        | 1400237791                                | 1418688520 |           |        |        |            |            |
| 5 | 386891       | NA                                                | NA                                        | NA         |           |        |        |            |            |
| 6 | NA           | NA                                                | 63064912                                  | 1764252    |           |        |        |            |            |

```
> require(plyr)
> Aid90s00sJoin <- join(x = Aid_90s, y = Aid_00s, by = c("Country.Name",
+ "Program.Name"))
> head(Aid90s00sJoin)
```

|   | Country.Name |            | Program.Name                                      |            |           |            |            |        |        |
|---|--------------|------------|---------------------------------------------------|------------|-----------|------------|------------|--------|--------|
| 1 | Afghanistan  |            | Child Survival and Health                         |            |           |            |            |        |        |
| 2 | Afghanistan  |            | Department of Defense Security Assistance         |            |           |            |            |        |        |
| 3 | Afghanistan  |            | Development Assistance                            |            |           |            |            |        |        |
| 4 | Afghanistan  |            | Economic Support Fund/Security Support Assistance |            |           |            |            |        |        |
| 5 | Afghanistan  |            | Food For Education                                |            |           |            |            |        |        |
| 6 | Afghanistan  |            | Global Health and Child Survival                  |            |           |            |            |        |        |
|   | FY1990       | FY1991     | FY1992                                            | FY1993     | FY1994    | FY1995     | FY1996     | FY1997 | FY1998 |
| 1 | NA           | NA         | NA                                                | NA         | NA        | NA         | NA         | NA     | NA     |
| 2 | NA           | NA         | NA                                                | NA         | NA        | NA         | NA         | NA     | NA     |
| 3 | NA           | NA         | NA                                                | NA         | NA        | NA         | NA         | NA     | NA     |
| 4 | NA           | NA         | NA                                                | 14178135   | 2769948   | NA         | NA         | NA     | NA     |
| 5 | NA           | NA         | NA                                                | NA         | NA        | NA         | NA         | NA     | NA     |
| 6 | NA           | NA         | NA                                                | NA         | NA        | NA         | NA         | NA     | NA     |
|   | FY1999       | FY2000     | FY2001                                            | FY2002     | FY2003    | FY2004     | FY2005     |        |        |
| 1 | NA           | NA         | NA                                                | 2586555    | 56501189  | 40215304   | 39817970   |        |        |
| 2 | NA           | NA         | NA                                                | 2964313    | NA        | 45635526   | 151334908  |        |        |
| 3 | NA           | NA         | 4110478                                           | 8762080    | 54538965  | 180539337  | 193598227  |        |        |
| 4 | NA           | NA         | 61144                                             | 31827014   | 341306822 | 1025522037 | 1157530168 |        |        |
| 5 | NA           | NA         | NA                                                | NA         | 3957312   | 2610006    | 3254408    |        |        |
| 6 | NA           | NA         | NA                                                | NA         | NA        | NA         | NA         |        |        |
|   | FY2006       | FY2007     | FY2008                                            | FY2009     |           |            |            |        |        |
| 1 | 40856382     | 72527069   | 28397435                                          | NA         |           |            |            |        |        |
| 2 | 230501318    | 214505892  | 495539084                                         | 552524990  |           |            |            |        |        |
| 3 | 212648440    | 173134034  | 150529862                                         | 3675202    |           |            |            |        |        |
| 4 | 1357750249   | 1266653993 | 1400237791                                        | 1418688520 |           |            |            |        |        |
| 5 | 386891       | NA         | NA                                                | NA         |           |            |            |        |        |
| 6 | NA           | NA         | 63064912                                          | 1764252    |           |            |            |        |        |

```
> # first figure out the names of the data.frames  
> frameNames <- str_sub(string = theFiles, start = 12, end = 18)  
> # build an empty list  
> frameList <- vector("list", length(frameNames))  
> names(frameList) <- frameNames  
> # add each data.frame into the list  
> for (a in frameNames)  
+ {  
+     frameList[[a]] <- eval(parse(text = a))  
+ }
```

```
> head(frameList[[1]])
```

|   | Country.Name |                                                   | Program.Name                              |           |            |            |            |
|---|--------------|---------------------------------------------------|-------------------------------------------|-----------|------------|------------|------------|
| 1 | Afghanistan  |                                                   | Child Survival and Health                 |           |            |            |            |
| 2 | Afghanistan  |                                                   | Department of Defense Security Assistance |           |            |            |            |
| 3 | Afghanistan  |                                                   | Development Assistance                    |           |            |            |            |
| 4 | Afghanistan  | Economic Support Fund/Security Support Assistance |                                           |           |            |            |            |
| 5 | Afghanistan  |                                                   | Food For Education                        |           |            |            |            |
| 6 | Afghanistan  |                                                   | Global Health and Child Survival          |           |            |            |            |
|   | FY2000       | FY2001                                            | FY2002                                    | FY2003    | FY2004     | FY2005     | FY2006     |
| 1 | NA           | NA                                                | 2586555                                   | 56501189  | 40215304   | 39817970   | 40856382   |
| 2 | NA           | NA                                                | 2964313                                   | NA        | 45635526   | 45635526   | 230501318  |
| 3 | NA           | 4110478                                           | 8762080                                   | 54538965  | 180539337  | 193598227  | 212648440  |
| 4 | NA           | 61144                                             | 31827014                                  | 341306822 | 1025522037 | 1157530168 | 1357750249 |
| 5 | NA           | NA                                                | NA                                        | 3957312   | 2610006    | 3254408    | 386891     |
| 6 | NA           | NA                                                | NA                                        | NA        | NA         | NA         | NA         |
|   | FY2007       |                                                   | FY2008                                    |           | FY2009     |            |            |
| 1 | 72527069     |                                                   | 28397435                                  |           | NA         |            |            |
| 2 | 214505892    |                                                   | 495539084                                 |           | 552524990  |            |            |
| 3 | 173134034    |                                                   | 150529862                                 |           | 3675202    |            |            |
| 4 | 1266653993   |                                                   | 1400237791                                |           | 1418688520 |            |            |
| 5 |              | NA                                                |                                           | NA        |            | NA         |            |
| 6 |              | NA                                                | 63064912                                  |           | 1764252    |            |            |

```
> head(frameList[["Aid_00s"]])
```

|   | Country.Name |                                                   | Program.Name                              |           |            |            |            |
|---|--------------|---------------------------------------------------|-------------------------------------------|-----------|------------|------------|------------|
| 1 | Afghanistan  |                                                   | Child Survival and Health                 |           |            |            |            |
| 2 | Afghanistan  |                                                   | Department of Defense Security Assistance |           |            |            |            |
| 3 | Afghanistan  |                                                   | Development Assistance                    |           |            |            |            |
| 4 | Afghanistan  | Economic Support Fund/Security Support Assistance |                                           |           |            |            |            |
| 5 | Afghanistan  |                                                   | Food For Education                        |           |            |            |            |
| 6 | Afghanistan  |                                                   | Global Health and Child Survival          |           |            |            |            |
|   | FY2000       | FY2001                                            | FY2002                                    | FY2003    | FY2004     | FY2005     | FY2006     |
| 1 | NA           | NA                                                | 2586555                                   | 56501189  | 40215304   | 39817970   | 40856382   |
| 2 | NA           | NA                                                | 2964313                                   | NA        | 45635526   | 151334908  | 230501318  |
| 3 | NA           | 4110478                                           | 8762080                                   | 54538965  | 180539337  | 193598227  | 212648440  |
| 4 | NA           | 61144                                             | 31827014                                  | 341306822 | 1025522037 | 1157530168 | 1357750249 |
| 5 | NA           | NA                                                | NA                                        | 3957312   | 2610006    | 3254408    | 386891     |
| 6 | NA           | NA                                                | NA                                        | NA        | NA         | NA         | NA         |
|   | FY2007       |                                                   | FY2008                                    |           | FY2009     |            |            |
| 1 | 72527069     |                                                   | 28397435                                  |           | NA         |            |            |
| 2 | 214505892    |                                                   | 495539084                                 |           | 552524990  |            |            |
| 3 | 173134034    |                                                   | 150529862                                 |           | 3675202    |            |            |
| 4 | 1266653993   |                                                   | 1400237791                                |           | 1418688520 |            |            |
| 5 | NA           |                                                   | NA                                        |           | NA         |            |            |
| 6 | NA           |                                                   | 63064912                                  |           | 1764252    |            |            |

```
> head(frameList[[5]])
```



```
> head(frameList[["Aid_60s"]])
```

|   | Country.Name |                                                   | Program.Name                              |        |        |        |        |        |        |
|---|--------------|---------------------------------------------------|-------------------------------------------|--------|--------|--------|--------|--------|--------|
| 1 | Afghanistan  |                                                   | Child Survival and Health                 |        |        |        |        |        |        |
| 2 | Afghanistan  |                                                   | Department of Defense Security Assistance |        |        |        |        |        |        |
| 3 | Afghanistan  |                                                   | Development Assistance                    |        |        |        |        |        |        |
| 4 | Afghanistan  | Economic Support Fund/Security Support Assistance |                                           |        |        |        |        |        |        |
| 5 | Afghanistan  |                                                   | Food For Education                        |        |        |        |        |        |        |
| 6 | Afghanistan  |                                                   | Global Health and Child Survival          |        |        |        |        |        |        |
|   | FY1960       | FY1961                                            | FY1962                                    | FY1963 | FY1964 | FY1965 | FY1966 | FY1967 | FY1968 |
| 1 | NA           | NA                                                | NA                                        | NA     | NA     | NA     | NA     | NA     | NA     |
| 2 | NA           | NA                                                | NA                                        | NA     | NA     | NA     | NA     | NA     | NA     |
| 3 | NA           | NA                                                | NA                                        | NA     | NA     | NA     | NA     | NA     | NA     |
| 4 | NA           | NA                                                | 181177853                                 | NA     | NA     | NA     | NA     | NA     | NA     |
| 5 | NA           | NA                                                | NA                                        | NA     | NA     | NA     | NA     | NA     | NA     |
| 6 | NA           | NA                                                | NA                                        | NA     | NA     | NA     | NA     | NA     | NA     |
|   | FY1969       |                                                   |                                           |        |        |        |        |        |        |
| 1 | NA           |                                                   |                                           |        |        |        |        |        |        |
| 2 | NA           |                                                   |                                           |        |        |        |        |        |        |
| 3 | NA           |                                                   |                                           |        |        |        |        |        |        |
| 4 | NA           |                                                   |                                           |        |        |        |        |        |        |
| 5 | NA           |                                                   |                                           |        |        |        |        |        |        |
| 6 | NA           |                                                   |                                           |        |        |        |        |        |        |

```
> allAid <- Reduce(function(...)  
+ {  
+   join(..., by = c("Country.Name", "Program.Name"))  
+ }, frameList)  
> dim(allAid)  
  
[1] 2453    67  
  
> require(useful)  
> corner(allAid, c = 15)  
  
          Country.Name                      Program.Name  
1 Afghanistan             Child Survival and Health  
2 Afghanistan      Department of Defense Security Assistance  
3 Afghanistan           Development Assistance  
4 Afghanistan Economic Support Fund/Security Support Assistance  
5 Afghanistan            Food For Education  
FY2000   FY2001   FY2002   FY2003   FY2004   FY2005   FY2006  
1       NA       NA 2586555  56501189  40215304  39817970  40856382  
2       NA       NA 2964313        NA  45635526 151334908 230501318  
3       NA 4110478  8762080  54538965 180539337 193598227 212648440  
4       NA  61144 31827014 341306822 1025522037 1157530168 1357750249  
5       NA       NA        NA  3957312   2610006   3254408   386891
```

|   | FY2007     | FY2008     | FY2009     | FY2010     | FY1946 | FY1947 |
|---|------------|------------|------------|------------|--------|--------|
| 1 | 72527069   | 28397435   | NA         | NA         | NA     | NA     |
| 2 | 214505892  | 495539084  | 552524990  | 316514796  | NA     | NA     |
| 3 | 173134034  | 150529862  | 3675202    | NA         | NA     | NA     |
| 4 | 1266653993 | 1400237791 | 1418688520 | 2797488331 | NA     | NA     |
| 5 | NA         | NA         | NA         | NA         | NA     | NA     |

> **bottomleft**(allAid, c = 15)

|      | Country.Name | Program.Name           | FY2000   | FY2001  | FY2002    |           |           |
|------|--------------|------------------------|----------|---------|-----------|-----------|-----------|
| 2449 | Zimbabwe     | Other State Assistance | 1341952  | 322842  | NA        |           |           |
| 2450 | Zimbabwe     | Other USAID Assistance | 3033599  | 8464897 | 6624408   |           |           |
| 2451 | Zimbabwe     | Peace Corps            | 2140530  | 1150732 | 407834    |           |           |
| 2452 | Zimbabwe     | Title I                | NA       | NA      | NA        |           |           |
| 2453 | Zimbabwe     | Title II               | NA       | NA      | 31019776  |           |           |
|      | FY2003       | FY2004                 | FY2005   | FY2006  | FY2007    | FY2008    | FY2009    |
| 2449 | NA           | 318655                 | 44553    | 883546  | 1164632   | 2455592   | 2193057   |
| 2450 | 11580999     | 12805688               | 10091759 | 4567577 | 10627613  | 11466426  | 41940500  |
| 2451 | NA           | NA                     | NA       | NA      | NA        | NA        | NA        |
| 2452 | NA           | NA                     | NA       | NA      | NA        | NA        | NA        |
| 2453 | NA           | NA                     | NA       | 277468  | 100053600 | 180000717 | 174572685 |
|      | FY2010       | FY1946                 | FY1947   |         |           |           |           |
| 2449 | 1605765      | NA                     | NA       |         |           |           |           |
| 2450 | 30011970     | NA                     | NA       |         |           |           |           |
| 2451 | NA           | NA                     | NA       |         |           |           |           |
| 2452 | NA           | NA                     | NA       |         |           |           |           |
| 2453 | 79545100     | NA                     | NA       |         |           |           |           |

```
> require(data.table)
> dt90 <- data.table(Aid_90s, key = c("Country.Name", "Program.Name"))
> dt00 <- data.table(Aid_00s, key = c("Country.Name", "Program.Name"))
```

```
> head(Aid_00s)
```

| Country.Name  | Program.Name                                      |            |           |            |            |            |
|---------------|---------------------------------------------------|------------|-----------|------------|------------|------------|
| 1 Afghanistan | Child Survival and Health                         |            |           |            |            |            |
| 2 Afghanistan | Department of Defense Security Assistance         |            |           |            |            |            |
| 3 Afghanistan | Development Assistance                            |            |           |            |            |            |
| 4 Afghanistan | Economic Support Fund/Security Support Assistance |            |           |            |            |            |
| 5 Afghanistan | Food For Education                                |            |           |            |            |            |
| 6 Afghanistan | Global Health and Child Survival                  |            |           |            |            |            |
| FY2000        | FY2001                                            | FY2002     | FY2003    | FY2004     | FY2005     | FY2006     |
| 1 NA          | NA                                                | 2586555    | 56501189  | 40215304   | 39817970   | 40856382   |
| 2 NA          | NA                                                | 2964313    | NA        | 45635526   | 151334908  | 230501318  |
| 3 NA          | 4110478                                           | 8762080    | 54538965  | 180539337  | 193598227  | 212648440  |
| 4 NA          | 61144                                             | 31827014   | 341306822 | 1025522037 | 1157530168 | 1357750249 |
| 5 NA          | NA                                                | NA         | 3957312   | 2610006    | 3254408    | 386891     |
| 6 NA          | NA                                                | NA         | NA        | NA         | NA         | NA         |
| FY2007        | FY2008                                            | FY2009     |           |            |            |            |
| 1 72527069    | 28397435                                          | NA         |           |            |            |            |
| 2 214505892   | 495539084                                         | 552524990  |           |            |            |            |
| 3 173134034   | 150529862                                         | 3675202    |           |            |            |            |
| 4 1266653993  | 1400237791                                        | 1418688520 |           |            |            |            |
| 5 NA          | NA                                                | NA         |           |            |            |            |
| 6 NA          | 63064912                                          | 1764252    |           |            |            |            |

```
> require(reshape2)
> melt00 <- melt(Aid_00s, id.vars=c("Country.Name", "Program.Name"),
+                   variable.name="Year", value.name="Dollars")
> tail(melt00, 10)

  Country.Name
24521    Zimbabwe
24522    Zimbabwe
24523    Zimbabwe
24524    Zimbabwe
24525    Zimbabwe
24526    Zimbabwe
24527    Zimbabwe
24528    Zimbabwe
24529    Zimbabwe
24530    Zimbabwe

   Program.Name     Year
24521                               Migration and Refugee Assistance FY2009
24522                               Narcotics Control FY2009
24523 Nonproliferation, Anti-Terrorism, Demining and Related FY2009
24524                               Other Active Grant Programs FY2009
24525                               Other Food Aid Programs FY2009
24526                               Other State Assistance FY2009
24527                               Other USAID Assistance FY2009
24528                               Peace Corps FY2009
24529                               Title I FY2009
24530                               Title II FY2009

  Dollars
24521    3627384
24522      NA
24523      NA
24524    7951032
24525      NA
24526    2193057
24527   41940500
24528      NA
24529      NA
24530  174572685
```



```
> cast00 <- dcast(melt00, Country.Name ~ Program.Name ~ Year,  
+     value.var = "Dollars")  
> head(cast00)
```

|   | Country.Name |                                | Program.Name                              | 2000       |            |            |
|---|--------------|--------------------------------|-------------------------------------------|------------|------------|------------|
| 1 | Afghanistan  |                                | Child Survival and Health                 | NA         |            |            |
| 2 | Afghanistan  |                                | Department of Defense Security Assistance | NA         |            |            |
| 3 | Afghanistan  |                                | Development Assistance                    | NA         |            |            |
| 4 | Afghanistan  | Economic Support Fund/Security | Support Assistance                        | NA         |            |            |
| 5 | Afghanistan  |                                | Food For Education                        | NA         |            |            |
| 6 | Afghanistan  |                                | Global Health and Child Survival          | NA         |            |            |
|   | 2001         | 2002                           | 2003                                      | 2004       | 2005       | 2006       |
| 1 | NA           | 2586555                        | 56501189                                  | 40215304   | 39817970   | 40856382   |
| 2 | NA           | 2964313                        | NA                                        | 45635526   | 151334908  | 230501318  |
| 3 | 4110478      | 8762080                        | 54538965                                  | 180539337  | 193598227  | 212648440  |
| 4 | 61144        | 31827014                       | 341306822                                 | 1025522037 | 1157530168 | 1357750249 |
| 5 | NA           | NA                             | 3957312                                   | 2610006    | 3254408    | 386891     |
| 6 | NA           | NA                             | NA                                        | NA         | NA         | NA         |
|   | 2007         | 2008                           | 2009                                      |            |            |            |
| 1 | 72527069     | 28397435                       | NA                                        |            |            |            |
| 2 | 214505892    | 495539084                      | 552524990                                 |            |            |            |
| 3 | 173134034    | 150529862                      | 3675202                                   |            |            |            |
| 4 | 1266653993   | 1400237791                     | 1418688520                                |            |            |            |
| 5 | NA           | NA                             | NA                                        |            |            |            |
| 6 | NA           | 63064912                       | 1764252                                   |            |            |            |



```
> paste("Hello", "Jared", "and others")  
[1] "Hello Jared and others"
```

```
> paste("Hello", "Jared", "and others", sep = "")  
[1] "Hello/Jared/and others"
```

```
> paste(c("Hello", "Hey", "Howdy"), c("Jared", "Bob", "David"))  
[1] "Hello Jared" "Hey Bob"      "Howdy David"
```

```
> paste("Hello", c("Jared", "Bob", "David"))
```

```
[1] "Hello Jared" "Hello Bob"    "Hello David"
```

```
> paste("Hello", c("Jared", "Bob", "David"), c("Goodbye", "Seeya"))
```

```
[1] "Hello Jared Goodbye" "Hello Bob Seeya"      "Hello David Goodbye"
```

```
> vectorOfText <- c("Hello", "Everyone", "out there", ".")  
> paste(vectorOfText, collapse = " ")  
[1] "Hello Everyone out there ."  
  
> paste(vectorOfText, collapse = "*")  
[1] "Hello*Everyone*out there*."
```

```
> paste("Hello ", person, ", your party of ", partySize,  
+         " will be seated in ", waitTime, " minutes.", sep="")
```

```
[1] "Hello Jared, your party of eight will be seated in 25 minutes."
```

```
> sprintf("Hello %s, your party of %s will be seated in %s minutes",
+       person, partySize, waitTime)
[1] "Hello Jared, your party of eight will be seated in 25 minutes"
```

```
> sprintf("Hello %s, your party of %s will be seated in %s minutes",
+       c("Jared", "Bob"), c("eight", 16, "four", 10), waitTime)

[1] "Hello Jared, your party of eight will be seated in 25 minutes"
[2] "Hello Bob, your party of 16 will be seated in 25 minutes"
[3] "Hello Jared, your party of four will be seated in 25 minutes"
[4] "Hello Bob, your party of 10 will be seated in 25 minutes"
```

```
> load("data/presidents.rdata")
> theURL <- "http://www.loc.gov/rr/print/list/057_chron.html"
> presidents <- readHTMLTable(theURL, which=3, as.data.frame=TRUE,
+                               skip.rows=1, header=TRUE,
+                               stringsAsFactors=FALSE)
```

```
> head(presidents)
```

|   | YEAR      | PRESIDENT         |
|---|-----------|-------------------|
| 1 | 1789-1797 | George Washington |
| 2 | 1797-1801 | John Adams        |
| 3 | 1801-1805 | Thomas Jefferson  |
| 4 | 1805-1809 | Thomas Jefferson  |
| 5 | 1809-1812 | James Madison     |
| 6 | 1812-1813 | James Madison     |

|   | FIRST LADY                                   | VICE PRESIDENT   |
|---|----------------------------------------------|------------------|
| 1 | Martha Washington                            | John Adams       |
| 2 | Abigail Adams                                | Thomas Jefferson |
| 3 | Martha Wayles Skelton Jefferson\n (no image) | Aaron Burr       |
| 4 | Martha Wayles Skelton Jefferson\n (no image) | George Clinton   |
| 5 | Dolley Madison                               | George Clinton   |
| 6 | Dolley Madison                               | office vacant    |

```
> tail(presidents$YEAR)

[1] "2001-2009"
[2] "2009-"
[3] "Presidents: Introduction (Rights/Ordering\n          Info.) | Adams\n- Cleveland | Clinton - Harding Harrison\n          - Jefferson | Johnson\n- McKinley | Monroe\n          - Roosevelt | Taft - Truman |\nTyler\n          - WilsonList of names, Alphabetically"
[4] "First Ladies: Introduction\n(Rights/Ordering Info.) | Adams\n          - Coolidge | Eisenhower\n- HooverJackson\n          - Pierce | \nPolk - Wilson | List\n          of names, Alphabetically"
[5] "Vice Presidents: Introduction (Rights/Ordering Info.) |\nAdams - Coolidge | Curtis - Hobart Humphrey - Rockefeller | Roosevelt\n- WilsonList of names, Alphabetically"
[6] "Top\n          of Page"
```

```
> presidents <- presidents[1:64, ]
```

```
> require(stringr)
> # split the string
> yearList <- str_split(string = presidents$YEAR, pattern = "-")
> head(yearList)

[[1]]
[1] "1789" "1797"

[[2]]
[1] "1797" "1801"

[[3]]
[1] "1801" "1805"

[[4]]
[1] "1805" "1809"

[[5]]
[1] "1809" "1812"

[[6]]
[1] "1812" "1813"
```

```
> # combine them into one matrix
> yearMatrix <- data.frame(Reduce(rbind, yearList))
> head(yearMatrix)

  X1    X2
1 1789 1797
2 1797 1801
3 1801 1805
4 1805 1809
5 1809 1812
6 1812 1813

> # give the columns good names
> names(yearMatrix) <- c("Start", "Stop")
> # bind the new columns onto the data.frame
> presidents <- cbind(presidents, yearMatrix)
> # convert the start and stop columns into numeric
> presidents$Start <- as.numeric(as.character(presidents$Start))
> presidents$Stop <- as.numeric(as.character(presidents$Stop))
> # view the changes
> head(presidents)

  YEAR      PRESIDENT
1 1789-1797 George Washington
2 1797-1801      John Adams
3 1801-1805 Thomas Jefferson
4 1805-1809 Thomas Jefferson
5 1809-1812     James Madison
6 1812-1813     James Madison
```

|   |                                   | FIRST LADY        | VICE PRESIDENT   |
|---|-----------------------------------|-------------------|------------------|
| 1 |                                   | Martha Washington | John Adams       |
| 2 |                                   | Abigail Adams     | Thomas Jefferson |
| 3 | Martha Wayles Skelton Jefferson\n | (no image)        | Aaron Burr       |
| 4 | Martha Wayles Skelton Jefferson\n | (no image)        | George Clinton   |
| 5 |                                   | Dolley Madison    | George Clinton   |
| 6 |                                   | Dolley Madison    | office vacant    |

|   | Start | Stop |
|---|-------|------|
| 1 | 1789  | 1797 |
| 2 | 1797  | 1801 |
| 3 | 1801  | 1805 |
| 4 | 1805  | 1809 |
| 5 | 1809  | 1812 |
| 6 | 1812  | 1813 |

> **tail**(presidents)

|    | YEAR      | PRESIDENT      | FIRST LADY             | VICE PRESIDENT    |
|----|-----------|----------------|------------------------|-------------------|
| 59 | 1977-1981 | Jimmy Carter   | Rosalynn Carter        | Walter F. Mondale |
| 60 | 1981-1989 | Ronald Reagan  | Nancy Reagan           | George Bush       |
| 61 | 1989-1993 | George Bush    | Barbara Bush           | Dan Quayle        |
| 62 | 1993-2001 | Bill Clinton   | Hillary Rodham Clinton | Albert Gore       |
| 63 | 2001-2009 | George W. Bush | Laura Bush             | Richard Cheney    |
| 64 | 2009-     | Barack Obama   | Michelle Obama         | Joseph R. Biden   |

|    | Start | Stop |
|----|-------|------|
| 59 | 1977  | 1981 |
| 60 | 1981  | 1989 |
| 61 | 1989  | 1993 |
| 62 | 1993  | 2001 |
| 63 | 2001  | 2009 |
| 64 | 2009  | NA   |

```
> # get the first 3 characters  
> str_sub(string = presidents$PRESIDENT, start = 1, end = 3)
```

```
[1] "Geo" "Joh" "Tho" "Tho" "Jam" "Jam" "Jam" "Jam" "Joh" "And"  
[12] "And" "Mar" "Wil" "Joh" "Jam" "Zac" "Mil" "Fra" "Fra" "Jam" "Abr"  
[23] "Abr" "And" "Uly" "Uly" "Uly" "Rut" "Jam" "Che" "Gro" "Gro" "Ben"  
[34] "Gro" "Wil" "Wil" "Wil" "The" "The" "Wil" "Wil" "Woo" "War" "Cal"  
[45] "Cal" "Her" "Fra" "Fra" "Har" "Har" "Dwi" "Joh" "Lyn" "Lyn"  
[56] "Ric" "Ric" "Ger" "Jim" "Ron" "Geo" "Bil" "Geo" "Bar"
```

```
> # get the 4th through 8th characters
```

```
> str_sub(string = presidents$PRESIDENT, start = 4, end = 8)
```

```
[1] "rge W" "n Ada" "mas J" "mas J" "es Ma" "es Ma" "es Ma"  
[9] "es Mo" "n Qui" "rew J" "rew J" "tin V" "liam" "n Tyl" "es K."  
[17] "hary" "lard" "nklin" "nklin" "es Bu" "aham" "aham" "rew J"  
[25] "sses" "sses" "sses" "herfo" "es A." "ster" "ver C" "ver C"  
[33] "jamin" "ver C" "liam" "liam" "liam" "odore" "odore" "liam"  
[41] "liam" "drow" "ren G" "vin C" "vin C" "bert" "nklin" "nklin"  
[49] "nklin" "ry S." "ry S." "ght D" "n F." "don B" "don B" "hard"  
[57] "hard" "ald R" "my Ca" "ald R" "rge B" "l Cli" "rge W" "ack O"
```

```
> presidents[str_sub(string = presidents$Start, start = 4,
+      end = 4) == 1, c("YEAR", "PRESIDENT", "Start", "Stop")]

  YEAR          PRESIDENT Start Stop
3 1801-1805    Thomas Jefferson 1801 1805
14 1841 William Henry Harrison 1841 1841
15 1841-1845    John Tyler     1841 1845
22 1861-1865    Abraham Lincoln 1861 1865
29 1881        James A. Garfield 1881 1881
30 1881-1885    Chester A. Arthur 1881 1885
37 1901        William McKinley 1901 1901
38 1901-1905    Theodore Roosevelt 1901 1905
43 1921-1923    Warren G. Harding 1921 1923
48 1941-1945 Franklin D. Roosevelt 1941 1945
53 1961-1963    John F. Kennedy 1961 1963
60 1981-1989    Ronald Reagan 1981 1989
63 2001-2009    George W. Bush 2001 2009
```

```
> # returns TRUE/FALSE if John was found in the name
> johnPos <- str_detect(string = presidents$PRESIDENT, pattern = "John")
> presidents[johnPos, c("YEAR", "PRESIDENT", "Start", "Stop")]
   YEAR      PRESIDENT Start Stop
2 1797-1801    John Adams 1797 1801
10 1825-1829 John Quincy Adams 1825 1829
15 1841-1845    John Tyler 1841 1845
24 1865-1869 Andrew Johnson 1865 1869
53 1961-1963  John F. Kennedy 1961 1963
54 1963-1965 Lyndon B. Johnson 1963 1965
55 1963-1969 Lyndon B. Johnson 1963 1969
```

```
> badSearch <- str_detect(presidents$PRESIDENT, "john")
> goodSearch <- str_detect(presidents$PRESIDENT, ignore.case("John"))
> sum(badSearch)

[1] 0

> sum(goodSearch)

[1] 7
```

```
> con <- url("http://www.jaredlander.com/data/warTimes.rdata")
> load(con)
> close(con)
```

```
> head(warTimes, 10)
```

```
[1] "September 1, 1774 ACAEA September 3, 1783"  
[2] "September 1, 1774 ACAEA March 17, 1776"  
[3] "1775ACAEA1783"  
[4] "June 1775 ACAEA October 1776"  
[5] "July 1776 ACAEA March 1777"  
[6] "June 14, 1777 ACAEA October 17, 1777"  
[7] "1777ACAEA1778"  
[8] "1775ACAEA1782"  
[9] "1776ACAEA1794"  
[10] "1778ACAEA1782"
```

```
> warTimes[str_detect(string = warTimes, pattern = "-")]  
[1] "6 June 1944 ACAEA mid-July 1944"  
[2] "25 August-17 December 1944"
```

```
> theTimes <- str_split(string = warTimes, pattern = "(ACAEA) | -", n = 2)
> head(theTimes)

[[1]]
[1] "September 1, 1774" "September 3, 1783"

[[2]]
[1] "September 1, 1774" "March 17, 1776"

[[3]]
[1] "1775" "1783"

[[4]]
[1] "June 1775" "October 1776"

[[5]]
[1] "July 1776" "March 1777"

[[6]]
[1] "June 14, 1777" "October 17, 1777"
```

```
> which(str_detect(string = warTimes, pattern = "-"))  
[1] 147 150  
  
> theTimes[[147]]  
[1] "6 June 1944"     "mid-July 1944"  
  
> theTimes[[150]]  
[1] "25 August"       "17 December 1944"
```

```
> theStart <- sapply(theTimes, FUN = function(x) x[1])  
> head(theStart)  
  
[1] "September 1, 1774" "September 1, 1774" "1775"  
[4] "June 1775" "July 1776" "June 14, 1777"
```

```
> theStart <- str_trim(theStart)
> head(theStart)

[1] "September 1, 1774" "September 1, 1774" "1775"
[4] "June 1775"          "July 1776"          "June 14, 1777"
```

```
> # pull out 'January' anywhere it's found, otherwise return NA
> str_extract(string = theStart, pattern = "January")

[1] NA      NA      NA      NA      NA      NA
[7] NA      NA      NA      NA      NA      NA
[13] "January" NA      NA      NA      NA      NA
[19] NA      NA      NA      NA      NA      NA
[25] NA      NA      NA      NA      NA      NA
[31] NA      NA      NA      NA      NA      NA
[37] NA      NA      NA      NA      NA      NA
[43] NA      NA      NA      NA      NA      NA
[49] NA      NA      NA      NA      NA      NA
[55] NA      NA      NA      NA      NA      NA
[61] NA      NA      NA      NA      NA      NA
[67] NA      NA      NA      NA      NA      NA
[73] NA      NA      NA      NA      NA      NA
[79] NA      NA      NA      NA      NA      NA
[85] NA      NA      NA      NA      NA      NA
[91] NA      NA      NA      NA      NA      NA
[97] NA      NA      "January" NA      NA      NA
[103] NA     NA      NA      NA      NA      NA
[109] NA     NA      NA      NA      NA      NA
[115] NA     NA      NA      NA      NA      NA
[121] NA     NA      NA      NA      NA      NA
[127] NA     NA      NA      NA      "January" NA
[133] NA     NA      "January" NA      NA      NA
[139] NA     NA      NA      NA      NA      NA
[145] "January" "January" NA      NA      NA      NA
[151] NA     NA      NA      NA      NA      NA
[157] NA     NA      NA      NA      NA      NA
[163] NA     NA      NA      NA      NA      NA
[169] "January" NA      NA      NA      NA      NA
[175] NA     NA      NA      NA      NA      NA
[181] "January" NA      NA      NA      NA      "January"
[187] NA     NA      NA      NA      NA      NA
```

```
> # just return elements where 'January' was detected
> theStart[str_detect(string = theStart, pattern = "January")]
[1] "January"           "January 21"        "January 1942"
[4] "January"           "January 22, 1944"  "22 January 1944"
[7] "January 4, 1989"   "15 January 2002"  "January 14, 2010"
```

```
> # get incidents of 4 numeric digits in a row
> head(str_extract(string = theStart, "[0-9][0-9][0-9][0-9]"), 20)

[1] "1774" "1774" "1775" "1775" "1776" "1777" "1777" "1775" "1776"
[10] "1778" "1775" "1779" NA      "1785" "1798" "1801" NA      "1812"
[19] "1812" "1813"
```

```
> # a smarter way to search for four numbers
> head(str_extract(string = theStart, "[0-9]{4}"), 20)
[1] "1774" "1774" "1775" "1775" "1776" "1776" "1777" "1777" "1775" "1776"
[10] "1778" "1775" "1779" NA       "1785" "1798" "1801" NA       "1812"
[19] "1812" "1813"
```

```
> # "\d" is a shortcut for "[0-9]"
> head(str_extract(string = theStart, "\d{4}"), 20)
[1] "1774" "1774" "1775" "1775" "1776" "1776" "1777" "1777" "1775" "1776"
[10] "1778" "1775" "1779" NA      "1785" "1798" "1801" NA      "1812"
[19] "1812" "1813"
```

```
> # this looks for any digit that occurs either once, twice or thrice
> str_extract(string = theStart, "\\\d{1,3}")
```

|       |       |       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| [1]   | "1"   | "1"   | "177" | "177" | "177" | "14"  | "177" | "177" | "177" | "177" |
| [11]  | "177" | "177" | NA    | "178" | "179" | "180" | NA    | "18"  | "181" | "181" |
| [21]  | "181" | "181" | "181" | "181" | "181" | "181" | "181" | "181" | "181" | "181" |
| [31]  | "22"  | "181" | "181" | "5"   | "182" | "182" | "182" | NA    | "6"   | "183" |
| [41]  | "23"  | "183" | "19"  | "11"  | "25"  | "184" | "184" | "184" | "184" | "184" |
| [51]  | "185" | "184" | "28"  | "185" | "13"  | "4"   | "185" | "185" | "185" | "185" |
| [61]  | "185" | "185" | "6"   | "185" | "6"   | "186" | "12"  | "186" | "186" | "186" |
| [71]  | "186" | "186" | "17"  | "31"  | "186" | "20"  | "186" | "186" | "186" | "186" |
| [81]  | "186" | "17"  | "1"   | "6"   | "12"  | "27"  | "187" | "187" | "187" | "187" |
| [91]  | "187" | "187" | NA    | "30"  | "188" | "189" | "22"  | "189" | "21"  | "189" |
| [101] | "25"  | "189" | "189" | "189" | "189" | "189" | "189" | "2"   | "189" | "28"  |
| [111] | "191" | "21"  | "28"  | "191" | "191" | "191" | "191" | "191" | "191" | "191" |
| [121] | "191" | "191" | "191" | "7"   | "194" | "194" | NA    | NA    | "3"   | "7"   |
| [131] | "194" | "194" | NA    | "20"  | NA    | "1"   | "16"  | "194" | "8"   | "194" |
| [141] | "17"  | "9"   | "194" | "3"   | "22"  | "22"  | "6"   | "6"   | "15"  | "25"  |
| [151] | "25"  | "16"  | "8"   | "6"   | "194" | "195" | "195" | "195" | "195" | "197" |
| [161] | "28"  | "25"  | "15"  | "24"  | "19"  | "198" | "15"  | "198" | "4"   | "20"  |
| [171] | "2"   | "199" | "199" | "199" | "19"  | "20"  | "24"  | "7"   | "7"   | "7"   |
| [181] | "15"  | "7"   | "6"   | "20"  | "16"  | "14"  | "200" | "19"  |       |       |

```
> # extract 4 digits at the beginning of the text
> head(str_extract(string = theStart, pattern = "^\d{4}"), 30)

[1] NA      NA      "1775"  NA      NA      NA      "1777"  "1775"  "1776"
[10] "1778"  "1775"  "1779"  NA      "1785"  "1798"  "1801"  NA      NA
[19] "1812"  "1813"  "1812"  "1812"  "1813"  "1813"  "1813"  "1814"  "1813"
[28] "1814"  "1813"  "1815"

> # extract 4 digits at the end of the text
> head(str_extract(string = theStart, pattern = "\d{4}$"), 30)

[1] "1774"  "1774"  "1775"  "1775"  "1776"  "1777"  "1777"  "1775"  "1776"
[10] "1778"  "1775"  "1779"  NA      "1785"  "1798"  "1801"  NA      "1812"
[19] "1812"  "1813"  "1812"  "1812"  "1813"  "1813"  "1813"  "1814"  "1813"
[28] "1814"  "1813"  "1815"

> # extract 4 digits at the beginning AND the end of the text
> head(str_extract(string = theStart, pattern = "^\d{4}$"), 30)

[1] NA      NA      "1775"  NA      NA      NA      "1777"  "1775"  "1776"
[10] "1778"  "1775"  "1779"  NA      "1785"  "1798"  "1801"  NA      NA
[19] "1812"  "1813"  "1812"  "1812"  "1813"  "1813"  "1813"  "1814"  "1813"
[28] "1814"  "1813"  "1815"
```

```
> # replace the first digit seen with "x"
> head(str_replace(string=theStart, pattern="\d", replacement="x"), 30)

[1] "September x, 1774" "September x, 1774" "x775"
[4] "June x775"          "July x776"          "June x4, 1777"
[7] "x777"               "x775"              "x776"
[10] "x778"               "x775"              "x779"
[13] "January"             "x785"              "x798"
[16] "x801"               "August"             "June x8, 1812"
[19] "x812"               "x813"              "x812"
[22] "x812"               "x813"              "x813"
[25] "x813"               "x814"              "x813"
[28] "x814"               "x813"              "x815"

> # replace all digits seen with "x"
> # this means "7" -> "x" and "382" -> "xxx"
> head(str_replace_all(string=theStart, pattern="\d", replacement="x"),
+       30)

[1] "September x, xxxx" "September x, xxxx" "xxxx"
[4] "June xxxx"           "July xxxx"          "June xx, xxxx"
[7] "xxxx"                "xxxx"              "xxxx"
[10] "xxxx"                "xxxx"              "xxxx"
[13] "January"              "xxxx"              "xxxx"
[16] "xxxx"                "August"             "June xx, xxxx"
[19] "xxxx"                "xxxx"              "xxxx"
[22] "xxxx"                "xxxx"              "xxxx"
[25] "xxxx"                "xxxx"              "xxxx"
[28] "xxxx"                "xxxx"              "xxxx"
```

```
> # replace any strings of digits from 1 to 4 in length with "x"
> # this means "7" -> "x" and "382" -> "x"
> head(str_replace_all(string=theStart, pattern="\d{1,4}",
+ replacement="x"), 30)
```

|      |                  |                      |             |
|------|------------------|----------------------|-------------|
| [1]  | "September x, x" | "September x, x" "x" |             |
| [4]  | "June x"         | "July x"             | "June x, x" |
| [7]  | "x"              | "x"                  | "x"         |
| [10] | "x"              | "x"                  | "x"         |
| [13] | "January"        | "x"                  | "x"         |
| [16] | "x"              | "August"             | "June x, x" |
| [19] | "x"              | "x"                  | "x"         |
| [22] | "x"              | "x"                  | "x"         |
| [25] | "x"              | "x"                  | "x"         |
| [28] | "x"              | "x"                  | "x"         |

```
> # create a vector of HTML commands  
> commands <- c("<a href=index.html>The Link is here</a>",  
+                  "<b>This is bold text</b>")
```

```
> # get the text between the HTML tags
> # the content in (.+?) is substituted using 1
> str_replace(string=commands, pattern="<.+\?>(.+\?)<.+\?>",
+             replacement="\\"1")
```

[1] "The Link is here" "This is bold text"



```
> # 10 draws from the standard 0-1 normal distribution
> rnorm(n = 10)

[1] -2.1654005 0.7044448 0.1545891 1.3325220 -0.1965996 1.3166821
[7] 0.2055784 0.7698138 0.4276115 -0.6209493

> # 10 draws from the 100-20 distribution
> rnorm(n = 10, mean = 100, sd = 20)

[1] 99.50443 86.81502 73.57329 113.36646 70.55072 95.70594
[7] 67.10154 99.49917 111.02245 114.16694
```

```
> randNorm10 <- rnorm(10)
> randNorm10
[1] -1.2376217  0.2989008  1.8963171 -1.1609135 -0.9199759  0.4251059
[7] -1.1112031 -0.3353926 -0.5533266 -0.5985041

> dnorm(randNorm10)
[1] 0.18548296 0.38151338 0.06607612 0.20335569 0.26129210 0.36447547
[7] 0.21517046 0.37712348 0.34231507 0.33352345

> dnorm(c(-1, 0, 1))
[1] 0.2419707 0.3989423 0.2419707
```

```
> # generate the normal variables
> randNorm <- rnorm(30000)
> # calcualte their distributions
> randDensity <- dnorm(randNorm)
> # load ggplot2
> require(ggplot2)
> # plot them
> ggplot(data.frame(x = randNorm, y = randDensity)) + aes(x = x, y = y) +
+     geom_point() + labs(x = "Random Normal Variables", y = "Density")
```

```
> pnorm(randNorm10)
```

```
[1] 0.1079282 0.6174921 0.9710409 0.1228385 0.1787927 0.6646203  
[7] 0.1332405 0.3686645 0.2900199 0.2747518
```

```
> pnorm(c(-3, 0, 3))
```

```
[1] 0.001349898 0.500000000 0.998650102
```

```
> pnorm(-1)
```

```
[1] 0.1586553
```

```
> # a few things happen with this first line of code
> # the idea is to build a ggplot2 object that we can build upon later
> # that is why it is saved to p
> # we take randNorm and randDensity and put them into a data.frame
> # we declare the x and y axes outside of any other function
> # this just gives more flexibility
> # we add lines with geom_line()
> # x- and y-axis labels with labs(x="x", y="Density")
> p <- ggplot(data.frame(x=randNorm, y=randDensity)) + aes(x=x, y=y) +
+     geom_line() + labs(x="x", y="Density")
>
> # plotting p will print a nice distribution
> # to create a shaded area under the curve we first calculate that area
> # generate a sequence of numbers going from the far left to -1
> neg1Seq <- seq(from=min(randNorm), to=-1, by=.1)
>
> # build a data.frame of that sequence as x
> # the distribution values for that sequence as y
> lessThanNeg1 <- data.frame(x=neg1Seq, y=dnorm(neg1Seq))
>
> head(lessThanNeg1)
```

|   | x         | y            |
|---|-----------|--------------|
| 1 | -3.873328 | 0.0002203542 |
| 2 | -3.773328 | 0.0003229731 |
| 3 | -3.673328 | 0.0004686713 |
| 4 | -3.573328 | 0.0006733293 |
| 5 | -3.473328 | 0.0009577314 |
| 6 | -3.373328 | 0.0013487051 |

```
>
> # combine this with endpoints at the far left and far right
> # the height is 0
> lessThanNeg1 <- rbind(c(min(randNorm), 0),
+                         lessThanNeg1,
+                         c(max(lessThanNeg1$x), 0))
>
> # use that shaded region as a polygon
> p + geom_polygon(data=lessThanNeg1, aes(x=x, y=y))
>
> # create a similar sequence going from -1 to 1
> neg1Pos1Seq <- seq(from=-1, to=1, by=.1)
>
```

```
> # build a data.frame of that sequence as x
> # the distribution values for that sequence as y
> neg1To1 <- data.frame(x=neg1Pos1Seq, y=dnorm(neg1Pos1Seq))
>
> head(neg1To1)

      x         y
1 -1.0 0.2419707
2 -0.9 0.2660852
3 -0.8 0.2896916
4 -0.7 0.3122539
5 -0.6 0.3332246
6 -0.5 0.3520653

>
> # combine this with endpoints at the far left and far right
> # the height is 0
> neg1To1 <- rbind(c(min(neg1To1$x), 0),
+                   neg1To1,
+                   c(max(neg1To1$x), 0))
>
> # use that shaded region as a polygon
> p + geom_polygon(data=neg1To1, aes(x=x, y=y))
```

```
> randProb <- pnorm(randNorm)
> ggplot(data.frame(x=randNorm, y=randProb)) + aes(x=x, y=y) +
+     geom_point() + labs(x="Random Normal Variables", y="Probability")
```

```
> randNorm10
```

```
[1] -1.2376217  0.2989008  1.8963171 -1.1609135 -0.9199759  0.4251059  
[7] -1.1112031 -0.3353926 -0.5533266 -0.5985041
```

```
> qnorm(pnorm(randNorm10))  
[1] -1.2376217  0.2989008  1.8963171 -1.1609135 -0.9199759  0.4251059  
[7] -1.1112031 -0.3353926 -0.5533266 -0.5985041  
  
> all.equal(randNorm10, qnorm(pnorm(randNorm10)))  
[1] TRUE
```

```
> rbinom(n = 1, size = 10, prob = 0.4)  
[1] 6
```

```
> rbinom(n = 1, size = 10, prob = 0.4)
[1] 3

> rbinom(n = 5, size = 10, prob = 0.4)
[1] 5 3 6 5 4

> rbinom(n = 10, size = 10, prob = 0.4)
[1] 5 3 4 4 5 3 3 5 3 3
```

```
> rbinom(n = 1, size = 1, prob = 0.4)
[1] 1

> rbinom(n = 5, size = 1, prob = 0.4)
[1] 0 0 1 1 1

> rbinom(n = 10, size = 1, prob = 0.4)
[1] 0 0 0 1 0 1 0 0 1 0
```

```
> binomData <- data.frame(Successes = rbinom(n = 10000, size = 10,  
+ prob = 0.3))  
> ggplot(binomData, aes(x = Successes)) + geom_histogram(binwidth = 1)
```

```
> # create a data.frame with Successes being the 10,000 random draws
> # Size equals 5 for all 10,000 rows

> binom5 <- data.frame(Successes=rbinom(n=10000, size=5,
+           prob=.3), Size=5)
> dim(binom5)

[1] 10000      2

> head(binom5)

  Successes Size
1         1     5
2         1     5
3         2     5
4         2     5
5         3     5
6         0     5

>
> # similar to before, still 10,000 rows
> # numbers are drawn from a distribution with a different size
> # Size now equals 10 for all 10,000 rows
> binom10 <- data.frame(Successes=rbinom(n=10000, size=10,
+           prob=.3), Size=10)
> dim(binom10)

[1] 10000      2

> head(binom10)

  Successes Size
```

```
1      1 10
2      3 10
3      3 10
4      3 10
5      0 10
6      3 10

>
> binom100 <- data.frame(Successes=rbinom(n=10000, size=100,
+      prob=.3), Size=100)
>
> binom1000 <- data.frame(Successes=rbinom(n=10000, size=1000,
+      prob=.3), Size=1000)
>
> # combine them all into one data.frame
> binomAll <- rbind(binom5, binom10, binom100, binom1000)
> dim(binomAll)

[1] 40000      2

> head(binomAll, 10)

  Successes Size
1      1     5
2      1     5
3      2     5
4      2     5
5      3     5
6      0     5
7      1     5
```

```
8          1    5
9          1    5
10         1    5

> tail(binomAll, 10)

  Successes Size
39991      316 1000
39992      311 1000
39993      296 1000
39994      316 1000
39995      288 1000
39996      286 1000
39997      264 1000
39998      291 1000
39999      300 1000
40000      302 1000

>
> # build the plot
> # histograms only need an x aesthetic
> # it is faceted (broken up) based on the values of Size
> # these are 5, 10, 100, 1000
> ggplot(binomAll, aes(x=Successes)) + geom_histogram() +
+   facet_wrap(~ Size, scales="free")
```

```
> # probability of 3 successes out of 10
> dbinom(x = 3, size = 10, prob = 0.3)

[1] 0.2668279

> # probability of 3 or fewer successes out of 10
> pbinom(q = 3, size = 10, prob = 0.3)

[1] 0.6496107

> # both functions can be vectorized
> dbinom(x = 1:10, size = 10, prob = 0.3)

[1] 0.1210608210 0.2334744405 0.2668279320 0.2001209490 0.1029193452
[6] 0.0367569090 0.0090016920 0.0014467005 0.0001377810 0.0000059049

> pbinom(q = 1:10, size = 10, prob = 0.3)

[1] 0.1493083 0.3827828 0.6496107 0.8497317 0.9526510 0.9894079
[7] 0.9984096 0.9998563 0.9999941 1.0000000
```

```
> qbinom(p = 0.3, size = 10, prob = 0.3)
```

```
[1] 2
```

```
> qbinom(p = c(0.3, 0.35, 0.4, 0.5, 0.6), size = 10, prob = 0.3)
```

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

```
> # generate 10,000 random counts from 5 different Poisson distributions
> pois1 <- rpois(n=10000, lambda=1)
> pois2 <- rpois(n=10000, lambda=2)
> pois5 <- rpois(n=10000, lambda=5)
> pois10 <- rpois(n=10000, lambda=10)
> pois20 <- rpois(n=10000, lambda=20)
> pois <- data.frame(Lambda.1=pois1, Lambda.2=pois2,
+                      Lambda.5=pois5, Lambda.10=pois10, Lambda.20=pois20)
> # load reshape2 package to melt the data to make it easier to plot
> require(reshape2)
> # melt the data into a long format
> pois <- melt(data=pois, variable.name="Lambda", value.name="x")
> # load the stringr package to help clean up the new column name
> require(stringr)
> # clean up the Lambda to just show the value for that lambda
> pois$Lambda <- as.factor(as.numeric(str_extract(string=pois$Lambda,
+   pattern="\d+")))
> head(pois)

  Lambda x
1      1 0
2      1 2
3      1 0
4      1 1
5      1 2
6      1 0

> tail(pois)

  Lambda x
49995 20 26
49996 20 14
49997 20 26
49998 20 22
49999 20 20
50000 20 23
```

```
> require(ggplot2)
> ggplot(pois, aes(x=x)) + geom_histogram(binwidth=1) +
+   facet_wrap(~ Lambda) + ggtitle("Probability Mass Function")
```

```
> ggplot(pois, aes(x=x)) +
+   geom_density(aes(group=Lambda, color=Lambda, fill=Lambda),
+               adjust=4, alpha=1/2) +
+   scale_color_discrete() + scale_fill_discrete() +
+   ggtitle("Probability Mass Function")
```



```
> x <- sample(x = 1:100, size = 100, replace = TRUE)
> x

[1] 93 98 84 62 18 12 40 13 30 4 95 18 55 46 2 24
[17] 54 91 9 57 74 6 11 38 67 13 40 87 2 85 4 6
[33] 61 28 37 61 10 87 41 10 11 4 37 84 54 69 21 33
[49] 37 44 46 78 6 50 88 74 76 31 67 68 1 23 31 51
[65] 22 64 100 12 20 56 74 61 52 4 28 62 90 66 34 11
[81] 21 78 17 94 9 80 92 83 72 43 20 44 3 43 46 72
[97] 32 61 16 12
```

```
> # copy x
> y <- x
> # choose a random 20 elements, using sample, to set to NA
> y[sample(x = 1:100, size = 20, replace = FALSE)] <- NA
> y
[1] 93 98 84 62 18 12 40 NA 30 4 95 18 55 46 2 24
[17] 54 91 NA 57 NA 6 11 38 67 NA 40 87 2 NA 4 6
[33] 61 28 37 NA 10 NA 41 10 11 4 37 84 54 69 21 33
[49] 37 44 46 78 6 50 88 74 76 NA 67 68 NA 23 31 51
[65] 22 64 100 12 20 56 74 NA 52 4 NA 62 90 NA 34 11
[81] 21 78 17 NA 9 80 NA 83 NA NA 20 44 NA NA 46 NA
[97] 32 61 NA 12
```

```
> grades <- c(95, 72, 87, 66)
> weights <- c(1/2, 1/4, 1/8, 1/8)
> mean(grades)
```

```
[1] 80
```

```
> weighted.mean(x = grades, w = weights)
```

```
[1] 84.625
```

```
> var(x)
```

```
[1] 865.5049
```

```
> sum((x - mean(x))^2) / (length(x) - 1)
```

```
[1] 865.5049
```

```
> summary(x)
```

|   | Min. | 1st Qu. | Median | Mean  | 3rd Qu. | Max.   |
|---|------|---------|--------|-------|---------|--------|
| x | 1.00 | 17.75   | 43.00  | 44.51 | 68.25   | 100.00 |

```
> summary(y)
```

|   | Min. | 1st Qu. | Median | Mean  | 3rd Qu. | Max.   | NA's |
|---|------|---------|--------|-------|---------|--------|------|
| y | 2.00 | 18.00   | 40.50  | 43.59 | 67.00   | 100.00 | 20   |

```
> # calculate the 25th and 75th quantile  
> quantile(x, probs = c(0.25, 0.75))  
  
25%    75%  
17.75  68.25
```

```
> # try the same on y  
> quantile(y, probs = c(0.25, 0.75))
```

Error: missing values and NaN's not allowed if 'na.rm' is FALSE

```
> # this time use na.rm=TRUE  
> quantile(y, probs = c(0.25, 0.75), na.rm = TRUE)
```

```
25% 75%  
18   67
```

```
> # compute other quantiles  
> quantile(x, probs = c(0.1, 0.25, 0.5, 0.75, 0.99))
```

```
10%    25%    50%    75%    99%  
6.00  17.75  43.00  68.25  98.02
```

```
> require(ggplot2)
> head(economics)
```

|   | date       | pce   | pop    | psavert | uempmed | unemploy | year | month |
|---|------------|-------|--------|---------|---------|----------|------|-------|
| 1 | 1967-06-30 | 507.8 | 198712 | 9.8     | 4.5     | 2944     | 1967 | Jun   |
| 2 | 1967-07-31 | 510.9 | 198911 | 9.8     | 4.7     | 2945     | 1967 | Jul   |
| 3 | 1967-08-31 | 516.7 | 199113 | 9.0     | 4.6     | 2958     | 1967 | Aug   |
| 4 | 1967-09-30 | 513.3 | 199311 | 9.8     | 4.9     | 3143     | 1967 | Sep   |
| 5 | 1967-10-31 | 518.5 | 199498 | 9.7     | 4.7     | 3066     | 1967 | Oct   |
| 6 | 1967-11-30 | 526.2 | 199657 | 9.4     | 4.8     | 3018     | 1967 | Nov   |

```
> cor(economics$pce, economics$psavert)  
[1] -0.9271222
```

```
> # use cor to calculate correlation
> cor(economics$pce, economics$psavert)

[1] 0.9271222

>
> ## calculate each part of correlation
> xPart <- economics$pce - mean(economics$pce)
> yPart <- economics$psavert - mean(economics$psavert)
> nMinusOne <- (nrow(economics) - 1)
> xSD <- sd(economics$pce)
> ySD <- sd(economics$psavert)
> # use correlation formula
> sum(xPart * yPart) / (nMinusOne * xSD * ySD)

[1] -0.9271222
```

```
> cor(economics[, c(2, 4:6)])
```

|          | pce        | psavert     | uempmed    | unemploy    |
|----------|------------|-------------|------------|-------------|
| pce      | 1.0000000  | -0.92712221 | 0.5145862  | 0.32441514  |
| psavert  | -0.9271222 | 1.00000000  | -0.3615301 | -0.07641651 |
| uempmed  | 0.5145862  | -0.36153012 | 1.0000000  | 0.78427918  |
| unemploy | 0.3244151  | -0.07641651 | 0.7842792  | 1.00000000  |

```
> GGally::ggpairs(economics[, c(2, 4:6)], params = list(labelSize = 8))
```

```
> # load the reshape package for melting the data
> require(reshape2)
> # load the scales package for some extra plotting features
> require(scales)
> # build the correlation matrix
> econCor <- cor(economics[, c(2, 4:6)])
> # melt it into the long format
> econMelt <- melt(econCor, varnames=c("x", "y"),
+                     value.name="Correlation")
> # order it according to the correlation
> econMelt <- econMelt[order(econMelt$Correlation), ]
> # display the melted data
> econMelt
```

|    | x        | y        | Correlation |
|----|----------|----------|-------------|
| 2  | psavert  | pce      | -0.92712221 |
| 5  | pce      | psavert  | -0.92712221 |
| 7  | uempmed  | psavert  | -0.36153012 |
| 10 | psavert  | uempmed  | -0.36153012 |
| 8  | unemploy | psavert  | -0.07641651 |
| 14 | psavert  | unemploy | -0.07641651 |
| 4  | unemploy | pce      | 0.32441514  |
| 13 | pce      | unemploy | 0.32441514  |
| 3  | uempmed  | pce      | 0.51458618  |
| 9  | pce      | uempmed  | 0.51458618  |
| 12 | unemploy | uempmed  | 0.78427918  |
| 15 | uempmed  | unemploy | 0.78427918  |
| 1  | pce      | pce      | 1.00000000  |

```
6   psavert  psavert    1.00000000
11  uempmed  uempmed    1.00000000
16  unemploy  unemploy   1.00000000

> ## plot it with ggplot
> # initialize the plot with x and y on the x and y axes
> ggplot(econMelt, aes(x=x, y=y)) +
+   # draw tiles filling the color based on Correlation
+   geom_tile(aes(fill=Correlation)) +
+   # make the fill (color) scale a three color gradient with muted
+   # red for the low point, white for the middle and steel blue
+   # for the high point
+   # the guide should be a colorbar with no ticks, whose height is
+   # 10 lines
+   # limits indicates the scale should be filled from -1 to 1
+   scale_fill_gradient2(low=muted("red"), mid="white",
+                      high="steelblue",
+                      guide=guide_colorbar(ticks=FALSE, barheight=10),
+                      limits=c(-1, 1)) +
+   # use the minimal theme so there are no extras in the plot
+   theme_minimal() +
+   # make the x and y labels blank
+   labs(x=NULL, y=NULL)
```

```
> m <- c(9, 9, NA, 3, NA, 5, 8, 1, 10, 4)
> n <- c(2, NA, 1, 6, 6, 4, 1, 1, 6, 7)
> p <- c(8, 4, 3, 9, 10, NA, 3, NA, 9, 9)
> q <- c(10, 10, 7, 8, 4, 2, 8, 5, 5, 2)
> r <- c(1, 9, 7, 6, 5, 6, 2, 7, 9, 10)
> # combine them together
> theMat <- cbind(m, n, p, q, r)
```

```
> cor(theMat, use = "everything")
```

|   | m  | n  | p  | q          | r          |
|---|----|----|----|------------|------------|
| m | 1  | NA | NA | NA         | NA         |
| n | NA | 1  | NA | NA         | NA         |
| p | NA | NA | 1  | NA         | NA         |
| q | NA | NA | NA | 1.0000000  | -0.4242958 |
| r | NA | NA | NA | -0.4242958 | 1.0000000  |

```
> cor(theMat, use = "all.obs")
```

Error: missing observations in cov/cor

```
> cor(theMat, use = "complete.obs")
```

|   | m          | n          | p          | q          | r          |
|---|------------|------------|------------|------------|------------|
| m | 1.0000000  | -0.5228840 | -0.2893527 | 0.2974398  | -0.3459470 |
| n | -0.5228840 | 1.0000000  | 0.8090195  | -0.7448453 | 0.9350718  |
| p | -0.2893527 | 0.8090195  | 1.0000000  | -0.3613720 | 0.6221470  |
| q | 0.2974398  | -0.7448453 | -0.3613720 | 1.0000000  | -0.9059384 |
| r | -0.3459470 | 0.9350718  | 0.6221470  | -0.9059384 | 1.0000000  |

```
> cor(theMat, use = "na.or.complete")
```

|   | m          | n          | p          | q          | r          |
|---|------------|------------|------------|------------|------------|
| m | 1.0000000  | -0.5228840 | -0.2893527 | 0.2974398  | -0.3459470 |
| n | -0.5228840 | 1.0000000  | 0.8090195  | -0.7448453 | 0.9350718  |
| p | -0.2893527 | 0.8090195  | 1.0000000  | -0.3613720 | 0.6221470  |
| q | 0.2974398  | -0.7448453 | -0.3613720 | 1.0000000  | -0.9059384 |
| r | -0.3459470 | 0.9350718  | 0.6221470  | -0.9059384 | 1.0000000  |

```
> # calculate the correlation just on complete rows
```

```
> cor(theMat[c(1, 4, 7, 9, 10), ])
```

|   | m          | n          | p          | q          | r          |
|---|------------|------------|------------|------------|------------|
| m | 1.0000000  | -0.5228840 | -0.2893527 | 0.2974398  | -0.3459470 |
| n | -0.5228840 | 1.0000000  | 0.8090195  | -0.7448453 | 0.9350718  |
| p | -0.2893527 | 0.8090195  | 1.0000000  | -0.3613720 | 0.6221470  |
| q | 0.2974398  | -0.7448453 | -0.3613720 | 1.0000000  | -0.9059384 |
| r | -0.3459470 | 0.9350718  | 0.6221470  | -0.9059384 | 1.0000000  |

```
> # compare "complete.obs" and computing on select rows
```

```
> # should give the same result
```

```
> identical(cor(theMat, use = "complete.obs"),
+           cor(theMat[c(1, 4, 7, 9, 10), ]))
```

```
[1] TRUE
```

```
> # the entire correlation matrix  
> cor(theMat, use = "pairwise.complete.obs")
```

|   | m           | n           | p          | q          | r          |
|---|-------------|-------------|------------|------------|------------|
| m | 1.00000000  | -0.02511812 | -0.3965859 | 0.4622943  | -0.2001722 |
| n | -0.02511812 | 1.00000000  | 0.8717389  | -0.5070416 | 0.5332259  |
| p | -0.39658588 | 0.87173889  | 1.0000000  | -0.5197292 | 0.1312506  |
| q | 0.46229434  | -0.50704163 | -0.5197292 | 1.0000000  | -0.4242958 |
| r | -0.20017222 | 0.53322585  | 0.1312506  | -0.4242958 | 1.0000000  |

```
> # compare the entries for m vs n to this matrix  
> cor(theMat[, c("m", "n")], use = "complete.obs")
```

|   | m           | n           |
|---|-------------|-------------|
| m | 1.00000000  | -0.02511812 |
| n | -0.02511812 | 1.00000000  |

```
> # compare the entries for m vs p to this matrix  
> cor(theMat[, c("m", "p")], use = "complete.obs")
```

|   | m          | p          |
|---|------------|------------|
| m | 1.0000000  | -0.3965859 |
| p | -0.3965859 | 1.0000000  |

```
> data(tips, package = "reshape2")
> head(tips)
```

|   | total_bill | tip  | sex    | smoker | day | time | size   |   |
|---|------------|------|--------|--------|-----|------|--------|---|
| 1 | 16.99      | 1.01 | Female |        | No  | Sun  | Dinner | 2 |
| 2 | 10.34      | 1.66 | Male   |        | No  | Sun  | Dinner | 3 |
| 3 | 21.01      | 3.50 | Male   |        | No  | Sun  | Dinner | 3 |
| 4 | 23.68      | 3.31 | Male   |        | No  | Sun  | Dinner | 2 |
| 5 | 24.59      | 3.61 | Female |        | No  | Sun  | Dinner | 4 |
| 6 | 25.29      | 4.71 | Male   |        | No  | Sun  | Dinner | 4 |

```
> GGally::ggpairs(tips)
```

```
> cov(economics$pce, economics$psavert)
```

```
[1] -8412.231
```

```
> cov(economics[, c(2, 4:6)])
```

|          | pce         | psavert      | uempmed     | unemploy     |
|----------|-------------|--------------|-------------|--------------|
| pce      | 6810308.380 | -8412.230823 | 2202.786256 | 1573882.2016 |
| psavert  | -8412.231   | 12.088756    | -2.061893   | -493.9304    |
| uempmed  | 2202.786    | -2.061893    | 2.690678    | 2391.6039    |
| unemploy | 1573882.202 | -493.930390  | 2391.603889 | 3456013.5176 |

```
> # check that cov and cor*sd*sd are the same
```

```
> identical(cov(economics$pce, economics$psavert),  
+           cor(economics$pce, economics$psavert) *  
+           sd(economics$pce) * sd(economics$psavert))
```

```
[1] TRUE
```

```
> head(tips)

  total_bill  tip    sex smoker day time size
1      16.99 1.01 Female   No Sun Dinner 2
2      10.34 1.66  Male   No Sun Dinner 3
3      21.01 3.50  Male   No Sun Dinner 3
4      23.68 3.31  Male   No Sun Dinner 2
5      24.59 3.61 Female  No Sun Dinner 4
6      25.29 4.71  Male   No Sun Dinner 4

> # sex of the server
> unique(tips$sex)

[1] Female Male
Levels: Female Male

> # day of the week
> unique(tips$day)

[1] Sun Sat Thur Fri
Levels: Fri Sat Sun Thur
```

```
> t.test(tips$tip, alternative = "two.sided", mu = 2.5)

One Sample t-test

data: tips$tip
t = 5.6253, df = 243, p-value = 5.08e-08
alternative hypothesis: true mean is not equal to 2.5
95 percent confidence interval:
 2.823799 3.172758
sample estimates:
mean of x
2.998279
```

```
> ## build a t distribution
> randT <- rt(30000, df=NROW(tips)-1)
>
> # get t-statistic and other information
> tipTTest <- t.test(tips$tip, alternative="two.sided", mu=2.50)
>
> # plot it
> ggplot(data.frame(x=randT)) +
+   geom_density(aes(x=x), fill="grey", color="grey") +
+   geom_vline(xintercept=tipTTest$statistic) +
+   geom_vline(xintercept=mean(randT) + c(-2, 2)*sd(randT), linetype=2)
```

```
> t.test(tips$tip, alternative = "greater", mu = 2.5)
```

One Sample t-test

data: tips\$tip

t = 5.6523, df = 243, p-value = 2.54e-08

alternative hypothesis: true mean is greater than 2.5

95 percent confidence interval:

2.852023 Inf

sample estimates:

mean of x

2.998279

```
> # first just compute the variance for each group;  
> # using the the formula interface  
> # calculate the variance of tip for each level of sex  
> aggregate(tip ~ sex, data=tips, var)  
  
      sex      tip  
1 Female 1.3444282  
2   Male 2.217424  
  
> # now test for normality of tip distribution  
> shapiro.test(tips$tip)
```

Shapiro-Wilk normality test

```
data: tips$tip  
W = 0.8978, p-value = 8.2e-12
```

```
> shapiro.test(tips$tip[tips$sex == "Female"])
```

Shapiro-Wilk normality test

```
data: tips$tip[tips$sex == "Female"]  
W = 0.9568, p-value = 0.005448
```

```
> shapiro.test(tips$tip[tips$sex == "Male"])
```

Shapiro-Wilk normality test

```
data: tips$tip[tips$sex == "Male"]  
W = 0.8759, p-value = 3.708e-10
```

```
> # all the tests fail so inspect visually  
> ggplot(tips, aes(x=tip, fill=sex)) +  
+     geom_histogram(binwidth=.5, alpha=1/2)
```

```
> ansari.test(tip ~ sex, tips)
```

Ansari-Bradley test

data: tip by sex

AB = 5582.5, p-value = 0.376

alternative hypothesis: true ratio of scales is not equal to 1

```
> # setting var.equal=TRUE runs a standard two sample t-test whereas  
> # var.equal=FALSE (the default) would run the Welch test  
> t.test(tip ~ sex, data = tips, var.equal = TRUE)
```

### Two Sample t-test

```
data: tip by sex  
t = -1.3879, df = 242, p-value = 0.1665  
alternative hypothesis: true difference in means is not equal to 0  
95 percent confidence interval:  
 -0.6197558 0.1074167  
sample estimates:  
mean in group Female mean in group Male  
 2.833448 3.089618
```

```
> require(plyr)
> tipSummary <- ddply(tips, "sex", summarize,
+                         tip.mean=mean(tip), tip.sd=sd(tip),
+                         Lower=tip.mean - 2*tip.sd/sqrt(NROW(tip)),
+                         Upper=tip.mean + 2*tip.sd/sqrt(NROW(tip)))
> tipSummary
```

|   | sex    | tip.mean | tip.sd   | Lower    | Upper    |
|---|--------|----------|----------|----------|----------|
| 1 | Female | 2.833448 | 1.159495 | 2.584827 | 3.082070 |
| 2 | Male   | 3.089618 | 1.489102 | 2.851931 | 3.327304 |

```
> ggplot(tipSummary, aes(x=tip.mean, y=sex)) + geom_point() +
+     geom_errorbarh(aes(xmin=Lower, xmax=Upper), height=.2)
```

```
> require(UsingR)
> head(father.son)

  fheight  sheight
1 65.04851 59.77827
2 63.25094 63.21404
3 64.95532 63.34242
4 65.75250 62.79238
5 61.13723 64.28113
6 63.02254 64.24221

> t.test(father.son$fheight, father.son$sheight, paired = TRUE)
```

Paired t-test

```
data: father.son$fheight and father.son$sheight
t = -11.7885, df = 1077, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0

95 percent confidence interval:
 -1.1629160 -0.8310296
sample estimates:
mean of the differences
 -0.9969728
```

```
> heightDiff <- father.son$fheight - father.son$sheight
> ggplot(father.son, aes(x=fheight - sheight)) +
+   geom_density() +
+   geom_vline(xintercept=mean(heightDiff)) +
+   geom_vline(xintercept=mean(heightDiff) +
+               2*c(-1, 1)*sd(heightDiff)/sqrt(nrow(father.son)),
+               linetype=2)
```

```
> tipAnova <- aov(tip ~ day - 1, tips)
```

```
> tipIntercept <- aov(tip ~ day, tips)
> tipAnova$coefficients
```

|  | dayFri   | daySat   | daySun   | dayThur  |
|--|----------|----------|----------|----------|
|  | 2.734737 | 2.993103 | 3.255132 | 2.771452 |

```
> tipIntercept$coefficients
```

| (Intercept) | daySat     | daySun     | dayThur    |
|-------------|------------|------------|------------|
| 2.73473684  | 0.25836661 | 0.52039474 | 0.03671477 |

```
> summary(tipAnova)
```

|           | Df  | Sum Sq | Mean Sq | F value | Pr(>F)     |
|-----------|-----|--------|---------|---------|------------|
| day       | 4   | 2203.0 | 550.8   | 290.1   | <2e-16 *** |
| Residuals | 240 | 455.7  | 1.9     |         |            |

---

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

```
> tipsByDay <- ddply(tips, "day", summarize,
+                      tip.mean=mean(tip), tip.sd=sd(tip),
+                      Length=NROW(tip),
+                      tfrac=qt(p=.90, df=Length-1),
+                      Lower=tip.mean - tfrac*tip.sd/sqrt(Length),
+                      Upper=tip.mean + tfrac*tip.sd/sqrt(Length)
+                    )
>
> ggplot(tipsByDay, aes(x=tip.mean, y=day)) + geom_point() +
+   geom_errorbarh(aes(xmin=Lower, xmax=Upper), height=.3)
```



```
> require(UsingR)
> require(ggplot2)
> head(father.son)

      fheight     sheight
1   65.04851   59.77827
2   63.25094   63.21404
3   64.95532   63.34242
4   65.75250   62.79238
5   61.13723   64.28113
6   63.02254   64.24221

> ggplot(father.son, aes(x=fheight, y=sheight)) + geom_point() +
+     geom_smooth(method="lm") + labs(x="Fathers", y="Sons")
```

```
> heightsLM <- lm(sheight ~ fheight, data = father.son)
> heightsLM
```

Call:

```
lm(formula = sheight ~ fheight, data = father.son)
```

Coefficients:

| (Intercept) | fheight |
|-------------|---------|
| 33.8866     | 0.5141  |

```
> summary(heightsLM)
```

Call:

```
lm(formula = sheight ~ fheight, data = father.son)
```

Residuals:

| Min     | 1Q      | Median  | 3Q     | Max    |
|---------|---------|---------|--------|--------|
| -8.8772 | -1.5144 | -0.0079 | 1.6285 | 8.9685 |

Coefficients:

|                | Estimate | Std. Error | t value    | Pr(> t )   |
|----------------|----------|------------|------------|------------|
| (Intercept)    | 33.88660 | 1.83235    | 18.49      | <2e-16 *** |
| fheight        | 0.51409  | 0.02705    | 19.01      | <2e-16 *** |
| ---            |          |            |            |            |
| Signif. codes: | 0        | '***'      | 0.001 '**' | 0.01 '*'   |
|                | 0.05 '.' | 0.1 ' '    | 1          |            |

Residual standard error: 2.437 on 1076 degrees of freedom

Multiple R-squared: 0.2513, Adjusted R-squared: 0.2506

F-statistic: 361.2 on 1 and 1076 DF, p-value: <2.2e-16

```
> data(tips, package = "reshape2")
> head(tips)

 total_bill  tip    sex smoker day   time size
1       16.99 1.01 Female     No Sun Dinner 2
2       10.34 1.66   Male     No Sun Dinner 3
3       21.01 3.50   Male     No Sun Dinner 3
4       23.68 3.31   Male     No Sun Dinner 2
5       24.59 3.61 Female     No Sun Dinner 4
6       25.29 4.71   Male     No Sun Dinner 4

> tipsAnova <- aov(tip ~ day - 1, data = tips)
> # putting -1 in the formula indicates that the intercept should not
> # be included in the model; the categorical variable day is
> # automatically setup to have a coefficient for each level
> tipsLM <- lm(tip ~ day - 1, data = tips)
> summary(tipsAnova)

Df Sum Sq Mean Sq F value Pr(>F)
day      4 2203.0   550.8   290.1 <2e-16 ***
Residuals 240  455.7      1.9
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
> summary(tipsLM)
```

Call:

```
lm(formula = tip ~ day - 1, data = tips)
```

Residuals:

| Min     | 1Q      | Median  | 3Q     | Max    |
|---------|---------|---------|--------|--------|
| -2.2451 | -0.9931 | -0.2347 | 0.5382 | 7.0069 |

Coefficients:

|         | Estimate | Std. Error | t value | Pr(> t )     |
|---------|----------|------------|---------|--------------|
| dayFri  | 2.7347   | 0.3161     | 8.651   | 7.46e-16 *** |
| daySat  | 2.9931   | 0.1477     | 20.261  | < 2e-16 ***  |
| daySun  | 3.2551   | 0.1581     | 20.594  | < 2e-16 ***  |
| dayThur | 2.7715   | 0.1750     | 15.837  | < 2e-16 ***  |

---

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

Residual standard error: 1.378 on 240 degrees of freedom

Multiple R-squared: 0.8286, Adjusted R-squared: 0.8257

F-statistic: 290.1 on 4 and 240 DF, p-value: <2.2e-16

```
> # first calculate the means and CI manually
> require(plyr)
> tipsByDay <- ddply(tips, "day", summarize,
+                      tip.mean=mean(tip), tip.sd=sd(tip),
+                      Length=NROW(tip),
+                      tfrac=qt(p=.90, df=Length-1),
+                      Lower=tip.mean - tfrac*tip.sd/sqrt(Length),
+                      Upper=tip.mean + tfrac*tip.sd/sqrt(Length)
+                     )
>
> # now extract them from the summary for tipsLM
> tipsInfo <- summary(tipsLM)
> tipsCoef <- as.data.frame(tipsInfo$coefficients[, 1:2])
> tipsCoef <- within(tipsCoef, {
+   Lower <- Estimate - qt(p=0.90, df=tipsInfo$df[2]) * `Std. Error`
+   Upper <- Estimate + qt(p=0.90, df=tipsInfo$df[2]) * `Std. Error`
+   day <- rownames(tipsCoef)
+ })
> # plot them both
> ggplot(tipsByDay, aes(x=tip.mean, y=day)) + geom_point() +
+   geom_errorbarh(aes(xmin=Lower, xmax=Upper), height=.3) +
+   ggtitle("Tips by day calculated manually")
>
> ggplot(tipsCoef, aes(x=Estimate, y=day)) + geom_point() +
+   geom_errorbarh(aes(xmin=Lower, xmax=Upper), height=.3) +
+   ggtitle("Tips by day calculated from regression model")
```



```
> names(housing) <- c("Neighborhood", "Class", "Units", "YearBuilt",
+                         "SqFt", "Income", "IncomePerSqFt", "Expense",
+                         "ExpensePerSqFt", "NetIncome", "Value",
+                         "ValuePerSqFt", "Boro")
> head(housing)

  Neighborhood          Class  Units YearBuilt    SqFt Income
1 FINANCIAL R9-CONDOMINIUM    42    1920 36500 1332615
2 FINANCIAL R4-CONDOMINIUM    78    1985 126420 6633257
3 FINANCIAL RR-CONDOMINIUM   500      NA 554174 17310000
4 FINANCIAL R4-CONDOMINIUM   282    1930 249076 11776313
5 TRIBECA R4-CONDOMINIUM    239    1985 219495 10004582
6 TRIBECA R4-CONDOMINIUM    133    1986 139719 5127687

  IncomePerSqFt Expense ExpensePerSqFt NetIncome     Value
1        36.51 342005           9.37  990610 7300000
2        52.47 1762295          13.94  4870962 30690000
3        31.24 3543000           6.39 13767000 90970000
4        47.28 2784670          11.18  8991643 67556006
5        45.58 2783197          12.68  7221385 54320996
6        36.70 1497788          10.72  3629899 26737996

  ValuePerSqFt      Boro
1      200.00 Manhattan
2      242.76 Manhattan
3      164.15 Manhattan
4      271.23 Manhattan
5      247.48 Manhattan
6      191.37 Manhattan
```

```
> ggplot(housing, aes(x=ValuePerSqFt)) +  
+     geom_histogram(binwidth=10) + labs(x="Value per Square Foot")
```

```
> ggplot(housing, aes(x=ValuePerSqFt, fill=Boro)) +
+     geom_histogram(binwidth=10) + labs(x="Value per Square Foot")
> ggplot(housing, aes(x=ValuePerSqFt, fill=Boro)) +
+     geom_histogram(binwidth=10) + labs(x="Value per Square Foot") +
+     facet_wrap(~Boro)
```

```
> ggplot(housing, aes(x=SqFt)) + geom_histogram()
> ggplot(housing, aes(x=Units)) + geom_histogram()
> ggplot(housing[housing$Units < 1000, ],
+         aes(x=SqFt)) + geom_histogram()
> ggplot(housing[housing$Units < 1000, ],
+         aes(x=Units)) + geom_histogram()
```

```
> ggplot(housing, aes(x = SqFt, y = ValuePerSqFt)) + geom_point()
> ggplot(housing, aes(x = Units, y = ValuePerSqFt)) + geom_point()
> ggplot(housing[housing$Units < 1000, ], aes(x = SqFt,
+     y = ValuePerSqFt)) + geom_point()
> ggplot(housing[housing$Units < 1000, ], aes(x = Units,
+     y = ValuePerSqFt)) + geom_point()

> # how many need to be removed?
> sum(housing$Units >= 1000)

[1] 6

> # remove them
> housing <- housing[housing$Units < 1000, ]
```

```
> # plot ValuePerSqFt against SqFt  
> ggplot(housing, aes(x=SqFt, y=ValuePerSqFt)) + geom_point()  
> ggplot(housing, aes(x=log(SqFt), y=ValuePerSqFt)) + geom_point()  
> ggplot(housing, aes(x=SqFt, y=log(ValuePerSqFt))) + geom_point()  
> ggplot(housing, aes(x=log(SqFt), y=log(ValuePerSqFt))) +  
+     geom_point()
```

```
> # plot ValuePerSqFt against Units
> ggplot(housing, aes(x=Units, y=ValuePerSqFt)) + geom_point()
> ggplot(housing, aes(x=log(Units), y=ValuePerSqFt)) + geom_point()
> ggplot(housing, aes(x=Units, y=log(ValuePerSqFt))) + geom_point()
> ggplot(housing, aes(x=log(Units), y=log(ValuePerSqFt))) +
+     geom_point()
```

```
> house1 <- lm(ValuePerSqFt ~ Units + SqFt + Boro, data = housing)
> summary(house1)
```

Call:

```
lm(formula = ValuePerSqFt ~ Units + SqFt + Boro, data = housing)
```

Residuals:

| Min      | 1Q      | Median | 3Q     | Max     |
|----------|---------|--------|--------|---------|
| -168.458 | -22.680 | 1.493  | 26.290 | 261.761 |

Coefficients:

|                   | Estimate   | Std. Error | t value | Pr(> t )     |
|-------------------|------------|------------|---------|--------------|
| (Intercept)       | 4.430e+01  | 5.342e+00  | 8.293   | < 2e-16 ***  |
| Units             | -1.532e-01 | 2.421e-02  | -6.330  | 2.88e-10 *** |
| SqFt              | 2.070e-04  | 2.129e-05  | 9.723   | < 2e-16 ***  |
| BoroBrooklyn      | 3.258e+01  | 5.561e+00  | 5.858   | 5.28e-09 *** |
| BoroManhattan     | 1.274e+02  | 5.459e+00  | 23.343  | < 2e-16 ***  |
| BoroQueens        | 3.011e+01  | 5.711e+00  | 5.272   | 1.46e-07 *** |
| BoroStaten Island | -7.114e+00 | 1.001e+01  | -0.711  | 0.477        |

---

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

Residual standard error: 43.2 on 2613 degrees of freedom

Multiple R-squared: 0.6034, Adjusted R-squared: 0.6025

F-statistic: 662.6 on 6 and 2613 DF, p-value: < 2.2e-16

```
> house1$coefficients
```

|                   | Units         | SqFt         |
|-------------------|---------------|--------------|
| (Intercept)       |               |              |
| 4.430325e+01      | -1.532405e-01 | 2.069727e-04 |
| BoroBrooklyn      | BoroManhattan | BoroQueens   |
| 3.257554e+01      | 1.274259e+02  | 3.011000e+01 |
| BoroStaten Island |               |              |
| -7.113688e+00     |               |              |

```
> coef(house1)
```

|                   | Units         | SqFt         |
|-------------------|---------------|--------------|
| (Intercept)       |               |              |
| 4.430325e+01      | -1.532405e-01 | 2.069727e-04 |
| BoroBrooklyn      | BoroManhattan | BoroQueens   |
| 3.257554e+01      | 1.274259e+02  | 3.011000e+01 |
| BoroStaten Island |               |              |
| -7.113688e+00     |               |              |

```
> # works the same as coef
```

```
> coefficients(house1)
```

|                   | Units         | SqFt         |
|-------------------|---------------|--------------|
| (Intercept)       |               |              |
| 4.430325e+01      | -1.532405e-01 | 2.069727e-04 |
| BoroBrooklyn      | BoroManhattan | BoroQueens   |
| 3.257554e+01      | 1.274259e+02  | 3.011000e+01 |
| BoroStaten Island |               |              |
| -7.113688e+00     |               |              |

```
> house2 <- lm(ValuePerSqFt ~ Units * SqFt + Boro, data = housing)
> house3 <- lm(ValuePerSqFt ~ Units:SqFt + Boro, data = housing)
> house2$coefficients

(Intercept)          Units           SqFt
4.093685e+01      -1.024579e-01    2.362293e-04
BoroBrooklyn       BoroManhattan     BoroQueens
3.394544e+01      1.272102e+02    3.040115e+01
BoroStaten Island   Units:SqFt
-8.419682e+00     -1.809587e-07

> house3$coefficients

(Intercept)      BoroBrooklyn      BoroManhattan
4.804972e+01      3.141208e+01    1.302084e+02
BoroQueens BoroStaten Island   Units:SqFt
2.841669e+01      -7.199902e+00   1.088059e-07

> coefplot(house2)
> coefplot(house3)
```

```
> house4 <- lm(ValuePerSqFt ~ SqFt * Units * Income, housing)
> house4$coefficients
```

|               |                   | SqFt          | Units |
|---------------|-------------------|---------------|-------|
| (Intercept)   |                   |               |       |
| 1.116433e+02  | -1.694688e-03     | 7.142611e-03  |       |
| Income        | SqFt:Units        | SqFt:Income   |       |
| 7.250830e-05  | 3.158094e-06      | -5.129522e-11 |       |
| Units:Income  | SqFt:Units:Income |               |       |
| -1.279236e-07 | 9.107312e-14      |               |       |

```
> house5 <- lm(ValuePerSqFt ~ Class * Boro, housing)
> house5$coefficients

(Intercept) 47.041481
ClassR4 - CONDOMINIUM 4.023852
ClassR9 - CONDOMINIUM -2.838624
ClassRR - CONDOMINIUM 3.688519
BoroBrooklyn 27.627141
BoroManhattan 89.598397
BoroQueens 19.144780
BoroStaten Island -9.203410
ClassR4 - CONDOMINIUM:BoroBrooklyn 4.117977
ClassR9 - CONDOMINIUM:BoroBrooklyn 2.660419
```

|                                         |             |
|-----------------------------------------|-------------|
| ClassRR - CONDOMINIUM:BoroBrooklyn      |             |
|                                         | - 25.607141 |
| ClassR4 - CONDOMINIUM:BoroManhattan     |             |
|                                         | 47.198900   |
| ClassR9 - CONDOMINIUM:BoroManhattan     |             |
|                                         | 33.479718   |
| ClassRR - CONDOMINIUM:BoroManhattan     |             |
|                                         | 10.619231   |
| ClassR4 - CONDOMINIUM:BoroQueens        |             |
|                                         | 13.588293   |
| ClassR9 - CONDOMINIUM:BoroQueens        |             |
|                                         | - 9.830637  |
| ClassRR - CONDOMINIUM:BoroQueens        |             |
|                                         | 34.675220   |
| ClassR4 - CONDOMINIUM:BoroStaten Island |             |
|                                         | NA          |
| ClassR9 - CONDOMINIUM:BoroStaten Island |             |
|                                         | NA          |
| ClassRR - CONDOMINIUM:BoroStaten Island |             |
|                                         | NA          |

```
> house6 <- lm(ValuePerSqFt ~ I(SqFt/Units) + Boro, housing)
> house6$coefficients
```

|               | I(SqFt/Units) | BoroBrooklyn      |
|---------------|---------------|-------------------|
| (Intercept)   | 43.754838763  | 30.774343209      |
| BoroManhattan | BoroQueens    | BoroStaten Island |
| 130.769502685 | 29.767922792  | -6.134446417      |

```
> house7 <- lm(ValuePerSqFt ~ (Units + SqFt)^2, housing)
> house7$coefficients

(Intercept)          Units           SqFt      Units:SqFt
1.070301e+02 -1.125194e-01  4.964623e-04 -5.159669e-07

> house8 <- lm(ValuePerSqFt ~ Units * SqFt, housing)
> identical(house7$coefficients, house8$coefficients)

[1] TRUE

> house9 <- lm(ValuePerSqFt ~ I(Units + SqFt)^2, housing)
> house9$coefficients

(Intercept) I(Units + SqFt)
1.147034e+02    2.107231e-04
```

```
> # also from the coefplot package  
> multiplot(house1, house2, house3)
```

```
> housingNew <- read.table("http://www.jaredlander.com/data/  
+ housingNew.csv", sep = ",", header = TRUE, stringsAsFactors = FALSE)
```

```
> # make prediction with new data and 95% confidence bounds
> housePredict <- predict(house1, newdata = housingNew, se.fit = TRUE,
+                               interval = "prediction", level = .95)
> # view predictions with upper and lower bounds based on
> # standard errors
> head(housePredict$fit)

      fit      lwr      upr
1 74.00645 -10.813887 158.8268
2 82.04988  -2.728506 166.8283
3 166.65975  81.808078 251.5114
4 169.00970  84.222648 253.7968
5 80.00129  -4.777303 164.7799
6 47.87795 -37.480170 133.2361

> # view the standard errors for the prediction
> head(housePredict$se.fit)

      1      2      3      4      5      6
2.118509 1.624063 2.423006 1.737799 1.626923 5.318813
```



```
> acs <- read.table("http://jaredlander.com/data/acs_ny.csv", sep = ",",  
+ header = TRUE, stringsAsFactors = FALSE)
```

```
> acs$Income <- with(acs, FamilyIncome >= 150000)
> require(ggplot2)
> require(useful)
> ggplot(acs, aes(x=FamilyIncome)) +
+   geom_density(fill="grey", color="grey") +
+   geom_vline(xintercept=150000) +
+   scale_x_continuous(label=multiple.dollar, limits=c(0, 1000000))
```

```
> head(acs)
```

|   | Acres          | FamilyIncome    | FamilyType   | NumBedrooms | NumChildren | NumPeople |
|---|----------------|-----------------|--------------|-------------|-------------|-----------|
| 1 | 1-10           | 150             | Married      | 4           | 1           | 3         |
| 2 | 1-10           | 180             | Female Head  | 3           | 2           | 4         |
| 3 | 1-10           | 280             | Female Head  | 4           | 0           | 2         |
| 4 | 1-10           | 330             | Female Head  | 2           | 1           | 2         |
| 5 | 1-10           | 330             | Male Head    | 3           | 1           | 2         |
| 6 | 1-10           | 480             | Male Head    | 0           | 3           | 4         |
|   | NumRooms       | NumUnits        | NumVehicles  | NumWorkers  | OwnRent     |           |
| 1 | 9              | Single detached | 1            | 0           | Mortgage    |           |
| 2 | 6              | Single detached | 2            | 0           | Rented      |           |
| 3 | 8              | Single detached | 3            | 1           | Mortgage    |           |
| 4 | 4              | Single detached | 1            | 0           | Rented      |           |
| 5 | 5              | Single attached | 1            | 0           | Mortgage    |           |
| 6 | 1              | Single detached | 0            | 0           | Rented      |           |
|   | YearBuilt      | HouseCosts      | ElectricBill | FoodStamp   | HeatingFuel | Insurance |
| 1 | 1950-1959      | 1800            | 90           | No          | Gas         | 2500      |
| 2 | Before 1939    | 850             | 90           | No          | Oil         | 0         |
| 3 | 2000-2004      | 2600            | 260          | No          | Oil         | 6600      |
| 4 | 1950-1959      | 1800            | 140          | No          | Oil         | 0         |
| 5 | Before 1939    | 860             | 150          | No          | Gas         | 660       |
| 6 | Before 1939    | 700             | 140          | No          | Gas         | 0         |
|   | Language       | Income          |              |             |             |           |
| 1 | English        | FALSE           |              |             |             |           |
| 2 | English        | FALSE           |              |             |             |           |
| 3 | Other European | FALSE           |              |             |             |           |
| 4 | English        | FALSE           |              |             |             |           |
| 5 | Spanish        | FALSE           |              |             |             |           |
| 6 | English        | FALSE           |              |             |             |           |

```

> income1 <- glm(Income ~ HouseCosts + NumWorkers + OwnRent +
+                         NumBedrooms + FamilyType,
+                         data=acs, family=binomial(link="logit"))
> summary(income1)

Call:
glm(formula = Income ~ HouseCosts + NumWorkers + OwnRent + NumBedrooms +
    FamilyType, family = binomial(link = "logit"), data = acs)

Deviance Residuals:
    Min      1Q  Median      3Q     Max 
-2.8452 -0.6246 -0.4231 -0.1743  2.9503 

Coefficients:
   Estimate Std. Error z value Pr(>|z|)    
(Intercept)                  -5.738e+00  1.185e-01 -48.421  <2e-16 ***  
HouseCosts                     7.398e-04  1.724e-05  42.908  <2e-16 ***  
NumWorkers                      5.611e-01  2.588e-02  21.684  <2e-16 ***  
OwnRentOutright                1.772e+00  2.075e-01   8.541  <2e-16 ***  
OwnRentRented                  -8.886e-01  1.002e-01  -8.872  <2e-16 ***  
NumBedrooms                     2.339e-01  1.683e-02  13.895  <2e-16 ***  
FamilyTypeMale Head            3.336e-01  1.472e-01   2.266   0.0235 *   
FamilyTypeMarried              1.405e+00  8.704e-02  16.143  <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: 22808  on 22744  degrees of freedom
Residual deviance: 18073  on 22737  degrees of freedom
AIC: 18089

Number of Fisher Scoring iterations: 6

> require(coefplot)
> coefplot(income1)

```

```
> invlogit <- function(x)
+ {
+   1/(1 + exp(-x))
+ }
> invlogit(income1$coefficients)
```

|                     |                   |             |
|---------------------|-------------------|-------------|
| (Intercept)         | HouseCosts        | NumWorkers  |
| 0.003211572         | 0.500184950       | 0.636702036 |
| OwnRentOutright     | OwnRentRented     | NumBedrooms |
| 0.854753527         | 0.291408659       | 0.558200010 |
| FamilyTypeMale Head | FamilyTypeMarried |             |
| 0.582624773         | 0.802983719       |             |

```
> ggplot(acs, aes(x = NumChildren)) + geom_histogram(binwidth = 1)
```

```
> children1 <- glm(NumChildren ~ FamilyIncome + FamilyType + OwnRent,  
+                         data=acs, family=poisson(link="log"))  
> summary(children1)
```

Call:

```
glm(formula = NumChildren ~ FamilyIncome + FamilyType + OwnRent,  
family = poisson(link = "log"), data = acs)
```

Deviance Residuals:

| Min     | 1Q      | Median  | 3Q     | Max    |
|---------|---------|---------|--------|--------|
| -1.9950 | -1.3235 | -1.2045 | 0.9464 | 6.3781 |

Coefficients:

|                     | Estimate   | Std. Error | z value | Pr(> z )     |
|---------------------|------------|------------|---------|--------------|
| (Intercept)         | -3.257e-01 | 2.103e-02  | -15.491 | < 2e-16 ***  |
| FamilyIncome        | 5.420e-07  | 6.572e-08  | 8.247   | < 2e-16 ***  |
| FamilyTypeMale Head | -6.298e-02 | 3.847e-02  | -1.637  | 0.102        |
| FamilyTypeMarried   | 1.440e-01  | 2.147e-02  | 6.707   | 1.98e-11 *** |
| OwnRentOutright     | -1.974e+00 | 2.292e-01  | -8.611  | < 2e-16 ***  |
| OwnRentRented       | 4.086e-01  | 2.067e-02  | 19.773  | < 2e-16 ***  |
| ---                 |            |            |         |              |

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

(Dispersion parameter for poisson family taken to be 1)

Null deviance: 35240 on 22744 degrees of freedom  
Residual deviance: 34643 on 22739 degrees of freedom  
AIC: 61370

Number of Fisher Scoring iterations: 5

```
> coefplot(children1)
```

```
> # the standardized residuals  
> z <- (acs$NumChildren - children1$fitted.values) /  
+      sqrt(children1$fitted.values)  
> # Overdispersion Factor  
> sum(z^2) / children1$df.residual  
  
[1] 1.469747  
  
> # Overdispersion p-value  
> pchisq(sum(z^2), children1$df.residual)  
  
[1] 1
```

```
> children2 <- glm(NumChildren ~ FamilyIncome + FamilyType + OwnRent,  
+                         data=acs, family=quasipoisson(link="log"))  
> multiplot(children1, children2)
```

```
> require(survival)
> head(bladder)
```

|   | id | rx | number | size | stop | event | enum |
|---|----|----|--------|------|------|-------|------|
| 1 | 1  | 1  |        | 1    | 3    | 1     | 0    |
| 2 | 1  | 1  |        | 1    | 3    | 1     | 0    |
| 3 | 1  | 1  |        | 1    | 3    | 1     | 0    |
| 4 | 1  | 1  |        | 1    | 3    | 1     | 0    |
| 5 | 2  | 1  |        | 2    | 1    | 4     | 0    |
| 6 | 2  | 1  |        | 2    | 1    | 4     | 0    |

```
> # first look at a piece of the data  
> bladder[100:105, ]
```

|     | id | rx | number | size | stop | event | enum |
|-----|----|----|--------|------|------|-------|------|
| 100 | 25 | 1  | 2      | 1    | 12   | 1     | 4    |
| 101 | 26 | 1  | 1      | 3    | 12   | 1     | 1    |
| 102 | 26 | 1  | 1      | 3    | 15   | 1     | 2    |
| 103 | 26 | 1  | 1      | 3    | 24   | 1     | 3    |
| 104 | 26 | 1  | 1      | 3    | 31   | 0     | 4    |
| 105 | 27 | 1  | 1      | 2    | 32   | 0     | 1    |

```
> # now look at the response variable built by build.y  
> survObject <- with(bladder[100:105, ], Surv(stop, event))  
> # nicely printed form  
> survObject
```

```
[1] 12 12 15 24 31+ 32+
```

```
> # see its matrix form  
> survObject[, 1:2]
```

|      | time | status |
|------|------|--------|
| [1,] | 12   | 1      |
| [2,] | 12   | 1      |
| [3,] | 15   | 1      |
| [4,] | 24   | 1      |
| [5,] | 31   | 0      |
| [6,] | 32   | 0      |

```
> cox1 <- coxph(Surv(stop, event) ~ rx + number + size + enum,  
+                      data=bladder)  
> summary(cox1)
```

Call:

```
coxph(formula = Surv(stop, event) ~ rx + number + size + enum,  
       data = bladder)
```

n= 340, number of events= 112

|        | coef     | exp(coef) | se(coef) | z      | Pr(> z ) |     |
|--------|----------|-----------|----------|--------|----------|-----|
| rx     | -0.59739 | 0.55024   | 0.20088  | -2.974 | 0.00294  | **  |
| number | 0.21754  | 1.24301   | 0.04653  | 4.675  | 2.93e-06 | *** |
| size   | -0.05677 | 0.94481   | 0.07091  | -0.801 | 0.42333  |     |
| enum   | -0.60385 | 0.54670   | 0.09401  | -6.423 | 1.34e-10 | *** |
| ---    |          |           |          |        |          |     |

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

|        | exp(coef) | exp(-coef) | lower .95 | upper .95 |  |
|--------|-----------|------------|-----------|-----------|--|
| rx     | 0.5502    | 1.8174     | 0.3712    | 0.8157    |  |
| number | 1.2430    | 0.8045     | 1.1347    | 1.3617    |  |
| size   | 0.9448    | 1.0584     | 0.8222    | 1.0857    |  |
| enum   | 0.5467    | 1.8291     | 0.4547    | 0.6573    |  |

Concordance= 0.753 (se = 0.029 )

Rsquare= 0.179 (max possible= 0.971 )

Likelihood ratio test= 67.21 on 4 df, p=8.804e-14

Wald test = 64.73 on 4 df, p=2.932e-13

Score (logrank) test = 69.42 on 4 df, p=2.998e-14

```
> plot(survfit(cox1), xlab="Days", ylab="Survival Rate",  
+       conf.int=TRUE)
```

```

> cox2 <- coxph(Surv(stop, event) ~ strata(rx) + number + size + enum,
+                   data=bladder)
> summary(cox2)

Call:
coxph(formula = Surv(stop, event) ~ strata(rx) + number + size +
    enum, data = bladder)

n= 340, number of events= 112

            coef exp(coef)  se(coef)      z Pr(>|z|)
number   0.21371   1.23826  0.04648  4.598 4.27e-06 ***
size     -0.05485   0.94662  0.07097 -0.773   0.44
enum     -0.60695   0.54501  0.09408 -6.451 1.11e-10 ***
...
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

            exp(coef) exp(-coef) lower .95 upper .95
number     1.2383      0.8076    1.1304    1.3564
size       0.9466      1.0564    0.8237    1.0879
enum       0.5450      1.8348    0.4532    0.6554

Concordance= 0.74  (se = 0.04 )
Rsquare= 0.166  (max possible= 0.954 )
Likelihood ratio test= 61.84  on 3 df,  p=2.379e-13
Wald test          = 60.04  on 3 df,  p=5.751e-13
Score (logrank) test = 65.05  on 3 df,  p=4.896e-14

> plot(survfit(cox2), xlab="Days", ylab="Survival Rate",
+       conf.int=TRUE, col=1:2)
> legend("bottomleft", legend=c(1, 2), lty=1, col=1:2,
+        text.col=1:2, title="rx")

```

```
> cox.zph(cox1)
```

|        | rho     | chisq   | p        |
|--------|---------|---------|----------|
| rx     | 0.0299  | 0.0957  | 7.57e-01 |
| number | 0.0900  | 0.6945  | 4.05e-01 |
| size   | -0.1383 | 2.3825  | 1.23e-01 |
| enum   | 0.4934  | 27.2087 | 1.83e-07 |
| GLOBAL | NA      | 32.2101 | 1.73e-06 |

```
> cox.zph(cox2)
```

|        | rho     | chisq  | p        |
|--------|---------|--------|----------|
| number | 0.0966  | 0.785  | 3.76e-01 |
| size   | -0.1331 | 2.197  | 1.38e-01 |
| enum   | 0.4972  | 27.237 | 1.80e-07 |
| GLOBAL | NA      | 32.101 | 4.98e-07 |

```
> head(bladder2)
   id rx number size start stop event enum
1  1  1      1    3      0     1     0     1
2  2  1      2    1      0     4     0     1
3  3  1      1    1      0     7     0     1
4  4  1      5    1      0    10     0     1
5  5  1      4    1      0     6     1     1
6  5  1      4    1      6    10     0     2

> ag1 <- coxph(Surv(start, stop, event) ~ rx + number + size + enum +
+                  cluster(id), data=bladder2)
> ag2 <- coxph(Surv(start, stop, event) ~ strata(rx) + number + size +
+                  enum + cluster(id), data=bladder2)
> plot(survfit(ag1), conf.int=TRUE)
> plot(survfit(ag2), conf.int=TRUE, col=1:2)
> legend("topright", legend=c(1, 2), lty=1, col=1:2,
+         text.col=1:2, title="rx")
```



```
> # read in the data
> housing <- read.table("data/housing.csv", sep=",", header=TRUE,
+                         stringsAsFactors=FALSE)
> # give the data good names
> names(housing) <- c("Neighborhood", "Class", "Units", "YearBuilt",
+                       "SqFt", "Income", "IncomePerSqFt", "Expense",
+                       "ExpensePerSqFt", "NetIncome", "Value",
+                       "ValuePerSqFt", "Boro")
> # eliminate some outliers
> housing <- housing[housing$Units < 1000, ]
> head(housing)
```

|   | Neighborhood  | Class          | Units          | YearBuilt | SqFt     | Income          |
|---|---------------|----------------|----------------|-----------|----------|-----------------|
| 1 | FINANCIAL     | R9-CONDOMINIUM | 42             | 1920      | 36500    | 1332615         |
| 2 | FINANCIAL     | R4-CONDOMINIUM | 78             | 1985      | 126420   | 6633257         |
| 3 | FINANCIAL     | RR-CONDOMINIUM | 500            |           | NA       | 554174 17310000 |
| 4 | FINANCIAL     | R4-CONDOMINIUM | 282            | 1930      | 249076   | 11776313        |
| 5 | TRIBECA       | R4-CONDOMINIUM | 239            | 1985      | 219495   | 10004582        |
| 6 | TRIBECA       | R4-CONDOMINIUM | 133            | 1986      | 139719   | 5127687         |
|   | IncomePerSqFt | Expense        | ExpensePerSqFt | NetIncome | Value    |                 |
| 1 | 36.51         | 342005         |                | 9.37      | 990610   | 7300000         |
| 2 | 52.47         | 1762295        |                | 13.94     | 4870962  | 30690000        |
| 3 | 31.24         | 3543000        |                | 6.39      | 13767000 | 90970000        |
| 4 | 47.28         | 2784670        |                | 11.18     | 8991643  | 67556006        |
| 5 | 45.58         | 2783197        |                | 12.68     | 7221385  | 54320996        |
| 6 | 36.70         | 1497788        |                | 10.72     | 3629899  | 26737996        |

```
ValuePerSqFt      Boro
1      200.00 Manhattan
2      242.76 Manhattan
3      164.15 Manhattan
4      271.23 Manhattan
5      247.48 Manhattan
6      191.37 Manhattan

>
> # fit a model
> house1 <- lm(ValuePerSqFt ~ Units + SqFt + Boro, data=housing)
> summary(house1)
```

Call:

```
lm(formula = ValuePerSqFt ~ Units + SqFt + Boro, data = housing)
```

Residuals:

| Min      | 1Q      | Median | 3Q     | Max     |
|----------|---------|--------|--------|---------|
| -168.458 | -22.680 | 1.493  | 26.290 | 261.761 |

Coefficients:

|                   | Estimate   | Std. Error | t value | Pr(> t ) |     |
|-------------------|------------|------------|---------|----------|-----|
| (Intercept)       | 4.430e+01  | 5.342e+00  | 8.293   | < 2e-16  | *** |
| Units             | -1.532e-01 | 2.421e-02  | -6.330  | 2.88e-10 | *** |
| SqFt              | 2.070e-04  | 2.129e-05  | 9.723   | < 2e-16  | *** |
| BoroBrooklyn      | 3.258e+01  | 5.561e+00  | 5.858   | 5.28e-09 | *** |
| BoroManhattan     | 1.274e+02  | 5.459e+00  | 23.343  | < 2e-16  | *** |
| BoroQueens        | 3.011e+01  | 5.711e+00  | 5.272   | 1.46e-07 | *** |
| BoroStaten Island | -7.114e+00 | 1.001e+01  | -0.711  | 0.477    |     |

---

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

Residual standard error: 43.2 on 2613 degrees of freedom  
Multiple R-squared: 0.6034, Adjusted R-squared: 0.6025  
F-statistic: 662.6 on 6 and 2613 DF, p-value: <2.2e-16

>

```
# visualize the model
> require(coefplot)
> coefplot(house1)
```

```

> require(ggplot2)
> # see what a fortified lm model looks like
> head(fortify(house1))

  ValuePerSqFt Units     SqFt      Boro     .hat   .sigma
1       200.00    42  36500 Manhattan 0.0009594821 43.20952
2       242.76    78 126420 Manhattan 0.0009232393 43.19848
3       164.15   500 554174 Manhattan 0.0089836758 43.20347
4       271.23   282 249076 Manhattan 0.0035168641 43.17583
5       247.48   239 219495 Manhattan 0.0023865978 43.19289
6       191.37   133 139719 Manhattan 0.0008934957 43.21225
       .cooksdi .fitted   .resid   .stdresid
1 5.424169e-05 172.8475  27.15248  0.6287655
2 2.285253e-04 185.9418  56.81815  1.3157048
3 1.459368e-03 209.8077 -45.65775 -1.0615607
4 2.252653e-03 180.0672  91.16278  2.1137487
5 8.225193e-04 180.5341  66.94589  1.5513636
6 8.446170e-06 180.2661  11.10385  0.2571216

> # save a plot to an object
> # notice we are using the created columns for the x- and y-axes
> # they are .fitted and .resid
> h1 <- ggplot(aes(x=.fitted, y=.resid), data = house1) +
+   geom_point() +
+   geom_hline(yintercept = 0) +
+   geom_smooth(se = FALSE) +
+   labs(x="Fitted Values", y="Residuals")
>
> # print the plot
> h1

```

```
> h1 + geom_point(aes(color = Boro))
```

```
> # same plot but colored by Boro  
> plot(house1, which=1, col=as.numeric(factor(house1$model$Boro)))  
> # corresponding legend  
> legend("topright", legend=levels(factor(house1$model$Boro)), pch=1,  
+       col=as.numeric(factor(levels(factor(house1$model$Boro)))),  
+       text.col=as.numeric(factor(levels(factor(house1$model$Boro)))),  
+       title="Boro")
```

```
> plot(house1, which = 2)
> ggplot(house1, aes(sample = .stdresid)) + stat_qq() + geom_abline()
```

```
> ggplot(house1, aes(x = .resid)) + geom_histogram()
```

```
> house2 <- lm(ValuePerSqFt ~ Units * SqFt + Boro, data=housing)
> house3 <- lm(ValuePerSqFt ~ Units + SqFt * Boro + Class,
+                 data=housing)
> house4 <- lm(ValuePerSqFt ~ Units + SqFt * Boro + SqFt*Class,
+                 data=housing)
> house5 <- lm(ValuePerSqFt ~ Boro + Class, data=housing)
```

```
> multiplot(house1, house2, house3, house4, house5, pointSize = 2)
```

```
> anova(house1, house2, house3, house4, house5)
```

### Analysis of Variance Table

Model 1: ValuePerSqFt ~ Units + SqFt + Boro

Model 2: ValuePerSqFt ~ Units \* SqFt + Boro

Model 3:  $\text{ValuePerSqFt} \sim \text{Units} + \text{SqFt} * \text{Boro} + \text{Class}$

Model 4: ValuePerSqFt ~ Units + SqFt \* Boro + SqFt \* Class

Model 5: ValuePerSqFt ~ Boro + Class

```
> AIC(house1, house2, house3, house4, house5)
```

|        | df | AIC      |
|--------|----|----------|
| house1 | 8  | 27177.78 |
| house2 | 9  | 27163.82 |
| house3 | 15 | 27025.04 |
| house4 | 18 | 27001.69 |
| house5 | 9  | 27189.50 |

```
> BIC(house1, house2, house3, house4, house5)
```

|        | df | BIC      |
|--------|----|----------|
| house1 | 8  | 27224.75 |
| house2 | 9  | 27216.66 |
| house3 | 15 | 27113.11 |
| house4 | 18 | 27107.37 |
| house5 | 9  | 27242.34 |

```
> # create the binary variable based on whether ValuePerSqFt is above 150
> housing$HighValue <- housing$ValuePerSqFt >= 150
>
> # fit a few models
> high1 <- glm(HighValue ~ Units + SqFt + Boro,
+                      data=housing, family=binomial(link="logit"))
> high2 <- glm(HighValue ~ Units * SqFt + Boro,
+                      data=housing, family=binomial(link="logit"))
> high3 <- glm(HighValue ~ Units + SqFt * Boro + Class,
+                      data=housing, family=binomial(link="logit"))
> high4 <- glm(HighValue ~ Units + SqFt * Boro + SqFt*Class,
+                      data=housing, family=binomial(link="logit"))
> high5 <- glm(HighValue ~ Boro + Class,
+                      data=housing, family=binomial(link="logit"))
>
> # test the models using ANOVA (deviance), AIC and BIC
> anova(high1, high2, high3, high4, high5)
```

#### Analysis of Deviance Table

Model 1: HighValue ~ Units + SqFt + Boro  
Model 2: HighValue ~ Units \* SqFt + Boro  
Model 3: HighValue ~ Units + SqFt \* Boro + Class  
Model 4: HighValue ~ Units + SqFt \* Boro + SqFt \* Class  
Model 5: HighValue ~ Boro + Class

|   | Resid. | Df | Resid. | Dev | Df | Deviance |
|---|--------|----|--------|-----|----|----------|
| 1 | 2613   |    | 1687.5 |     |    |          |
| 2 | 2612   |    | 1678.8 | 1   |    | 8.648    |
| 3 | 2606   |    | 1627.5 | 6   |    | 51.331   |
| 4 | 2603   |    | 1606.1 | 3   |    | 21.420   |
| 5 | 2612   |    | 1662.3 | -9  |    | -56.205  |

```
> AIC(high1, high2, high3, high4, high5)
```

|       | df | AIC      |
|-------|----|----------|
| high1 | 7  | 1701.484 |
| high2 | 8  | 1694.835 |
| high3 | 14 | 1655.504 |
| high4 | 17 | 1640.084 |
| high5 | 8  | 1678.290 |

```
> BIC(high1, high2, high3, high4, high5)
```

|       | df | BIC      |
|-------|----|----------|
| high1 | 7  | 1742.580 |
| high2 | 8  | 1741.803 |
| high3 | 14 | 1737.697 |
| high4 | 17 | 1739.890 |
| high5 | 8  | 1725.257 |

```
> require(boot)
> # refit house1 using glm instead of lm
> houseG1 <- glm(ValuePerSqFt ~ Units + SqFt + Boro,
+                   data=housing, family=gaussian(link="identity"))
>
> # ensure it gives the same results as lm
> identical(coef(house1), coef(houseG1))

[1] TRUE

>
> # run the cross-validation with 5 folds
> houseCV1 <- cv.glm(housing, houseG1, K=5)
> # check the error
> houseCV1$delta

[1] 1878.596 1876.691
```

```

> # refit the models using glm
> houseG2 <- glm(ValuePerSqFt ~ Units * SqFt + Boro, data=housing)
> houseG3 <- glm(ValuePerSqFt ~ Units + SqFt * Boro + Class,
+                      data=housing)
> houseG4 <- glm(ValuePerSqFt ~ Units + SqFt * Boro + SqFt*Class,
+                      data=housing)
> houseG5 <- glm(ValuePerSqFt ~ Boro + Class, data=housing)
>
> # run cross-validation
> houseCV2 <- cv.glm(housing, houseG2, K=5)
> houseCV3 <- cv.glm(housing, houseG3, K=5)
> houseCV4 <- cv.glm(housing, houseG4, K=5)
> houseCV5 <- cv.glm(housing, houseG5, K=5)
>
> ## check the error results
> # build a data.frame of the results
> cvResults <- as.data.frame(rbind(houseCV1$delta, houseCV2$delta,
+                                     houseCV3$delta, houseCV4$delta,
+                                     houseCV5$delta))
> ## do some cleaning up to make the results more presentable
> # give better column names
> names(cvResults) <- c("Error", "Adjusted.Error")
> # add model name
> cvResults$Model <- sprintf("houseG%s", 1:5)
>
> # check the results
> cvResults

```

|   | Error    | Adjusted.Error | Model   |
|---|----------|----------------|---------|
| 1 | 1878.596 | 1876.691       | houseG1 |
| 2 | 1862.247 | 1860.900       | houseG2 |
| 3 | 1767.268 | 1764.953       | houseG3 |
| 4 | 1764.370 | 1760.102       | houseG4 |
| 5 | 1882.631 | 1881.067       | houseG5 |

```

> # visualize the results
> # test with ANOVA
> cvANOVA <- anova(houseG1, houseG2, houseG3, houseG4, houseG5)
> cvResults$ANOVA <- cvANOVA$`Resid. Dev`
> # measure with AIC
> cvResults$AIC <- AIC(houseG1, houseG2, houseG3, houseG4, houseG5)$AIC
>
> # make the data.frame suitable for plotting
> require(reshape2)
> cvMelt <- melt(cvResults, id.vars="Model", variable.name="Measure",
+                  value.name="Value")
> cvMelt

```

|    | Model   | Measure        | Value       |
|----|---------|----------------|-------------|
| 1  | houseG1 | Error          | 1878.596    |
| 2  | houseG2 | Error          | 1862.247    |
| 3  | houseG3 | Error          | 1767.268    |
| 4  | houseG4 | Error          | 1764.370    |
| 5  | houseG5 | Error          | 1882.631    |
| 6  | houseG1 | Adjusted.Error | 1876.691    |
| 7  | houseG2 | Adjusted.Error | 1860.900    |
| 8  | houseG3 | Adjusted.Error | 1764.953    |
| 9  | houseG4 | Adjusted.Error | 1760.102    |
| 10 | houseG5 | Adjusted.Error | 1881.067    |
| 11 | houseG1 | ANOVA          | 4877506.411 |
| 12 | houseG2 | ANOVA          | 4847886.327 |
| 13 | houseG3 | ANOVA          | 4576768.981 |
| 14 | houseG4 | ANOVA          | 4525782.873 |
| 15 | houseG5 | ANOVA          | 4895630.307 |
| 16 | houseG1 | AIC            | 27177.781   |
| 17 | houseG2 | AIC            | 27163.822   |
| 18 | houseG3 | AIC            | 27025.042   |
| 19 | houseG4 | AIC            | 27001.691   |
| 20 | houseG5 | AIC            | 27189.499   |

```

>
> ggplot(cvMelt, aes(x=Model, y=Value)) +
+   geom_line(aes(group=Measure, color=Measure)) +
+   facet_wrap(~Measure, scales="free_y") +
+   theme(axis.text.x=element_text(angle=90, vjust=.5)) +
+   guides(color=FALSE)

```

```
> cv.work <- function(fun, k = 5, data,
+                      cost = function(y, yhat) mean((y - yhat)^2),
+                      response="y", ...)
+ {
+   # generate folds
+   folds <- data.frame(Fold=sample(rep(x=1:k, length.out=nrow(data))),
+                        Row=1:nrow(data))
+
+   # start the error at 0
+   error <- 0
+
+   ## loop through each of the folds
+   ## for each fold:
+   ## fit the model on the training data
+   ## predict on the test data
+   ## compute the error and accumulate it
+   for(f in 1:max(folds$Fold))
+   {
+     # rows that are in test set
+     theRows <- folds$Row[folds$Fold == f]
+
+     ## call fun on data[-theRows, ]
+     ## predict on data[theRows, ]
+     mod <- fun(data=data[-theRows, ], ...)
+     pred <- predict(mod, data[theRows, ])
+
+     # add new error weighted by the number of rows in this fold
+     error <- error +
+       cost(data[theRows, response], pred) *
+       (length(theRows)/nrow(data))
+   }
+
+   return(error)
+ }
```

```
> cv1 <- cv.work(fun=lm, k=5, data=housing, response="ValuePerSqFt",
+                     formula=ValuePerSqFt ~ Units + SqFt + Boro)
> cv2 <- cv.work(fun=lm, k=5, data=housing, response="ValuePerSqFt",
+                     formula=ValuePerSqFt ~ Units * SqFt + Boro)
> cv3 <- cv.work(fun=lm, k=5, data=housing, response="ValuePerSqFt",
+                     formula=ValuePerSqFt ~ Units + SqFt * Boro + Class)
> cv4 <- cv.work(fun=lm, k=5, data=housing, response="ValuePerSqFt",
+                     formula=ValuePerSqFt ~ Units + SqFt * Boro + SqFt*Class)
> cv5 <- cv.work(fun=lm, k=5, data=housing, response="ValuePerSqFt",
+                     formula=ValuePerSqFt ~ Boro + Class)
> cvResults <- data.frame(Model=sprintf("house%s", 1:5),
+                           Error=c(cv1, cv2, cv3, cv4, cv5))
> cvResults
```

|   | Model  | Error    |
|---|--------|----------|
| 1 | house1 | 1875.582 |
| 2 | house2 | 1859.388 |
| 3 | house3 | 1766.066 |
| 4 | house4 | 1764.343 |
| 5 | house5 | 1880.926 |

```
> require(plyr)
> baseball <- baseball[baseball$year >= 1990, ]
> head(baseball)
```

|       | id        | year | stint | team | lg  | g   | ab  | r    | h         | X2b | X3b | hr | rbi | sb |
|-------|-----------|------|-------|------|-----|-----|-----|------|-----------|-----|-----|----|-----|----|
|       | cs        | bb   | so    | ibb  | hbp | sh  | sf  | gidp |           |     |     |    |     |    |
| 67412 | alomasa02 | 1990 |       | CLE  | AL  | 132 | 445 | 60   | 129       | 26  | 2   | 9  | 66  | 4  |
| 67414 | anderbr01 | 1990 |       | BAL  | AL  | 89  | 234 | 24   | 54        | 5   | 2   | 3  | 24  | 15 |
| 67422 | baergca01 | 1990 |       | CLE  | AL  | 108 | 312 | 46   | 81        | 17  | 2   | 7  | 47  | 0  |
| 67424 | baineha01 | 1990 |       | TEX  | AL  | 103 | 321 | 41   | 93        | 10  | 1   | 13 | 44  | 0  |
| 67425 | baineha01 | 1990 | 2     | OAK  | AL  | 32  | 94  | 11   | 25        | 5   | 0   | 3  | 21  | 0  |
| 67442 | bergmda01 | 1990 |       | DET  | AL  | 100 | 205 | 21   | 57        | 10  | 1   | 2  | 26  | 3  |
|       |           |      |       |      |     |     |     |      |           |     |     |    |     |    |
| 67412 | 1         | 25   | 46    | 2    | 2   | 5   | 6   | 10   | 0.3263598 |     |     |    |     |    |
| 67414 | 2         | 31   | 46    | 2    | 5   | 4   | 5   | 4    | 0.3272727 |     |     |    |     |    |
| 67422 | 2         | 16   | 57    | 2    | 4   | 1   | 5   | 4    | 0.2997033 |     |     |    |     |    |
| 67424 | 1         | 47   | 63    | 9    | 0   | 0   | 3   | 13   | 0.3773585 |     |     |    |     |    |
| 67425 | 2         | 20   | 17    | 1    | 0   | 0   | 4   | 4    | 0.3813559 |     |     |    |     |    |
| 67442 | 2         | 33   | 17    | 3    | 0   | 1   | 2   | 7    | 0.3750000 |     |     |    |     |    |

```
> ## build a function for calculating batting average
> # data is the data
> # boot will pass varying sets of indices
> # some rows will be represented multiple times in a single pass
> # other rows will not be represented at all
> # on average about 63% of the rows will be present
> # this function is called repeatedly by boot
> bat.avg <- function(data, indices=1:NROW(data), hits="h",
+                         at.bats="ab")
+ {
+   sum(data[indices, hits], na.rm=TRUE) /
+   sum(data[indices, at.bats], na.rm=TRUE)
+ }
>

> # test it on the original data
> bat.avg(baseball)

[1] 0.2745988

>
> # bootstrap it
> # using the baseball data, call bat.avg 1,200 times
> # pass indices to the function
> avgBoot <- boot(data=baseball, statistic=bat.avg, R=1200, stype="i")
>
```

```
> # print original measure and estimates of bias and standard error  
> avgBoot
```

## ORDINARY NONPARAMETRIC BOOTSTRAP

Call:

```
boot(data = baseball, statistic = bat.avg, R = 1200, stype = "i")
```

Bootstrap Statistics :

|     | original  | bias         | std. error   |
|-----|-----------|--------------|--------------|
| t1* | 0.2745988 | 1.071011e-05 | 0.0006843765 |

```
> # print the confidence interval
```

```
> boot.ci(avgBoot, conf=.95, type="norm")
```

## BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS

Based on 1200 bootstrap replicates

CALL :

```
boot.ci(boot.out = avgBoot, conf = 0.95, type = "norm")
```

Intervals :

Level Normal

95% ( 0.2732, 0.2759 )

Calculations and Intervals on Original Scale

```
> ggplot() +  
+   geom_histogram(aes(x=avgBoot$t), fill="grey", color="grey") +  
+   geom_vline(xintercept=avgBoot$t0 + c(-1, 1)*2*sqrt(var(avgBoot$t)),  
+               linetype=2)
```

```
> # the lowest model is the null model, basically the straight average
> nullModel <- lm(ValuePerSqFt ~ 1, data=housing)
> # the largest model we will accept
> fullModel <- lm(ValuePerSqFt ~ Units + SqFt*Boro + Boro*Class,
+                     data=housing)
> # try different models
> # start with nullModel
> # do not go above fullModel
> # work in both directions
> houseStep <- step(nullModel,
+                      scope=list(lower=nullModel, upper=fullModel),
+                      direction="both")
```

Start: AIC=22151.56

ValuePerSqFt ~ 1

|         | Df | Sum of Sq | RSS      | AIC   |
|---------|----|-----------|----------|-------|
| + Boro  | 4  | 7160206   | 5137931  | 19873 |
| + SqFt  | 1  | 1310379   | 10987758 | 21858 |
| + Class | 3  | 1264662   | 11033475 | 21873 |
| + Units | 1  | 778093    | 11520044 | 21982 |
| <none>  |    | 12298137  |          | 22152 |

Step: AIC=19872.83

ValuePerSqFt ~ Boro

|         | Df | Sum of Sq | RSS      | AIC   |
|---------|----|-----------|----------|-------|
| + Class | 3  | 242301    | 4895630  | 19752 |
| + SqFt  | 1  | 185635    | 4952296  | 19778 |
| + Units | 1  | 83948     | 5053983  | 19832 |
| <none>  |    |           | 5137931  | 19873 |
| - Boro  | 4  | 7160206   | 12298137 | 22152 |

Step: AIC=19752.26

ValuePerSqFt ~ Boro + Class

|              | Df | Sum of Sq | RSS      | AIC   |
|--------------|----|-----------|----------|-------|
| + SqFt       | 1  | 182170    | 4713460  | 19655 |
| + Units      | 1  | 100323    | 4795308  | 19700 |
| + Boro:Class | 9  | 111838    | 4783792  | 19710 |
| <none>       |    |           | 4895630  | 19752 |
| - Class      | 3  | 242301    | 5137931  | 19873 |
| - Boro       | 4  | 6137845   | 11033475 | 21873 |

Step: AIC=19654.91

ValuePerSqFt ~ Boro + Class + SqFt

|              | Df | Sum of Sq | RSS      | AIC   |
|--------------|----|-----------|----------|-------|
| + SqFt:Boro  | 4  | 113219    | 4600241  | 19599 |
| + Boro:Class | 9  | 94590     | 4618870  | 19620 |
| + Units      | 1  | 37078     | 4676382  | 19636 |
| <none>       |    |           | 4713460  | 19655 |
| - SqFt       | 1  | 182170    | 4895630  | 19752 |
| - Class      | 3  | 238836    | 4952296  | 19778 |
| - Boro       | 4  | 5480928   | 10194388 | 21668 |

Step: AIC=19599.21

ValuePerSqFt ~ Boro + Class + SqFt + Boro:SqFt

|              | Df | Sum of Sq | RSS     | AIC   |
|--------------|----|-----------|---------|-------|
| + Boro:Class | 9  | 68660     | 4531581 | 19578 |
| + Units      | 1  | 23472     | 4576769 | 19588 |
| <none>       |    |           | 4600241 | 19599 |
| - Boro:SqFt  | 4  | 113219    | 4713460 | 19655 |
| - Class      | 3  | 258642    | 4858883 | 19737 |

Step: AIC=19577.81

ValuePerSqFt ~ Boro + Class + SqFt + Boro:SqFt + Boro:Class

|              | Df | Sum of Sq | RSS     | AIC   |
|--------------|----|-----------|---------|-------|
| + Units      | 1  | 20131     | 4511450 | 19568 |
| <none>       |    |           | 4531581 | 19578 |
| - Boro:Class | 9  | 68660     | 4600241 | 19599 |
| - Boro:SqFt  | 4  | 87289     | 4618870 | 19620 |

Step: AIC=19568.14

ValuePerSqFt ~ Boro + Class + SqFt + Units + Boro:SqFt + Boro:Class

|              | Df | Sum of Sq | RSS     | AIC   |
|--------------|----|-----------|---------|-------|
| <none>       |    |           | 4511450 | 19568 |
| - Units      | 1  | 20131     | 4531581 | 19578 |
| - Boro:Class | 9  | 65319     | 4576769 | 19588 |
| - Boro:SqFt  | 4  | 75955     | 4587405 | 19604 |

> # reveal the chosen model

> houseStep

Call:

```
lm(formula = ValuePerSqFt ~ Boro + Class + SqFt + Units + Boro:SqFt +
  Boro:Class, data = housing)
```

Coefficients:

|                     |            |
|---------------------|------------|
| (Intercept)         |            |
|                     | 4.848e+01  |
| BoroBrooklyn        |            |
|                     | 2.655e+01  |
| BoroManhattan       |            |
|                     | 8.672e+01  |
| BoroQueens          |            |
|                     | 1.999e+01  |
| BoroStaten Island   |            |
|                     | -1.132e+01 |
| ClassR4-CONDOMINIUM |            |
|                     | 6.586e+00  |
| ClassR9-CONDOMINIUM |            |
|                     | 4.553e+00  |
| ClassRR-CONDOMINIUM |            |
|                     | 8.130e+00  |
| SqFt                |            |
|                     | 1.373e-05  |
| Units               |            |
|                     | -8.296e-02 |
| BoroBrooklyn:SqFt   |            |
|                     | 3.798e-05  |
| BoroManhattan:SqFt  |            |
|                     | 1.594e-04  |
| BoroQueens:SqFt     |            |

|                                       |            |
|---------------------------------------|------------|
|                                       | 2.753e-06  |
| BoroStaten Island:SqFt                | 4.362e-05  |
| BoroBrooklyn:ClassR4-CONDOMINIUM      | 1.933e+00  |
| BoroManhattan:ClassR4-CONDOMINIUM     | 3.436e+01  |
| BoroQueens:ClassR4-CONDOMINIUM        | 1.274e+01  |
| BoroStaten Island:ClassR4-CONDOMINIUM | NA         |
| BoroBrooklyn:ClassR9-CONDOMINIUM      | -3.440e+00 |
| BoroManhattan:ClassR9-CONDOMINIUM     | 1.497e+01  |
| BoroQueens:ClassR9-CONDOMINIUM        | -9.967e+00 |
| BoroStaten Island:ClassR9-CONDOMINIUM | NA         |
| BoroBrooklyn:ClassRR-CONDOMINIUM      | -2.901e+01 |
| BoroManhattan:ClassRR-CONDOMINIUM     | -6.850e+00 |
| BoroQueens:ClassRR-CONDOMINIUM        | 2.989e+01  |
| BoroStaten Island:ClassRR-CONDOMINIUM | NA         |



```
> acs <- read.table("http://jaredlander.com/data/acs_ny.csv", sep = ",",  
+ header = TRUE, stringsAsFactors = FALSE)
```

```

> # build a data.frame where the first three columns are numeric
> testFrame <-
+   data.frame(First=sample(1:10, 20, replace=TRUE),
+             Second=sample(1:20, 20, replace=TRUE),
+             Third=sample(1:10, 20, replace=TRUE),
+             Fourth=factor(rep(c("Alice", "Bob", "Charlie", "David"),
+                               5)),
+             Fifth=ordered(rep(c("Edward", "Frank", "Georgia",
+                               "Hank", "Isaac"), 4)),
+             Sixth=rep(c("a", "b"), 10), stringsAsFactors=F)
> head(testFrame)

```

|   | First | Second | Third | Fourth  | Fifth   | Sixth |
|---|-------|--------|-------|---------|---------|-------|
| 1 | 3     | 8      | 6     | Alice   | Edward  | a     |
| 2 | 3     | 16     | 4     | Bob     | Frank   | b     |
| 3 | 9     | 14     | 6     | Charlie | Georgia | a     |
| 4 | 9     | 2      | 2     | David   | Hank    | b     |
| 5 | 5     | 17     | 6     | Alice   | Isaac   | a     |
| 6 | 6     | 3      | 4     | Bob     | Edward  | b     |

```

>
> head(model.matrix(First ~ Second + Fourth + Fifth, testFrame))

(Intercept) Second FourthBob FourthCharlie FourthDavid Fifth.L
1           1      8        0        0        0 -0.6324555
2           1     16        1        0        0 -0.3162278
3           1     14        0        1        0  0.0000000
4           1      2        0        0        0  0.3162278
5           1     17        0        0        0  0.6324555
6           1      3        1        0        0 -0.6324555

Fifth.Q      Fifth.C      Fifth^4
1 0.5345225 -3.162278e-01  0.1195229
2 -0.2672612  6.324555e-01 -0.4780914
3 -0.5345225 -4.095972e-16  0.7171372
4 -0.2672612 -6.324555e-01 -0.4780914
5  0.5345225  3.162278e-01  0.1195229
6  0.5345225 -3.162278e-01  0.1195229

```

```
> require(useful)
> # always use all levels
> head(build.x(First ~ Second + Fourth + Fifth, testFrame,
+                 contrasts=FALSE))
```

|   | (Intercept) | Second | FourthAlice | FourthBob | FourthCharlie | FourthDavid |
|---|-------------|--------|-------------|-----------|---------------|-------------|
| 1 | 1           | 8      | 1           | 0         | 0             | 0           |
| 2 | 1           | 16     | 0           | 1         | 0             | 0           |
| 3 | 1           | 14     | 0           | 0         | 1             | 0           |
| 4 | 1           | 2      | 0           | 0         | 0             | 1           |
| 5 | 1           | 17     | 1           | 0         | 0             | 0           |
| 6 | 1           | 3      | 0           | 1         | 0             | 0           |

|   | FifthEdward | FifthFrank | FifthGeorgia | FifthHank | FifthIsaac |
|---|-------------|------------|--------------|-----------|------------|
| 1 | 1           | 0          | 0            | 0         | 0          |
| 2 | 0           | 1          | 0            | 0         | 0          |
| 3 | 0           | 0          | 1            | 0         | 0          |
| 4 | 0           | 0          | 0            | 1         | 0          |
| 5 | 0           | 0          | 0            | 0         | 1          |
| 6 | 1           | 0          | 0            | 0         | 0          |

```
> # just use all levels for Fourth
> head(build.x(First ~ Second + Fourth + Fifth, testFrame,
+                 contrasts=c(Fourth=FALSE, Fifth=TRUE)))
```

|   | (Intercept) | Second | FourthAlice | FourthBob | FourthCharlie | FourthDavid |
|---|-------------|--------|-------------|-----------|---------------|-------------|
| 1 | 1           | 8      | 1           | 0         | 0             | 0           |
| 2 | 1           | 16     | 0           | 1         | 0             | 0           |
| 3 | 1           | 14     | 0           | 0         | 1             | 0           |
| 4 | 1           | 2      | 0           | 0         | 0             | 1           |
| 5 | 1           | 17     | 1           | 0         | 0             | 0           |
| 6 | 1           | 3      | 0           | 1         | 0             | 0           |

|   | Fifth.L    | Fifth.Q    | Fifth.C       | Fifth^4    |
|---|------------|------------|---------------|------------|
| 1 | -0.6324555 | 0.5345225  | -3.162278e-01 | 0.1195229  |
| 2 | -0.3162278 | -0.2672612 | 6.324555e-01  | -0.4780914 |
| 3 | 0.0000000  | -0.5345225 | -4.095972e-16 | 0.7171372  |
| 4 | 0.3162278  | -0.2672612 | -6.324555e-01 | -0.4780914 |
| 5 | 0.6324555  | 0.5345225  | 3.162278e-01  | 0.1195229  |
| 6 | -0.6324555 | 0.5345225  | -3.162278e-01 | 0.1195229  |

```
> # make a binary Income variable for building a logistic regression  
> acs$Income <- with(acs, FamilyIncome >= 150000)  
>  
> head(acs)
```

|   | Acres       | FamilyIncome    | FamilyType   | NumBedrooms | NumChildren | NumPeople |
|---|-------------|-----------------|--------------|-------------|-------------|-----------|
| 1 | 1-10        | 150             | Married      | 4           | 1           | 3         |
| 2 | 1-10        | 180             | Female Head  | 3           | 2           | 4         |
| 3 | 1-10        | 280             | Female Head  | 4           | 0           | 2         |
| 4 | 1-10        | 330             | Female Head  | 2           | 1           | 2         |
| 5 | 1-10        | 330             | Male Head    | 3           | 1           | 2         |
| 6 | 1-10        | 480             | Male Head    | 0           | 3           | 4         |
|   | NumRooms    | NumUnits        | NumVehicles  | NumWorkers  | OwnRent     |           |
| 1 | 9           | Single detached | 1            | 0           | Mortgage    |           |
| 2 | 6           | Single detached | 2            | 0           | Rented      |           |
| 3 | 8           | Single detached | 3            | 1           | Mortgage    |           |
| 4 | 4           | Single detached | 1            | 0           | Rented      |           |
| 5 | 5           | Single attached | 1            | 0           | Mortgage    |           |
| 6 | 1           | Single detached | 0            | 0           | Rented      |           |
|   | YearBuilt   | HouseCosts      | ElectricBill | FoodStamp   | HeatingFuel | Insurance |
| 1 | 1950-1959   | 1800            | 90           | No          | Gas         | 2500      |
| 2 | Before 1939 | 850             | 90           | No          | Oil         | 0         |
| 3 | 2000-2004   | 2600            | 260          | No          | Oil         | 6600      |
| 4 | 1950-1959   | 1800            | 140          | No          | Oil         | 0         |
| 5 | Before 1939 | 860             | 150          | No          | Gas         | 660       |
| 6 | Before 1939 | 700             | 140          | No          | Gas         | 0         |

```
Language Income
1      English FALSE
2      English FALSE
3 Other European FALSE
4      English FALSE
5      Spanish FALSE
6      English FALSE

>
> # build predictor matrix
> # do not include the intercept as glmnet will add that automatically
> acsX <- build.x(Income ~ NumBedrooms + NumChildren + NumPeople +
+                         NumRooms + NumUnits + NumVehicles + NumWorkers +
+                         OwnRent + YearBuilt + ElectricBill + FoodStamp +
+                         HeatingFuel + Insurance + Language - 1,
+                         data=acs, contrasts=FALSE)
>
> # check class and dimensions
> class(acsX)

[1] "matrix"

> dim(acsX)

[1] 22745     44

>
> # view the top left and top right of the data
> topleft(acsX, c=6)

  NumBedrooms NumChildren NumPeople NumRooms NumUnitsMobile home
1            4           1         3        9             0
2            3           2         4        6             0
3            4           0         2        8             0
4            2           1         2        4             0
5            3           1         2        5             0

  NumUnitsSingle attached
1                  0
2                  0
3                  0
4                  0
5                  1
```

```
> topright(acsX, c=6)

  Insurance LanguageAsian Pacific Language English LanguageOther
1      2500                 0                 1                 0
2          0                 0                 1                 0
3     6600                 0                 0                 0
4          0                 0                 1                 0
5      660                0                 0                 0

  LanguageOther European LanguageSpanish
1                  0                 0
2                  0                 0
3                  1                 0
4                  0                 0
5                  0                 1

>
> # build response predictor
> acsY <- build.y(Income ~ NumBedrooms + NumChildren + NumPeople +
+                         NumRooms + NumUnits + NumVehicles + NumWorkers +
+                         OwnRent + YearBuilt + ElectricBill + FoodStamp +
+                         HeatingFuel + Insurance + Language - 1, data=acs)
>
> head(acsY)

[1] FALSE FALSE FALSE FALSE FALSE FALSE

> tail(acsY)

[1] TRUE TRUE TRUE TRUE TRUE TRUE
```

```
> require(glmnet)
> set.seed(1863561)
> # run the cross-validated glmnet
> acsCV1 <- cv.glmnet(x = acsX, y = acsY, family = "binomial", nfold = 5)
```

```
> coef(acsCV1, s = "lambda.1se")
```

| 45 x 1 sparse Matrix of class "dgCMatrix" |               |
|-------------------------------------------|---------------|
|                                           | 1             |
| (Intercept)                               | -5.0552170103 |
| NumBedrooms                               | 0.0542621380  |
| NumChildren                               | .             |
| NumPeople                                 | .             |
| NumRooms                                  | 0.1102021934  |
| NumUnitsMobile home                       | -0.8960712560 |
| NumUnitssingle attached                   | .             |
| NumUnitssingle detached                   | .             |
| NumVehicles                               | 0.1283171343  |
| NumWorkers                                | 0.4806697219  |
| OwnRentMortgage                           | .             |
| OwnRentOutright                           | 0.2574766773  |
| OwnRentRented                             | -0.1790627645 |
| YearBuilt15                               | .             |
| YearBuilt1940-1949                        | -0.0253908040 |
| YearBuilt1950-1959                        | .             |
| YearBuilt1960-1969                        | .             |
| YearBuilt1970-1979                        | -0.0063336086 |
| YearBuilt1980-1989                        | 0.0147761442  |
| YearBuilt1990-1999                        | .             |
| YearBuilt2000-2004                        | .             |

|                        |               |
|------------------------|---------------|
| YearBuilt2005          | .             |
| YearBuilt2006          | .             |
| YearBuilt2007          | .             |
| YearBuilt2008          | .             |
| YearBuilt2009          | .             |
| YearBuilt2010          | .             |
| YearBuiltBefore 1939   | -0.1829643904 |
| ElectricBill           | 0.0018200312  |
| FoodStampNo            | 0.7071289660  |
| FoodStampYes           | .             |
| HeatingFuelCoal        | -0.2635263281 |
| HeatingFuelElectricity | .             |
| HeatingFuelGas         | .             |
| HeatingFuelNone        | .             |
| HeatingFuelOil         | .             |
| HeatingFuelOther       | .             |
| HeatingFuelSolar       | .             |
| HeatingFuelWood        | -0.7454315355 |
| Insurance              | 0.0004973315  |
| LanguageAsian Pacific  | 0.3606176925  |
| LanguageEnglish        | .             |
| LanguageOther          | .             |
| LanguageOther European | 0.0389641675  |
| LanguageSpanish        | .             |

```
> # plot the path  
> plot(acsCV1$glmnet.fit, xvar = "lambda")  
> # add in vertical lines for the optimal values of lambda  
> abline(v = log(c(acsCV1$lambda.min, acsCV1$lambda.1se))), lty = 2)
```

```
> # fit the ridge model
> set.seed(71623)
> acsCV2 <- cv.glmnet(x = acsX, y = acsY, family = "binomial", nfold = 5,
+   alpha = 0)

> # look at the lambda values
> acsCV2$lambda.min

[1] 0.01272576

> acsCV2$lambda.1se

[1] 0.04681018

>
> # look at the coefficients
> coef(acsCV2, s = "lambda.1se")

45 x 1 sparse Matrix of class "dgCMatrix"
   1
(Intercept) -4.8197810188
NumBedrooms  0.1027963294
NumChildren  0.0308893447
NumPeople    -0.0203037177
NumRooms     0.0918136969
```

|                         |               |
|-------------------------|---------------|
| NumUnitsMobile home     | -0.8470874369 |
| NumUnitsSingle attached | 0.1714879712  |
| NumUnitsSingle detached | 0.0841095530  |
| NumVehicles             | 0.1583881396  |
| NumWorkers              | 0.3811651456  |
| OwnRentMortgage         | 0.1985621193  |
| OwnRentOutright         | 0.6480126218  |
| OwnRentRented           | -0.2548147427 |
| YearBuilt15             | -0.6828640400 |
| YearBuilt1940-1949      | -0.1082928305 |
| YearBuilt1950-1959      | 0.0602009151  |
| YearBuilt1960-1969      | 0.0081133932  |
| YearBuilt1970-1979      | -0.0816541923 |
| YearBuilt1980-1989      | 0.1593567244  |
| YearBuilt1990-1999      | 0.1218212609  |
| YearBuilt2000-2004      | 0.1768690849  |
| YearBuilt2005           | 0.2923210334  |
| YearBuilt2006           | 0.2309044444  |
| YearBuilt2007           | 0.3765019705  |
| YearBuilt2008           | -0.0648999685 |
| YearBuilt2009           | 0.2382560699  |
| YearBuilt2010           | 0.3804282473  |

|                        |               |
|------------------------|---------------|
| YearBuiltBefore 1939   | -0.1648659906 |
| ElectricBill           | 0.0018576432  |
| FoodStampNo            | 0.3886474609  |
| FoodStampYes           | -0.3886013004 |
| HeatingFuelCoal        | -0.7005075763 |
| HeatingFuelElectricity | -0.1370927269 |
| HeatingFuelGas         | 0.0873505398  |
| HeatingFuelNone        | -0.5983944720 |
| HeatingFuelOil         | 0.1241958119  |
| HeatingFuelOther       | -0.1872564710 |
| HeatingFuelSolar       | -0.0870480957 |
| HeatingFuelWood        | -0.6699727752 |
| Insurance              | 0.0003881588  |
| LanguageAsian Pacific  | 0.3982023046  |
| LanguageEnglish        | -0.0851389569 |
| LanguageOther          | 0.1804675114  |
| LanguageOther European | 0.0964194255  |
| LanguageSpanish        | -0.1274688978 |

```
>
> # plot the cross-validation error path
> plot(acsCV2)

> # plot the coefficient path
> plot(acsCV2$glmnet.fit, xvar = "lambda")
> abline(v = log(c(acsCV2$lambda.min, acsCV2$lambda.1se))), lty = 2)
```

```
> require(parallel)
Loading required package: parallel
> require(doParallel)
Loading required package: doParallel
Loading required package: foreach
Loading required package: iterators
```

```
> # set the seed for repeatability of random results
> set.seed(2834673)
>
> # create folds, we want observations to be in the same fold each time
> # it is run
> theFolds <- sample(rep(x = 1:5, length.out = nrow(acsX)))
>
> # make sequence of alpha values
> alphas <- seq(from = 0.5, to = 1, by = 0.05)
```

```
> # set the seed for repeatability of random results
> set.seed(5127151)
>
> # start a cluster with two workers
> cl <- makeCluster(2)
> # register the workers
> registerDoParallel(cl)
>
> # keep track of timing
> before <- Sys.time()
>
> # build foreach loop to run in parallel
> ## several arguments
> acsDouble <- foreach(i=1:length(alphas), .errorhandling="remove",
+                         .inorder=FALSE, .multicombine=TRUE,
+                         .export=c("acsX", "acsY", "alphas", "theFolds"),
+                         .packages="glmnet") %dopar%
+ {
+   print(alphas[i])
+   cv.glmnet(x=acsX, y=acsY, family="binomial", nfolds=5,
+             foldid=theFolds, alpha=alphas[i])
+ }
>
> # stop timing
> after <- Sys.time()
>
> # make sure to stop the cluster when done
> stopCluster(cl)
>
> # time difference
> # this will depend on speed, memory & number of cores of the machine
> after - before
```

Time difference of 1.443783 mins

```
> sapply(acsDouble, class)
```

```
[1] "cv.glmnet" "cv.glmnet" "cv.glmnet" "cv.glmnet" "cv.glmnet"  
[6] "cv.glmnet" "cv.glmnet" "cv.glmnet" "cv.glmnet" "cv.glmnet"  
[11] "cv.glmnet"
```

```

> # function for extracting info from cv.glmnet object
> extractGlmnetInfo <- function(object)
+ {
+   # find lambdas
+   lambdaMin <- object$lambda.min
+   lambdalse <- object$lambda.lse
+
+   # figure out where those lambdas fall in the path
+   whichMin <- which(object$lambda == lambdaMin)
+   whichlse <- which(object$lambda == lambdalse)
+
+   # build a one line data.frame with each of the selected lambdas and
+   # its corresponding error figures
+   data.frame(lambda.min=lambdaMin, error.min=object$cvm[whichMin],
+             lambda.lse=lambdalse, error.lse=object$cvm[whichlse])
+ }
>
> # apply that function to each element of the list
> # combine it all into a data.frame
> alphaInfo <- Reduce(rbind, lapply(acsDouble, extractGlmnetInfo))
>
> # could also be done with ldply from plyr
> alphaInfo2 <- plyr::ldply(acsDouble, extractGlmnetInfo)
> identical(alphaInfo, alphaInfo2)

```

[1] TRUE

```

>
> # make a column listing the alphas
> alphaInfo$Alpha <- alphas
> alphaInfo

```

|    | lambda.min   | error.min | lambda.lse  | error.lse | Alpha |
|----|--------------|-----------|-------------|-----------|-------|
| 1  | 0.0009582333 | 0.8220267 | 0.008142621 | 0.8275331 | 0.50  |
| 2  | 0.0009560545 | 0.8220226 | 0.007402382 | 0.8273936 | 0.55  |
| 3  | 0.0008763832 | 0.8220197 | 0.006785517 | 0.8272771 | 0.60  |
| 4  | 0.0008089692 | 0.8220184 | 0.006263554 | 0.8271786 | 0.65  |
| 5  | 0.0008244253 | 0.8220168 | 0.005816158 | 0.8270917 | 0.70  |
| 6  | 0.0007694636 | 0.8220151 | 0.005428414 | 0.8270161 | 0.75  |
| 7  | 0.0007213721 | 0.8220139 | 0.005585323 | 0.8276118 | 0.80  |
| 8  | 0.0006789385 | 0.8220130 | 0.005256774 | 0.8275519 | 0.85  |
| 9  | 0.0006412197 | 0.8220123 | 0.004964731 | 0.8274993 | 0.90  |
| 10 | 0.0006074713 | 0.8220128 | 0.004703430 | 0.8274524 | 0.95  |
| 11 | 0.0005770977 | 0.8220125 | 0.004468258 | 0.8274120 | 1.00  |

```
> ## prepare the data.frame for plotting multiple pieces of information
> require(reshape2)
> require(stringr)
>
> # melt the data into long format
> alphaMelt <- melt(alphaInfo, id.vars="Alpha", value.name="Value",
+                      variable.name="Measure")
> alphaMelt$Type <- str_extract(string=alphaMelt$Measure,
+                                 pattern="(min)|(1se)")
>
> # some housekeeping
> alphaMelt$Measure <- str_replace(string=alphaMelt$Measure,
+                                    pattern="\.(min|1se)",
+                                    replacement="")
> alphaCast <- dcast(alphaMelt, Alpha + Type ~ Measure,
+                      value.var="Value")
>
> ggplot(alphaCast, aes(x=Alpha, y=error)) +
+   geom_line(aes(group=Type)) +
+   facet_wrap(~Type, scales="free_y", ncol=1) +
+   geom_point(aes(size=lambda))
```

```
> set.seed(5127151)
> acsCV3 <- cv.glmnet(x = acsX, y = acsY, family = "binomial", nfold = 5,
+   alpha = alphaInfo$Alpha[which.min(alphaInfo$error.1se)])
```

```
> plot(acscV3)

> plot(acscV3$glmnet.fit, xvar = "lambda")
> abline(v = log(c(acscV3$lambda.min, acscV3$lambda.1se)), lty = 2)
```

```
> theCoef <- as.matrix(coef(acscV3, s = "lambda.1se"))
> coefDF <- data.frame(Value = theCoef,
+   Coefficient = rownames(theCoef))
> coefDF <- coefDF[nonzeroCoef(coef(acscV3, s = "lambda.1se"))], ]
> ggplot(coefDF, aes(x = X1, y = reorder(Coefficient, X1))) +
+   geom_vline(xintercept = 0, color = "grey", linetype = 2) +
+   geom_point(color = "blue") + labs(x = "Value",
+   y = "Coefficient", title = "Coefficient Plot")
```

```
> load("data/ideo.rdata")
> head(ideo)
```

|   | Year | Vote       | Age | Gender | Race  |  |  |
|---|------|------------|-----|--------|-------|--|--|
| 1 | 1948 | democrat   | NA  | male   | white |  |  |
| 2 | 1948 | republican | NA  | female | white |  |  |
| 3 | 1948 | democrat   | NA  | female | white |  |  |
| 4 | 1948 | republican | NA  | female | white |  |  |
| 5 | 1948 | democrat   | NA  | male   | white |  |  |
| 6 | 1948 | republican | NA  | female | white |  |  |

|   |                                        | Education            | Income |
|---|----------------------------------------|----------------------|--------|
| 1 | grade school of less (0-8 grades)      | 34 to 67 percentile  |        |
| 2 | high school (12 grades or fewer, incl  | 96 to 100 percentile |        |
| 3 | high school (12 grades or fewer, incl  | 68 to 95 percentile  |        |
| 4 | some college(13 grades or more, but no | 96 to 100 percentile |        |
| 5 | some college(13 grades or more, but no | 68 to 95 percentile  |        |
| 6 | high school (12 grades or fewer, incl  | 96 to 100 percentile |        |

|   | Religion                  |
|---|---------------------------|
| 1 | protestant                |
| 2 | protestant                |
| 3 | catholic (roman catholic) |
| 4 | protestant                |
| 5 | catholic (roman catholic) |
| 6 | protestant                |



```
> require(coefplot)
> # get the coefficient information
> voteInfo <- multiplot(results, coefficients="Raceblack", plot=FALSE)
> head(voteInfo)

      Value Coefficient HighInner LowInner HighOuter
1  0.07119541  Raceblack  0.6297813 -0.4873905 1.1883673
2 -1.68490828  Raceblack -1.3175506 -2.0522659 -0.9501930
3 -0.89178359  Raceblack -0.5857195 -1.1978476 -0.2796555
4 -1.07674848  Raceblack -0.7099648 -1.4435322 -0.3431811
5 -16.85751152 Raceblack 382.1171424 -415.8321655 781.0917963
6 -3.65505395  Raceblack -3.0580572 -4.2520507 -2.4610605

      LowOuter Model
1 -1.045976 1948
2 -2.419624 1952
3 -1.503912 1956
4 -1.810316 1960
5 -814.806819 1964
6 -4.849047 1968

>
> # plot it restricting the window to (-20, 10)
> multiplot(results, coefficients="Raceblack", secret.weapon=TRUE) +
+   coord_flip(xlim=c(-20, 10))
```

```
> resultsB <- vector(mode="list", length=length(theYears))
> # give good names to the list
> names(resultsB) <- theYears
>
> ## loop through the years
> ## fit a model on the subset of data for that year
> for(i in theYears)
+ {
+   # fit model with Cauchy priors with a scale of 2.5
+   resultsB[[as.character(i)]] <-
+     arm::bayesglm(Vote ~ Race + Income + Gender + Education,
+                    data=ideo, subset=Year==i,
+                    family=binomial(link="logit"),
+                    prior.scale=2.5, prior.df=1)
+ }
>
> # build the coefficient plot
> multiplot(resultsB, coefficients="Raceblack", secret.weapon=TRUE)
```



```
> load("data/wifi.rdata")
> head(wifi)
```

|   | Distance | x        | y         |
|---|----------|----------|-----------|
| 1 | 21.87559 | 28.60461 | 68.429628 |
| 2 | 67.68198 | 90.29680 | 29.155945 |
| 3 | 79.25427 | 83.48934 | 0.371902  |
| 4 | 44.73767 | 61.39133 | 80.258138 |
| 5 | 39.71233 | 19.55080 | 83.805855 |
| 6 | 56.65595 | 71.93928 | 65.551340 |

```
> require(ggplot2)
> ggplot(wifi, aes(x=x, y=y, color=Distance)) + geom_point() +
+   scale_color_gradient2(low="blue", mid="white", high="red",
+                         midpoint=mean(wifi$Distance))
```

```
> # specify the square root model  
> # starting values are at the center of the grid  
> wifiMod1 <- nls(Distance ~ sqrt((betaX - x)^2 + (betaY - y)^2),  
+     data = wifi, start = list(betaX = 50, betaY = 50))  
> summary(wifiMod1)
```

Formula: Distance ~ sqrt((betaX - x)^2 + (betaY - y)^2)

Parameters:

|                | Estimate | Std. Error | t value | Pr(> t )   |      |     |      |      |     |    |   |
|----------------|----------|------------|---------|------------|------|-----|------|------|-----|----|---|
| betaX          | 17.851   | 1.289      | 13.85   | <2e-16 *** |      |     |      |      |     |    |   |
| betaY          | 52.906   | 1.476      | 35.85   | <2e-16 *** |      |     |      |      |     |    |   |
| ---            |          |            |         |            |      |     |      |      |     |    |   |
| Signif. codes: | 0        | '***'      | 0.001   | '**'       | 0.01 | '*' | 0.05 | '..' | 0.1 | '' | 1 |

Residual standard error: 13.73 on 198 degrees of freedom

Number of iterations to convergence: 6

Achieved convergence tolerance: 3.846e-06

```
> ggplot(wifi, aes(x = x, y = y, color = Distance)) + geom_point() +
+   scale_color_gradient2(low = "blue", mid = "white", high = "red",
+                         midpoint = mean(wifi$Distance)) +
+   geom_point(data = as.data.frame(t(coef(wifiMod1))),
+              aes(x = betaX, y = betaY), size = 5, color = "green")
```

```
> data(diamonds)
> # fit with a few different degrees of freedom
> # the degrees of freedom must be greater than 1
> # but less than the number of unique x values in the data
> diaSpline1 <- smooth.spline(x=diamonds$carat, y=diamonds$price)
> diaSpline2 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                               df=2)
> diaSpline3 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                               df=10)
> diaSpline4 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                               df=20)
> diaSpline5 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                               df=50)
> diaSpline6 <- smooth.spline(x=diamonds$carat, y=diamonds$price,
+                               df=100)
```

```
> get.spline.info <- function(object)
+ {
+   data.frame(x=object$x, y=object$y, df=object$df)
+ }
>
> require(plyr)
> # combine results into one data.frame
> splineDF <- ldply(list(diaSpline1, diaSpline2, diaSpline3,
+                         diaSpline4, diaSpline5, diaSpline6),
+                         get.spline.info)
> head(splineDF)

      x        y      df
1 0.20 361.9112 101.9053
2 0.21 397.1761 101.9053
3 0.22 437.9095 101.9053
4 0.23 479.9756 101.9053
5 0.24 517.0467 101.9053
6 0.25 542.2470 101.9053

>
> g <- ggplot(diamonds, aes(x=carat, y=price)) + geom_pointgeom_line(data=splineDF,
+                  aes(x=x, y=y, color=factor(round(df, 0)),
+                  group=df)) + scale_color_discrete("Degrees of \nFreedom")
```

```
> require(splines)
> head(ns(diamonds$carat, df = 1))

           1
[1,] 0.00500073
[2,] 0.00166691
[3,] 0.00500073
[4,] 0.01500219
[5,] 0.01833601
[6,] 0.00666764

> head(ns(diamonds$carat, df = 2))

           1           2
[1,] 0.013777685 -0.007265289
[2,] 0.004593275 -0.002422504
[3,] 0.013777685 -0.007265289
[4,] 0.041275287 -0.021735857
[5,] 0.050408348 -0.026525299
[6,] 0.018367750 -0.009684459

> head(ns(diamonds$carat, df = 3))
```

|      | 1           | 2          | 3           | 4 |
|------|-------------|------------|-------------|---|
| [1,] | -0.03025012 | 0.06432178 | -0.03404826 |   |
| [2,] | -0.01010308 | 0.02146773 | -0.01136379 |   |
| [3,] | -0.03025012 | 0.06432178 | -0.03404826 |   |
| [4,] | -0.08915435 | 0.19076693 | -0.10098109 |   |
| [5,] | -0.10788271 | 0.23166685 | -0.12263116 |   |
| [6,] | -0.04026453 | 0.08566738 | -0.04534740 |   |

```
> head(ns(diamonds$carat, df = 4))
```

|      | 1            | 2           | 3          | 4           |
|------|--------------|-------------|------------|-------------|
| [1,] | 3.214286e-04 | -0.04811737 | 0.10035562 | -0.05223825 |
| [2,] | 1.190476e-05 | -0.01611797 | 0.03361632 | -0.01749835 |
| [3,] | 3.214286e-04 | -0.04811737 | 0.10035562 | -0.05223825 |
| [4,] | 8.678571e-03 | -0.13796549 | 0.28774667 | -0.14978118 |
| [5,] | 1.584524e-02 | -0.16428790 | 0.34264579 | -0.17835789 |
| [6,] | 7.619048e-04 | -0.06388053 | 0.13323194 | -0.06935141 |

```
> g <- ggplot(diamonds, aes(x = carat, y = price)) + geom_point()  
> g + stat_smooth(method = "lm", formula = y ~ ns(x, 6), color = "blue")  
> g + stat_smooth(method = "lm", formula = y ~ ns(x, 3), color = "red")
```

```

> # make vector of column names
> creditNames <- c("Checking", "Duration", "CreditHistory",
+     "Purpose", "CreditAmount", "Savings", "Employment",
+     "InstallmentRate", "GenderMarital", "OtherDebtors",
+     "YearsAtResidence", "RealEstate", "Age",
+     "OtherInstallment", "Housing", "ExistingCredits", "Job",
+     "NumLiable", "Phone", "Foreign", "Credit")
>
> # use read.table to read the file
> # specify that headers are not included
> # the col.names are from creditNames
> theURL <- "http://archive.ics.uci.edu/ml/
+             machine-learning-databases/statlog/german/german.data"
> credit <- read.table(the URL sep = " ", header = FALSE,
+                       col.names = creditNames,
+                       stringsAsFactors = FALSE)
>
> head(credit)

```

|   | Checking   | Duration        | CreditHistory | Purpose      | CreditAmount | Savings |     |
|---|------------|-----------------|---------------|--------------|--------------|---------|-----|
| 1 | A11        | 6               |               | A34          | A43          | 1169    | A65 |
| 2 | A12        | 48              |               | A32          | A43          | 5951    | A61 |
| 3 | A14        | 12              |               | A34          | A46          | 2096    | A61 |
| 4 | A11        | 42              |               | A32          | A42          | 7882    | A61 |
| 5 | A11        | 24              |               | A33          | A40          | 4870    | A61 |
| 6 | A14        | 36              |               | A32          | A46          | 9055    | A65 |
|   | Employment | InstallmentRate | GenderMarital | OtherDebtors |              |         |     |

|   |     |   |     |      |
|---|-----|---|-----|------|
| 1 | A75 | 4 | A93 | A101 |
| 2 | A73 | 2 | A92 | A101 |
| 3 | A74 | 2 | A93 | A101 |
| 4 | A74 | 2 | A93 | A103 |
| 5 | A73 | 3 | A93 | A101 |
| 6 | A73 | 2 | A93 | A101 |

|   | YearsAtResidence | RealEstate | Age | OtherInstallment | Housing   |
|---|------------------|------------|-----|------------------|-----------|
| 1 | 4                | A121       | 67  |                  | A143 A152 |
| 2 | 2                | A121       | 22  |                  | A143 A152 |
| 3 | 3                | A121       | 49  |                  | A143 A152 |
| 4 | 4                | A122       | 45  |                  | A143 A153 |
| 5 | 4                | A124       | 53  |                  | A143 A153 |
| 6 | 4                | A124       | 35  |                  | A143 A153 |

|   | ExistingCredits | Job  | NumLiable | Phone | Foreign | Credit |
|---|-----------------|------|-----------|-------|---------|--------|
| 1 | 2               | A173 | 1         | A192  | A201    | 1      |
| 2 | 1               | A173 | 1         | A191  | A201    | 2      |
| 3 | 1               | A172 | 2         | A191  | A201    | 1      |
| 4 | 1               | A173 | 2         | A191  | A201    | 1      |
| 5 | 2               | A173 | 2         | A191  | A201    | 2      |
| 6 | 1               | A172 | 2         | A192  | A201    | 1      |

```
> # before
> head(credit[, c("CreditHistory", "Purpose", "Employment", "Credit")])

  CreditHistory Purpose Employment Credit
1          A34      A43       A75      1
2          A32      A43       A73      2
3          A34      A46       A74      1
4          A32      A42       A74      1
5          A33      A40       A73      2
6          A32      A46       A73      1

>
> creditHistory <- c(A30 = "All Paid", A31 = "All Paid This Bank",
+   A32 = "Up To Date", A33 = "Late Payment",
+   A34 = "Critical Account")
>
> purpose <- c(A40 = "car (new)", A41 = "car (used)",
+   A42 = "furniture/equipment", A43 = "radio/television",
+   A44 = "domestic appliances", A45 = "repairs",
+   A46 = "education", A47 = "(vacation - does not exist?)",
+   A48 = "retraining", A49 = "business", A410 = "others")
>
> employment <- c(A71 = "unemployed", A72 = "< 1 year",
+   A73 = "1 - 4 years", A74 = "4 - 7 years", A75 = ">= 7 years")
>
> credit$CreditHistory <- creditHistory[credit$CreditHistory]
```

```
> credit$Purpose <- purpose[credit$Purpose]
> credit$Employment <- employment[credit$Employment]
>
> # code credit as good/bad
> credit$Credit <- ifelse(credit$Credit == 1, "Good", "Bad")
> # make good the base levels
> credit$Credit <- factor(credit$Credit, levels = c("Good", "Bad"))
>
> # after
> head(credit[, c("CreditHistory", "Purpose", "Employment",
  "Credit")])
```

|   | CreditHistory    | Purpose             | Employment     | Credit |
|---|------------------|---------------------|----------------|--------|
| 1 | Critical Account | radio/television    | $\geq 7$ years | Good   |
| 2 | Up To Date       | radio/television    | 1 - 4 years    | Bad    |
| 3 | Critical Account | education           | 4 - 7 years    | Good   |
| 4 | Up To Date       | furniture/equipment | 4 - 7 years    | Good   |
| 5 | Late Payment     | car (new)           | 1 - 4 years    | Bad    |
| 6 | Up To Date       | education           | 1 - 4 years    | Good   |

```
> require(useful)
> ggplot(credit, aes(x=CreditAmount, y=Credit)) +
+   geom_jitter(position = position_jitter(height = .2)) +
+   facet_grid(CreditHistory ~ Employment) +
+   xlab("Credit Amount") +
+   theme(axis.text.x=element_text(angle=90, hjust=1, vjust=.5)) +
+   scale_x_continuous(labels=multiple)

>
> ggplot(credit, aes(x=CreditAmount, y=Age)) +
+   geom_point(aes(color=Credit)) +
+   facet_grid(CreditHistory ~ Employment) +
+   xlab("Credit Amount") +
+   theme(axis.text.x=element_text(angle=90, hjust=1, vjust=.5)) +
+   scale_x_continuous(labels=multiple)
```

```
> require(mgcv)
> # fit a logistic GAM
> # apply a tensor product on CreditAmount and a spline on Age
> creditGam <- gam(Credit ~ te(CreditAmount) + s(Age) + CreditHistory +
+                     Employment,
+                     data=credit, family=binomial(link="logit"))
> summary(creditGam)
```

Family: binomial

Link function: logit

Formula:

Credit ~ te(CreditAmount) + s(Age) + CreditHistory + Employment

Parametric coefficients:

|                                 |           | Estimate | Std. Error | z value  | Pr(> z ) |
|---------------------------------|-----------|----------|------------|----------|----------|
| (Intercept)                     |           | 0.662840 | 0.372377   | 1.780    | 0.07507  |
| CreditHistoryAll Paid This Bank | 0.008412  | 0.453267 | 0.019      | 0.98519  |          |
| CreditHistoryCritical Account   | -1.809046 | 0.376326 | -4.807     | 1.53e-06 |          |
| CreditHistoryLate Payment       | -1.136008 | 0.412776 | -2.752     | 0.00592  |          |
| CreditHistoryUp To Date         | -1.104274 | 0.355208 | -3.109     | 0.00188  |          |
| Employment>= 7 years            | -0.388518 | 0.240343 | -1.617     | 0.10598  |          |
| Employment1 - 4 years           | -0.380981 | 0.204292 | -1.865     | 0.06220  |          |
| Employment4 - 7 years           | -0.820943 | 0.252069 | -3.257     | 0.00113  |          |
| Employmentunemployed            | -0.092727 | 0.334975 | -0.277     | 0.78192  |          |

(Intercept) .  
CreditHistoryAll Paid This Bank  
CreditHistoryCritical Account \*\*\*  
CreditHistoryLate Payment \*\*  
CreditHistoryUp To Date \*\*  
Employment>= 7 years  
Employment1 - 4 years .  
Employment4 - 7 years \*\*  
Employmentunemployed  
---  
Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:

|                  | edf   | Ref.df | Chi.sq | p-value      |
|------------------|-------|--------|--------|--------------|
| te(CreditAmount) | 2.415 | 2.783  | 20.79  | 0.000112 *** |
| s(Age)           | 1.932 | 2.435  | 6.13   | 0.068957 .   |
| ---              |       |        |        |              |

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

R-sq.(adj) = 0.0922 Deviance explained = 8.57%  
UBRE score = 0.1437 Scale est. = 1 n = 1000

```
> plot(creditGam, select = 1, se = TRUE, shade = TRUE)
> plot(creditGam, select = 2, se = TRUE, shade = TRUE)
```

```
> require(rpart)
> creditTree <- rpart(Credit ~ CreditAmount + Age +
+   CreditHistory + Employment, data = credit)
```

Printing the object displays the tree in text form.

```
> creditTree
```

```
n= 1000
```

```
node), split, n, loss, yval, (yprob)
  * denotes terminal node
```

- 1) root 1000 300 Good (0.7000000 0.3000000)
- 2) CreditHistory=Critical Account,Late Payment,Up To Date 911 247 Good (0.7288694 0.2711306)
  - 4) CreditAmount< 7760.5 846 211 Good (0.7505910 0.2494090) \*
  - 5) CreditAmount>=7760.5 65 29 Bad (0.4461538 0.5538462)
    - 10) Age>=29.5 40 17 Good (0.5750000 0.4250000)
      - 20) Age< 38.5 19 4 Good (0.7894737 0.2105263) \*
      - 21) Age>=38.5 21 8 Bad (0.3809524 0.6190476) \*
    - 11) Age< 29.5 25 6 Bad (0.2400000 0.7600000) \*
  - 3) CreditHistory>All Paid,All Paid This Bank 89 36 Bad (0.4044944 0.5955056) \*

```
> require(rpart.plot)
> rpart.plot(creditTree, extra = 4)
```

```
> require(useful)
> require(randomForest)
> # build the predictor and response matrices
> creditFormula <- Credit ~ CreditHistory + Purpose + Employment +
+     Duration + Age + CreditAmount
> creditX <- build.x(creditFormula, data=credit)
> creditY <- build.y(creditFormula, data=credit)
>
> # fit the random forest
> creditForest <- randomForest(x=creditX, y=creditY)
>
> creditForest
```

Call:

```
randomForest(x = creditX, y = creditY)
Type of random forest: classification
Number of trees: 500
```

No. of variables tried at each split: 4

OOB estimate of error rate: 28.2%

Confusion matrix:

|      | Good | Bad | class.error |
|------|------|-----|-------------|
| Good | 649  | 51  | 0.07285714  |
| Bad  | 231  | 69  | 0.77000000  |



```
> # load the World Bank API package
> require(WDI)
> # pull the data
> gdp <- WDI(country=c("US", "CA", "GB", "DE", "CN", "JP", "SG", "IL"),
+               indicator=c("NY.GDP.PCAP.CD", "NY.GDP.MKTP.CD"),
+               start=1960, end=2011)
> # give it good names
> names(gdp) <- c("iso2c", "Country", "Year", "PerCapGDP", "GDP")
```

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