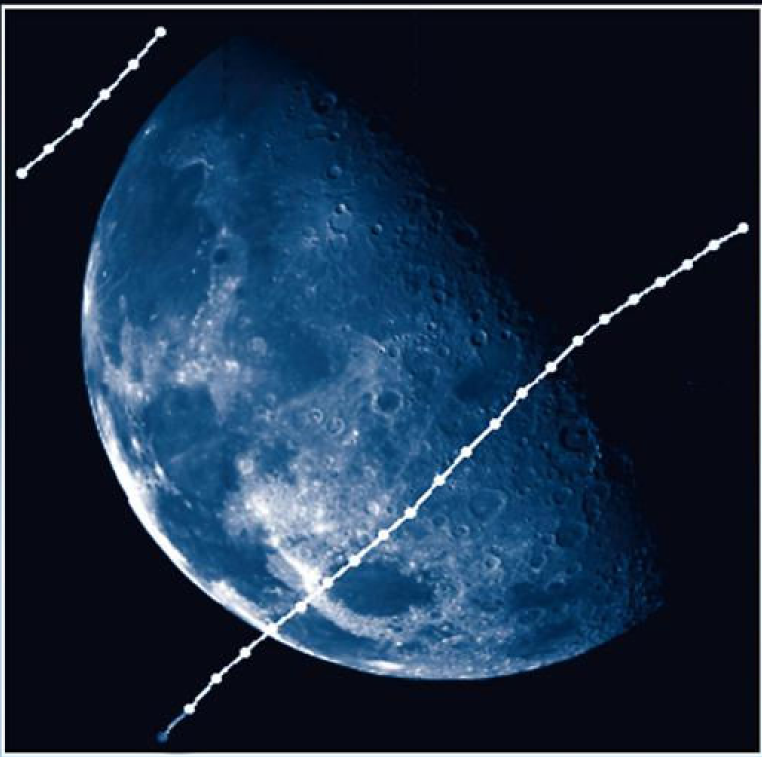
Computer Science and Data Analysis Series

R Graphics



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1

An Introduction to R Graphics

Chapter preview

This chapter provides the most basic information to get started producing plots in R. First of all, there is a three-line code example that demonstrates the fundamental steps involved in producing a plot. This is followed by a series of figures to demonstrate the range of images that R can produce. There is also a section on the organization of R graphics giving information on where to look for a particular function. The final section describes the different graphical output formats that R can produce and how to obtain a particular output format.

The following code provides a simple example of how to produce a plot using R (see Figure 1.1).

```
> plot(pressure)
> text(150, 600,
       "Pressure (mm Hg)\nversus\nTemperature (Celsius)")
```

The expression `plot(pressure)` produces a scatterplot of pressure versus temperature, including axes, labels, and a bounding rectangle.* The call to the `text()` function adds the label at the data location `(150, 600)` within the plot.

*The `pressure` data set, available in the `datasets` package, contains 19 recordings of the relationship between vapor pressure (in millimeters of mercury) and temperature (in degrees Celsius).

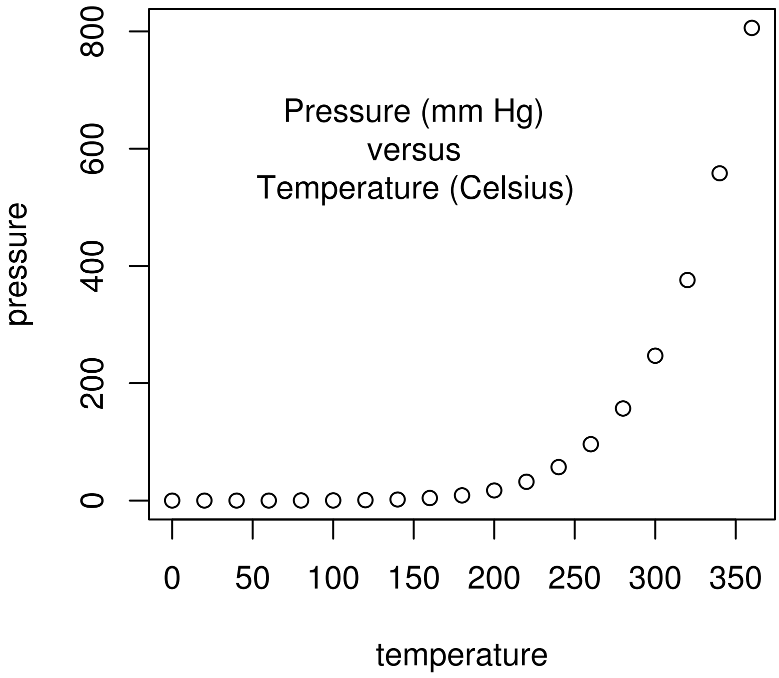

Figure 1.1
A simple scatterplot of vapor pressure of mercury as a function of temperature. The plot is produced from two simple R expressions: one expression to draw the basic plot, consisting of axes, data symbols, and bounding rectangle; and another expression to add the text label within the plot.

This example is basic R graphics in a nutshell. In order to produce graphical output, the user calls a series of graphics functions, each of which produces either a complete plot, or adds some output to an existing plot. R graphics follows a "painters model," which means that graphics output occurs in steps, with later output obscuring any previous output that it overlaps.

There are very many graphical functions provided by R and the add-on packages for R, so before describing individual functions, Section 1.1 demonstrates the variety of results that can be achieved using R graphics. This should provide some idea of what users can expect to be able to achieve with R graphics.

Section 1.2 gives an overview of how the graphics functions in R are organized. This should provide users with some basic ideas of where to look for a function to do a specific task. Section 1.3 describes the set of functions involved with the selection of a particular graphical output format. By the end of this chapter, the reader will be in a position to start understanding in more detail the core R functions that produce graphical output.

1.1 R graphics examples

This section provides an introduction to R graphics by way of a series of examples. None of the code used to produce these images is shown, but it is available from the web site for this book. The aim for now is simply to provide an overall impression of the range of graphical images that can be produced using R. The figures are described over the next few pages and the images themselves are all collected together on pages 7 to 15.

1.1.1 Standard plots

R provides the usual range of standard statistical plots, including scatterplots, boxplots, histograms, barplots, piecharts, and basic 3D plots. Figure 1.2 shows some examples.*

In R, these basic plot types can be produced by a single function call (e.g.,

*The barplot makes use of data on death rates in the state of Virginia for different age groups and population groups, available as the `VADeaths` data set in the `datasets` package. The boxplot example makes use of data on the effect of vitamin C on tooth growth in guinea pigs, available as the `ToothGrowth` data set, also from the `datasets` package. These and many other data sets distributed with R were obtained from "Interactive Data Analysis" by Don McNeil[40] rather than directly from the original source.

`pie(pie.sales)` will produce a piechart), but plots can also be considered merely as starting points for producing more complex images. For example, in the scatterplot in Figure 1.2, a text label has been added within the body of the plot (in this case to show a subject identification number) and a secondary y-axis has been added on the right-hand side of the plot. Similarly, in the histogram, lines have been added to show a theoretical normal distribution for comparison with the observed data. In the barplot, labels have been added to the elements of the bars to quantify the contribution of each element to the total bar and, in the boxplot, a legend has been added to distinguish between the two data sets that have been plotted.

This ability to add several graphical elements together to create the final result is a fundamental feature of R graphics. The flexibility that this allows is demonstrated in Figure 1.3, which illustrates the estimation of the original number of vessels based on broken fragments gathered at an archaeological site: a measure of "completeness" is obtained from the fragments at the site; a theoretical relationship is used to produce an estimated range of "sampling fraction" from the observed completeness; and another theoretical relationship dictates the original number of vessels from a sampling fraction[19]. This plot is based on a simple scatterplot, but requires the addition of many extra lines, polygons, and pieces of text, and the use of multiple overlapping coordinate systems to produce the final result.

For more information on the R functions that produce these standard plots, see Chapter 2. Chapter 3 describes the various ways that further output can be added to a plot.

1.1.2 Trellis plots

In addition to the traditional statistical plots, R provides an implementation of Trellis plots[6] via the package `lattice`[54] by Deepayan Sarkar. Trellis plots embody a number of design principles proposed by Bill Cleveland[12][13] that are aimed at ensuring accurate and faithful communication of information via statistical plots. These principles are evident in a number of new plot types in Trellis and in the default choice of colors, symbol shapes, and line styles provided by Trellis plots. Furthermore, Trellis plots provide a feature known as "multi-panel conditioning," which creates multiple plots by splitting the data being plotted according to the levels of other variables.

Figure 1.4 shows an example of a Trellis plot. The data are yields of several different varieties of barley at six sites, over two years. The plot consists of six "panels," one for each site. Each panel consists of a dotplot showing yield for each variety with different symbols used to distinguish different years, and a "strip" showing the name of the site.

For more information on the Trellis system and how to produce Trellis plots using the lattice package, see Chapter 4.

1.1.3 Special-purpose plots

As well as providing a wide variety of functions that produce complete plots, R provides a set of functions for producing graphical output primitives, such as lines, text, rectangles, and polygons. This makes it possible for users to write their own functions to create plots that occur in more specialized areas. There are many examples of special-purpose plots in add-on packages for R. For example, Figure 1.5 shows a map of New Zealand produced using R and the add-on packages `maps`[7] and `mapproj`[39].

R graphics works mostly in rectangular Cartesian coordinates, but functions have been written to display data in other coordinate systems. Figure 1.6 shows three plots based on polar coordinates. The top-left image was produced using the `stars()` function. Such star plots are useful for representing data where many variables have been measured on a relatively small number of subjects. The top-right image was produced using customized code by Karsten Bjerre and the bottom-left image was produced using the `rose.diag()` function from the `CircStats` package[36]. Plots such as these are useful for presenting geographic, or compass-based data. The bottom-right image in Figure 1.6 is a ternary plot producing using `ternaryplot()` from the `vcd` package[41]. A ternary plot can be used to plot categorical data where there are exactly three levels.

In some cases, researchers are inspired to produce a totally new type of plot for their data. R is not only a good platform for experimenting with novel plots, but it is also a good way to deliver new plotting techniques to other researchers. Figure 1.7 shows a novel display for decision trees, visualizing the distribution of the dependent variable in each terminal node[30] (produced using the `party` package).

For more information on how to generate a plot starting from an empty page with traditional graphics functions, see Chapter 3. The grid package provides even more power and flexibility for producing customized graphical output (see Chapters 5 and 6), especially for the purpose of producing functions for others to use (see Chapter 7).

1.1.4 General graphical scenes

The generality and flexibility of R graphics makes it possible to produce graphical images that go beyond what is normally considered to be statistical graphics, although the information presented can usually be thought of as data of some kind. A good mainstream example is the ability to embed tabular arrangements of text as graphical elements within a plot as in Figure 1.8. This is a standard way of presenting the results of a meta-analysis. Figure 1.12 and Figure 3.6 provide other examples of tabular graphical output produced by R.*

R has also been used to produce figures that help to visualize important concepts or teaching points. Figure 1.9 shows two examples that provide a geometric representation of extensions to F-tests (provided by Arden Miller[42]). A more unusual example of a general diagram is provided by the musical score in Figure 1.10 (provided by Steven Miller). R graphics can even be used like a general-purpose painting program to produce "clip art" as shown by Figure 1.11. These examples tend to require more effort to achieve the final result as they cannot be produced from a single function call. However, R's graphics facilities, especially those provided by the grid system (Chapters 5 and 6), provide a great deal of support for composing arbitrary images like these.

These examples present only a tiny taste of what R graphics (and clever and enthusiastic users) can do. They highlight the usefulness of R graphics not only for producing what are considered to be standard plot types (for little effort), but also for providing tools to produce final images that are well beyond the standard plot types (including going beyond the boundaries of what is normally considered statistical graphics).

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*All of the figures in this book, apart from the figures in Chapter 7 that only contain R code, were produced using R.

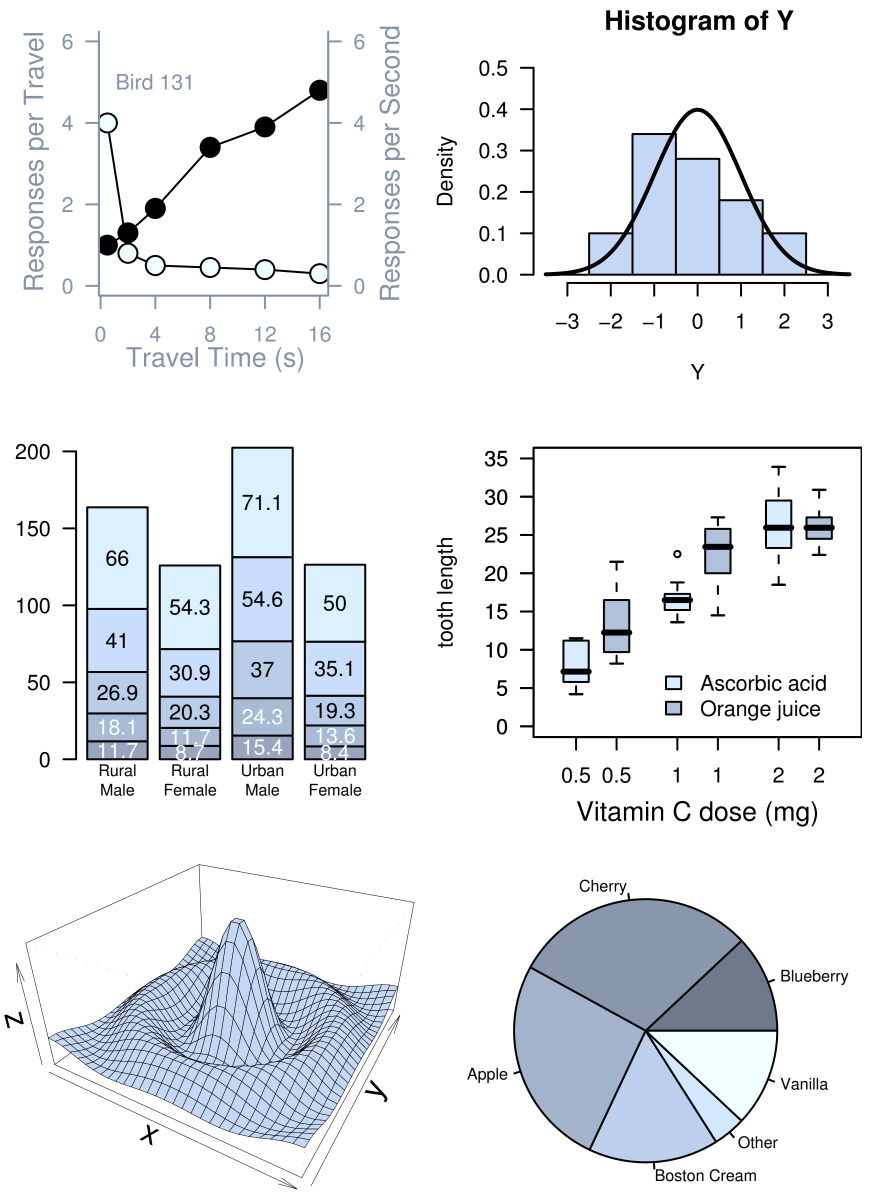

Figure 1.2
Some standard plots produced using R: (from left-to-right and top-to-bottom) a scatterplot, a histogram, a barplot, a boxplot, a 3D surface, and a piechart. In the first four cases, the basic plot type has been augmented by adding additional labels, lines, and axes. (The boxplot is adapted from an idea by Roger Bivand.)

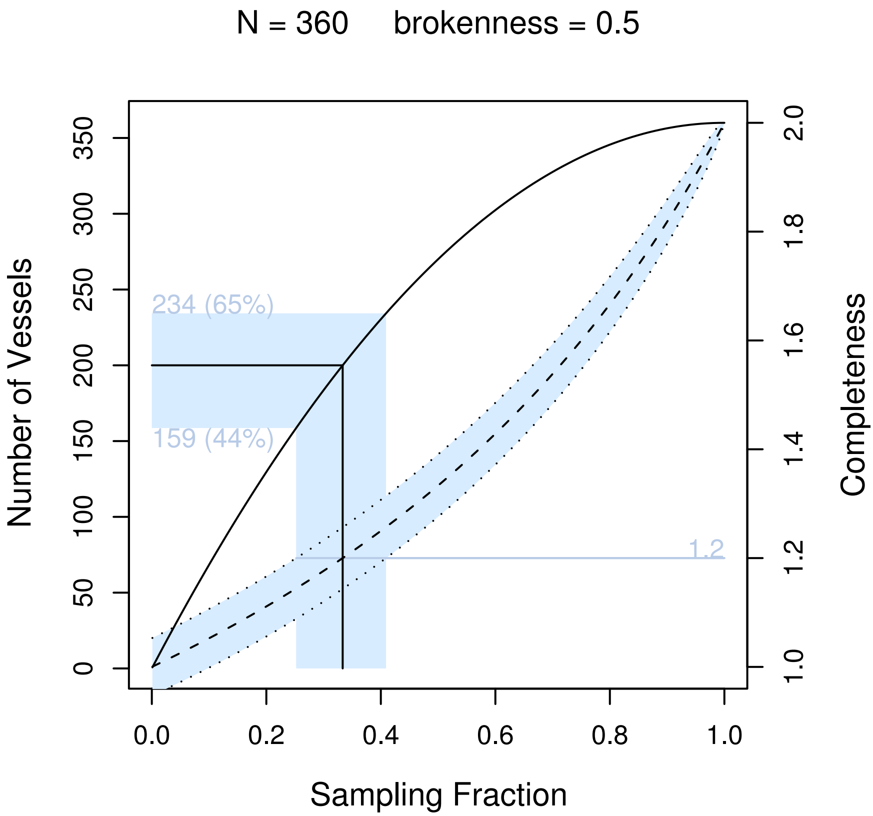

Figure 1.3
A customized scatterplot produced using R. This is created by starting with a simple scatterplot and augmenting it by adding an additional y-axis and several additional sets of lines, polygons, and text labels.

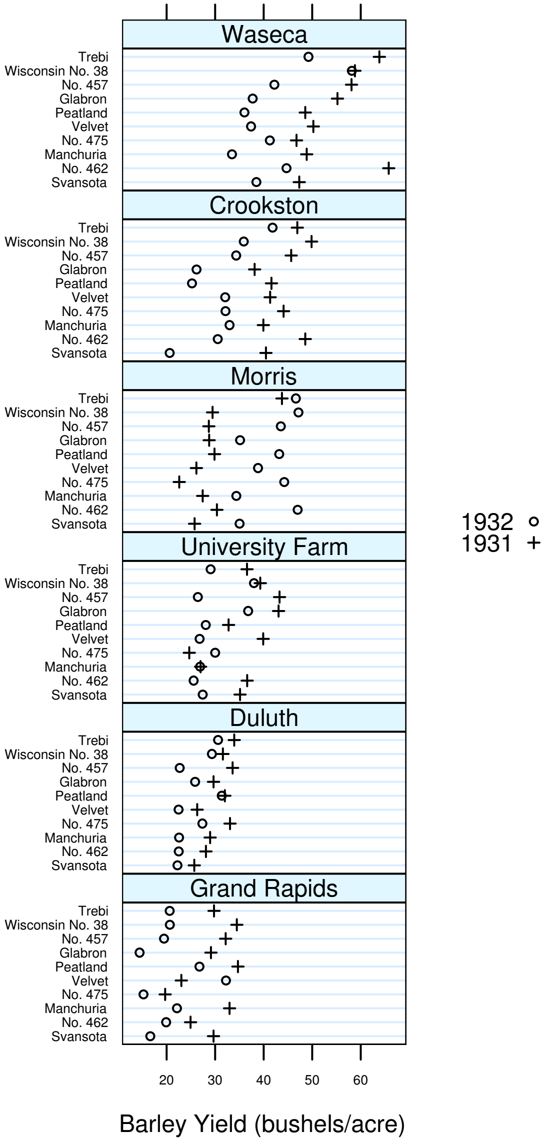

Figure 1.4
A Trellis dotplot produced using R. The relationship between the yield of barley and species of barley is presented, with a separate dotplot for different experimental sites and different plotting symbols for data gathered in different years. This is a small modification of Figure 1.1 from Bill Cleveland's "Visualizing Data" (reproduced with permission from Hobart Press).

Figure 1.5
A map of New Zealand produced using R, Ray Brownrigg's `maps` package, and Thomas Minka's `mapproj` package. The map (of New Zealand) is drawn as a series of polygons, and then text, an arrow, and a data point have been added to indicate the location of Auckland, the birthplace of R. A separate world map has been drawn in the bottom-right corner, with a circle to help people locate New Zealand.

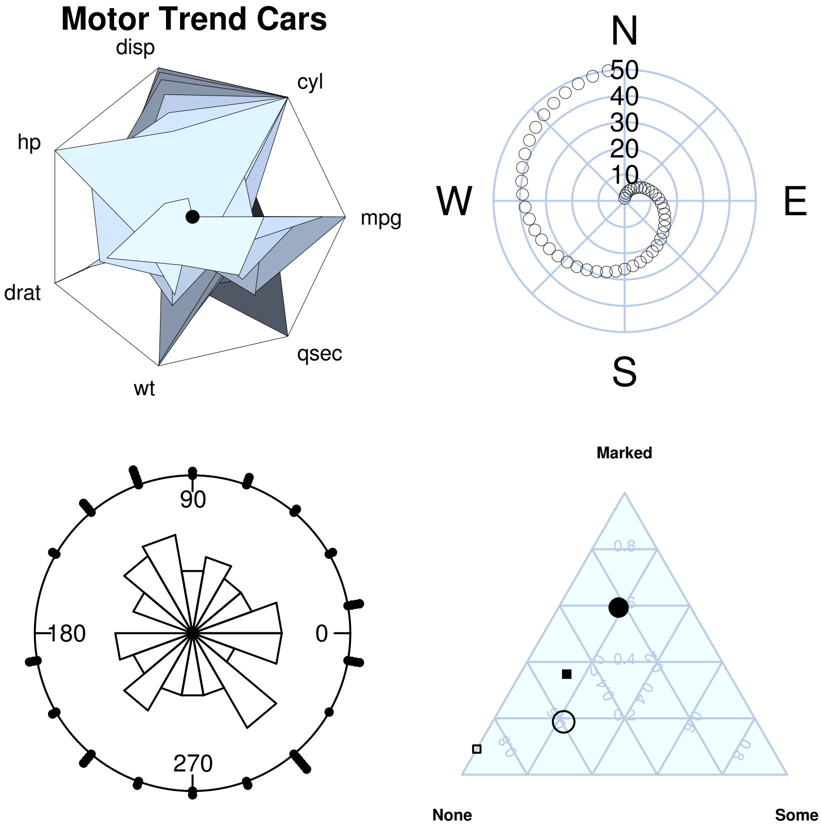

Figure 1.6
Some polar-coordinate plots produced using R (top-left), the `CircStats` package by Ulric Lund and Claudio Agostinelli (top-right), and code submitted to the `R-help` mailing list by Karsten Bjerre (bottom-left). The plot at bottom-right is a ternary plot produced using the `vcd` package (by David Meyer, Achim Zeileis, Alexandros Karatzoglou, and Kurt Hornik)

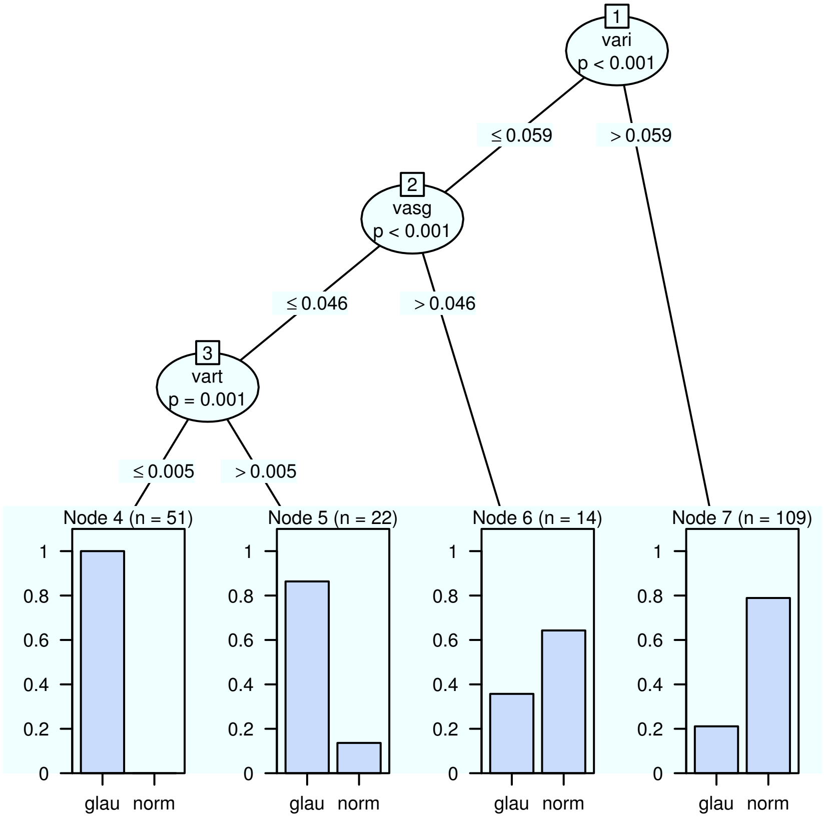

Figure 1.7
A novel decision tree plot, visualizing the distribution of the dependent variable in each terminal node. Produced using the `party` package by Torsten Hothorn, Kurt Hornik, and Achim Zeileis.

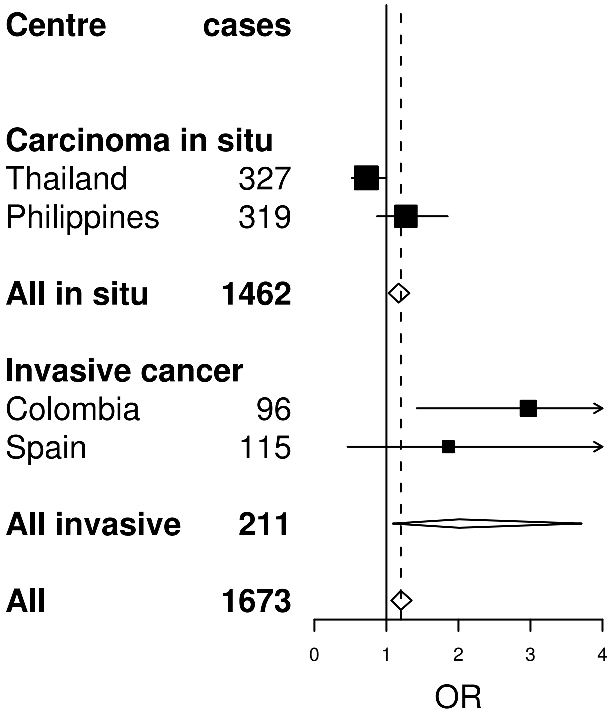

Figure 1.8
A table-like plot produced using R. This is a typical presentation of the results from a meta-analysis. The original motivation and data were provided by Martyn Plummer[48].

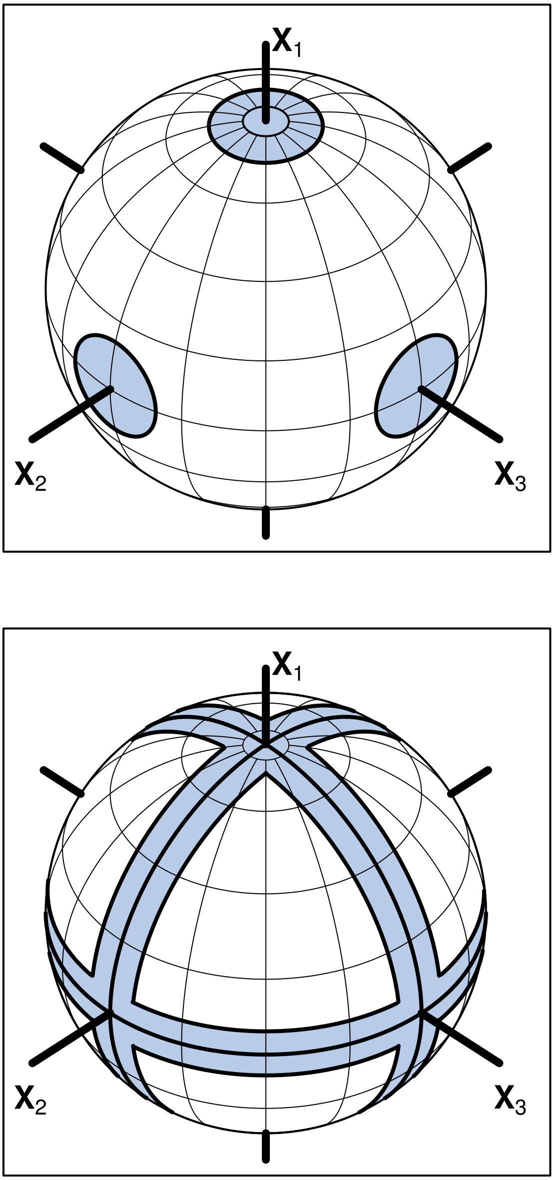

Figure 1.9
Didactic diagrams produced using R and functions provided by Arden Miller. The figures show a geometric representation of extensions to F-tests.

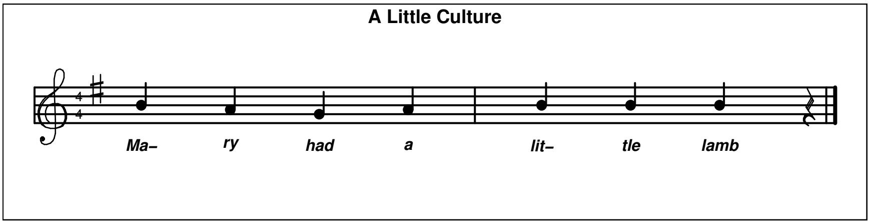

Figure 1.10
A music score produced using R (code by Steven Miller).

Figure 1.11
A piece of clip art produced using R.

1.2 The organization of R graphics

This section briefly describes how R's graphics functions are organized so that the user knows where to start looking for a particular function.

The R graphics system can be broken into four distinct levels: graphics packages; graphics systems; a graphics engine, including standard graphics devices; and graphics device packages (see Figure 1.12).

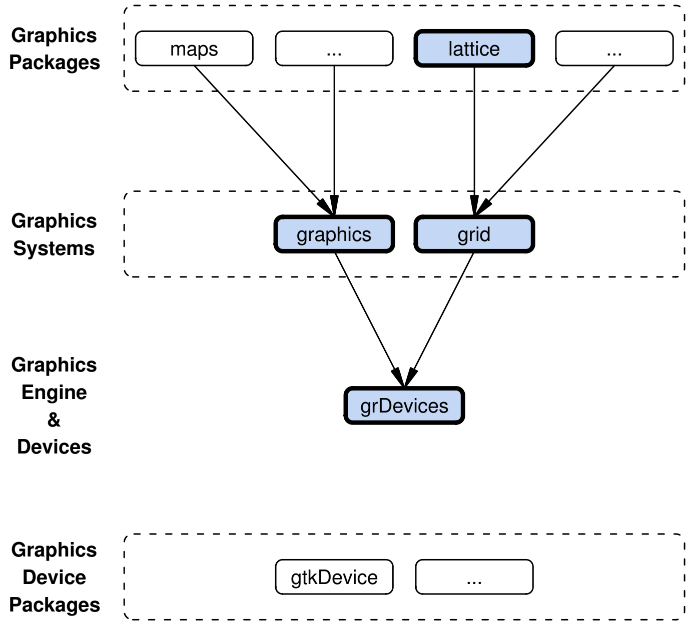

Figure 1.12
The structure of the R graphics system showing the main packages that provide graphics functions in R. Arrows indicate where one package builds on the functions in another package. The packages described in this book are highlighted with thicker borders and grey backgrounds.

The core R graphics functionality described in this book is provided by the graphics engine and the two graphics systems, traditional graphics and grid. The graphics engine consists of functions in the `grDevices` package and provides fundamental support for handling such things as colors and fonts (see Section 3.2), and graphics devices for producing output in different graphics formats (see Section 1.3).

The traditional graphics system consists of functions in the `graphics` package and is described in Part I. The grid graphics system consists of functions in the `grid` package and is described in Part II.

There are many other graphics functions provided in add-on graphics packages, which build on the functions in the graphics systems. Only one such package, the `lattice` package, is described in any detail in this book. The `lattice` package builds on the grid system to provide Trellis plots (see Chapter 4).

There are also add-on graphics device packages that provide additional graphical output formats.

1.2.1 Types of graphics functions

Functions in the graphics systems and graphics packages can be broken down into three main types: *high-level* functions that produce complete plots; *low-level* functions that add further output to an existing plot; and functions for working interactively with graphical output.

The traditional system, or graphics packages built on top of it, provide the majority of the high-level functions currently available in R. The most significant exception is the lattice package (see Chapter 4), which provides complete plots based on the grid system.

Both the traditional and grid systems provide many low-level graphics functions, and grid also provides functions for interacting with graphical output (editing, extracting, deleting parts of an image).

Most functions in graphics packages produce complete plots and typically offer specialized plots for a specific sort of analysis or a specific field of study. For example: the `hexbin` package[10] from the BioConductor project has functions for producing hexagonal binning plots for visualizing large amounts of data; the `maps` package[7] provides functions for visualizing geographic data (see, for example, Figure 1.5); and the package `scatterplot3d`[35] produces a variety of 3-dimensional plots. If there is a need for a particular sort of plot, there is a reasonable chance that someone has already written a function to do it. For example, a common request on the `R-help` mailing list is for a way to add error bars to scatterplots or barplots and this can be achieved via the functions `plotCI()` from the `gplots` package in the `gregmisc` bundle or the `errbar()` function from the `Hmisc` package. There are some search facilities linked off the main R home page web site to help to find a particular function for a particular purpose (also see Section A.2.10).

While there is no detailed discussion of the high-level graphics functions in graphics packages other than lattice, the general comments in Chapter 2 concerning the behavior of high-level functions in the traditional graphics system will often apply as well to high-level graphics functions in graphics packages built on the traditional system.

1.2.2 Traditional graphics versus grid graphics

The existence of two distinct graphics systems in R raises the issue of when to use each system.

For the purpose of producing complete plots from a single function call, which graphics system to use will largely depend on what type of plot is required. The choice of graphics system is largely irrelevant if no further output needs to be added to the plot.

If it is necessary to add further output to a plot, the most important thing to know is which graphics system was used to produce the original plot. In general, the same graphics system should be used to add further output (though see Appendix B for ways around this).

In some cases, the same sort of plot can be produced by both lattice and traditional functions. The lattice versions offer more flexibility for adding further output and for interacting with the plot, plus Trellis plots have a better design in terms of visually decoding the information in the plot.

For producing graphical scenes starting from a blank page, the grid system offers the benefit of a much wider range of possibilities, at the cost of having to learn a few additional concepts.

For the purpose of writing new graphical functions for others to use, grid again provides better support for producing more general output that can be combined with other output more easily. Grid also provides more possibilities for interaction.

1.3 Graphical output formats

At the start of this chapter (page 1), there is a simple example of the sort of R expressions that are required to produce a plot. When using R interactively, the result is a plot drawn on screen. However, it is also possible to produce a file that contains the plot, for example, as a PostScript document. This section describes how to control the format in which a plot is produced.

R graphics output can be produced in a wide variety of graphical formats. In R's terminology, output is directed to a particular output *device* and that dictates the output format that will be produced. A device must be created or "opened" in order to receive graphical output and, for devices that create a file on disk, the device must also be closed in order to complete the output. For example, for producing PostScript output, R has a function `postscript()` that opens a file to receive PostScript commands. Graphical output sent to this device is recorded by writing PostScript commands into the file. The function `dev.off()` closes a device.

The following code shows how to produce a simple scatterplot in PostScript format. The output is stored in a file called `myplot.ps`:

```
> postscript(file="myplot.ps")
> plot(pressure)
> dev.off()
```

To produce the same output in PNG format (in a file called `myplot.png`), the code simply becomes:

```
> png(file="myplot.png")
> plot(pressure)
> dev.off()
```

When working in an interactive session, output is often produced, at least initially, on the screen. When R is installed, an appropriate screen format is selected as the default device and this default device is opened automatically the first time that any graphical output occurs. For example, on the various Unix systems, the default device is an X11 window so the first time a graphics function gets called, a window is created to draw the output on screen. The user can control the format of the default device using the `options()` function.

Table 1.1
Graphics formats that R supports and the functions that open an appropriate graphics device

Device Function	Graphical Format
Screen/GUI Devices	
`x11()` or `X11()`	X Window window
`windows()`	Microsoft Windows window
`quartz()`	Mac OS X Quartz window
File Devices	
`postscript()`	Adobe PostScript file
`pdf()`	Adobe PDF file
`pictex()`	LaTeX PicTeX file
`xfig()`	XFIG file
`bitmap()`	GhostScript conversion to file
`png()`	PNG bitmap file
`jpeg()`	JPEG bitmap file
(Windows only)	
`win.metafile()`	Windows Metafile file
`bmp()`	Windows BMP file
Devices provided by add-on packages	
`devGTK()`	GTK window (`gtkDevice`)
`devJava()`	Java Swing window (`RJavaDevice`)
`devSVG()`	SVG file (`RSvgDevice`)

1.3.1 Graphics devices

Table 1.1 gives a full list of functions that open devices and the output formats that they correspond to.

All of these functions provide several arguments to allow the user to specify things such as the physical size of the window or document being created. The documentation for individual functions should be consulted for descriptions of these arguments.

It is possible to have more than one device open at the same time, but only one device is currently "active" and all graphics output is sent to that device.

If multiple devices are open, there are functions to control which device is active. The list of open devices can be obtained using `dev.list()`. This gives the name (the device format) and number for each open device. The function `dev.cur()` returns this information only for the currently active device. The `dev.set()` function can be used to make a device active, by specifying the appropriate device number and the functions `dev.next()` and `dev.prev()` can be used to make the next/previous device on the device list the active device.

All open devices can be closed at once using the function `graphics.off()`. When an R session ends, all open devices are closed automatically.

1.3.2 Multiple pages of output

For a screen device, starting a new page involves clearing the window before producing more output. On Windows there is a facility for returning to previous screens of output (see the "History" menu, which is available when a graphics window has focus), but on most screen devices, the output of previous pages is lost.

For file devices, the output format dictates whether multiple pages are supported. For example, PostScript and PDF allow multiple pages, but PNG does not. It is usually possible, especially for devices that do not support multiple pages of output, to specify that each page of output produces a separate file. This is achieved by specifying the argument `onefile=FALSE` when opening a device and specifying a pattern for the file name like `file="myplot%03d"` so that the `%03d` is replaced by a three-digit number (padded with zeroes) indicating the "page number" for each file that is created.

1.3.3 Display lists

R maintains a *display list* for each open device, which is a record of the output on the current page of a device. This is used to redraw the output when a device is resized and can also be used to copy output from one device to another.

The function `dev.copy()` copies all output from the active device to another device. The copy may be distorted if the aspect ratio of the destination device — the ratio of the physical height and width of the device — is not the same as the aspect ratio of the active device. The function `dev.copy2eps()` is similar to `dev.copy()`, but it preserves the aspect ratio of the copy and creates a file in EPS (Encapsulated PostScript) format that is ideal for embedding in other documents (e.g., a LaTeX document). The `dev2bitmap()` function is similar in that it also tries to preserve the aspect ratio of the image, but it produces one of the output formats available via the `bitmap()` device.

The function `dev.print()` attempts to print the output on the active device. By default, this involves making a PostScript copy and then invoking the print command given by `options("printcmd")`.

The display list can consume a reasonable amount of memory if a plot is particularly complex or if there are very many devices open at the same time. For this reason it is possible to disable the display list, by typing the expression `dev.control(displaylist="inhibit")`. If the display list is disabled, output will not be redrawn when a device is resized, and output cannot be copied between devices.

Chapter summary

R graphics can produce a wide variety of graphical output, including (but not limited to) many different kinds of statistical plots, and the output can be produced in a wide variety of formats. Graphical output is produced by calling functions that either draw a complete plot or add further output to an existing plot.

There are two main graphics systems in R: a traditional system similar to the original S graphics system and a newer grid system that is unique to R. Additional graphics functionality is provided by a large number of add-on packages that build on these graphics systems.

4

Trellis Graphics: the Lattice Package

Chapter preview

This chapter describes how to produce Trellis plots using R. There is a description of what Trellis plots are as well as a description of the functions used to produce them. Trellis plots are designed to be easy to interpret and at the same time provide some modern and sophisticated plotting styles, such as multipanel conditioning.

The grid graphics system provides no high-level plotting functions itself, so this chapter also describes the best way to produce a complete plot using the grid system. There are several advantages to producing a plot using the grid system, including greater flexibility in adding further output to the plot, and the ability to interactively edit the plot.

This chapter describes the lattice package, developed by Deepayan Sarkar[54]. Lattice is based on the grid graphics system, but can be used as a complete graphics system in itself and a great deal can be achieved without encountering any of the underlying grid concepts.* This chapter deals with lattice as a self-contained system consisting of functions for producing complete plots, functions for controlling the appearance of the plots, and functions for opening and closing devices. Section 5.8 and Section 6.7 describe some of the benefits that can be gained from viewing lattice plots as grid output and dealing directly with the grid concepts and objects that underly the lattice system.

*To give Deepayan proper credit, lattice uses grid only to *render* plots. Lattice performs a lot of work itself to deconstruct formulae, rearrange the data, and manage many user-settable options.

The graphics functions that make up the lattice graphics system are provided in an add-on package called `lattice`. The lattice system is loaded into R as follows.

```
> library(lattice)
```

The lattice package implements the Trellis Graphics system[6] with some novel extensions. The Trellis Graphics system has a large number of sophisticated features and many of these are described in this section, but more information, examples, and background are available from the Trellis Display web site:

`http://cm.bell-labs.com/cm/ms/departments/sia/project/trellis/index.html`

4.1 The lattice graphics model

In simple usage, lattice functions appear to work just like traditional graphics functions where the user calls a function and output is generated on the current device. The following example plots the locations of 1000 earthquakes that have occurred in the Pacific Ocean (near Fiji) since 1964 (see Figure 4.1).*

```
> xyplot(lat ~ long, data=quakes, pch=".")
```

It is perfectly valid to use lattice this way; however, lattice graphics functions do not produce graphical output directly. Instead they produce an object of class `"trellis"`, which contains a description of the plot. The `print()` method for objects of this class does the actual drawing of the plot. This can be demonstrated quite easily. For example, the following code creates a `trellis` object, but does not draw anything.

```
> tplot <- xyplot(lat ~ long, data=quakes, pch=".")
```

The result of the call to `xyplot()` is assigned to the variable `tplot` so it is not printed. The plot can be drawn by calling print on the `trellis` object (the result is exactly the same as Figure 4.1).

```
> print(tplot)
```

*The data are available as the data set `quakes` in the `datasets` package.

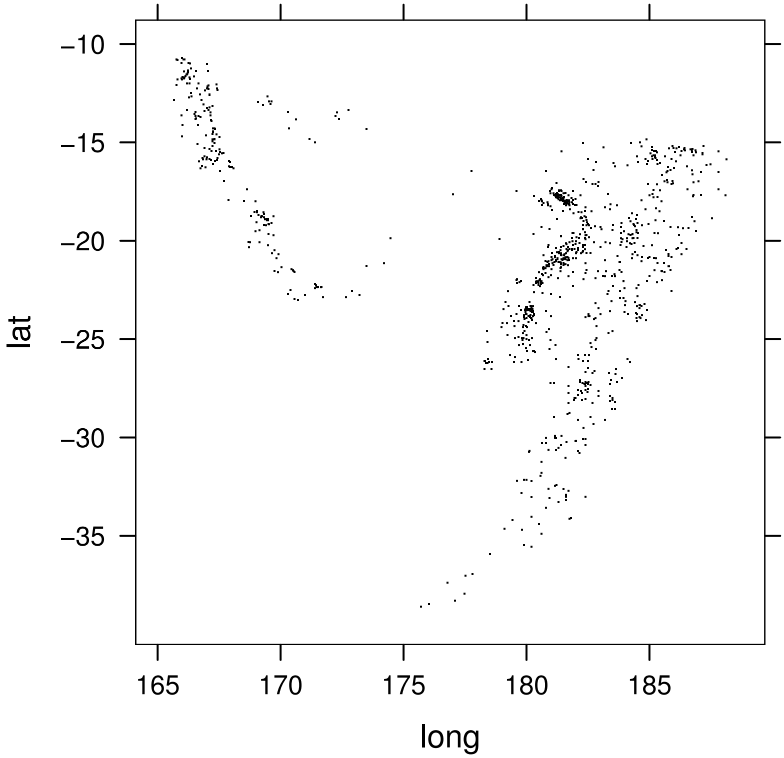

Figure 4.1
A scatterplot using lattice (showing the locations of earthquakes in the Pacific Ocean). A basic lattice plot has a very similar appearance to an analogous traditional plot.

This design makes it possible to work with the `trellis` object and modify it using the `update()` method for `trellis` objects, which is an alternative to modifying the original R expression used to create the `trellis` object. The following code demonstrates this idea by modifying the `trellis` object `tplot` to redefine the main title of the plot (it was empty). The resulting output is shown in Figure 4.2. A subtle change to look for is the fact that extra space has been introduced to allow room for adding the new main title text (the height of the plot region is slightly smaller compared to Figure 4.1).

```
> update(tplot,
         main="Earthquakes in the Pacific Ocean\n(since 1964)")
```

The side-effect of the code above is to produce new output that is a modification of the original plot, represented by `tplot`. However, it is important to remember that `tplot` has not been changed in any way (typing `tplot` again will produce output like Figure 4.1 again). In order to retain an R object representing the modified plot, the user must assign the value returned by the `update()` function, as in the following code.

```
> tplot2 <-
    update(tplot,
           main="Earthquakes in the Pacific Ocean (since 1964)")
```

4.1.1 Lattice devices

For each graphics device, lattice maintains its own set of graphical parameter settings that control the appearance of plots (colors of lines, fonts for text, and many more — see Section 4.3)*. The default settings depend on the type of device being opened (e.g., the settings are different for a PostScript device compared to a PDF device). In simple usage this causes no problems, because lattice automatically initializes these settings the first time that lattice output is produced on a device. If it is necessary to control the initial values for these settings the `trellis.device()` function can be used to explicitly open a device with specific lattice graphical parameter settings (or just to enforce specific lattice settings on an existing device). Section 4.3 describes more functions for manipulating the lattice graphical parameter settings.

*One of the features of Trellis Graphics is that carefully selected default settings are provided for colors, data symbols, and so on. These settings are selected to maximize the interpretability of plots and are based on principles of human perception[15].

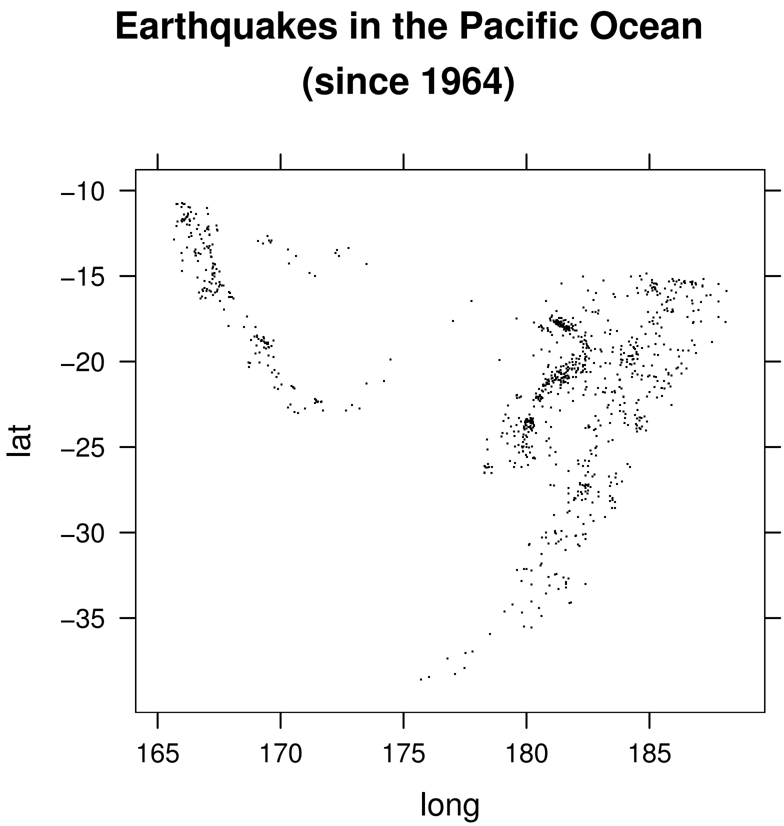

Figure 4.2
The result of modifying a lattice object. Lattice creates an object representing the plot. If this object is modified, the plot is redrawn. This figure shows the result of modifying the object representing the plot in Figure 4.1 to add a title to the plot.

4.2 Lattice plot types

Lattice provides functions to produce a number of standard plot types, plus some more modern and specialized plots. Table 4.1 describes the functions that are available and Figure 4.3 provides a basic idea of the sort of output that they produce.

There are a number of functions that produce output very similar to the output of functions in the traditional graphics system, but there are three possible reasons for using lattice functions instead of the traditional counterparts:

1. The default appearance of the lattice plots is superior in some areas. For example, the default colors and the default data symbols have been deliberately chosen to make it easy to distinguish between groups when more than one data series is plotted. There are also some subtle things such as the fact that tick labels on the y-axes are written horizontally by default, which makes them easier to read.

2. The lattice plot functions can be extended in several very powerful ways. For example, several data series can be plotted at once in a convenient manner and multiple panels of plots can be produced easily (see Section 4.2.1).

3. The output from lattice functions is grid output, so many powerful grid features are available for annotating, editing, and saving the graphics output. See Section 5.8 and Section 6.7 for examples of these features.

Most of the lattice plotting functions provide a very long list of arguments and produce a wide range of different types of output. Many of the arguments are shared by different functions and the on-line help for the `xyplot()` function provides an explanation of these standard arguments. The following sections address some of the important shared arguments, but for a full explanation of all arguments, the documentation for each specific function should be consulted. The next section discusses two important arguments, `formula` and `data`. The use of several other arguments is demonstrated in Section 4.2.2 in the context of a more complex example. Section 4.3 mentions the `par.settings` argument and Section 4.4 describes the `layout` argument. Section 4.5 describes the `panel` and `strip` arguments.

Table 4.1
The plotting functions available in lattice

Lattice Function	**Description**	**Traditional Analogue**
`barchart()`	Barcharts	`barplot()`
`bwplot()`	Boxplots Box-and-whisker plots	`boxplot()`
`densityplot()`	Conditional kernel density plots Smoothed density estimate	*none*
`dotplot()`	Dotplots Continuous versus categorical	`dotchart()`
`histogram()`	Histograms	`hist()`
`qqmath()`	Quantile–quantile plots Data set versus theoretical distribution	`qqnorm()`
`stripplot()`	Stripplots One-dimensional scatterplot	`stripchart()`
`qq()`	Quantile–quantile plots Data set versus data set	`qqplot()`
`xyplot()`	Scatterplots	`plot()`
`levelplot()`	Level plots	`image()`
`contourplot()`	Contour plots	`contour()`
`cloud()`	3-dimensional scatterplot	*none*
`wireframe()`	3-dimensional surfaces	`persp()`
`splom()`	Scatterplot matrices	`pairs()`
`parallel()`	Parallel coordinate plots	*none*

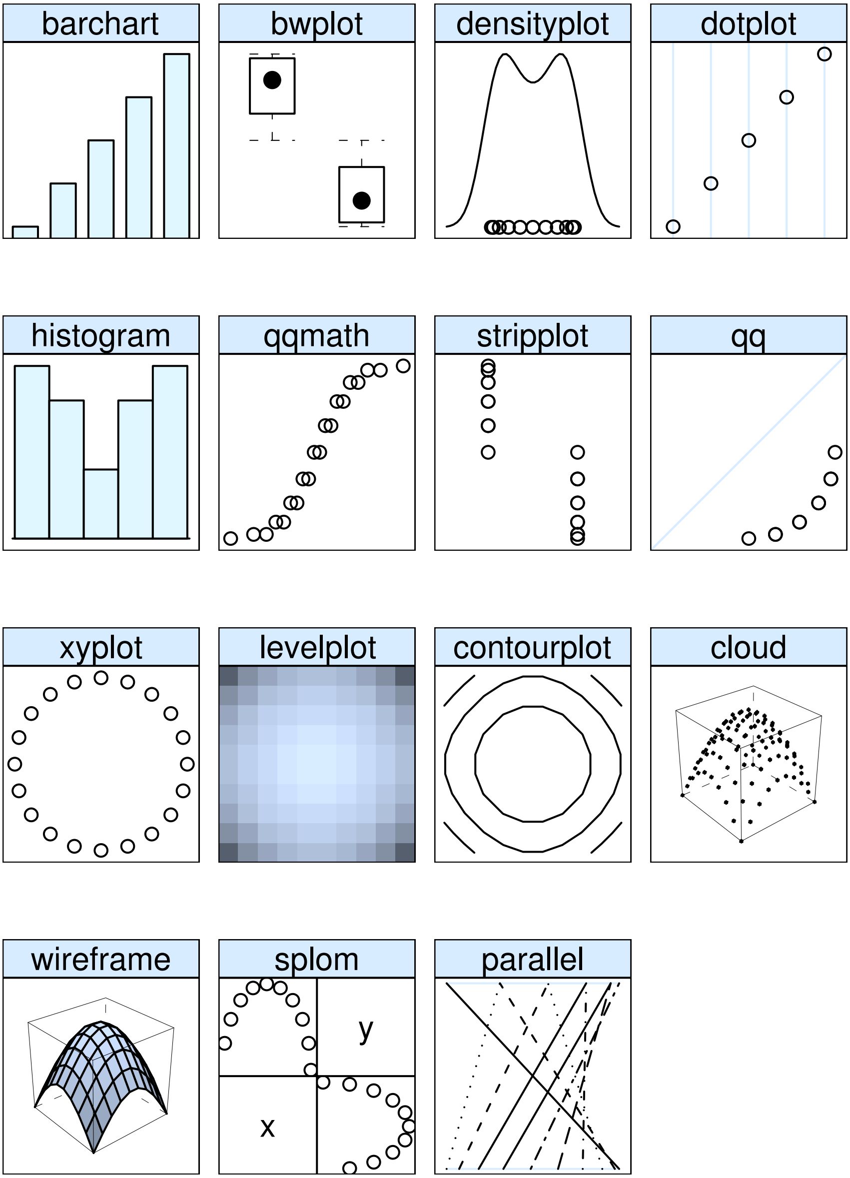

Figure 4.3
Plot types available in lattice. The name of the function used to produce the different plot types is shown in the strip above each plot.

4.2.1 The `formula` argument and multipanel conditioning

In most cases, the first argument to the lattice plotting functions is an R formula (see Section A.2.6) that describes which variables to plot. The simplest case has already been demonstrated. A formula of the form `y ~ x` plots variable `y` against variable `x`. There are some variations for plots of only one variable or plots of more than two variables. For example, for the `bwplot()` function, the formula can be of the form `~ x` and for the `cloud()` and `wireframe()` functions something of the form `z ~ x * y` is required to specify the three variables to plot. Another useful variation is the ability to specify multiple y-variables. Something of the form `y1 + y2 ~ x` produces a plot of both the `y1` variable and the `y2` variable against `x`. Multiple x-variables can be specified as well.

The second argument to a lattice plotting function is typically `data`, which allows the user to specify a data frame within which lattice can find the variables specified in the formula.

One of the very powerful features of Trellis Graphics is the ability to specify conditioning variables within the formula argument. Something of the form `y ~ x | g` indicates that several plots should be generated, showing the variable `y` against the variable `x` for each level of the variable `g`. In order to demonstrate this feature, the following code produces several scatterplots, with each scatterplot showing the locations of earthquakes that occurred within a particular depth range (see Figure 4.4). First of all, a new variable `depthgroup` is defined, which is a binning of the original `depth` variable in the `quakes` data set.

```
> depthgroup <- equal.count(quakes$depth, number=3, overlap=0)
```

Now this `depthgroup` variable can be used to produce a scatterplot for each depth range.

```
> xyplot(lat ~ long | depthgroup, data=quakes, pch=".")
```

In the Trellis terminology, the plot in Figure 4.4 consists of three *panels*. Each panel in this case contains a scatterplot and above each panel there is a *strip* that presents the level of the conditioning variable.

There can be more than one conditioning variable in the formula argument, in which case a panel is produced for each combination of the conditioning variables. An example of this is given in Section 4.2.2.

The most natural type of variable to use as a conditioning variable is a categorical variable (factor), but there is also support for using a continuous

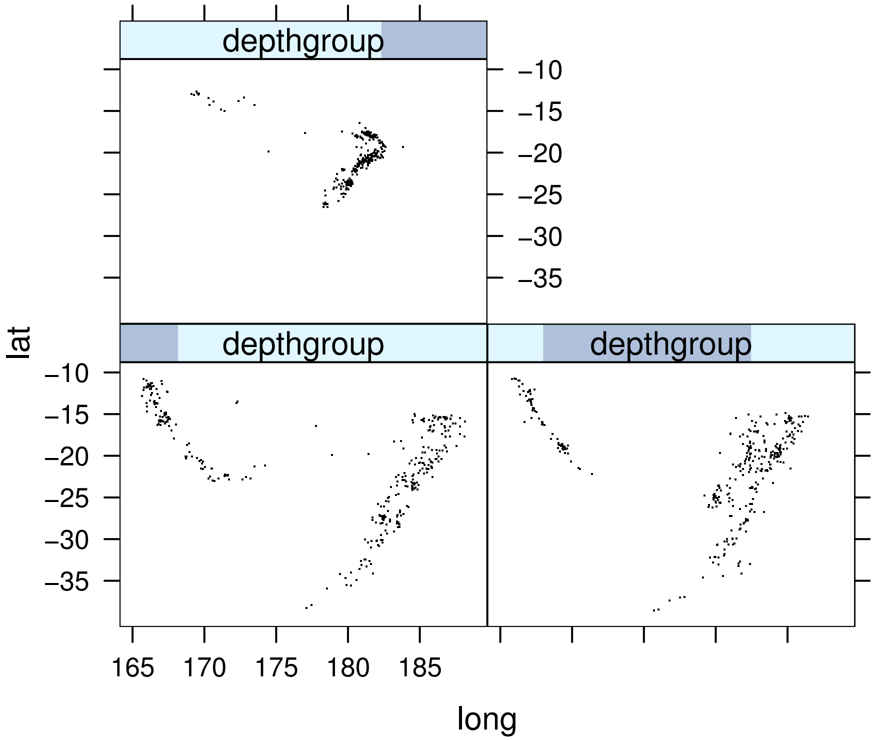

Figure 4.4
A lattice multipanel conditioning plot. A single function call produces several scatterplots of the locations of earthquakes for different earthquake depths.

(numeric) conditioning variable. For this purpose, Trellis Graphics introduces the concept of a *shingle*. This is a continuous variable with a number of ranges associated with it. The ranges are used to split the continuous values into (possibly overlapping) groups. The `shingle()` function can be used to explicitly control the ranges, or the `equal.count()` function can be used to generate ranges automatically given a number of groups (as was done to produce the `depthgroup` variable above).

4.2.2 A nontrivial example

This section describes an example that makes use of some of the common arguments to the lattice plotting functions to produce a more complex final result (see Figure 4.5). First of all, another grouping variable, `magnitude`, is defined, which is a shingle indicating whether an earthquake is big or small.

```
> magnitude <- equal.count(quakes$mag, number=2, overlap=0)
```

The plot is still produced from a single function call, but there are two conditioning variables, so there is a panel for each possible combination of depth and magnitude. A title and axis labels have been specified for the plot using the `main`, `xlab`, and `ylab` arguments. The `between` argument has been used to introduce a vertical gap between the top row of panels (big earthquakes) and the bottom row of panels (small earthquakes). The `par.strip.text` argument is used to control the size of text in the strips above each panel. The `scales` argument is used to control the drawing of axis labels; in this case the specification says that the x-axis labels should go at the bottom for both panels. This is to avoid the axis tick marks interfering with the main title. Finally, the `par.settings` argument is used to control the size of the tick labels on the axes.

```
> xyplot(lat ~ long | depthgroup * magnitude,
         data=quakes,
         main="Fiji Earthquakes",
         ylab="latitude", xlab="longitude",
         pch=".",
         scales=list(x=list(alternating=c(1, 1, 1))),
         between=list(y=1),
         par.strip.text=list(cex=0.7),
         par.settings=list(axis.text=list(cex=0.7)))
```

This example demonstrates that it is possible to have very fine control over many aspects of a lattice plot, given sufficient willingness to learn about all of the arguments that are available.

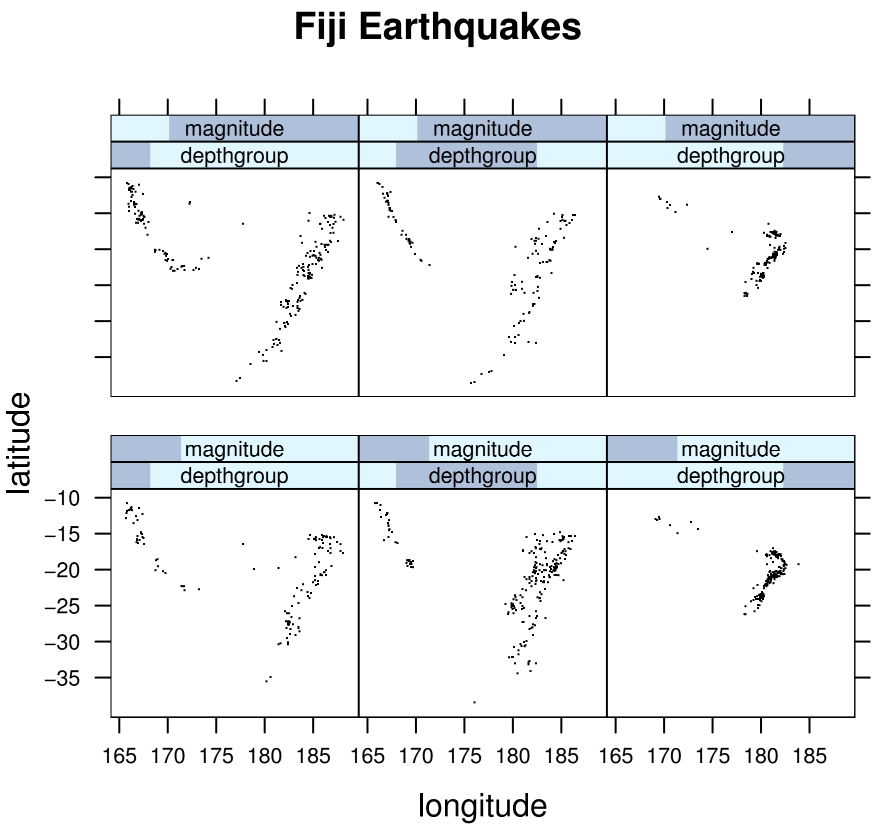

Figure 4.5
A complex lattice plot. There are a large number of arguments to lattice plotting functions to allow control over many details of a plot, such as the text to use for labels and titles, the size and placement of axis tick labels, and the size of the gaps between columns and rows of panels.

4.3 Controlling the appearance of lattice plots

An important feature of Trellis Graphics is the careful selection of default settings that are provided for many of the features of lattice plots. For example, the default data symbols and colors used to distinguish between different data series have been chosen so that it is easy to visually discriminate between them. Nevertheless, it is still sometimes desirable to be able to make alterations to the default settings for aspects like color and text size. It is also useful to be able to control the layout or arrangement of the components (panels and strips) of a lattice plot, but that is dealt with separately in Section 4.4. This section is only concerned with graphical parameters that control colors, line types, fonts and the like.

The lattice graphical parameter settings consist of a large list of parameter groups and each parameter group is a list of parameter settings. For example, there is a `plot.line` parameter group consisting of `col`, `lty`, and `lwd` settings to control the color, line type, and line width for lines drawn between data locations. There is a separate `plot.symbol` group consisting of `cex`, `col`, `font`, and `pch` settings to control the size, shape, and color of data symbols. The settings in each parameter group affect some aspect of a lattice plot: some have a "global" effect; for example, the `fontsize` settings affect all text in a plot; some are more specific; for example, the `strip.background` setting affects the background color of strips; and some only affect a certain aspect of a certain sort of plot; for example, the `box.dot` settings affect only the dot that is plotted at the median value in boxplots.

A separate list of graphical parameters is maintained for each graphics device. Changes to parameter settings (see below) only affect the current device.

The function `show.settings()` produces a picture representing some of the current graphical parameter settings. Figure 4.6 shows the settings for a black-and-white PostScript device.

The current value of graphical parameter settings can be obtained using the `trellis.par.get()` function. For a list of all current graphical parameter settings, type `trellis.par.get()`. If a name is specified as the argument to this function, then only the relevant settings are returned. The following code shows how to obtain only the `fontsize` group of settings (the output is on page 139).

```
> trellis.par.get("fontsize")
```

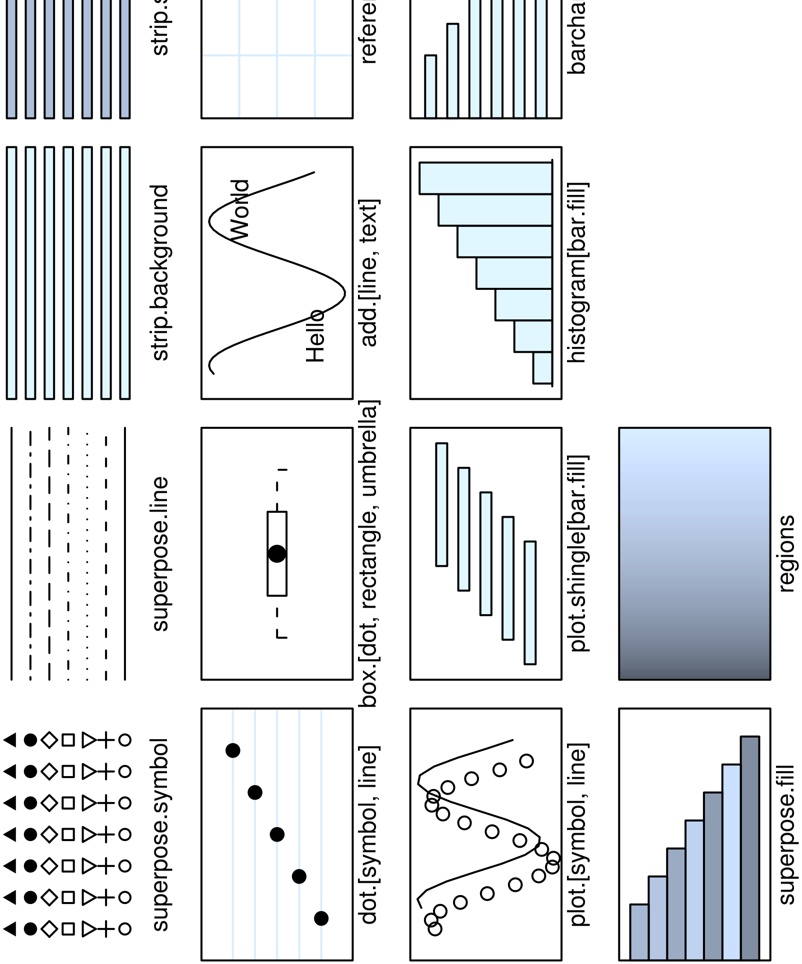

Figure 4.6
Some default lattice settings for a black-and-white PostScript device. This figure was produced by the lattice function `show.settings()`.

```
$text
[1] 9

$points
[1] 8
```

There are two ways to set new values for graphical parameters. The values can be set persistently (i.e., they will affect all subsequent plots until a new setting is specified) using the `trellis.par.set()` function, or they can be set temporarily for a single plot by specifying settings as an argument to a plotting function.

The `trellis.par.set()` function can be used in several ways. For back-compatibility with the original implementation of Trellis, it is possible to provide a name as the first argument and a list of settings as the second argument. This will modify the values for one parameter group.

A new approach is to provide a list of lists that can be used to modify multiple parameter groups at once. Lattice also introduces the concept of *themes*, which is a comprehensive and coherent set of graphical parameter values. It is possible to specify such a theme and enforce a new "look and feel" for a plot in one function call. Lattice currently provides one such theme via the `col.whitebg()` function. It is also possible to obtain the default theme for a particular device using the `canonical.theme()` function.

The following code demonstrates how to use `trellis.par.set()` in either the backwards-compatible, one-parameter-group-at-a-time way, or the new list-of-lists way, to specify `fontsize` settings.

```
> trellis.par.set("fontsize", list(text=14, points=10))
> trellis.par.set(list(fontsize=list(text=14, points=10)))
```

The theme approach is usually more convenient, especially when setting only one value within a parameter group. For example, the following code demonstrates the difference between the two approaches for modifying just the `text` setting within the `fontsize` parameter group (old way first, new way second).

```
> fontsize <- trellis.par.get("fontsize")
> fontsize$text <- 20
> trellis.par.set("fontsize", fontsize)
```

```
> trellis.par.set(list(fontsize=list(text=20)))
```

The concept of themes is an example of a lattice-specific extension to the original Trellis Graphics system.

The other way to modify lattice graphical parameter settings is on a per-plot basis, by specifying a `par.settings` argument in the call to a plotting function. The value for this argument should be a theme (a list of lists). Such a setting will only be enforced for the relevant plot and will not affect any subsequent plots. The following code demonstrates how to modify the `fontsize` settings just for a single plot.

```
> xyplot(lat ~ long, data=quakes,
         par.settings=list(fontsize=list(text=14, points=10)))
```

4.4 Arranging lattice plots

There are two types of arrangements to consider when dealing with lattice plots: the arrangement of panels and strips within a single lattice plot; and the arrangement of several complete lattice plots together on a single page.

In the first case (the arrangement of panels and strips within a single plot) there are two useful arguments that can be specified in a call to a lattice plotting function: the `layout` argument and the `aspect` argument.

The `layout` argument consists of up to three values. The first two indicate the number of columns and rows of panels on each page and the third value indicates the number of pages. It is not necessary to specify all three values, as lattice provides sensible default values for any unspecified values. The following code produces a variation on Figure 4.4 by explicitly specifying that there should be a single column of three panels via the `layout` argument, and that each panel must be "square" via the `aspect` argument. The `index.cond` argument has also been used to specify that the panels should be ordered from top to bottom (see Figure 4.7).

```
> xyplot(lat ~ long | depthgroup, data=quakes, pch=".",
         layout=c(1, 3), aspect=1, index.cond=list(3:1))
```

The `aspect` argument specifies the aspect ratio (height divided by width) for the panels. The default value is `"fill"`, which means that panels expand to occupy as much space as possible. In the example above, the panels were all forced to be square by specifying `aspect=1`. This argument will also accept the special value `"xy"`, which means that the aspect ratio is calculated to satisfy the "banking to 45 degrees" rule proposed by Bill Cleveland[13].

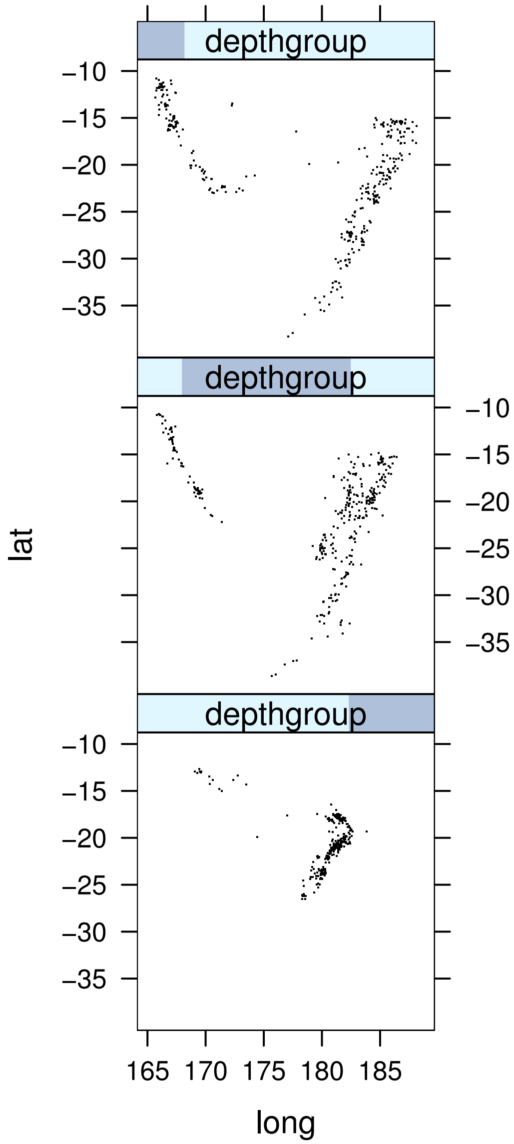

Figure 4.7
Controlling the layout of lattice panels. Lattice arranges panels in a sensible way by default, but there are several ways to force the panels to be arranged in a particular layout. This figure shows a custom arrangement of the panels in the plot from Figure 4.4.

As with the choice of colors and data symbols, a lot of work is done to select sensible default values for the arrangement of panels, so in many cases nothing special needs to be specified.

Another issue in the arrangement of a single lattice plot is the placement and structure of the key or legend. This can be controlled using the `auto.key` or `key` argument to plotting functions, which will accept complex specifications of the contents, layout, and positioning of the key.

The problem of arranging multiple lattice plots on a page requires a different approach. A `trellis` object must be created (but not plotted) for each lattice plot, then the `print()` function is called, supplying arguments to specify the position of each plot. The following code provides a simple demonstration using the average yearly number of sunspots from 1749 to 1983, available as the `sunspots` data set in the `datasets` package (see Figure 4.8). Two lattice plots are produced and then positioned one above the other on a page. The `position` argument is used to specify their location, `(left, bottom, right, top)`, as a proportion of the total page, and the `more` argument is used in the first `print()` call to ensure that the second `print()` call draws on the same page. The `scales` argument is also used to draw the x-axis at the top of the top plot.

```
> spots <- by(sunspots, gl(235, 12, lab=1749:1983), mean)
> plot1 <- xyplot(spots ~ 1749:1983, xlab="", type="l",
                  main="Average Yearly Sunspots",
                  scales=list(x=list(alternating=2)))
> plot2 <- xyplot(spots ~ 1749:1983, xlab="Year", type="l")
> print(plot1, position=c(0, 0.2, 1, 1), more=TRUE)
> print(plot2, position=c(0, 0, 1, 0.33))
```

Section 5.8 describes additional options for controlling the arrangements of panels within a lattice plot, and more flexible options for arranging multiple lattice plots, using the concepts and facilities of the grid system.

4.5 Annotating lattice plots

In the original Trellis Graphics system, plots are completely self-contained. There is no real concept of adding output to a plot once the plot has been drawn. This constraint has been lifted in lattice, though the traditional approach is still supported.

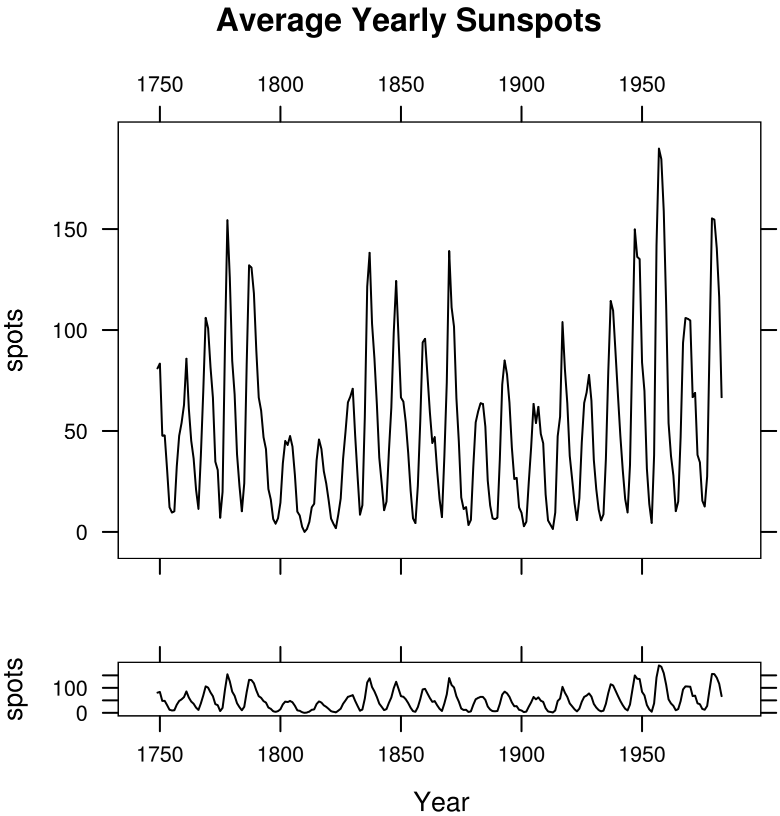

Figure 4.8
Arranging multiple lattice plots. This shows two separate lattice plots arranged together on a single page.

4.5.1 Panel functions and strip functions

The `trellis` object that is produced by a lattice plotting function is a complete description of a plot. The usual way to add extra output to a plot (e.g., add text labels to data symbols), is to add extra information to the `trellis` object. This is achieved by specifying a *panel function* via the `panel` argument of lattice plotting functions.

The panel function is called for each panel in a lattice plot. All lattice plotting functions have a default panel function, which is usually the name of the function with a "`panel.`" prefix. For example, the default panel function for the `xyplot()` function is `panel.xyplot()`. The default panel function draws the default contents for a panel so it is typical to call this default as part of a custom panel function.

The arguments available to the panel function differ depending on the plotting function. The documentation for individual panel functions should be consulted for full details, but some common arguments to expect are `x` and `y` (and possibly `z`), giving locations at which to plot data symbols, and `subscripts`, which provides the indices used to obtain the subset of the data for each panel.

In addition to the panel function, it is possible to specify a *prepanel function* for controlling the scaling and size of panels and a *strip function* for controlling what gets drawn in the strips of a lattice plot.

The following code provides a simple demonstration of the use of panel, prepanel and strip functions. The plot is a lattice multi-panel scatterplot with text labels added to the data points and a custom strip showing both levels of the conditioning variable with the relevant level bold and the other level grey (see Figure 4.9).

The panel function calls the default `panel.xyplot()` to draw data symbols, then calls `ltext()` to draw the labels. Because lattice is based on grid, traditional graphics functions will not work in a panel function (though see Appendix B for a way around this constraint). However, there are several lattice functions that correspond to traditional functions and can be used in much the same way as the corresponding traditional functions. The names of the lattice analogues are the traditional function names with an "`l`" prefix added. In this case, the code draws letters as the labels, using the `subscripts` argument to select an appropriate subset. The labels are drawn slightly to the left of and above the data symbols by subtracting 1 from the `x` values and adding 1 to the `y` values.

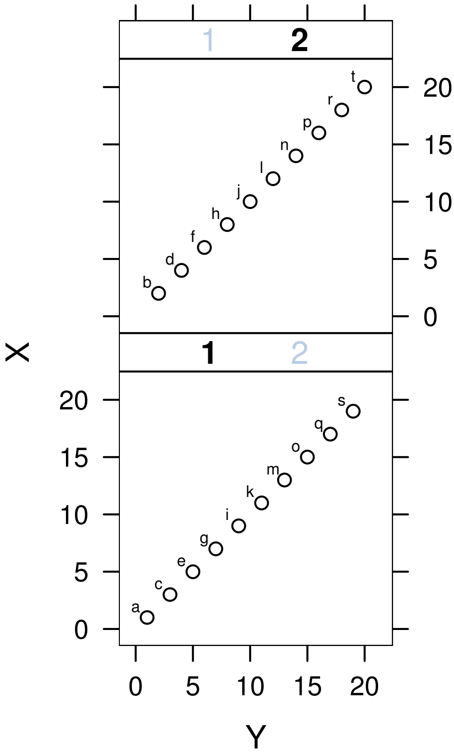

Figure 4.9
Annotating a lattice plot using panel and strip functions. The text labels have been added beside the data symbols using a custom panel function and the bold and grey numerals in the strips have been produced using a custom strip function.

```
> myPanel <- function(x, y, subscripts, ...) {
    panel.xyplot(x, y, ...)
    ltext(x - 1, y + 1, letters[subscripts], cex=0.5)
  }
```

The strip function also uses `ltext()`. Locations within the strip are based on a "normalized" coordinate system with the location `(0, 0)` at the bottom-left corner and `(1, 1)` at the top-right corner. The font face and color for the text is calculated using the `which.panel` argument. This supplies the current level for each conditioning variable in the panel.

```
> myStrip <- function(which.panel, ...) {
    font <- rep(1, 2)
    font[which.panel] <- 2
    col=rep("grey", 2)
    col[which.panel] <- "black"
    llines(c(0, 1, 1, 0, 0), c(0, 0, 1, 1, 0))
    ltext(c(0.33, 0.66), rep(0.5, 2), 1:2,
          font=font, col=col)
  }
```

The prepanel function calculates the limits of the scales for each panel by extending the range of data by 1 unit (this allows room for the text labels that are added in the panel function).

```
> myPrePanel <- function(x, y, ...) {
    list(xlim=c(min(x) - 1, max(x) + 1),
         ylim=c(min(y) - 1, max(y) + 1))
  }
```

We now generate some data to plot and create the plot using `xyplot()`, with the special panel functions provided as arguments. The final result is shown in Figure 4.9.

```
> X <- 1:20
> Y <- 1:20
> G <- factor(rep(1:2, 10))
```

```
> xyplot(X ~ Y | G, aspect=1, layout=c(1, 2),
         panel=myPanel, strip=myStrip,
         prepanel=myPrePanel)
```

A great deal more can be done with panel functions using grid concepts and functions. See Sections 5.8 and 6.7 for some examples.

4.5.2 Adding output to a lattice plot

Unlike in the original Trellis implementation, it is also possible to add output to a complete lattice plot (i.e., without using a panel function). The function `trellis.focus()` can be used to return to a particular panel or strip of the current lattice plot in order to add further output using, for example, `llines()` or `lpoints()`. The function `trellis.panelArgs()` may be useful for retrieving the arguments (including the data) used to originally draw the panel. Also, the `trellis.identify()` function provides basic mouse interaction for labelling data points within a panel. Again, Sections 5.8 and 6.7 show how grid provides more flexibility for navigating to different parts of a lattice plot and for adding further output.

4.6 Creating new lattice plots

The lattice plotting functions have many arguments and are very flexible in the variety of output that they can produce. However, lattice is not designed to be the best environment for developing new types of graphical display. For example, there is no mechanism for adding new graphical parameters to the list of values that control the appearance of plots (see Section 4.3).

Nevertheless, a lot can be done by defining a panel function that does not just add extra output to the default output, but replaces the default output with some sort of completely different display. For example, the lattice `dotplot()` function is really only a call to the `bwplot()` function with a different panel function supplied.

Users wanting to develop a new lattice plotting function along these lines are advised to read Chapter 5 to gain an understanding of the grid system that is used in the production of lattice output.

Chapter summary

The lattice package implements and extends the Trellis graphics system for producing complete statistical plots. This system provides most standard plot types and a number of modern plot types with several important extensions. For a start, the layout and appearance of the plots is designed to maximize readability and comprehension of the information represented in the plot. Also, the system provides a feature called multipanel conditioning, which produces multiple panels of plots from a single data set, where each panel contains a different subset of the data. The lattice functions provide an extensive set of arguments for customizing the detailed appearance of a plot and there are functions that allow the user to add further output to a plot.

5

The Grid Graphics Model

Chapter preview

> This chapter describes the fundamental tools that grid provides for drawing graphical scenes (including plots). There are basic features such as functions for drawing lines, rectangles, and text, together with more sophisticated and powerful concepts such as viewports, layouts, and units, which allow basic output to be located and sized in very flexible ways.
>
> This chapter is useful for drawing a wide variety of pictures, including statistical plots from scratch, and for adding output to lattice plots.

The functions that make up the grid graphics system are provided in an add-on package called `grid`. The grid system is loaded into R as follows.

```
> library(grid)
```

In addition to the standard on-line documentation available via the `help()` function, grid provides both broader and more in-depth on-line documentation in a series of vignettes, which are available via the `vignette()` function.

The grid graphics system only provides low-level graphics functions. There are no high-level functions for producing complete plots. Section 5.1 briefly introduces the concepts underlying the grid system, but this only provides an indication of how to work with grid and some of the things that are possible. An effective direct use of grid functions requires a deeper understanding of the grid system (see later sections of this chapter and Chapter 6).

The lattice package described in Chapter 4 provides a good demonstration of the high-level results that can be achieved using grid. Other examples in this book are Figure 1.7 in Chapter 1 and Figures 7.1 and 7.18 in Chapter 7.

5.1 A brief overview of grid graphics

This chapter describes how to use grid to produce graphical output. There are functions to produce basic output, such as lines and rectangles and text, and there are functions to establish the context for drawing, such as specifying where output should be placed and what colors and fonts to use for drawing.

Like the traditional system, all grid output occurs on the current device,* and later output obscures any earlier output that it overlaps (i.e.,output follows the "painters model"). In this way, images can be constructed incrementally using grid by calling functions in sequence to add more and more output.

There are grid functions to draw primitive graphical output such as lines, text, and polygons, plus some slightly higher-level graphical components such as axes (see Section 5.2). Complex graphical output is produced by making a sequence of calls to these primitive functions.

The colors, line types, fonts, and other aspects that affect the appearance of graphical output are controlled via a set of graphical parameters (see Section 5.4).

Grid provides no predefined regions for graphical output, but there is a powerful facility for defining regions, based on the idea of a *viewport* (see Section 5.5). It is quite simple to produce a set of regions that are convenient for producing a single plot (see the example in the next section), but it is also possible to produce very complex sets of regions such as those used in the production of Trellis plots (see Chapter 4).

All viewports have a large set of coordinate systems associated with them so that it is possible to position and size output in physical terms (e.g., in centimeters) as well as relative to the scales on axes, and in a variety of other ways (see Section 5.3).

All grid output occurs relative to the current viewport (region) on a page. In order to start a new page of output, the user must call the `grid.newpage()`

*See Section 1.3.1 for information on devices and selecting a current device when more than one device is open.

function. The function `grid.prompt()` controls whether the user is prompted when moving to a new page.

As well as the side effect of producing graphical output, grid graphics functions produce objects representing output. These objects can be saved to produce a persistent record of a plot, and other grid functions exist to modify these graphical objects (for example, it is possible to interactively edit a plot). It is also possible to work entirely with graphical descriptions, without producing any output. Functions for working with graphical objects are described in detail in Chapter 6.

5.1.1 A simple example

The following example demonstrates the construction of a simple scatterplot using grid. This is more work than a single function call to produce the plot, but it shows some of the advantages that can be gained by producing the plot using grid.

This example uses the `pressure` data to produce a scatterplot much like that in Figure 1.1.

Firstly, some regions are created that will correspond to the "plot region" (the area within which the data symbols will be drawn) and the "margins" (the area used to draw axes and labels).

The following code creates two viewports. The first viewport is a rectangular region that leaves space for 5 lines of text at the bottom, 4 lines of text at the left side, 2 lines at the top, and 2 lines to the right. The second viewport is in the same location as the first, but it has x- and y-scales corresponding to the range of the pressure data to be plotted.

```
> pushViewport(plotViewport(c(5, 4, 2, 2)))
> pushViewport(dataViewport(pressure$temperature,
                            pressure$pressure,
                            name="plotRegion"))
```

The following code draws the scatterplot one piece at a time. Grid output occurs relative to the most recent viewport, which in this case is the viewport with the appropriate axis scales. The data symbols are drawn relative to the x- and y-scales, a rectangle is drawn around the entire plot region, and x- and y-axes are drawn to represent the scales.

```
> grid.points(pressure$temperature, pressure$pressure,
              name="dataSymbols")
> grid.rect()
> grid.xaxis()
> grid.yaxis()
```

Adding labels to the axes demonstrates the use of the different coordinate systems available. The label text is drawn outside the edges of the plot region and is positioned in terms of a number of lines of text (i.e.,the height that a line of text would occupy).

```
> grid.text("temperature", y=unit(-3, "lines"))
> grid.text("pressure", x=unit(-3, "lines"), rot=90)
```

The obvious result of running the above code is the graphical output (see the top-left image in Figure 5.1). Less obvious is the fact that several objects have been created. There are objects representing the viewport regions and there are objects representing the graphical output. The following code makes use of this fact to modify the plotting symbol from a circle to a triangle (see the top-right image in Figure 5.1). The object representing the data symbols was named `"dataSymbols"` (see the code above) and this name is used to find that object and modify it using the `grid.edit()` function.

```
> grid.edit("dataSymbols", pch=2)
```

The next piece of code makes use of the objects representing the viewports. The `upViewport()` and `downViewport()` functions are used to navigate between the different viewport regions to perform some extra annotations. First of all, a call to the `upViewport()` function is used to go back to working within the entire device so that a dashed rectangle can be drawn around the complete plot. Next, the `downViewport()` function is used to return to the plot region to add a text annotation that is positioned relative to the scale on the axes of the plot (see bottom-right image in Figure 5.1).

```
> upViewport(2)
> grid.rect(gp=gpar(lty="dashed"))
> downViewport("plotRegion")
> grid.text("Pressure (mm Hg)\nversus\nTemperature (Celsius)",
            x=unit(150, "native"), y=unit(600, "native"))
```

The final scatterplot is still quite simple in this example, but the techniques that were used to produce it are very general and powerful. It is possible to

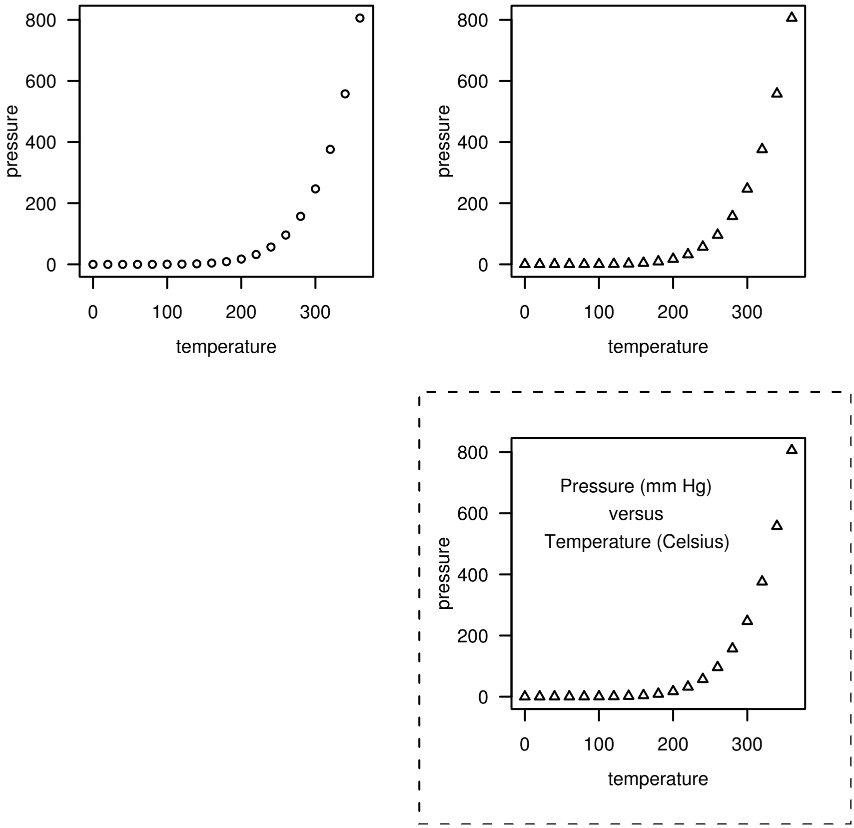

Figure 5.1
A simple scatterplot produced using grid. The top-left plot was constructed from a series of calls to primitive grid functions that produce graphical output. The top-right plot shows the result of calling the `grid.edit()` function to interactively modify the plotting symbol. The bottom-right plot was created by making calls to `upViewport()` and `downViewport()` to navigate between different drawing regions and adding further output (a dashed border and text within the plot).

produce a very complex plot, yet still have complete access to modify and add to any part of the plot.

In the remaining sections of this chapter, and in Chapter 6, the basic grid concepts of viewports and units are discussed in full detail. A complete understanding of the grid system will be useful in two ways: it will allow the user to produce very complex images from scratch (the issue of making them available to others is addressed in Chapter 7) and it will allow the user to work effectively with (e.g., modify and add to) complex grid output that is produced by other people's code (e.g. lattice plots).

5.2 Graphical primitives

The most simple grid functions to understand are those that draw something. There are a set of grid functions for producing basic graphical output such as lines, circles, and text.* Table 5.1 lists the full set of these functions.

The first arguments to most of these functions is a set of locations and dimensions for the graphical object to draw. For example, `grid.rect()` has arguments `x`, `y`, `width`, and `height` for specifying the locations and sizes of the rectangles to draw. An important exception is the `grid.text()` function, which requires the text to draw as its first argument.

In most cases, multiple locations and sizes can be specified and multiple primitives will be produced in response. For example, the following function call produces 100 circles because 100 locations and radii are specified (see Figure 5.2).

```
> grid.circle(x=seq(0.1, 0.9, length=100),
              y=0.5 + 0.4*sin(seq(0, 2*pi, length=100)),
              r=abs(0.1*cos(seq(0, 2*pi, length=100))))
```

The `grid.move.to()` and `grid.line.to()` functions are unusual in that they both only accept one location. These functions refer to and modify a "current location." The `grid.move.to()` function sets the current location and `grid.line.to()` draws from the current location to a new location, then sets

*All of these functions are of the form `grid.*()` and, for each one, there is a corresponding `*Grob()` function that creates an object containing a description of primitive graphical output, but does not draw anything. The `*Grob()` versions are addressed fully in Chapter 6.

Table 5.1
Graphical primitives in grid. This is the complete set of low-level functions that produce graphical output. For each function that produces graphical output (left-most column), there is a corresponding function that returns a graphical object containing a description of graphical output instead of producing graphical output (right-most column). The latter set of functions is described further in Chapter 6.

Function to Produce Output	Description	Function to Produce Object
`grid.move.to()`	Set the current location	`moveToGrob()`
`grid.line.to()`	Draw a line from the current location to a new location and reset the current location.	`lineToGrob()`
`grid.lines()`	Draw a single line through multiple locations in sequence.	`linesGrob()`
`grid.segments()`	Draw multiple lines between pairs of locations.	`segmentsGrob()`
`grid.rect()`	Draw rectangles given locations and sizes.	`rectGrob()`
`grid.circle()`	Draw circles given locations and radii.	`circleGrob()`
`grid.polygon()`	Draw polygons given vertexes.	`polygonGrob()`
`grid.text()`	Draw text given strings, locations and rotations.	`textGrob()`
`grid.arrows()`	Draw arrows at either end of lines given locations or an object describing lines.	`arrowsGrob()`
`grid.points()`	Draw data symbols given locations.	`pointsGrob()`
`grid.xaxis()`	Draw x-axis.	`xaxisGrob()`
`grid.yaxis()`	Draw y-axis.	`yaxisGrob()`

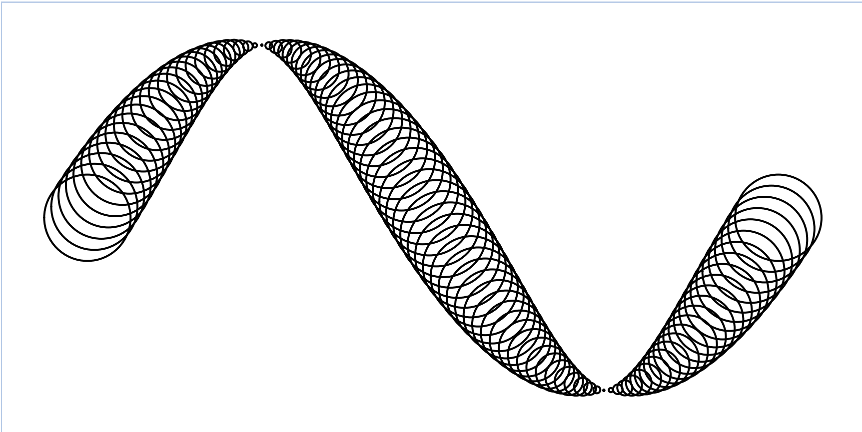

Figure 5.2
Primitive grid output. A demonstration of basic graphical output produced using a single call to the `grid.circle()` function. There are 100 circles of varying sizes, each at a different `(x, y)` location.

the current location to be the new location. The current location is not used by the other drawing functions*. In most cases, `grid.lines()` will be more convenient, but `grid.move.to()` and `grid.line.to()` are useful for drawing lines across multiple viewports (an example is given in Section 5.5.1).

The `grid.arrows()` function is used to add arrows to lines. A single line can be specified by `x` and `y` locations (through which a line will be drawn), *or* the `grob` argument can be used to specify an object that describes one or more lines (produced by `linesGrob()`, `segmentsGrob()`, or `lineToGrob()`). In the latter case, `grid.arrows()` will add arrows at the ends of the line(s). The following code demonstrates the different uses (see Figure 5.3). The first `grid.arrows()` call specifies locations via the `x` and `y` arguments to produce a single line, at the end of which an arrow is drawn. The second call specifies a `segments` graphical object via the `grob` argument, which describes three lines, and an arrow is added to the end of each of these lines.

```
> angle <- seq(0, 2*pi, length=50)
> grid.arrows(x=seq(0.1, 0.5, length=50),
              y=0.5 + 0.3*sin(angle))
> grid.arrows(grob=segmentsGrob(6:8/10, 0.2, 7:9/10, 0.8))
```

*There is one exception: the `grid.arrows()` function makes use of the current location when an arrow is added to a `line.to` graphical object produced by `lineToGrob()`.

Figure 5.3
Drawing arrows using the `grid.arrows()` function. Arrows can be added to: a single line through multiple points, as generated by `grid.lines()` (e.g., the sine curve in the left half of the figure); multiple straight line segments, as generated by `grid.segments()` (e.g., the three straight lines in the right half of the figure); the result of a line-to operation, as generated by `grid.line.to()` (example not shown here).

In simple usage, the `grid.polygon()` function draws a single polygon through the specified `x` and `y` locations (automatically joining the last location to the first to close the polygon). It is possible to produce multiple polygons from a single call (which is much faster than making multiple calls) if the `id` argument is specified. In this case, a polygon is drawn for each set of `x` and `y` locations corresponding to a different value of `id`. The following code demonstrates both usages (see Figure 5.4). The two `grid.polygon()` calls use the same `x` and `y` locations, but the second call splits the locations into three separate polygons using the `id` argument.

```
> angle <- seq(0, 2*pi, length=10)[-10]
> grid.polygon(x=0.25 + 0.15*cos(angle), y=0.5 + 0.3*sin(angle),
               gp=gpar(fill="grey"))
> grid.polygon(x=0.75 + 0.15*cos(angle), y=0.5 + 0.3*sin(angle),
               id=rep(1:3, each=3),
               gp=gpar(fill="grey"))
```

The `grid.xaxis()` and `grid.yaxis()` functions are not really graphical primitives as they produce relatively complex output consisting of both lines and text. They are included here because they complete the set of grid functions that produce graphical output. The main argument to these functions is the

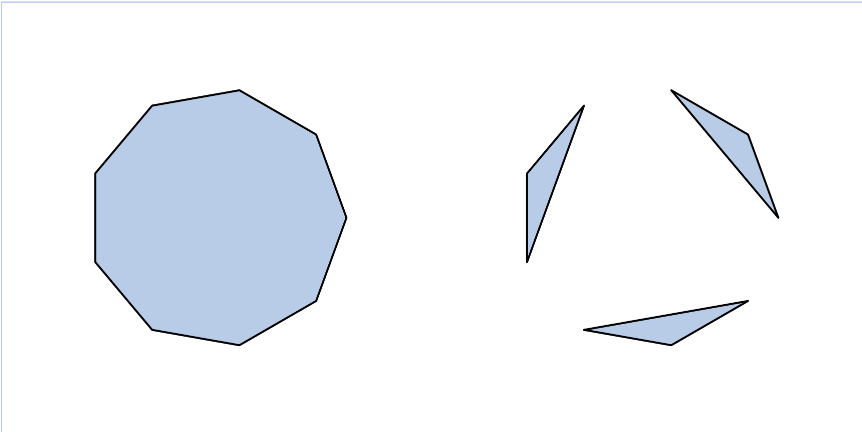

Figure 5.4
Drawing polygons using the `grid.polygon()` function. By default, a single polygon is produced from multiple `(x, y)` locations (the nonagon on the left), but it is possible to associate subsets of the locations with separate polygons using the `id` argument (the three triangles on the right).

`at` argument. This is used to specify where tick-marks should be placed. If the argument is not specified, sensible tick-marks are drawn based on the current scales in effect (see Section 5.5 for information about viewport scales). The values specified for the `at` argument are always relative to the current scales (see the concept of the `"native"` coordinate system in Section 5.3). These functions are much less flexible and general than the traditional `axis()` function. For example, they do not provide automatic support for generating labels from time- or date-based `at` locations.

Drawing curves

There is no native curve-drawing function in grid, but an approximation to a smooth curve consisting of many straight line segments is often sufficient. The example on the left of Figure 5.3 demonstrates how a series of line segments can appear very much like a smooth curve, if enough line segments are used.

5.2.1 Standard arguments

All primitive graphics functions accept a `gp` argument that allows control over aspects such as the color and line type of the relevant output. For example, the following code specifies that the boundary of the rectangle should be dashed and colored red.

```
> grid.rect(gp=gpar(col="red", lty="dashed"))
```

Section 5.4 provides more information about setting graphical parameters.

All primitive graphics functions also accept a `vp` argument that can be used to specify a viewport in which to draw the relevant output. The following code shows a simple example of the syntax (the result is a rectangle drawn in the left half of the page); Section 5.5 describes viewports and the use of `vp` arguments in full detail.

```
> grid.rect(vp=viewport(x=0, width=0.5, just="left"))
```

Finally, all primitive graphics functions also accept a `name` argument. This can be used to identify the graphical object produced by the function. It is useful for interactively editing graphical output and when working with graphical objects (see Chapter 6). The following code demonstrates how to associate a name with a rectangle.

```
> grid.rect(name="myrect")
```

5.3 Coordinate systems

When drawing in grid, there are always a large number of coordinate systems available for specifying the locations and sizes of graphical output. For example, it is possible to specify an `x` location as a proportion of the width of the drawing region, or as a number of inches (or centimeters, or millimeters) from the left-hand edge of the drawing region, or relative to the current x-scale. The full set of coordinate systems available is shown in Table 5.2. The meaning of some of these will only become clear with an understanding of viewports (Section 5.5) and graphical objects (Chapter 6).*

With so many coordinate systems available, it is necessary to specify which coordinate system a location or size refers to. The `unit()` function is used

*Absolute units, such as inches, may not be rendered with full accuracy on screen devices (see the footnote on page 100).

Table 5.2
The full set of coordinate systems available in grid.

Coordinate System Name	Description
`"native"`	Locations and sizes are relative to the x- and y-scales for the current viewport.
`"npc"`	Normalized Parent Coordinates. Treats the bottom-left corner of the current viewport as the location $(0, 0)$ and the top-right corner as $(1, 1)$.
`"snpc"`	Square Normalized Parent Coordinates. Locations and sizes are expressed as a proportion of the *smaller* of the width and height of the current viewport.
`"inches"`	Locations and sizes are in terms of physical inches. For locations, $(0, 0)$ is at the bottom-left of the viewport.
`"cm"`	Same as `"inches"`, except in centimeters.
`"mm"`	Millimeters.
`"points"`	Points. There are 72.27 points per inch.
`"bigpts"`	Big points. There are 72 big points per inch.
`"picas"`	Picas. There are 12 points per pica.
`"dida"`	Dida. 1157 dida equals 1238 points.
`"cicero"`	Cicero. There are 12 dida per cicero.
`"scaledpts"`	Scaled points. There are 65536 scaled points per point.
`"char"`	Locations and sizes are specified in terms of multiples of the current nominal font size (dependent on the current `fontsize` and `cex`).
`"lines"`	Locations and sizes are specified in terms of multiples of the height of a line of text (dependent on the current `fontsize`, `cex`, and `lineheight`).
`"strwidth"` `"strheight"`	Locations and sizes are expressed as multiples of the width (or height) of a given string (dependent on the string and the current `fontsize`, `cex`, `fontfamily`, and `fontface`).
`"grobwidth"` `"grobheight"`	Locations and sizes are expressed as multiples of the width (or height) of a given graphical object (dependent on the type, location, and graphical settings of the graphical object).

to associate a numeric value with a coordinate system. This function creates an object of class `"unit"` (hereafter referred to simply as a *unit*), which acts very much like a normal `numeric` object — it is possible to perform basic operations such as sub-setting units, and adding and subtracting units.

Each value in a unit can be associated with a different coordinate system and each location and dimension of a graphical object is a separate unit, so for example, a rectangle can have its x-location, y-location, width, and height all specified relative to different coordinate systems.

The following pieces of code demonstrate some of the flexibility of grid units. The first code examples show some different uses of the `unit()` function: a single value is associated with a coordinate system, then several values are associated with a coordinate system (notice the recycling of the coordinate system value), then several values are associated with different coordinate systems.

```
> unit(1, "mm")

[1] 1mm

> unit(1:4, "mm")

[1] 1mm 2mm 3mm 4mm

> unit(1:4, c("npc", "mm", "native", "lines"))

[1] 1npc    2mm     3native 4lines
```

The next code examples show how units can be manipulated in many of the ways that normal numeric vectors can: firstly by sub-setting, then simple addition (again notice the recycling), then finally the use of a summary function (`max()` in this case).

```
> unit(1:4, "mm")[2:3]

[1] 2mm 3mm

> unit(1, "npc") - unit(1:4, "mm")

[1] 1npc-1mm 1npc-2mm 1npc-3mm 1npc-4mm
```

```
> max(unit(1:4, c("npc", "mm", "native", "lines")))

[1] max(1npc, 2mm, 3native, 4lines)
```

Some operations on units are not as straightforward as with numeric vectors, but require the use of functions written specifically for units. For example, the length of units must be obtained using the `unit.length()` function rather than `length()`, units must be concatenated (in the sense of the `c()` function) using `unit.c()`, and there are special functions for repeating units and for calculating parallel maxima and minima (`unit.rep()`, `unit.pmin()`, and `unit.pmax()`).

The following code provides an example of using units to locate and size a rectangle. The rectangle is at a location 40% of the way across the drawing region and 1 inch from the bottom of the drawing region. It is as wide as the text `"very snug"`, and it is one line of text high (see Figure 5.5).

```
> grid.rect(x=unit(0.4, "npc"), y=unit(1, "inches"),
            width=stringWidth("very snug"),
            height=unit(1, "lines"),
            just=c("left", "bottom"))
```

5.3.1 Conversion functions

As demonstrated in the previous section, a unit is not simply a numeric value. Units only reduce to a simple numeric value (a physical location on a graphics device) when drawing occurs. A consequence of this is that a unit can mean very different things, depending on when it gets drawn (this should become more apparent with an understanding of graphical parameters in Section 5.4 and viewports in Section 5.5).

In some cases, it can be useful to convert a unit to a simple numeric value. For example, it is sometimes necessary to know the current scale limits for numerical calculations. There are several functions that can assist with this problem: `convertUnit()`, `convertX()`, `convertY()`, `convertWidth()`, and `convertHeight()`. The following code demonstrates how to calculate the current scale limits for the x-dimension. First of all, a scale is defined on the x-axis with the range `c(-10, 50)` (see Section 5.5 for more about viewports).

```
> pushViewport(viewport(xscale=c(-10, 50)))
```

The next expression performs a query to obtain the current x-axis scale. The expression `unit(0:1, "npc")` represents the left and right boundaries of the

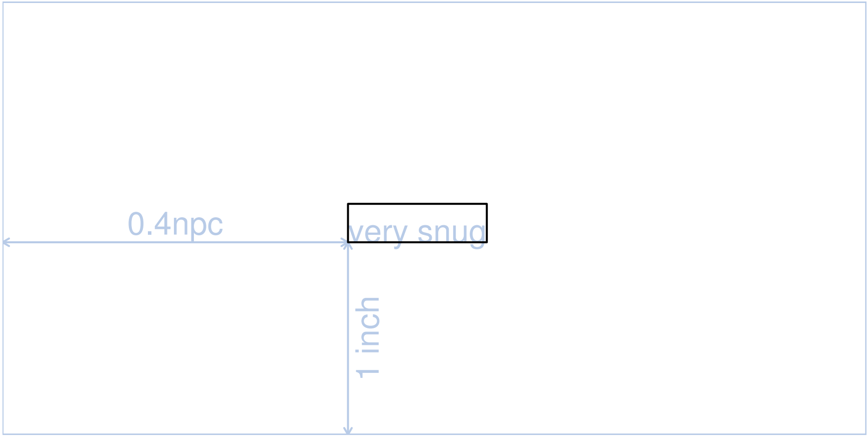

Figure 5.5
A demonstration of grid units. A diagram demonstrating how graphical output can be located and sized using grid units to associate numeric values with different coordinate systems. The grey border represents the current viewport. A black rectangle has been drawn with its bottom-left corner 40% of the way across the current viewport and 1 inch above the bottom of the current viewport. The rectangle is 1 line of text high and as wide as the text "very snug" (as it would be drawn in the current font).

current drawing region and `convertX()` is used to convert these locations into values in the `"native"` coordinate system, which is relative to the current scales.

```
> convertX(unit(0:1, "npc"), "native", valueOnly=TRUE)
```

```
[1] -10  50
```

WARNING: These conversion functions must be used with care. The output from these functions is only valid for the current device size. If, for example, a window on screen is resized, or output is copied from one device to another device with a different physical size, these calculations may no longer be correct. In other words, only rely on these functions when it is known that the size of the graphics device will not change. See Appendix B for more information on this topic and for a way to be able to use these functions on devices that may be resized. The discussion on the use of these functions in `drawDetails()` methods and the function `grid.record()` is also relevant (see "Calculations during drawing" in Section 7.3.10).

5.3.2 Complex units

There are two peculiarities of the "strwidth", "strheight", "grobwidth", and "grobheight" coordinate systems that require further explanation. In all of these cases, a value is interpreted as a multiple of the size of some other object. In the former two cases, the other object is just a text string (e.g., "a label"), but in the latter two cases, the other object can be any graphical object (see Chapter 6). It is necessary to specify the other object when generating a unit for these coordinate systems and this is achieved via the data argument. The following code shows some simple examples.

```
> unit(1, "strwidth", "some text")

[1] 1strwidth

> unit(1, "grobwidth", textGrob("some text"))

[1] 1grobwidth
```

A more convenient interface for generating units, when all values are relative to a single coordinate system, is also available via the stringWidth(), stringHeight(), grobWidth(), and grobHeight() functions. The following code is equivalent to the previous example.

```
> stringWidth("some text")

[1] 1strwidth

> grobWidth(textGrob("some text"))

[1] 1grobwidth
```

In this particular example, the "strwidth" and "grobwidth" units will be identical as they are based on identical pieces of text. The difference is that a graphical object can contain not only the text to draw, but other information that may affect the size of the text, such as the font family and size. In the following code, the two units are no longer identical because the text grob represents text drawn at font size of 18, whereas the simple string represents text at the default size of 10. The convertWidth() function is used to demonstrate the difference.

```
> convertWidth(stringWidth("some text"), "inches")
```

```
[1] 0.7175inches
```

```
> convertWidth(grobWidth(textGrob("some text",
                                   gp=gpar(fontsize=18))),
               "inches")
```

```
[1] 1.07625inches
```

For units that contain multiple values, there must be an object specified for every `"strwidth"`, `"strheight"`, `"grobwidth"`, and `"grobheight"` value. Where there is a mixture of coordinate systems within a unit, a value of `NULL` can be supplied for the coordinate systems that do not require data. The following code demonstrates this.

```
> unit(rep(1, 3), "strwidth", list("one", "two", "three"))
```

```
[1] 1strwidth 1strwidth 1strwidth
```

```
> unit(rep(1, 3),
       c("npc", "strwidth", "grobwidth"),
       list(NULL, "two", textGrob("three")))
```

```
[1] 1npc       1strwidth  1grobwidth
```

Again, there is a simpler interface for straightforward situations.

```
> stringWidth(c("one", "two", "three"))
```

```
[1] 1strwidth 1strwidth 1strwidth
```

For `"grobwidth"` and `"grobheight"` units, it is also possible to specify the name of a graphical object rather than the graphical object itself. This can be useful for establishing a reference to a graphical object, so that when the named graphical object is modified, the unit is updated for the change. The following code demonstrates this idea. First of all, a `text` grob is created with the name `"tgrob"`.

```
> grid.text("some text", name="tgrob")
```

Next, a unit is created that is based on the width of the grob called "tgrob".

```
> theUnit <- grobWidth("tgrob")
```

The convertWidth() function can be used to show the current value of the unit.

```
> convertWidth(theUnit, "inches")

[1] 0.7175inches
```

The following code modifies the grob named "tgrob" and convertWidth() is used to show that the value of the unit reflects the new width of the text grob.

```
> grid.edit("tgrob", gp=gpar(fontsize=18))
> convertWidth(theUnit, "inches")

[1] 1.07625inches
```

5.4 Controlling the appearance of output

All graphical primitives functions (and the viewport() function — see Section 5.5) — have a gp argument that can be used to provide a set of graphical parameters to control the appearance of the graphical output. There is a fixed set of graphical parameters (see Table 5.3), all of which can be specified for all types of graphical output.

The value supplied for the gp argument must be an object of class "gpar", and a gpar object can be produced using the gpar() function. For example, the following code produces a gpar object containing graphical parameter settings controlling color and line type.

```
> gpar(col="red", lty="dashed")

$col
[1] "red"

$lty
[1] "dashed"
```

Table 5.3
The full set of graphical parameters available in grid. The `lex` parameter has only been available since R version 2.1.0.

Parameter	Description
`col`	Color of lines, text, rectangle borders, ...
`fill`	Color for filling rectangles, circles, polygons, ...
`gamma`	Gamma correction for colors
`alpha`	Alpha blending coefficient for transparency
`lwd`	Line width
`lex`	Line width expansion multiplier applied to `lwd` to obtain final line width
`lty`	Line type
`lineend`	Line end style (round, butt, square)
`linejoin`	Line join style (round, mitre, bevel)
`linemitre`	Line mitre limit
`cex`	Character expansion multiplier applied to `fontsize` to obtain final font size
`fontsize`	Size of text (in points)
`fontface`	Font face (bold, italic, ...)
`fontfamily`	Font family
`lineheight`	Multiplier applied to final font size to obtain the height of a line

The function `get.gpar()` can be used to obtain current graphical parameter settings. The following code shows how to query the current line type and fill color. When called with no arguments, the function returns a complete list of current settings.

```
> get.gpar(c("lty", "fill"))
```

```
$lty
[1] "solid"

$fill
[1] "transparent"
```

A `gpar` object represents an *explicit graphical context* — settings for a small number of specific graphical parameters. The example above produces a graphical context that ensures that the color setting is `"red"` and the line-type setting is `"dashed"`. There is always an *implicit graphical context* consisting of default settings for all graphical parameters. The implicit graphical context is initialized automatically by grid for every graphics device and can be modified by viewports (see Section 5.5.5) or by gTrees (see Section 6.2.1).*

A graphical primitive will be drawn with graphical parameter settings taken from the implicit graphical context, except where there are explicit graphical parameter settings from the graphical primitive's `gp` argument. For graphical primitives, the explicit graphical context is only in effect for the duration of the drawing of the graphical primitive. The following code example demonstrates these rules.

The default initial implicit graphical context includes settings such as `lty="solid"` and `fill="transparent"`. The first (left-most) rectangle has an explicit setting `fill="black"` so it only uses the implicit setting `lty="solid"`. The second (right-most) rectangle uses all of the implicit graphical parameter settings. In particular, it is not at all affected by the explicit settings of the first rectangle (see Figure 5.6).

```
> grid.rect(x=0.33, height=0.7, width=0.2,
            gp=gpar(fill="black"))
> grid.rect(x=0.66, height=0.7, width=0.2)
```

*The ideas of implicit and explicit graphical contexts are similar to the specification of settings in Cascading Style Sheets[34] and the graphics state in PostScript[3].

Figure 5.6
Graphical parameters for graphical primitives. The grey rectangle represents the current viewport. The right-hand rectangle has been drawn with no specific graphical parameters so it inherits the defaults for the current viewport (which in this case are a black border and no fill color). The left-hand rectangle has been drawn with a specific fill color of black (it is still drawn with the inherited black border). The graphical parameter settings for one rectangle have no effect on the other rectangle.

5.4.1 Specifying graphical parameter settings

The values that can be specified for colors, line types, line widths, line ends, line joins, and fonts are mostly the same as for the traditional graphics system. Sections 3.2.1, 3.2.2, and 3.2.3 contain descriptions of these specifications (for example, see the sub-section "Specifying colors"). In many cases, the graphical parameter in grid also has the same name as the traditional graphics state setting (e.g., `col`), though several of the grid parameters are slightly more verbose (e.g. `lineend` and `fontfamily`). Some other differences in the specification of graphical parameter values in the grid graphics system are described below.

In grid, the `fontface` value can be a string instead of an integer. Table 5.4 shows the possible string values.

In grid, the `cex` value is cumulative. This means that it is multiplied by the previous `cex` value to obtain a current `cex` value. The following code shows a simple example. A viewport is pushed with `cex=0.5`. This means that text will be half size. Next, some text is drawn, also with `cex=0.5`. This text is drawn quarter size because `cex` was already `0.5` from the viewport (`0.5*0.5 = 0.25`).

Table 5.4
Possible font face specifications in grid.

Integer	String	Description
1	`"plain"`	Roman or upright face
2	`"bold"`	Bold face
3	`"italic"` or `"oblique"`	Slanted face
4	`"bold.italic"`	Bold and slanted face
For the HersheySerif font family		
5	`"cyrillic"`	Cyrillic font
6	`"cyrillic.oblique"`	Slanted Cyrillic font
7	`"EUC"`	Japanese characters

```
> pushViewport(viewport(gp=gpar(cex=0.5)))
> grid.text("How small do you think?", gp=gpar(cex=0.5))
```

The `alpha` graphical parameter setting is unique to grid. It is a value between 1 (fully opaque) and 0 (fully transparent). The `alpha` value is combined with the alpha channel of colors by multiplying the two and this setting is cumulative like the `cex` setting. The following code shows a simple example. A viewport is pushed with `alpha=0.5`, then a rectangle is drawn using a semitransparent red fill color (alpha channel set to `0.5`). The final alpha channel for the fill color is `0.25` (`0.5*0.5 = 0.25`).

```
> pushViewport(viewport(gp=gpar(alpha=0.5)))
> grid.rect(width=0.5, height=0.5,
            gp=gpar(fill=rgb(1, 0, 0, 0.5)))
```

Grid does not support fill patterns (see page 58).

5.4.2 Vectorized graphical parameter settings

All graphical parameter settings may be vector values. Many graphical primitive functions produce multiple primitives as output and graphical parameter settings will be recycled over those primitives. The following code produces 100 circles, cycling through 50 different shades of grey for the circles (see Figure 5.7).

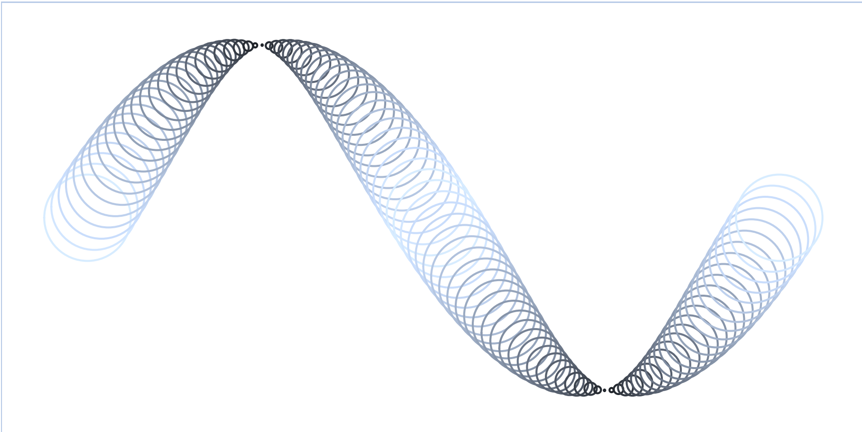

Figure 5.7
Recycling graphical parameters. The 100 circles are drawn by a single function call with 50 different greys specified for the border color (from a very light grey to a very dark grey and back to a very light grey). The 50 colors are recycled over the 100 circles so circle i gets the same color as circle $i + 50$.

```
> levels <- round(seq(90, 10, length=25))
> greys <- paste("grey", c(levels, rev(levels)), sep="")
> grid.circle(x=seq(0.1, 0.9, length=100),
              y=0.5 + 0.4*sin(seq(0, 2*pi, length=100)),
              r=abs(0.1*cos(seq(0, 2*pi, length=100))),
              gp=gpar(col=greys))
```

The `grid.polygon()` function is a slightly complex case. There are two ways in which this function will produce multiple polygons: when the `id` argument is specified *and* when there are `NA` values in the `x` or `y` locations (see Section 5.6). For `grid.polygon()`, a different graphical parameter will only be applied to each polygon identified by a different `id`. When a single polygon (as identified by a single `id` value) is split into multiple sub-polygons by `NA` values, all sub-polygons receive the same graphical parameter settings. The following code demonstrates these rules (see Figure 5.8). The first call to `grid.polygon()` draws two polygons as specified by the `id` argument. The `fill` graphical parameter setting contains two colors so the first polygon gets the first color (grey) and the second polygon gets the second color (white). In the second call, all that has changed is that an `NA` value has been introduced. This means that the first polygon as specified by the `id` argument is split into two separate polygons, but both of these polygons use the same `fill` setting because they both correspond to an `id` of `1`. Both of these polygons get the first color (grey).

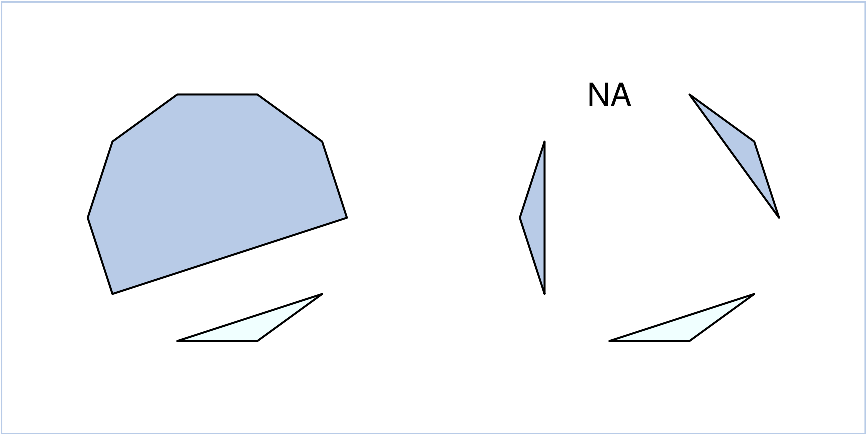

Figure 5.8
Recycling graphical parameters for polygons. On the left, a single function call produces two polygons with different fill colors by specifying an `id` argument and two fill colors. On the right, there are three polygons because an `NA value` has been introduced in the `(x, y)` locations for the polygon, but there are still only two colors specified. The colors are allocated to polygons using the `id` argument and ignoring any `NA` values.

```
> angle <- seq(0, 2*pi, length=11)[-11]
> grid.polygon(x=0.25 + 0.15*cos(angle), y=0.5 + 0.3*sin(angle),
               id=rep(1:2, c(7, 3)),
               gp=gpar(fill=c("grey", "white")))
> angle[4] <- NA
> grid.polygon(x=0.75 + 0.15*cos(angle), y=0.5 + 0.3*sin(angle),
               id=rep(1:2, c(7, 3)),
               gp=gpar(fill=c("grey", "white")))
```

All graphical primitives have a `gp` component, so it is possible to specify any graphical parameter setting for any graphical primitive. This may seem inefficient, and indeed in some cases the values are completely ignored (e.g., text drawing ignores the `lty` setting), but in many cases the values are potentially useful. For example, even when there is no text being drawn, the settings for `fontsize`, `cex`, and `lineheight` are always used to calculate the meaning of `"lines"` and `"char"` coordinates.

5.5 Viewports

A *viewport* is a rectangular region that provides a context for drawing.

A viewport provides a *drawing context* consisting of both a *geometric context* and a *graphical context*. A geometric context consists of a set of coordinate systems for locating and sizing output and all of the coordinate systems described in Section 5.3 are available within every viewport.* A graphical context consists of explicit graphical parameter settings for controlling the appearance of output. This is specified as a `gpar` object via the `gp` argument.

By default, grid creates a viewport that corresponds to the entire graphics device and, until another viewport is created, drawing occurs within the full extent of the device and using the default graphical parameter settings.

A new viewport is created using the `viewport()` function. A viewport has a location (given by `x` and `y`), a size (given by `width` and `height`), and it is justified relative to its location (according to the value of the `just` argument). The location and size of a viewport are specified in units, so a viewport can be positioned and sized within another viewport in a very flexible manner. The following code creates a viewport that is left-justified at an `x` location 0.4 of the way across the drawing region, and bottom-justified 1 centimeter from the bottom of the drawing region. It is as wide as the text `"very very snug indeed"`, and it is six lines of text high. Figure 5.9 shows a diagram representing this viewport.

```
> viewport(x=unit(0.4, "npc"), y=unit(1, "cm"),
           width=stringWidth("very very snug indeed"),
           height=unit(6, "lines"),
           just=c("left", "bottom"))
```

```
viewport[GRID.VP.33]
```

An important thing to notice in the above example is that the result of the `viewport()` function is an object of class `viewport`. No region has actually been created on a graphics device. In order to create regions on a graphics device, a `viewport` object must be *pushed* onto the device, as described in the next section.

*The idea of being able to define a geometric context is similar to the concept of the current transformation matrix (CTM) in PostScript[3] and the modeling transformation in OpenGL[55].

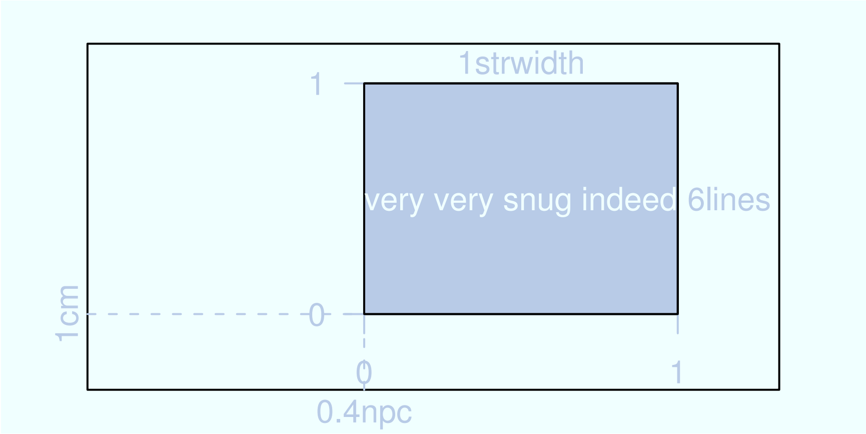

Figure 5.9
A diagram of a simple viewport. A viewport is a rectangular region specified by an `(x, y)` location, a `(width, height)` size, and a justification (and possibly a rotation). This diagram shows a viewport that is left-bottom justified 1 centimeter off the bottom of the page and 0.4 of the way across the page. It is 6 lines of text high and as wide as the text "very very snug indeed".

5.5.1 Pushing, popping, and navigating between viewports

The `pushViewport()` function takes a `viewport` object and uses it to create a region on the graphics device. This region becomes the drawing context for all subsequent graphical output, until the region is removed or another region is defined.

The following code demonstrates this idea (see Figure 5.10). To start with, the entire device, and the default graphical parameter settings, provide the drawing context. Within this context, the `grid.text()` call draws some text at the top-left corner of the device. A viewport is then pushed, which creates a region 80% as wide as the device, half the height of the device, and rotated at an angle of 10 degrees*. The viewport is given a name, `"vp1"`, which will help us to navigate back to this viewport from another viewport later.

Within the new drawing context defined by the viewport that has been pushed, *exactly the same* `grid.text()` call produces some text at the top-left corner of the viewport. A rectangle is also drawn to make the extent of the new viewport clear.

*It is not often very useful to rotate a viewport, but it helps in this case to dramatise the difference between the drawing regions.

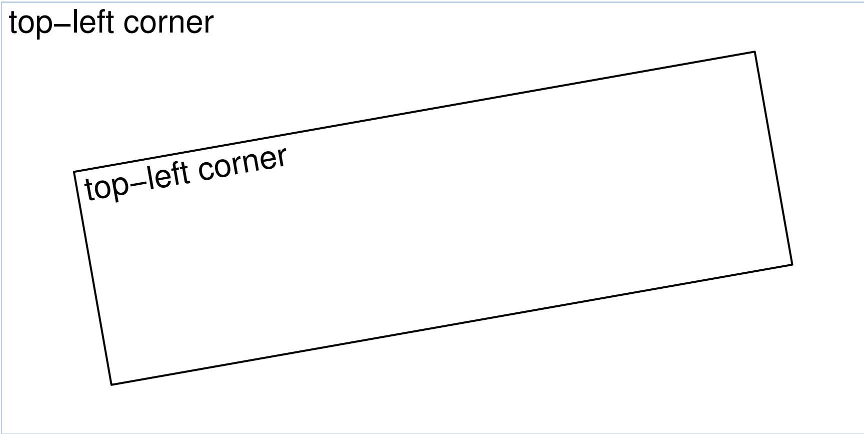

Figure 5.10
Pushing a viewport. Drawing occurs relative to the entire device until a viewport is pushed. For example, some text has been drawn in the top-left corner of the device. Once a viewport has been pushed, output is drawn relative to that viewport. The black rectangle represents a viewport that has been pushed and text has been drawn in the top-left corner of that viewport.

```
> grid.text("top-left corner", x=unit(1, "mm"),
            y=unit(1, "npc") - unit(1, "mm"),
            just=c("left", "top"))
> pushViewport(viewport(width=0.8, height=0.5, angle=10,
               name="vp1"))
> grid.rect()
> grid.text("top-left corner", x=unit(1, "mm"),
            y=unit(1, "npc") - unit(1, "mm"),
            just=c("left", "top"))
```

The pushing of viewports is entirely general. A viewport is pushed relative to the current drawing context. The following code slightly extends the previous example by pushing a further viewport, exactly like the first, and again drawing text at the top-left corner (see Figure 5.11). The location, size, and rotation of this second viewport are all relative to the context provided by the first viewport. Viewports can be nested like this to any depth.

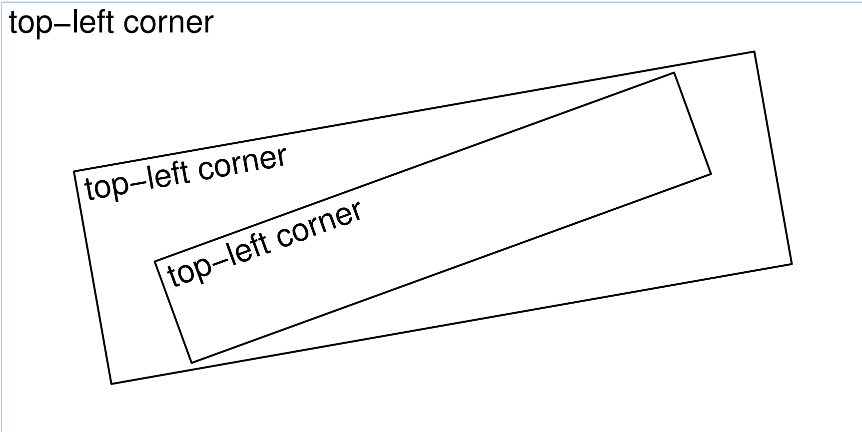

Figure 5.11
Pushing several viewports. Viewports are pushed relative to the current viewport. Here, a second viewport has been pushed relative to the viewport that was pushed in Figure 5.10. Again, text has been drawn in the top-left corner.

```
> pushViewport(viewport(width=0.8, height=0.5, angle=10,
                        name="vp2"))
> grid.rect()
> grid.text("top-left corner", x=unit(1, "mm"),
            y=unit(1, "npc") - unit(1, "mm"),
            just=c("left", "top"))
```

In grid, drawing is always within the context of the current viewport. One way to change the current viewport is to push a viewport (as in the previous examples), but there are other ways too. For a start, it is possible to *pop* a viewport using the `popViewport()` function. This removes the current viewport and the drawing context reverts to whatever it was before the current viewport was pushed*. The following code demonstrates popping viewports (see Figure 5.12). The call to `popViewport()` removes the last viewport created on the device. Text is drawn at the bottom-right of the resulting drawing region (which has reverted back to being the first viewport that was pushed).

```
> popViewport()
> grid.text("bottom-right corner",
            x=unit(1, "npc") - unit(1, "mm"),
            y=unit(1, "mm"), just=c("right", "bottom"))
```

*It is illegal to pop the top-most viewport that represents the entire device region and the default graphical parameter settings. Trying to do so will result in an error.

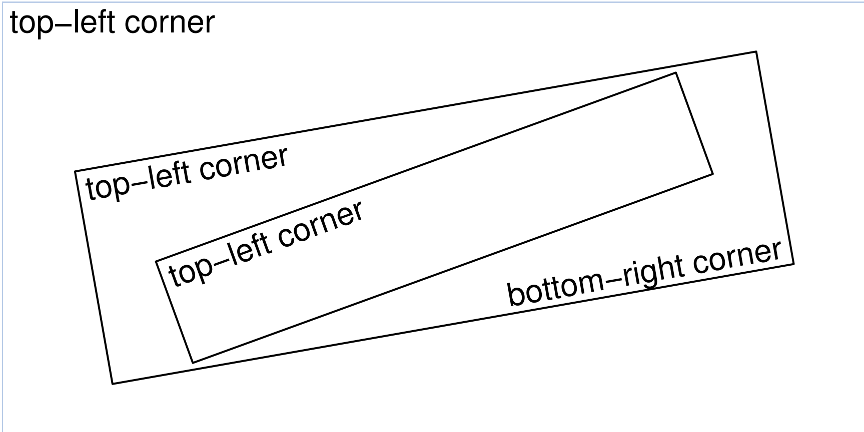

Figure 5.12
Popping a viewport. When a viewport is popped, the drawing context reverts to the parent viewport. In this figure, the second viewport (pushed in Figure 5.11) has been popped to go back to the first viewport (pushed in Figure 5.10). This time text has been drawn in the bottom-right corner.

The `popViewport()` function has an integer argument `n` that specifies how many viewports to pop. The default is `1`, but several viewports can be popped at once by specifying a larger value. The special value of `0` means that all viewports should be popped. In other words, the drawing context should revert to the entire device and the default graphical parameter settings.

Another way to change the current viewport is by using the `upViewport()` and `downViewport()` functions. The `upViewport()` function is similar to `popViewport()` in that the drawing context reverts to whatever it was prior to the current viewport being pushed. The difference is that `upViewport()` does not remove the current viewport from the device. This difference is significant because it means that that a viewport can be revisited without having to push it again. Revisiting a viewport is faster than pushing a viewport and it allows the creation of viewport regions to be separated from the production of output (see "viewport paths" in Section 5.5.3 and Chapter 7).

A viewport can be revisited using the `downViewport()` function. This function has an argument `name` that can be used to specify the name of an existing viewport. The result of `downViewport()` is to make the named viewport the current drawing context. The following code demonstrates the use of `upViewport()` and `downViewport()` (see Figure 5.13).

A call to `upViewport()` is made, which reverts the drawing context to the entire device (recall that prior to this navigation the current viewport was the first viewport that was pushed) and text is drawn in the bottom-right

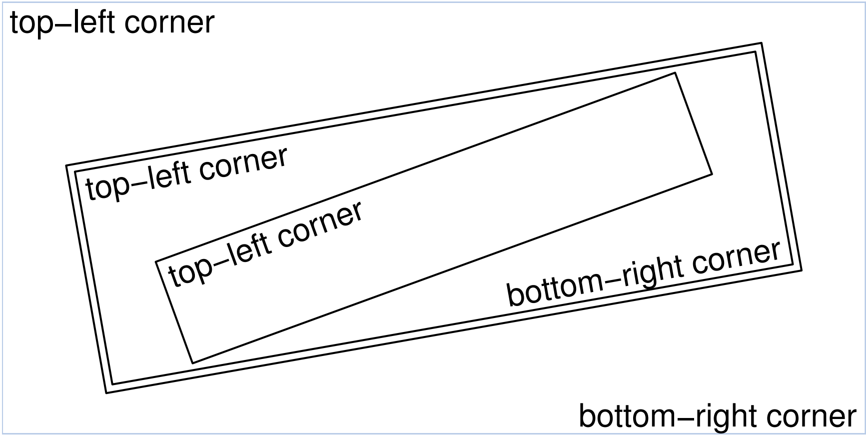

Figure 5.13
Navigating between viewports. Rather than popping a viewport, it is possible to navigate up from a viewport (and leave the viewport on the device). Here navigation has occurred from the first viewport to revert the drawing context to the entire device and text has been drawn in the bottom-right corner. Next, there has been a navigation down to the first viewport again and a second border has been drawn around the outside of the viewport.

corner. The `downViewport()` function is then used to navigate back down to the viewport that was first pushed and a second border is drawn around this viewport. The viewport to navigate down to is specified by its name, `"vp1"`.

```
> upViewport()
> grid.text("bottom-right corner",
            x=unit(1, "npc") - unit(1, "mm"),
            y=unit(1, "mm"), just=c("right", "bottom"))
> downViewport("vp1")
> grid.rect(width=unit(1, "npc") + unit(2, "mm"),
            height=unit(1, "npc") + unit(2, "mm"))
```

There is also a `seekViewport()` function that can be used to travel across the viewport tree. This can be convenient for interactive use, but the result is less predictable, so it is less suitable for use in writing grid functions for others to use. The call `seekViewport("avp")` is equivalent to `upViewport(0); downViewport("avp")`.

Drawing between viewports

Sometimes it is useful to be able to locate graphical output relative to more than one viewport. The only way to do this in grid is via the `grid.move.to()` and `grid.line.to()` functions. It is possible to call `grid.move.to()` within one viewport, change viewports, and call `grid.line.to()`. An example is provided in Section 5.8.2.

5.5.2 Clipping to viewports

Drawing can be restricted to only the interior of the current viewport (*clipped* to the viewport) by specifying the `clip` argument to the `viewport()` function. This argument has three values: `"on"` indicates that output should be clipped to the current viewport; `"off"` indicates that output should not be clipped at all; `"inherit"` means that the clipping region of the previous viewport should be used (this may not have been set by the previous viewport if that viewport's `clip` argument was also `"inherit"`). The following code provides a simple example (see Figure 5.14). A viewport is pushed with clipping on and a circle with a very thick black border is drawn relative to the viewport. A rectangle is also drawn to show the extent of the viewport. The circle partially extends beyond the limits of the viewport, so only those parts of the circle that lie within the viewport are drawn.

```
> pushViewport(viewport(w=.5, h=.5, clip="on"))
> grid.rect()
> grid.circle(r=.7, gp=gpar(lwd=20))
```

Next, another viewport is pushed and this viewport just inherits the clipping region from the first viewport. Another circle is drawn, this time with a grey and slightly thinner border and again the circle is clipped to the viewport.

```
> pushViewport(viewport(clip="inherit"))
> grid.circle(r=.7, gp=gpar(lwd=10, col="grey"))
```

Finally, a third viewport is pushed with clipping turned off. Now, when a third circle is drawn (with a thin, black border) all of the circle is drawn, even though parts of the circle extend beyond the viewport.

```
> pushViewport(viewport(clip="off"))
> grid.circle(r=.7)
> popViewport(3)
```

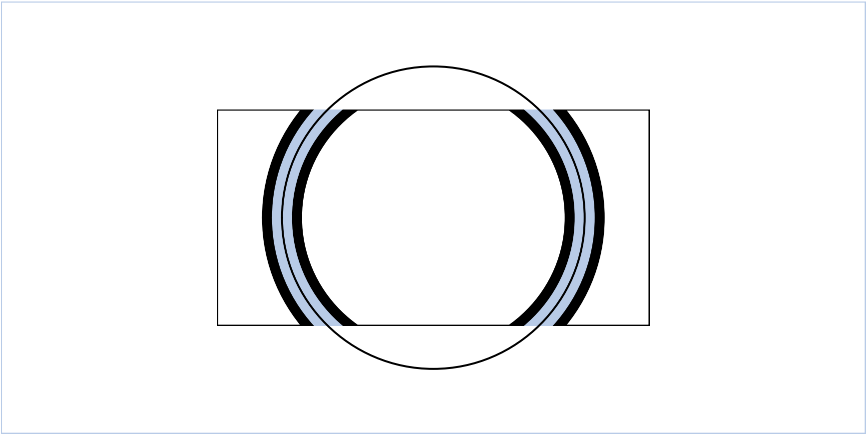

Figure 5.14
Clipping output in viewports. When a viewport is pushed, output can be clipped to that viewport, or the clipping region can be left in its current state, or clipping can be turned off entirely. In this figure, a viewport is pushed (the black rectangle) with clipping on. A circle is drawn with a very thick black border and it gets clipped. Next, another viewport is pushed (in the same location) with clipping left as it was. A second circle is drawn with a slightly thinner grey border and it is also clipped. Finally, a third viewport is pushed, which turns clipping off. A circle is drawn with a thin black border and this circle is not clipped.

5.5.3 Viewport lists, stacks, and trees

It can be convenient to work with several viewports at once and there are several facilities for doing this in grid. The `pushViewport()` function will accept multiple arguments and will push the specified viewports one after another. For example, the fourth expression below is a shorter equivalent version of the first three expressions.

```
> pushViewport(vp1)
> pushViewport(vp2)
> pushViewport(vp3)
```

```
> pushViewport(vp1, vp2, vp3)
```

The `pushViewport()` function will also accept objects that contain several viewports: viewport lists, viewport stacks, and viewport trees. The function `vpList()` creates a list of viewports and these are pushed "in parallel." The first viewport in the list is pushed, then grid navigates back up before the next viewport in the list is pushed. The `vpStack()` function creates a stack of viewports and these are pushed "in series." Pushing a stack of viewports is exactly the same as specifying the viewports as multiple arguments to `pushViewport()`. The `vpTree()` function creates a tree of viewports that consists of a parent viewport and any number of child viewports. The parent viewport is pushed first, then the child viewports are pushed in parallel within the parent.

The current set of viewports that have been pushed on the current device constitute a viewport tree and the `current.vpTree()` function prints out a representation of the current viewport tree. The following code demonstrates the output from `current.vpTree()` and the difference between lists, stacks, and trees of viewports. First of all, some (trivial) viewports are created to work with.

```
> vp1 <- viewport(name="A")
> vp2 <- viewport(name="B")
> vp3 <- viewport(name="C")
```

The next piece of code shows these three viewports pushed as a list. The output of `current.vpTree()` shows the root viewport (which represents the entire device) and then all three viewports as children of the root viewport.

```
> pushViewport(vpList(vp1, vp2, vp3))
> current.vpTree()
```

```
viewport[ROOT]->(viewport[A], viewport[B], viewport[C])
```

This next code pushes the three viewports as a stack. The viewport `vp1` is now the only child of the root viewport with `vp2` a child of `vp1`, and `vp3` a child of `vp2`.

```
> grid.newpage()
> pushViewport(vpStack(vp1, vp2, vp3))
> current.vpTree()
```

```
viewport[ROOT]->(viewport[A]->(viewport[B]->(viewport[C])))
```

Finally, the three viewports are pushed as a tree, with `vp1` as the parent and `vp2` and `vp3` as its children.

```
> grid.newpage()
> pushViewport(vpTree(vp1, vpList(vp2, vp3)))
> current.vpTree()
```

```
viewport[ROOT]->(viewport[A]->(viewport[B], viewport[C]))
```

As with single viewports, viewport lists, stacks, and trees can be provided as the `vp` argument for graphical functions (see Section 5.5.4).

Viewport paths

The `downViewport()` function, by default, searches down the current viewport tree as far as is necessary to find a given viewport name. This is convenient for interactive use, but can be ambiguous if there is more than one viewport with the same name in the viewport tree.

Grid provides the concept of a *viewport path* to resolve such ambiguity. A viewport path is an ordered list of viewport names, which specify a series of parent-child relations. A viewport path is created using the `vpPath()` function. For example, the following code produces a viewport path that specifies a viewport called `"C"` with a parent called `"B"`, which in turn has a parent called `"A"`.

```
> vpPath("A", "B", "C")
```

```
A::B::C
```

For convenience in interactive use, a viewport path may be specified directly as a string. For example, the previous viewport path could be specified simply as `"A::B::C"`. The `vpPath()` function should be used when writing graphics functions for others to use.

The `name` argument to the `downViewport()` function will accept a viewport path, in which case it searches for a viewport that matches the entire path. The `strict` argument to `downViewport()` ensures that a viewport will only be found if the full viewport path is found, *starting from the current location in the viewport tree.*

5.5.4 Viewports as arguments to graphical primitives

As mentioned in Section 5.2.1, a viewport may be specified as an argument to functions that produce graphical output (via an argument called `vp`). When a viewport is specified in this way, the viewport gets pushed before the graphical output is produced and popped afterwards. To make this completely clear, the following two code segments are identical. First of all, a simple viewport is defined.

```
> vp1 <- viewport(width=0.5, height=0.5, name="vp1")
```

The next code explicitly pushes the viewport, draws some text, then pops the viewport.

```
> pushViewport(vp1)
> grid.text("Text drawn in a viewport")
> popViewport()
```

This next piece of code does the same thing in a single call.

```
> grid.text("Text drawn in a viewport", vp=vp1)
```

It is also possible to specify the name of a viewport (or a viewport path) for a `vp` argument. In this case, the name (or path) is used to navigate down to the viewport (via a call to `downViewport()`) and then back up again afterwards (via a call to `upViewport()`). This promotes the practice of pushing viewports once, then specifying where to draw different output by simply naming the appropriate viewport. The following code does the same thing as the previous example, but leaves the viewport intact (so that it can be used for further drawing).

```
> pushViewport(vp1)
> upViewport()
> grid.text("Text drawn in a viewport", vp="vp1")
```

This feature is also very useful when annotating a plot produced by a high-level graphics function. As long as the graphics function names the viewports that it creates and does not pop them, it is possible to revisit the viewports to add further output. Examples of this are given in Section 5.8 and this approach to writing high-level grid functions is discussed further in Chapter 7.

5.5.5 Graphical parameter settings in viewports

A viewport can have graphical parameter settings associated with it via the `gp` argument to `viewport()`. When a viewport has graphical parameter settings, those settings affect all graphical objects drawn within the viewport, and all other viewports pushed within the viewport, unless the graphical objects or the other viewports specify their own graphical parameter setting. In other words, the graphical parameter settings for a viewport modify the implicit graphical context (see page 168).

The following code demonstrates this rule. A viewport is pushed that has a `fill="grey"` setting. A rectangle with no graphical parameter settings is drawn within that viewport and this rectangle "inherits" the `fill="grey"` setting. Another rectangle is drawn with its own `fill` setting so it does not inherit the viewport setting (see Figure 5.15).

```
> pushViewport(viewport(gp=gpar(fill="grey")))
> grid.rect(x=0.33, height=0.7, width=0.2)
> grid.rect(x=0.66, height=0.7, width=0.2,
            gp=gpar(fill="black"))
> popViewport()
```

The graphical parameter settings in a viewport only affect other viewports and graphical output within that viewport. The settings do not affect the viewport itself. For example, parameters controlling the size of text (`fontsize`, `cex`, etc.) do not affect the meaning of `"lines"` units when determining the location and size of the viewport (but they will affect the location and size of other viewports or graphical output within the viewport). A layout (see Section 5.5.6) counts as being within the viewport (i.e., it is affected by the graphical parameter settings of the viewport).

If there are multiple values for a graphical parameter setting, only the first is used when determining the location and size of a viewport.

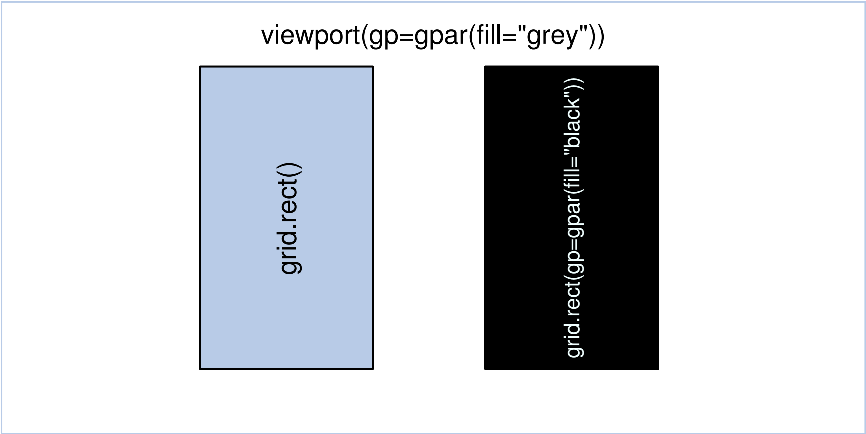

Figure 5.15
The inheritance of viewport graphical parameters. A diagram demonstrating how viewport graphical parameter settings are inherited by graphical output within the viewport. The viewport sets the default fill color to grey. The left-hand rectangle specifies no fill color itself so it is filled with grey. The right-hand rectangle specifies a black fill color that overrides the viewport setting.

5.5.6 Layouts

A viewport can have a *layout* specified via the `layout` argument. A layout in grid is similar to the same concept in traditional graphics (see Section 3.3.2). It divides the viewport region into several columns and rows, where each column can have a different width and each row can have a different height. For several reasons, however, layouts are much more flexible in grid: there are many more coordinate systems for specifying the widths of columns and the heights of rows (see Section 5.3); viewports can occupy overlapping areas within the layout; and each viewport within the viewport tree can have a layout (layouts can be nested). There is also a `just` argument to justify the layout within a viewport when the layout does not occupy the entire viewport region.

Layouts provide a convenient way to position viewports using the standard set of coordinate systems, and provide an extra coordinate system, `"null"`, which is specific to layouts.

The basic idea is that a viewport can be created with a layout and then subsequent viewports can be positioned relative to that layout. In simple cases, this can be just a convenient way to position viewports in a regular grid, but in more complex cases, layouts are the only way to apportion regions. There are very many ways that layouts can be used in grid; the following sections attempt to provide a glimpse of the possibilities by demonstrating a series of example uses.

A grid layout is created using the function `grid.layout()` (*not* the traditional function `layout()`).

A simple layout

The following code produces a simple layout with three columns and three rows, where the central cell (row two, column two) is forced to always be square (using the `respect` argument).

```
> vplay <- grid.layout(3, 3,
                       respect=rbind(c(0, 0, 0),
                                     c(0, 1, 0),
                                     c(0, 0, 0)))
```

The next piece of code uses this layout in a viewport. Any subsequent viewports may make use of the layout, or they can ignore it completely.

```
> pushViewport(viewport(layout=vplay))
```

In the next piece of code, two further viewports are pushed within the viewport with the layout. The `layout.pos.col` and `layout.pos.row` arguments are used to specify which cells within the layout each viewport should occupy. The first viewport occupies all of column two and the second viewport occupies all of row 2. This demonstrates that viewports can occupy overlapping regions within a layout. A rectangle has been drawn within each viewport to show the region that the viewport occupies (see Figure 5.16).

```
> pushViewport(viewport(layout.pos.col=2, name="col2"))
> upViewport()
> pushViewport(viewport(layout.pos.row=2, name="row2"))
```

A layout with units

This section describes a layout that makes use of grid units. In the context of specifying the widths of columns and the heights of rows for a layout, there is an additional unit available, the `"null"` unit. All other units (`"cm"`, `"npc"`, etc.) are allocated first within a layout, then the `"null"` units are used to divide the remaining space proportionally (see Section 3.3.2). The following

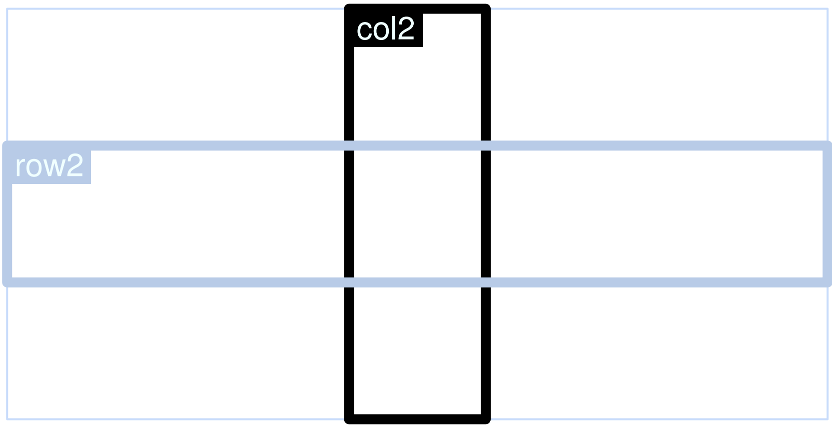

Figure 5.16
Layouts and viewports. Two viewports occupying overlapping regions within a layout. Each viewport is represented by a rectangle with the viewport name at the top-left corner. The layout has three columns and three rows with one viewport occupying all of row 2 and the other viewport occupying all of column 2.

code creates a layout with three columns and three rows. The left column is one inch wide and the top row is three lines of text high. The remainder of the current region is divided into two rows of equal height and two columns with the right column twice as wide as the left column (see Figure 5.17).

```
> unitlay <-
    grid.layout(3, 3,
                widths=unit(c(1, 1, 2),
                            c("inches", "null", "null")),
                heights=unit(c(3, 1, 1),
                             c("lines", "null", "null")))
```

With the use of `"strwidth"` and `"grobwidth"` units it is possible to produce columns that are just wide enough to fit graphical output that will be drawn in the column (and similarly for row heights — see Section 6.4).

A nested layout

This section demonstrates the nesting of layouts. The following code defines a function that includes a trivial use of a layout consisting of two equal-width columns to produce grid output.

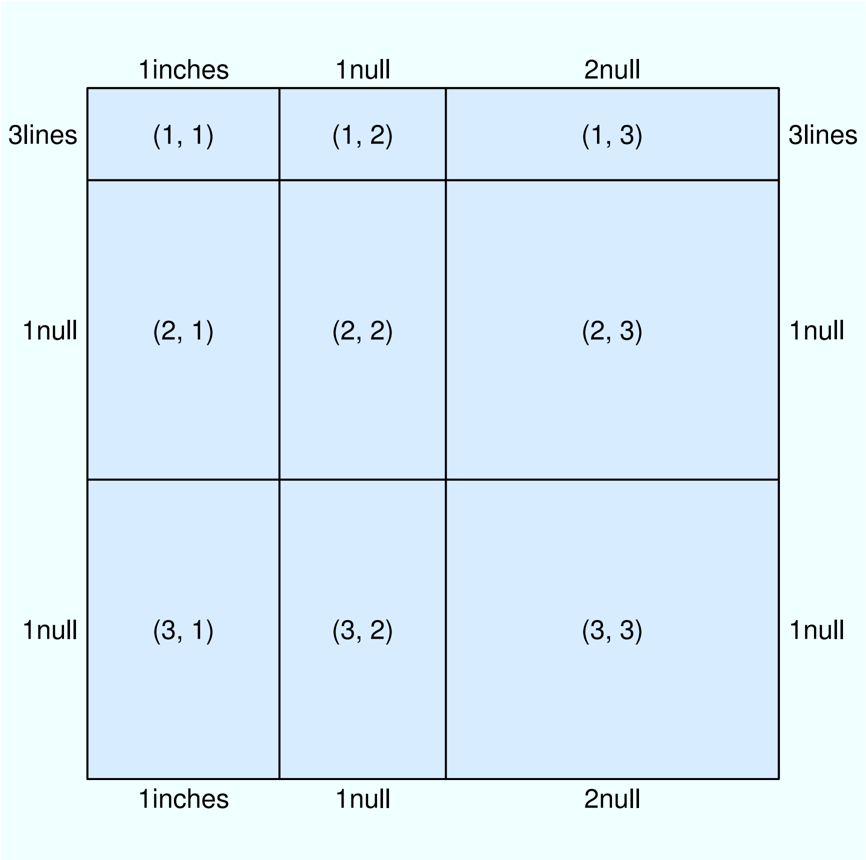

Figure 5.17
Layouts and units. A grid layout using a variety of coordinate systems to specify the widths of columns and the heights of rows.

```
> gridfun <- function() {
    pushViewport(viewport(layout=grid.layout(1, 2)))
    pushViewport(viewport(layout.pos.col=1))
    grid.rect()
    grid.text("black")
    grid.text("&", x=1)
    popViewport()
    pushViewport(viewport(layout.pos.col=2, clip="on"))
    grid.rect(gp=gpar(fill="black"))
    grid.text("white", gp=gpar(col="white"))
    grid.text("&", x=0, gp=gpar(col="white"))
    popViewport(2)
  }
```

The next piece of code creates a viewport with a layout and places the output from the above function within a particular cell of that layout (see Figure 5.18).

```
> pushViewport(
    viewport(
      layout=grid.layout(5, 5,
                         widths=unit(c(5, 1, 5, 2, 5),
                                     c("mm", "null", "mm",
                                       "null", "mm")),
                         heights=unit(c(5, 1, 5, 2, 5),
                                      c("mm", "null", "mm",
                                        "null", "mm")))))
> pushViewport(viewport(layout.pos.col=2, layout.pos.row=2))
> gridfun()
> popViewport()
> pushViewport(viewport(layout.pos.col=4, layout.pos.row=4))
> gridfun()
> popViewport(2)
```

Although the result of this particular example could be achieved using a single layout, what this shows is that it is possible to take grid code that makes use of a layout (and may have been written by someone else) and embed it within a layout of your own. A more sophisticated example of this involving lattice plots is given in Section 5.8.2.

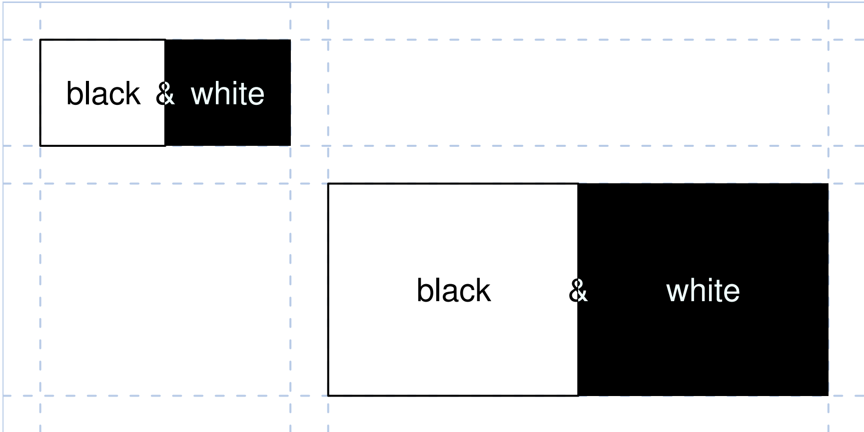

Figure 5.18
Nested layouts. An example of a layout nested within a layout. The black and white squares are drawn within a layout that has two equal-width columns. One instance of the black and white squares has been embedded within cell $(2, 2)$ of a layout consisting of five columns and five rows of varying widths and heights (as indicated by the dashed lines). Another instance has been embedded within cell $(4, 4)$.

5.6 Missing values and non-finite values

Non-finite values are not permitted in the location, size, or scales of a viewport. Viewport scales are checked when a viewport is created, but it is impossible to be certain that locations and sizes are not non-finite when the viewport is created, so this is only checked when the viewport is pushed. Non-finite values result in error messages.

The locations and sizes of graphical objects can be specified as missing values (`NA`, `"NA"`) or non-finite values (`NaN`, `Inf`, `-Inf`). For most graphical primitives, non-finite values for locations or sizes result in the corresponding primitive not being drawn. For the `grid.line.to()` function, a line segment is only drawn if the previous location and the new location are both not non-finite. For `grid.polygon()`, a non-finite value breaks the polygon into two separate polygons. This break happens within the current polygon as specified by the `id` argument. All polygons with the same `id` receive the same `gp` settings. For `grid.arrows()`, an arrow head is only drawn if the first or last line segment is drawn.

Figure 5.19 shows the behavior of these primitives where x- and y-locations are seven equally-spaced locations around the perimeter of a circle. In the top-left figure, all locations are not non-finite. In each of the other figures, two locations have been made non-finite (indicated in each case by grey text).

5.7 Interactive graphics

The strength of the grid system is in the production of static graphics. There is only very basic support for user interaction, consisting of the `grid.locator()` function. This function returns the location of a single mouse click relative to the current viewport. The result is a list containing an `x` and a `y` unit. The `unit` argument can be used to specify the coordinate system to be used for the result.

From R version 2.1.0, the `getGraphicsEvent()` function provides additional capability (on Windows) to respond to mouse movements, mouse ups, and key strokes. However, with this function, mouse activity is only reported relative to the native coordinate system of the device.

5.8 Customizing lattice plots

This section provides some demonstrations of the basic grid functions within the context of a complete lattice plot.

The lattice package described in Chapter 4 produces complete and very sophisticated plots using grid. It makes use of a sometimes large number of viewports to arrange the graphical output. A page of lattice output contains a top-level viewport with a quite complex layout that provides space for all of the panels and strips and margins used in the plot. Viewports are created for each panel and for each strip (among other things), and the plot is constructed from a large number of rectangles, lines, text, and data points.

In many cases, it is possible to use lattice without having to know anything about grid. However, a knowledge of grid provides a number of more advanced ways to work with lattice output (see Section 6.7). A simple example is provided by the `panel.width` and `panel.height` arguments to the `print.trellis()` method. These provide an alternative to the `aspect` argument for controlling the size of panels within a lattice plot using grid units.

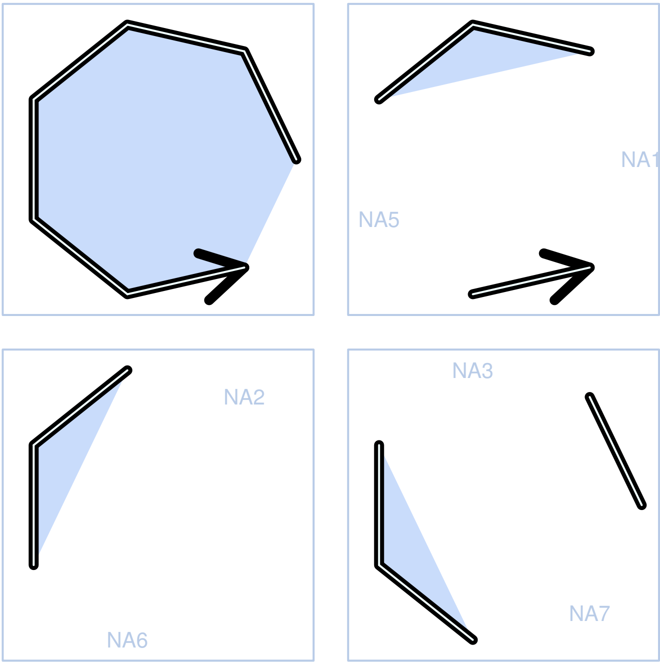

Figure 5.19
Non-finite values for line-tos, polygons, and arrows. The effect of non-finite values for `grid.line.to()`, `grid.polygon()`, and `grid.arrows`. In each panel, a single grey polygon, a single arrow (at the end of a thick black line), and a series of thin white line-tos are drawn through the same set of seven points. In some cases, certain locations have been set to `NA` (indicated by grey text), which causes the polygon to become cropped, creates gaps in the lines, and can cause the arrow head to disappear. In the bottom-left panel, the seventh location is not `NA`, but it produces no output.

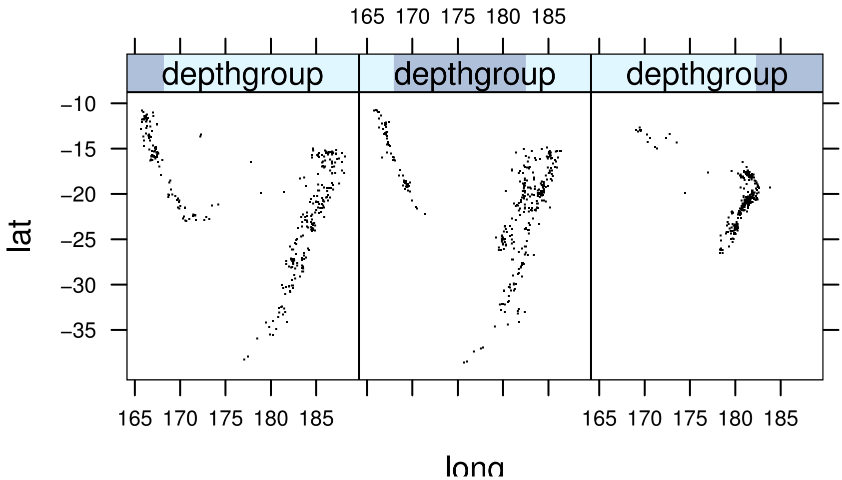

Figure 5.20
Controlling the size of lattice panels using grid units. Each panel is exactly 1.21 inches wide and 1.5 inches high.

The following code produces a multipanel lattice plot of the `quakes` data set (see page 126) where the size of each panel is fixed at 1.21 inches wide and 1.5 inches high (see Figure 5.20).*

```
> temp <- xyplot(lat ~ long | depthgroup,
                 data=quakes, pch=".",
                 layout=c(3, 1))
> print(temp,
        panel.width=list(1.21, "inches"),
        panel.height=list(1.5, "inches"))
```

5.8.1 Adding grid output to lattice output

The functions that lattice provides for adding output to panels (`ltext()`, `lpoints()`, etc) are designed to make it easier to port code between R and S-PLUS. However, they are restricted because they only allow output to be located and sized relative to the `"native"` coordinate system. Grid graphical primitives cannot be ported to S-PLUS, but they provide much more control

*These specific sizes were chosen for this particular data set so that one unit of longitude corresponds to the same physical size on the page as one unit of latitude.

over the location and size of additional panel output. Furthermore, it is possible to create and push extra viewports within a panel if desired (although it is very important that they are popped again or lattice will get very confused).

In a similar vein, the facilities provided by the `upViewport()` and `downViewport()` functions in grid allow for more flexible navigation of a lattice plot compared to the `trellis.focus()` function.

The following code provides an example of using low-level grid functions to add output within a lattice panel function. This produces a variation on Figure 4.4 with a dot and a text label added to indicate the location of Auckland, New Zealand relative to the earthquakes (see Figure 5.21).*

```
> xyplot(lat ~ long | depthgroup, data=quakes, pch=".",
         panel=function(...) {
           grid.points(174.75, -36.87, pch=16,
                       size=unit(2, "mm"),
                       default.units="native")
           grid.text("Auckland",
                     unit(174.75, "native") - unit(2, "mm"),
                     unit(-36.87, "native"),
                     just="right")
           panel.xyplot(...)
         })
```

5.8.2 Adding lattice output to grid output

As well as the advantages of using grid functions to add further output to lattice plots, an understanding that lattice output is really grid output makes it possible to embed lattice output within grid output. The following code provides a simple example (see Figure 5.22).

First of all, two viewports are defined. The viewport `tvp` occupies the rightmost 1 inch of the device and will be used to draw a label. The viewport `lvp` occupies the rest of the device and will be used to draw a lattice plot.

```
> lvp <- viewport(x=0,
                  width=unit(1, "npc") - unit(1, "inches"),
                  just="left", name="lvp")
> tvp <- viewport(x=1, width=unit(1, "inches"),
                  just="right", name="tvp")
```

*The data are from the `quakes` data set (see page 126).

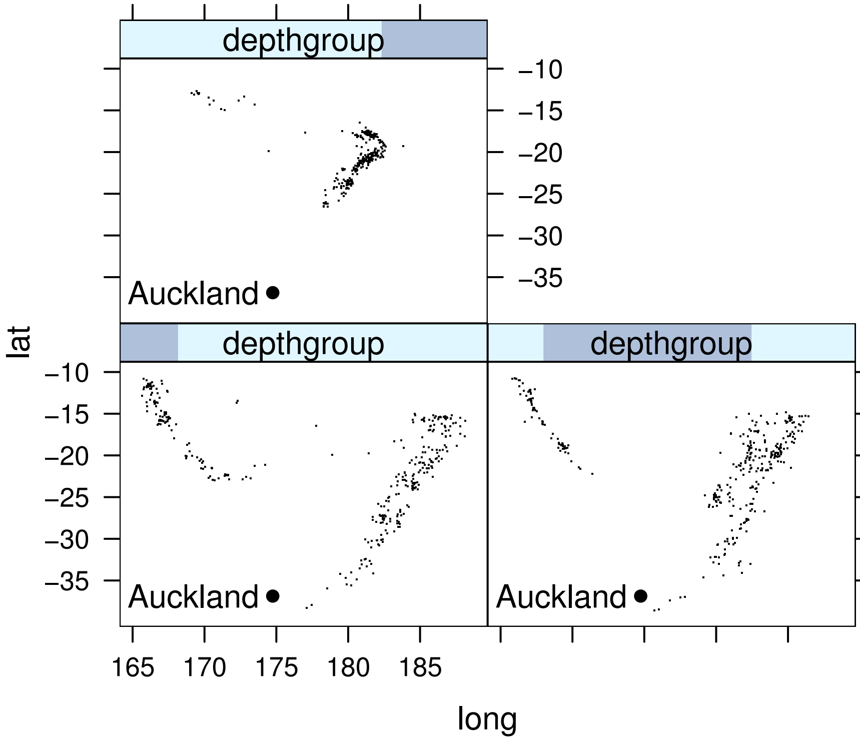

Figure 5.21
Adding grid output to a lattice plot (the lattice plot in Figure 4.4). The grid functions `grid.text()` and `grid.points()` are used within a lattice panel function to highlight the location of Auckland, New Zealand within each panel.

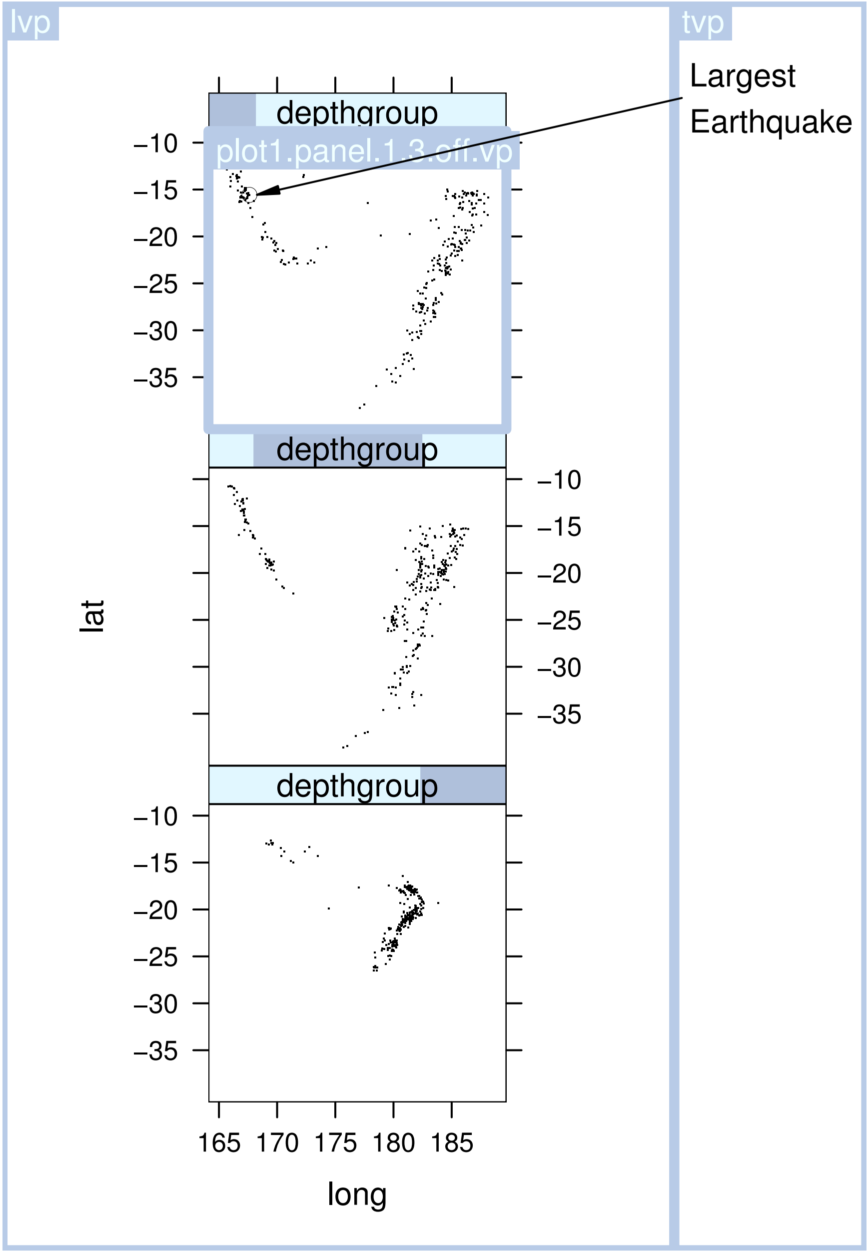

Figure 5.22
Embedding a lattice plot within grid output. The lattice plot is drawn within the viewport "lvp" and the text label is drawn within the viewport "tvp" (the viewports are indicated by grey rectangles with their names at the top-left corner). An arrow is drawn from viewport "tvp" where the text was drawn into viewport "panel.1.3.off.vp" — the top panel of the lattice plot.

The next piece of code produces (but does not draw) an object representing a multipanel scatterplot using the quakes data (see page 126).

```
> lplot <- xyplot(lat ~ long | depthgroup,
                  data=quakes, pch=".",
                  layout=c(1, 3), aspect=1,
                  index.cond=list(3:1))
```

The following pieces of code do all the drawing. First of all, the lvp viewport is pushed and the lattice plot is drawn inside that. The upViewport() function is used to navigate back up so that all of the lattice viewports are left intact.

```
> pushViewport(lvp)
> print(lplot, newpage=FALSE, prefix="plot1")
> upViewport()
```

Next, the tvp viewport is pushed and a text label is drawn in that.

```
> pushViewport(tvp)
> grid.text("Largest\nEarthquake", x=unit(2, "mm"),
            y=unit(1, "npc") - unit(0.5, "inches"),
            just="left")
```

The last step is to draw an arrow from the label to a data point within the lattice plot. While still in the tvp viewport, the grid.move.to() function is used to set the current location to a point just to the left of the text label. Next, seekViewport() is used to navigate to the top panel within the lattice plot.* Finally, grid.arrows() and lineToGrob() are used to draw a line from the text to an (x ,y) location within the top panel. A circle is also drawn to help identify the location being labelled.

*The name of the viewport representing the top panel in the lattice plot can be obtained using the trellis.vpname() function or by just visual inspection of the output of current.vpTree() and possibly some trial-and-error.

```
> grid.move.to(unit(1, "mm"),
               unit(1, "npc") - unit(0.5, "inches"))
> seekViewport("plot1.panel.1.3.off.vp")
> grid.arrows(grob=lineToGrob(unit(167.62, "native") +
                              unit(1, "mm"),
                              unit(-15.56, "native")),
              length=unit(3, "mm"), type="closed",
              angle=10, gp=gpar(fill="black"))
> grid.circle(unit(167.62, "native"),
              unit(-15.56, "native"),
              r=unit(1, "mm"),
              gp=gpar(lwd=0.1))
```

The final output is shown in Figure 5.22.

Chapter summary

Grid provides a number of functions for producing basic graphical output such as lines, polygons, rectangles, and text, plus some functions for producing slightly more complex output such as data symbols, arrows, and axes. Graphical output can be located and sized relative to a large number of coordinate systems and there are a number of graphical parameter settings for controlling the appearance of output, such as colors, fonts, and line types.

Viewports can be created to provide contexts for drawing. A viewport defines a rectangular region on the device and all coordinate systems are available within all viewports. Viewports can be arranged using layouts and nested within one another to produce sophisticated arrangements of graphical output.

Because lattice output is grid output, grid functions can be used to add further output to a lattice plot. Grid functions can also be used to control the size and placement of lattice plots.
