Technical Note: Literate Data Analysis

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1 Overview

In 1992 Donald Knuth published a book with the title "Literate Programming" [1], showing the advantages of, and techniques for, writing computer programs to be read and understood by humans, as well as executed by a digital computer. This technical note advocates the same approach for data analysis: the executable computer code (here, in the R environment) is an integral part of a document that explains what the analyst did, why, and what was discovered.

The advantages of this approach are several: (1) every processing step is transparent; (2) anyone else can repeat the analysis, if they are given access to the same data; (3) analysis can easily be expanded or adapted; (4) the results of the analysis are generated with the document, so they are by definition synchronized; (5) the analyst's motivations and interpretations are in the exact place where the results of the analysis are presented.

The tools we use are:

Data processing: The R environment for statistical computing[1] [6]

Literate programming: Sweave[2] [3]

Text processing: LaTeX[3] [2]

Text editor: There are several good choices:

- Emacs[4], with the AUCTeX extension for working with LaTeX documents and the ESS ("Emacs Speaks Statistics")[5] extension for running R under Emacs. Learning Emacs is an investment in a lifetime of programming productivity, but not an overnight business.
- Microsoft Windows only: WinEdt[6] and the `R-WinEdt` R package to communicate with it.
- Microsoft Windows only: Tinn-R[7]

The flow is as follows:

[1] http://www.r-project.org/
[2] http://www.stat.uni-muenchen.de/~leisch/Sweave/
[3] http://www.latex-project.org/
[4] http://www.gnu.org/software/emacs/
[5] http://ess.r-project.org/
[6] http://www.winedt.com/
[7] http://www.sciviews.org/Tinn-R/

1. You create a **source** document in a text editor with extension `.Rnw` (a so-called "NoWeb" file[8]); this source document includes LaTeX markup, your own text, and "chunks" of executable R code, using the NoWeb syntax (explained below) to show which parts of the source are executable code.

2. You run this through R with the R function `Sweave` ("S language Weave"); this produces a LaTeX file (extension `.tex`) which includes your original LaTeX markup and text, with the output from R (which may include graphics).

3. You process the LaTeX file with PDFLaTeX to produce a PDF document.

4. *Optional*: You run the original source through R with the R function `Stangle` ("S language Tangle") to produce an R source code file with the same name and extension `.R`; this can be executed with the R function `source`.

As you create your source document, you can also execute lines or chunks of code in the R console to see their effect. From some text editors (Emacs + ESS, Tinn-R) you can directly send lines or chunks of code from the NoWeb source to a linked R console; otherwise you have to work in the two environments separately. Thus you have an **interactive** data analysis as you work, but write it up in a document to be read by others.

> **Note:** The terms "Weave" and "Tangle" are from Knuth, a reference to a poem by Sir Walter Scott: "Oh, what a tangled web we weave when first we practise to deceive" *Marmion*, VI:17; Knuth's original literate programming system was called WEB, so he decided to use "Weave" for the process of making the readable document and "Tangle" for the process of making the executable code. So now you know.

We now give a tutorial example, and then get into some of the details and complications.

[8] NoWeb, `http://www.cs.tufts.edu/~nr/noweb/`

2 Tutorial

We will do a small literate data analysis on one of R's example datasets, `trees`:

1. Examine the dataset structure;
2. Summarize the variables;
3. Graph the relation between them;
4. Build a linear model to predict tree volume from tree girth and height.

All of this is accompanied by our commentary – this is where we explain ("literately" we hope) what we are doing, why, and what conclusions we draw.

2.1 First version

Task 1 : Create the LaTeX master file named `test.tex`, open it in the text editor, and set up the LaTeX document. •

This is the usual document skeleton, naming the document class, loading packages etc. A minimal skeleton is:

```
\documentclass[11pt]{article}
\begin{document}
% LaTeX macros and text go here
\end{document}
```

There is usually a title, author, and date:

```
\documentclass[11pt]{article}\
\title{Modelling tree volume}\author{D. Luo}\date{11-November-2011}
begin{document}
\maketitle
% LaTeX macros and text go here
\end{document}
```

To have properly-formatted Sweaved text, you must load that LaTeX package in the document preamble.

Task 2 : Add the following macros before `\begin{document}`, i.e., in the preamble:

```
\usepackage{Sweave}
```

•

Task 3 : Write the introductory text in the document section of LaTeX master file (i.e., within the `document` environment). •

This should be your description (to your reader) of the purpose of this data analysis. Here is my text:

```
Here we use the \verb|trees| dataset supplied with R to illustrate a
simple simple data analysis:
(1) describing the variables and cases;
(2) investigating the inter-relation between variables;
(3) modelling tree volume as a function of tree height and/or tree girth.
```

I find it easiest to have a master file with the LaTeX headers, package declarations, options, etc., and then use the `\input` or `\include` macro (if each section should start on a new page) to include one or more files which contain the results of R computation and my comments on them.

Below we will create a NoWeb source file named `test1.Rnw` and process it with Sweave to convert it to a LaTeX source named `test1.tex`. So we need to include this LaTeX file, which will be produced by Sweave, in the master file.

Task 4 : Use the `\input` LaTeX macro to include the Sweave output in the master file, after the introductory text.

```
\input{test1.tex}
```

•

After these steps, my master file is as shown in §A.1.

Task 5 : Create a new source file named `test1.Rnw`, and open it in the text editor. •

> **Note:** The `.Rnw` extension is used for NoWeb source files.

Task 6 : Write the code and commentary to load the example dataset. •

For this first example you just need to know one NoWeb syntax: a **code chunk** is written between `<<>>=` and `@`; these must be the only text on their respective lines of NoWeb source. Anything between these is considered R code and will be formatted, executed, and the output written to the LaTeX source file.

```
<<>>=
# R code here
@
```

Anything *not* in a code chunk is regular LaTeX source – this is where you write comments and explanations.

My code and commentary is shown in §A.2.

Task 7 : Sweave this source file within R, with the `Sweave` function; this creates a LaTeX file with the same name but extension `.tex`. •

```
> Sweave("test1.Rnw")

Writing to file test1.tex
Processing code chunks ...

You can now run LaTeX on 'test1.tex'
```

The resulting file should look like §B.1. Notice the LaTeX environments provided by the Sweave LaTeX package: `Schunk` for any S-language "chunk" produced from the NoWeb source, `Sinput` for formatted S-language input, and `Soutput` for formatted R output.

> **Note:** In general you never have to look at this file; it is generated automatically by Sweave and included in your PDFLaTeX output with the `\input` or `\include` macros. We show it so that you can see what Sweave does.

Task 8 : TeXify the document: run PDFLaTeX to produce the PDF file, which will be named `test.pdf`. •

The output should look like Figure 2.

2.2 Adding graphics

Sweave can produce graphical output in two ways:

1. The author specifies `fig=TRUE` in the code chunk header, and writes the usual graphics commands in the code chunk; a figure is automatically generated, named, stored on your computer, and incorporated in the PDF via the LaTeX `\includegraphics` macro;

2. The author explicitly opens a graphics device (e.g., a PDF file) and writes to it with the usual graphics commands, within a code chunk.

The second option is only needed if you want to generate a figure formatted for publication; see §3.1 for details.

There are a few details that make this process go smoothly. The first is to use the LaTeX-like `\SweaveOpts` macro in the NoWeb source (`.Rnw`) file **before** any R code that **produces graphics** to specify two things:

- The location and the prefix of the file name of automatically-produced graphics files; the default is the current directory and source file name;

- That we only need PDF figures; the default for `R < 2.13` is to also write Encapsulated Postscript (EPS) figures.

Second, it is good practice to **create a subdirectory** to hold the graphics; there will typically be a lot of them and they clutter up the main project directory.

Task 9 : Create a subdirectory named `graph` •

Task 10 : Add the following line at the beginning of your NoWeb source (i.e., the `.Rnw` file):

```
\SweaveOpts{prefix.string=graph/test,eps=false}
```

•

This says to put figures in the `graph` subdirectory (relative to the working directory), prefix the names with `test`, and not write EPS files. Graphs will be generated with the names `test-001.pdf`, `test-002.pdf`, etc. and these names will be used in the generated source file with the `\includegraphics` LaTeX command.

Another issue with graphics is their size on the page in the generated PDF document. By default the `Sweave` R package specifies 0.8 times the current text width; this leaves a space of 0.1 times the text width at each side. If the figure doesn't have much complexity you might want it narrower; if a wide figure (landscape orientation) you might want it wider. At any point in the document you can change it with the `Gin` "graphics inches" option of the `\setkeys` LaTeX command (defined by `Sweave.sty`), e.g.:

```
\setkeys{Gin}{width=0.6\textwidth}
```

Note: It's most convenient to define the width in terms of `\textwidth` as shown above; however, direct specification of width is also permitted.

The code chunk to produce a figure looks like this:

```
<<fig=T>>=
# R code to produce graphics, e.g., plot(), hist()
@
```

You can also specify the **dimensions of the PDF graphic** in the code chunk header, e.g.,

```
<<fig=T,width=10,height=5>>=
# R code to produce graphics, e.g., plot(), hist()
@
```

These dimensions are *inches*[9]; default is 6"x6". Fonts are scaled to look good for the graphic printed on standard A4 paper, so specifying a larger size results in smaller fonts relative to the graphic elements.

With this preparation, we can add a graph to our test document.

Task 11 :

1. Add code to the NoWeb source to draw a graph;

2. Also display the graph interactively, to check the graph is what you want and to interpret it;

3. Add some interpretative text to the NoWeb source explaining the graph;

[9] 1" = 2.54 cm = 72 points exactly

4. Sweave this source file within R, with the `Sweave` function;

5. TEXify the master file.

•

My interepretation was:

```
Comment: There  appears to be a very strong relation between girth and volume;
this seems slightly non-linear (parabolic). The relation between
height and volume is also positive but much weaker. Height and
girth are very weakly related; this suggests that the trees
have different morphologies.
```

Now when we Sweave the source, this commentary is given right after the figure. The reader can see the figure and the analyst's interpretation.

My revised NoWeb source, with graphics commands and some comments, is shown in §A.3.

After Sweaving this source:

```
> Sweave("test1.Rnw")
```

we get the PDF file shown in Figure 3.

2.3 In-line calculations

Sweave is also able to write calculated numbers right into the text. For example, you might want to comment on the success of a model with something like: "The adjusted R^2 of the model is quite high (0.86)". But how do you know the figure? You could compute it interactively in R and then cut-and-paste, but that is error-prone, and would have to be repeated if you change the model or dataset. Far better is to use the `\Sexpr` LATEX macro, provided by the Sweave LATEX style. Most R expressions that produce a single number can be arguments to this macro; the results of the R calculation are then written to the LATEX source when the source file is Sweaved.

For example, the LATEX source text:

```
\Sexpr{round(2*pi/360, 5)}
```

will produce `0.01745` in the document.

In practice, you compute interactively in R, see what works, and then add the relevant output to your in-line text in the NoWeb source. From some text editors (Emacs + ESS, Tinn-R) you can directly send lines or chunks of code from the NoWeb source to a linked R console; otherwise you have to work in the two environments separately.

Task 12 : Compute a linear model of tree volume modelled as an interaction between height and girth, and report its goodness-of-fit in-line with the `\Sexpr` LaTeX macro. Explain the processing steps in the text, and interpret the result. •

Here I examine the model summary interactively, and decide to report the goodness-of-fit as an adjusted R^2; this is given by the `adj.r.squared` field of the model summary given by `summary.lm`. My revised NoWeb source is shown in §A.4

After Sweaving this source, by running the R command:

```
> Sweave("test1.Rnw")
```

to produce file `"test1.tex"`, and TeXifying the master file, we get the PDF file shown in Figure 5.

2.4 Writing an R source code file

You may want the R code as a separate file, for inclusion in an automatic process, or as source for further experimentation. This is the function of the "Tangle" procedure. You do this interactively at the R prompt, using the `Stangle` function.

Task 13 : "Tangle" the final NoWeb source to produce R code. •

Recall, the source code is in file `test1.Rnw`. So, at the R prompt:

```
> Stangle("test1.Rnw")
```

The result is shown in §D. This source can now be run in R with the `source` function:

```
> source("test1.R")
```

This would run all the analysis and produce all the graphics (but not the document).

3 Details

The Sweave manual [4] has full explanation of the many options, useful examples, and some common tricks. Here we just list a few that may catch the unwary.

3.1 Production graphics

The graphics produced automatically with the `<<fig=TRUE>>=` code chunk header are included in your PDF document and stored on your system. Each graphic is a separate PDF file and may be used by itself, e.g., for a journal article or thesis. These will have names like `test-001.pdf`, according to the `prefix.string` argument to the `SweaveOpts` macro; see §2.2.

However, you may want a different formatting for a production graphic. To do this, within a code chunk open a graphics device with the `pdf`, `jpeg` or `png` functions, write code to produce the graph, and close the graphics device with the `dev.off` function. For example:

```
<<>>=
pdf(file="graph/scatterGirthHeight.pdf",
    width=5, height=5, title="Figure 1",
    bg="lightgray", fg="darkred")
plot(trees$Girth ~ trees$Height, pch=20, cex=1.5,
     xlab="Height (feet)", ylab="Girth (inches)")
dev.off()
@
```

Note there is *no* `fig=TRUE` in the chunk header, because we produce the graphic "by hand" rather than automatically. Also notice the many options that can be given the function that opens the graphics device, here `pdf`.

This produces the nice graphic shown in Figure 1.

3.2 Lattice graphics

R has several graphics systems; the example above uses base graphics from the `graphics` package, which is always loaded with R.

Another, very sophisticated, graphics system is provided by the `lattice` package [8, 9]; this is used by other packages such as the `gstat` geostatistics package [5]. Lattice graphics do not produce output directly, instead they return a `lattice` object, which can be printed with the generic `print` method. In interactive R this is done automatically by the package; but since Sweave is not interactive, the analyst must specify it directly. It's a simple trick, for example:

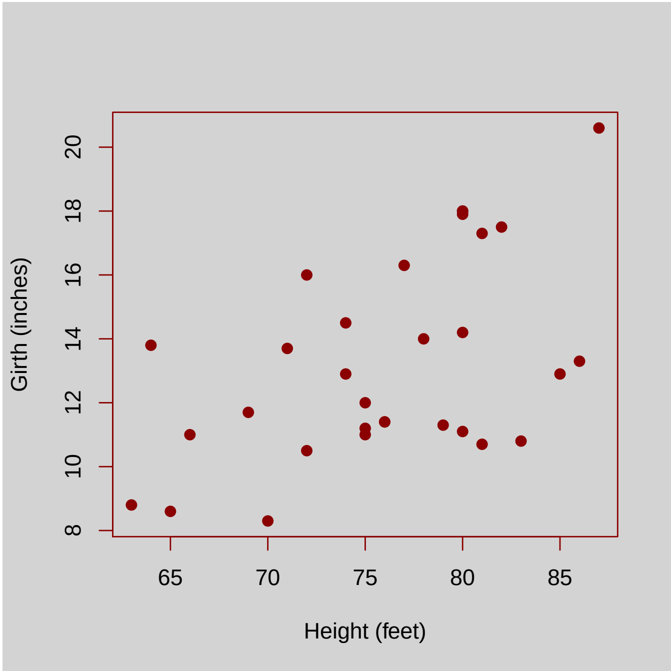

Figure 1: Relation between girth and height, 31 cherry trees

```
<<fig=TRUE>>=
require(lattice)
# provides the `xyplot' method for scatterplots
data(trees)
print(with(trees, xyplot(Volume ~ Girth)))
@
```

This behaviour is useful when collecting several lattice graphics for display in a matrix with the `split` and `more` arguments to `print`:

```
<<fig=TRUE, width=8, height=4>>=
require(lattice)
data(trees)
p1 <- with(trees, xyplot(Volume ~ Girth))
p2 <- with(trees, xyplot(Volume ~ Height))
print(p1, split=c(1,1,2,1), more=T)
print(p2, split=c(2,1,2,1), more=F)
@
```

3.3 Manipulating variables used in graphics

In the previous example, you might be tempted to add `rm(p1,p2)` to remove the temporary variables. This will cause an error because the chunk with graphics output is run twice (silently), once to produce the figure and once to produce any printed output. Hence, data manipulations, including deleting variables, should be done either in separate chunks.

```
<<>>=
rm(p1, p2)
@
```

3.4 R code formatting and comments

If you are an experienced R programmer, you probably do two things that are good programming practice:

- Formatting your code for readability, for example adding line breaks;
- Addding R comments (introduced with the `#` character) to explain your R code.

You can do these in your Sweave source, but by default they will *not* appear in your final document (however, they *will* appear in any R code generated with the `Stangle` function, see §2.4). This is because Sweave runs the source code through the R parser, and itself formats the result as printed output.

So what to do? Comments are not so necessary in literate programming, because you can explain things in the text, so in most cases the default behaviour is fine.

If you really want formatted code or comments in your document, you can use the `keep.source=TRUE` option for a single code chunk.

For example, suppose we want to keep our comment and formatting to explain a correlation test, using the `cor.test` function:

```
<<keep.source=T>>
# a non-parametric (rank) correlation between the two predictors
cor.test(trees$Girth,
         trees$Height,
         method = "spearman")
@
```

Here we separated the lines for easier reading, and explain with a comment that the test is non-parametric. Of course, this could have been explained in the text (not as a code comment).

This will appear in the document as:

```
> # now do the correlation
> cor.test(trees$Girth,
+          trees$Height,
+          method="spearman")

Spearman's rank correlation rho

data: trees$Girth and trees$Height
S = 2773.4, p-value = 0.01306
alternative hypothesis: true rho is not equal to 0
sample estimates:
    rho
0.44084
```

Note how the formatting and comment are preserved, along with R's first-line and continuation prompts.

You can also include this as one of the Sweave options for an entire source file; recall from §2.2 that the LaTeX-like `\SweaveOpts` macro is placed at the start of the NoWeb source (`.Rnw`) file. For example:

```
\SweaveOpts{keep.source=TRUE}
# remainder of source file
```

3.5 Hiding code from the reader

You may want to execute some code that is irrelevant to readers, for example, changing to a directory on your system that will not be on their systems. You can hide code with the `echo=FALSE` tag:

```
<<echo=F>>=
setwd("/Users/Goliath/projects/secret/notell")
@
```

Any output will not be hidden.

3.6 Hiding output from the reader

You may want to hide some output, probably because it is too long or verbose, but you want to show the reader what you did. You can hide output with the `results=hide` tag:

```
You can show all the PDF fonts on your system as follows:
<<results=hide>>=
str(pdfFonts())
@
```

This will appear in the document as:

> You can show all the PDF fonts on your system as follows:
>
> `> str(pdfFonts())`

without any of the voluminous output produced by `pdffonts`.

4 Learning to use the tools

We've explained the interaction between the various tools; here we list some resources to get you started if you don't know how to use them,

4.1 LaTeX

An excellent starting point is the LaTeX Wikibook[10]. This explains installation, simple and advanced usage, and tricks. It includes an "Absolute Beginners" section. Of course, the LaTeX project home page[11] is the definitive portal.

4.2 R

The R environment for statistical computing home page[12] is the entry point for information, downloads, and documentation.

I have written an introduction to R for ITC [7]; §10 lists some learning resources. The most useful for beginners is Appendix A "A sample session" of the *Introduction to R* from the R Project[13]. This will give you some familiarity with the style of R sessions and more importantly some instant feedback on what actually happens. Don't worry if you don't understand everything; this is just to give you a feel for how R works and what it can do. For individual commands, it is always best to look at its help topic.

Many other introductions R have been written, both as formal textbooks and on-line documents; see the "Documents" link in the table of contents of the R home page.

4.3 Emacs

If you choose to use Emacs, you face a steep learning curve but end up with a programming and text editing environment of unequalled power and speed.

The reference manual at the GNU Emacs home page[14] is comprehensive and systematic, but slow going. The same group produces an Emacs Tour[15] which shows some of the capabilities.

Probably the best way to get started is to follow the tutorial built in to Emacs . This is accessed by using the "help" system and then pressing the `t` (for "tutorial") key. Unfortunately, different platforms and even different keyboard mappings have different ways to access the "help" system.

[10] http://en.wikibooks.org/wiki/LaTeX
[11] http://www.latex-project.org/
[12] http://www.r-project.org/
[13] http://cran.r-project.org/doc/manuals/R-intro.pdf
[14] http://www.gnu.org/software/emacs/#Manuals
[15] http://www.gnu.org/software/emacs/tour/

- Under X11 or Mac OS/X terminal, press the <f1> key.

If you start Emacs without a file name, the opening screen explains how to access the help system.

Emacs has many useful extensions, which may be installed by default, or you may have to install them. For editing LaTeX source, the AUCTeX extension can be used[16]. For communicating with R, and running R within the Emacs editor, the solution is the ESS ("Emacs Speaks Statistics")[17] extension.

4.4 Sweave

The Sweave manual [4] has full explanation and useful examples.

[16] http://www.gnu.org/software/auctex/
[17] http://ess.r-project.org/

References

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[8] Deepayan Sarkar. Lattice. *R News*, 2(2):19–23, 2002. 12

[9] Deepayan Sarkar. *Lattice : multivariate data visualization with R*. Springer, 2008. ISBN 9780387759685 (pbk.) 0387759689 (pbk.) 9780387759692 (e-ISBN) 0387759697 (e-ISBN). URL `http://lmdvr.r-forge.r-project.org/`. 12

Index of R Concepts

A Source code

A.1 LaTeX master file

```
\documentclass[11pt]{article}
\usepackage{Sweave}
\title{Modelling tree volume}\author{D. Luo}\date{11-November-2011}
\begin{document}
\maketitle
Here we use the \verb|trees| dataset supplied with R to illustrate a
simple data analysis:
(1) describing the variables and cases;
(2) investigating the inter-relation between variables;
(3) modelling tree volume as a function of tree height and/or tree girth.
\input{test1.tex}
\end{document}
```

A.2 First version of Sweave source

```
\par
First, load the dataset, examine its structure, and summarize the variables:
\par
<<>>=
data(trees)
str(trees)
summary(trees)
@
\endinput
```

It is always good practice to end LaTeX source to be included in a master document with the `\endinput` macro.

A.3 Second version of Sweave source

```
\SweaveOpts{prefix.string=graph/test,eps=false}
\setkeys{Gin}{width=0.6\textwidth}
First, load the dataset, examine its structure, and summarize the variables:
<<>>=
data(trees)
str(trees)
summary(trees)
@
\par
Second, look at the pairwise scatterplots of the three variables:
<<fig=T,width=7,height=7>>=
pairs(trees, pch=20, cex=1.2)
@
\par
Comment: There appears to be a very strong relation between girth and volume;
this seems slightly non-linear (parabolic). The relation between
height and volume is also positive but much weaker. Height and
girth are very weakly related; this suggests that the trees
have different morphologies.
\endinput
```

A.4 Third version of Sweave source

```
\SweaveOpts{prefix.string=graph/test,eps=false}
\setkeys{Gin}{width=0.6\textwidth}
First, load the dataset, examine its structure, and summarize the variables:
<<>>=
data(trees)
str(trees)
summary(trees)
@
\par
Second, look at the pairwise scatterplots of the three variables:
<<fig=T,width=7,height=7>>=
pairs(trees, pch=20, cex=1.2)
@
\par
Comment: There  appears to be a very strong relation between girth and volume;
this seems slightly non-linear (parabolic). The relation between
height and volume is also positive but much weaker. Height and
girth are very weakly related; this suggests that the trees
have different morphologies.
\par
Third, model the tree volume by a full model with the two possible
predictors; include the interaction:
<<>>=
# note: `*' is used to specify an interaction effect
m <- lm(Volume ~ Girth * Height, data=trees)
summary(m)
@
The success is quite good, as measured by the adjusted $R^2$
(\Sexpr{round(summary(m)$adj.r.squared*100,1)}\%).
\endinput
```

Notice the calculation in the `\Sexpr` macro; the result is multipled by 100 to express it as a percentage, and then rounded to one decimal place.

B Intermediate files

B.1 First version of Sweave-generated LaTeX source

```
\par
First, load the dataset, examine its structure, and summarize the variables:
\par
\begin{Schunk}
\begin{Sinput}
R> data(trees)
R> str(trees)
\end{Sinput}
\begin{Soutput}
'data.frame': 31 obs. of  3 variables:
 $ Girth : num  8.3 8.6 8.8 10.5 10.7 10.8 11 11 11.1 11.2 ...
 $ Height: num  70 65 63 72 81 83 66 75 80 75 ...
 $ Volume: num  10.3 10.3 10.2 16.4 18.8 19.7 15.6 18.2 22.6 19.9 ...
\end{Soutput}
\begin{Sinput}
R> summary(trees)
\end{Sinput}
\begin{Soutput}
     Girth           Height       Volume
 Min.   : 8.3   Min.   :63   Min.   :10.2
 1st Qu.:11.1   1st Qu.:72   1st Qu.:19.4
 Median :12.9   Median :76   Median :24.2
 Mean   :13.2   Mean   :76   Mean   :30.2
 3rd Qu.:15.2   3rd Qu.:80   3rd Qu.:37.3
 Max.   :20.6   Max.   :87   Max.   :77.0
\end{Soutput}
\end{Schunk}
\endinput
```

Note the automatically-generated `Schunk`, `Sinput` and `Soutput` LaTeX environments, interpreted by the Sweave LaTeX package.

C Output

These are Figures 2, 3, and 5.

Modelling tree volume

D. Luo

11-November-2011

Here we use the `trees` dataset supplied with R to illustrate a simple data analysis: (1) describing the variables and cases; (2) investigating the inter-relation between variables; (3) modelling tree volume as a function of tree height and/or tree girth.

First, load the dataset, examine its structure, and summarize the variables:

```
R> data(trees)
R> str(trees)

'data.frame':	31 obs. of  3 variables:
 $ Girth : num  8.3 8.6 8.8 10.5 10.7 10.8 11 11 11.1 11.2 ...
 $ Height: num  70 65 63 72 81 83 66 75 80 75 ...
 $ Volume: num  10.3 10.3 10.2 16.4 18.8 19.7 15.6 18.2 22.6 19.9 ...

R> summary(trees)

     Girth          Height       Volume
 Min.   : 8.3   Min.   :63   Min.   :10.2
 1st Qu.:11.1   1st Qu.:72   1st Qu.:19.4
 Median :12.9   Median :76   Median :24.2
 Mean   :13.2   Mean   :76   Mean   :30.2
 3rd Qu.:15.2   3rd Qu.:80   3rd Qu.:37.3
 Max.   :20.6   Max.   :87   Max.   :77.0
```

1

Figure 2: First output

Modelling tree volume

D. Luo

11-November-2011

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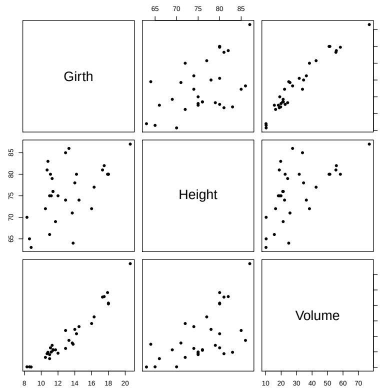
 Mean   :13.2   Mean   :76   Mean   :30.2
 3rd Qu.:15.2   3rd Qu.:80   3rd Qu.:37.3
 Max.   :20.6   Max.   :87   Max.   :77.0
```

Second, look at the pairwise scatterplots of the three variables:

```
R> pairs(trees, pch = 20, cex = 1.2)
```

1

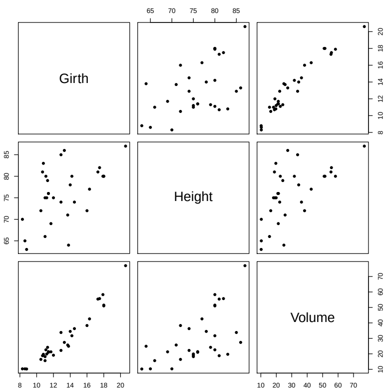
Figure 3: Second output, with a graph (page 1 of 2)



Comment: There appears to be a very strong relation between girth and volume; this seems slightly non-linear (parabolic). The relation between height and volume is also positive but much weaker. Height and girth are very weakly related; this suggests that the trees have different morphologies.

2

Figure 4: Second output, with a graph (page 2 of 2)



Comment: There appears to be a very strong relation between girth and volume; this seems slightly non-linear (parabolic). The relation between height and volume is also positive but much weaker. Height and girth are very weakly related; this suggests that the trees have different morphologies.

Third, model the tree volume by a full model with the two possible predictors; include the interaction:

```
R> m <- lm(Volume ~ Girth * Height, data = trees)
R> summary(m)
```

```
Call:
lm(formula = Volume ~ Girth * Height, data = trees)

Residuals:
   Min     1Q Median     3Q    Max 
-6.582 -1.067  0.303  1.564  4.665 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)   69.3963    23.8358    2.91  0.00713
Girth         -5.8558     1.9213   -3.05  0.00511
Height        -1.2971     0.3098   -4.19  0.00027
Girth:Height   0.1347     0.0244    5.52  7.5e-06

Residual standard error: 2.71 on 27 degrees of freedom
Multiple R-squared: 0.976,	Adjusted R-squared: 0.973 
F-statistic:  359 on 3 and 27 DF,  p-value: <2e-16
```

The success is quite good, as measured by the adjusted R^2 (97.3%).

2

Figure 5: Third output, with a graph and in-line calculation (page 2 of 2; Page 1 is the same as Figure 3)

D Generated R source code

```
###################################################
### chunk number 1:
###################################################
#line 5 "test3.Rnw"
data(trees)
str(trees)
summary(trees)


###################################################
### chunk number 2:
###################################################
#line 12 "test3.Rnw"
pairs(trees, pch=20, cex=1.2)


###################################################
### chunk number 3:
###################################################
#line 24 "test3.Rnw"
# note: `*' is used to specify an interaction effect
m <- lm(Volume ~ Girth * Height, data=trees)
summary(m)
```

Note the automatically-generated comments (marked with the # character). Also note that the line in the source NoWeb file is given, so we can easily find which code chunk produced with R code.