Introductory R Course

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Contents

1 Background

The purpose of these course notes is to introduce participants to basic programming, graphics and statistics in R.

1.1 R, S and S-Plus

R and S-PLUS are both implementations for the S language which is a language for 'programming with data'. R is free and open source.

1.2 Installation

Download the the most recent version of the base distribution binary for your platform from http://cran.r-project.org/ and install using the default options. Then start up R.

2 R Basics

2.1 Calculations

R can be used just like a calculator. An expression is entered at the `>` prompt and the result printed (the `print` command is redundant).

```
3 + 4
```

```
## [1] 7
```

```
3 * 4
```

```
## [1] 12
```

```
print(1/4)
```

```
## [1] 0.25
```

To faciliate cut and paste the R code in this document is not preceded by the `>` prompt and any output is preceded by two comment characters `##` (comments are introduced below).

The `[1]` at the start of each result indicates that the result is the first element in a *vector* (vectors are introduced below).

Exercise 1 *What is nine raised to the power of three?*

Exercise 2 *And nine raised to the power of 0.5?*

Exercise 3 *97 out of 284 eggs survive. What is the mortality expressed as a percentage?*

Exercise 4 *What is the result of `3 * 4 + 5`? And `5 + 3 * 4`? What does this indicate?*

2.2 Precedence

In R, if one operator has *precedence* over another then it is evaluated first. The order in which operators are evaluated can be controlled using brackets.

```
2 * 3 + 4
```

```
## [1] 10
```

```
2 * (3 + 4)
```

```
## [1] 14
```

Exercise 5 *Does the `*` operator have precedence over the `^` operator? Demonstrate with an example.*

2.3 Functions

Most of R's functionality comes from its *functions*. A function takes zero, one or multiple *arguments*, depending on the function, and returns a value. To call a function enter it's name followed by a pair of brackets - include any arguments in the brackets.

```
log(10)
```

```
## [1] 2.303
```

To find out more about a function called `function_name` type `?function_name`. To search for the functions associated with a topic type `??topic` or `??"multiple topics"`.

Exercise 6 *Which function calculates cumulative sums? And what arguments does it take?*

2.4 Arguments

The R Documentation for `log` indicates that the function requires an argument `x` that is a vector of *numeric* (real) or *complex* numbers and an argument `base` which is the base of the logarithm. If undefined the value of `base` is set to be `exp(1)`, i.e., `log` calculates natural logarithms by default.

When calling a function its arguments can be specified using *positional* and/or *named* matching.

```
log(x = 10, base = 2)
```

```
## [1] 3.322
```

```
log(base = 2, x = 10)
```

```
## [1] 3.322
```

```
log(10, 2)
```

```
## [1] 3.322
```

```
log(2, 10)
```

```
## [1] 0.301
```

Exercise 7 *What arguments does the function* `sqrt` *take?*

2.5 Assignment

The result of an expression can be *assigned* to an object using the `<-` operator. The object can then be used in subsequent expressions. To save finger strokes type alt-.

```
x <- 3 + 4
x
```

```
## [1] 7
```

```
x/2
```

```
## [1] 3.5
```

```
y <- x * x
y
```

```
## [1] 49
```

Exercise 8 *Set* `x` *to be* `7`*. What is the value of* `x^x`*. Save the value in a object called* `i`*. If you assign the value* `20` *to the object* `x` *does the value of* `i` *change? What does this indicate about how R assigns values to objects?*

2.6 Workspace

When a value is assigned to an object, the object can be used in subsequent calculations because it is stored in the *workspace*. The workspace is an area of memory associated with the current session.

The `ls()` function lists the objects in the workspace. Calling `rm(x)` deletes object `x` from the workspace. Typing `rm(list = ls())` removes all objects.

Exercise 9 *Using the* `rm` *function and the assignment operator arrange your workspace so that it contains three objects* `x`*,* `y` *and* `z` *with values of* `3`*,* `5` *and* `7`*, respectively.*

2.7 Vectors

A *vector* is a string of values.

2.7.1 Generation

Vectors can be created using the `c` (concatenate) and `seq` (sequence) functions.

```
c(1, 3, 5, 7, 13)
```

```
## [1]  1  3  5  7 13
```

```
seq(from = 1, to = 11, by = 2)
```

```
## [1]  1  3  5  7  9 11
```

```
seq(1, 6)
```

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

The `length` function returns the number of values in a vector.

Exercise 10 *Use the* `seq` *function to generate a vector of* `30` *evenly spaced numbers from* `0` *to* `1`*. Confirm its length.*

2.8 Vectorized calculations

In R, there are no scalars. Instead single values are considered vectors of length `1`. Even simple calculations are designed to be performed on vectors.

```
x <- seq(3, 5)
y <- c(1, 2, 2)
x - y
```

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

```
x/y
```

```
## [1] 3.0 2.0 2.5
```

If the vectors in an expression are of different lengths the shorter vector is *recycled*.

```
x <- seq(1, 4)
y <- seq(1, 2)
x/y
```

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

Exercise 11 *Create the vector that is the square root of all the whole numbers from `1` to `100`.*

Exercise 12 *Create a vector that gives the deviation of the values in the vector `seq(1, 10)` from their mean.*

2.9 Classes

The vectors you have dealt with so far have been of class `numeric` which have real numbers as their permissible values.

```
x <- c(1.5, 2.7)
class(x)
```

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

Another important vector class is `character` which has text values.

```
x <- c("txt", "one", "1", "1.9")
class(x)
```

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

Exercise 13 *Try combining character and numeric values together in the same vector. What happens?*

2.10 Missing values

Missing values are represented by `NA`. Functions such as `min`, `max` and `mean` that require knowledge of all the input values return an `NA` if one or more values are missing. This behaviour can be altered by setting the `na.rm` argument to be `TRUE`.

```r
x <- c(1, 2, 3, NA)
mean(x)
```

```
## [1] NA
```

```r
mean(x, na.rm = TRUE)
```

```
## [1] 2
```

2.11 Factors

Factors represent categorical variables.

Vectors can be coerced to class `factor` using the `as.factor` function.

```r
x <- c("blue", "green", "blue", "red", "green")
x <- as.factor(x)
class(x)
```

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

Exercise 14 *Coerce the factor* `x` *to a vector of class numeric using* `as.numeric`*. What happens?*

2.12 Data Frames

Data frames are the fundamental data structure in R. A data frame is a two-dimensional data set where the columns are variables (vectors) of equal length.

2.12.1 data

R packages often include data sets. To see the data sets in the current *search path* (introducted later) type `data()`. To print a summary of the `trees` data frame type `summary(trees)`. Type `trees` to print the data frame itself. To get more information on `trees` type `?trees`.

Exercise 15 *What are the data in the* `ToothGrowth` *data set?*

2.12.2 Referencing columns

When referencing a column (vector) in a data frame both the data frame and column name must be specified. The `$` operator is used to separate the data frame and column name.

```r
trees$Girth
```

```
##  [1]  8.3  8.6  8.8 10.5 10.7 10.8 11.0 11.0 11.1 11.2 11.3 11.4 11.4
## [14] 11.7 12.0 12.9 12.9 13.3 13.7 13.8 14.0 14.2 14.5 16.0 16.3 17.3
## [27] 17.5 17.9 18.0 18.0 20.6
```

The `$` operator can also be used to reference a new column in a data frame. In the following example the girth (circumference) is being used to estimate the cross-sectional area.

```
trees$Area <- trees$Girth^2/(4 * pi)
summary(trees)
```

```
##      Girth           Height       Volume           Area
##  Min.   : 8.3   Min.   :63   Min.   :10.2   Min.   : 5.48
##  1st Qu.:11.1   1st Qu.:72   1st Qu.:19.4   1st Qu.: 9.72
##  Median :12.9   Median :76   Median :24.2   Median :13.24
##  Mean   :13.2   Mean   :76   Mean   :30.2   Mean   :14.73
##  3rd Qu.:15.2   3rd Qu.:80   3rd Qu.:37.3   3rd Qu.:18.55
##  Max.   :20.6   Max.   :87   Max.   :77.0   Max.   :33.77
```

Exercise 16 *Add a column* `Diameter` *to* `trees` *bearing in mind that* `pi` *is the ratio of the circumference (girth) to the diameter.*

3 RStudio

Thus far you have been using R through its Graphical User Interface (GUI). However a number of third-party programs provide more powerful Integrated Development Environments (IDEs) for interfacing with R. I recommend RStudio - the desktop version of which can be downloaded from http://rstudio.org/download/desktop. Like R, RStudio is free and open source. The remainder of this course is taught assuming you are using RStudio.

3.1 Console

By default the pane in the bottom left of RStudio is the R console. You can enter expressions in the console in the same way you have been entering expressions in the R console in the R GUI.

3.2 Workspace

The first window in the top right pane provides an interface for viewing and manipulating the objects in the workspace.

3.3 History

The second window in the top right panel allows you to view and copy the expressions you have executed at the console.

3.4 Packages

Everything in the S language is an object - even the functions and operators. With the exception of the workspace, all of the available objects are contained within packages.

To see all the packages that are currently *loaded* on the *search path* type `search()`.

```
search()
```

```
##  [1] ".GlobalEnv"        "package:knitr"     "package:stats"
##  [4] "package:graphics"  "package:grDevices" "package:utils"
##  [7] "package:datasets"  "package:methods"   "Autoloads"
## [10] "package:base"
```

`.GlobalEnv` is the workspace. To see all the objects in a package type `ls("package:package_name")`. For example

```
ls("package:stats")
```

For a detailed description of how R searches and finds objects see http://obeautifulcode.com/R/How-R-Searches-And-Finds-Stuff/.

To see all the packages that are currently *installed* on your computer go to the Packages window in the bottom right pane of RStudio. Packages that are currently loaded are selected.

You can load an installed package by selecting it or by typing `library(package_name)` at the console.

Exercise 17 *Load the package* ***foreign****. What arguments does the function* ***read.dbf*** *in the* ***foreign*** *package take?*

To view the packages on the Comprehensive R Archive Network (CRAN) website that are currently available to install on your computer go to http://cran.r-project.org/web/packages/available_packages_by_name.html.

You can install a package from the CRAN site onto your computer by clicking Install on the Packages window and entering its name or alternatively by typing `install.packages("package_name")`?

Exercise 18 *Install the package* ***ggplot2*** *onto your computer and then load it. What arguments does the function* ***ggplot*** *take.*

Other packages are available from GitHub. To install a package from a GitHub repository you need to first load the `devtools` package and then use the `install_github` function. The following code demonstrates how to install (and load) version v0.4 of the `datalist` package from https://github.com/poissonconsulting/datalist.

```
install.packages("devtools")
library(devtools)
install_github("poissonconsulting/datalist@v0.4")
library(datalist)
```

Exercise 19 *Install the latest version of the* ***jaggernaut*** *package from GitHub at https://github.com/poissonconsulting/jaggernaut. As it uses a number of GitHub packages you should follow the installation instructions on the README file.*

3.5 Working Directory

Each R session is associated with a folder on your computer that is referred to as the working directory. To view the contents of the working directory go to the Files window in the bottom right pane. To change the working directory use the **Choose Directory...** suboption of the **Set Working Directory** option from the **Session** menu in the global toolbar. Alternatively use the functions `getwd()` and `setwd()`.

Exercise 20 *Create a new folder on your desktop called RCourse and make this folder the working directory. To ensure you have been successful confirm that the output of* ***getwd()*** *refers to your RCourse folder.*

3.6 Projects

Instead of setting the working directory each time you restart RStudio you can associate the contents of a folder with a *project* - then all you have to do is to select the project.

To create a new project use the **New Project** command (available on the **File** menu of the global toolbar).

Exercise 21 *Create a new project called RCourse in the RCourse folder on your desktop. As the folder already exists choose the* ***Create project from: Existing Directory*** *option. To confirm you were successful quit RStudio and double-click the RCourse.Rproj file in the RCourse folder - RStudio should restart with RCourse as the working directory.*

4 Transferring Data

4.1 Comma Separated Files

The simplest way to input and output data is in the form of comma separated files. Comma separated files, which have the suffix **.csv**, are recognised by almost all statistical and spreadsheet programs including `R`.

The following code creates a `data.frame` stocks, prints the first 6 rows using `head()` and saves it to the working directory as a csv file called `StocksMissing`.

```
stocks <- data.frame(time = 1:10, X = seq(-2, 3, length.out = 10), Y = 3:12,
    Z = -10:-1)

head(stocks)

write.csv(stocks, "StocksMissing.csv", row.names = FALSE)
```

Exercise 22 *Run the line of code above and then open the StocksMissing csv file in a spreadsheet program and replace the first five values in the* `X` *column with* `NA`*. Now use the* `read.csv` *function to import the StocksMissing csv file into the workspace. Use the* `na.omit` *function to delete the missing values. What happens to the data frame when the missing values are deleted?*

5 Manipulating Data

The **dplyr** package provides functions for manipulating data frames. Four key functions are:

- filter: chose a subset of rows based on conditions
- select: chose a subset of columns based on names
- arrange: sort rows
- mutate: add new columns

Exercise 23 *What does each of the following lines of R code do to the ToothGrowth data frame?*

```
install.packages("dplyr")
library(dplyr)

ToothGrowth <- filter(datasets::ToothGrowth, len < 30)
ToothGrowth <- mutate(datasets::ToothGrowth, len2 = len * 2)
ToothGrowth <- select(datasets::ToothGrowth, supp, dose)
ToothGrowth <- arrange(datasets::ToothGrowth, dose, supp, len)
```

The code fragment `datasets::` indicates that the following object must be taken from the datasets package. This can be useful for ensuring R uses the correct object if multiple objects with the same name exist in the search path. Later I use it to remind the reader that a particular package must be loaded to run the code.

If the functions were nested the code would look like the following which is almost unreadable.

```
ToothGrowth <- arrange(select(mutate(filter(datasets::ToothGrowth, len <
    30), len2 = len * 2), len2, supp, dose), dose, supp, len2)
```

To improve readability, the same operations can be joined in left to right order using the forward-pipe operator `%>%` (pronounced 'then') in the `magrittr` package to

```
install.packages("magrittr")
library(magrittr)

ToothGrowth <- datasets::ToothGrowth %>% filter(len < 30) %>% mutate(len2 = len *
    2) %>% select(len2, supp, dose) %>% arrange(dose, supp, len2)
```

The `dplyr` functions together with those in the `tidyr` package can be used to to clean and tidy data where

> data cleaning focusses on observations and data tidying focusses on variables

In tidy data:

1. Each variable forms a column.
2. Each observation forms a row.
3. Each type of observational unit forms a table.
4. Multiple tables include a column(s) that allow them to be linked.

The following code uses the `tidyr::gather` function to convert the a data frame from wide to long format so that it satisfies the first condition.

```
install.packages("tidyr")
library(tidyr)
```

```
dayCount <- data.frame(day = 1:3, year1 = seq(-3, -4, length.out = 3),
    year2 = 4:6, year3 = -1:1)
dayCount
```

```
##   day year1 year2 year3
## 1   1  -3.0     4    -1
## 2   2  -3.5     5     0
## 3   3  -4.0     6     1
```

```
dayCount <- gather(dayCount, year, count, -day)
dayCount
```

```
##   day  year count
## 1   1 year1  -3.0
## 2   2 year1  -3.5
```

```
## 3   3 year1  -4.0
## 4   1 year2   4.0
## 5   2 year2   5.0
## 6   3 year2   6.0
## 7   1 year3  -1.0
## 8   2 year3   0.0
## 9   3 year3   1.0
```

The complement to `tidyr::gather()` is the `tidyr::spread` function.

```
spread(dayCount, year, count)
```

```
##   day year1 year2 year3
## 1   1  -3.0     4    -1
## 2   2  -3.5     5     0
## 3   3  -4.0     6     1
```

Exercise 24 *What happens if you filter negative prices from the gathered* `dayCount` *data frame before spreading?*

6 Programming

6.1 Scripts

Rather than entering expressions into R one by one at the command line, a more efficient method is to type the expressions into a text file called a *script* and then send all of them to R at the same time. R scripts are indicated by the suffix `.R` or less commonly `.r`.

Open a new script using the R Script suboption of the New option in the File menu. Next paste the following expressions into the script.

```
# this is a comment!
graphics.off()
rm(list = ls())

summary(datasets::trees)
```

Now save the script in your working directory as `trees.R`. Finally type Command-A to select the entire script then Command-Enter to send it to the console.

Congratulations you've written and executed your first script. The first line is a comment - R ignores it. The second line closes any open graphics windows while the second line removes all objects from the workspace so that the script is starting with a blank slate.

6.2 Coding

For some reason some people still work in farenheit. The following equation converts a temperature in farenheit (F) to celsius (C).

$$C = (F - 32) * 5/9$$

Exercise 25 *Append code to the* `trees.R` *script to convert 45 farenheit to celcius. Note The correct answer is 7.22.*

Exercise 26 *Now use the code to convert the following temperatures in farenheit to celcius: 0 , 32, 64 and 100.*

For further information on R coding style see http://stat405.had.co.nz/r-style.html.

6.3 Functions

R's power stems from its extensibility - users can easily write their own functions. The following code defines a function `farenheit_to_kelvin` which converts a temperature in farenheit to kelvins. The inspiration for this example came from Software Carpentry's novice R bootcamp material.

```
farenheit_to_kelvin <- function(farenheit) {
    kelvin <- ((farenheit - 32) * 5/9) + 273.15
    return(kelvin)
}
```

The first line tells R that `farenheit_to_kelvin` is a function that takes a single argument named `farenheit`. The squiggly brackets tell R where the function definition starts and ends. The first line of code in the function definition converts `farenheit` to `kelvin` while the second and last line tells the function to return the value of `kelvin`.

Exercise 27 *Paste the code into a script and then execute it. What happens? Now type* `farenheit_to_kelvin`*. What happens? Finally type* `farenheit_to_kelvin(c(0, 32))`*. What happens now?*

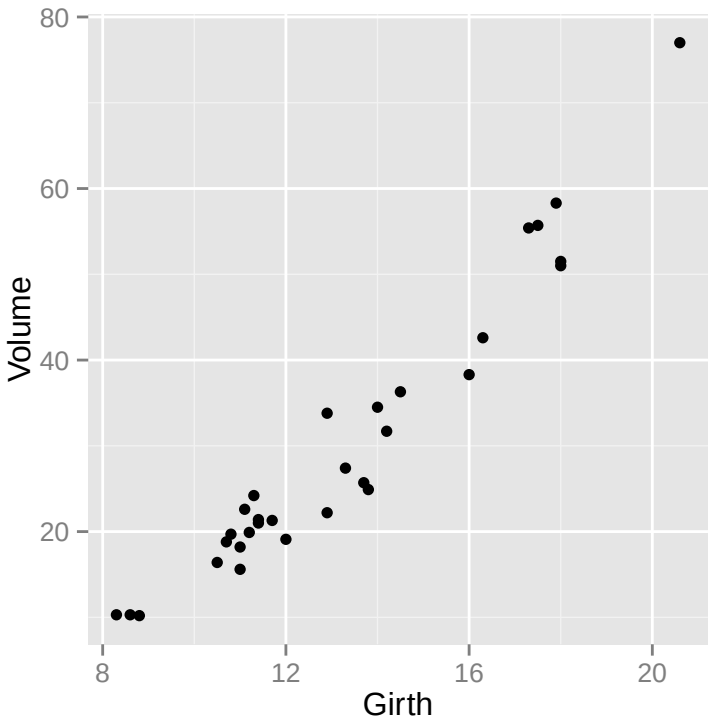
7 Graphics

The `ggplot2` library provides a family of functions for producing high-quality graphics within a unified conceptual framework.

7.1 Geoms

The following code produces a scatterplot of `Volume` on the y-axis against `Girth` on the x-axis for the `trees` data frame. The first line of code loads the `ggplot2` library while the second line specifies the data and relationships of interest. The third line indicates the method (geom) for representing the relationships among the data while the last line plots the ggplot object (in this case `gp`). Note: the same plot can be produced using the `ggplot2::qplot` wrapper function thus `qplot(Girth, Volume, data = trees)`.

```
library(ggplot2)
gp <- ggplot(data = trees, aes(x = Girth, y = Volume))
gp <- gp + geom_point()
print(gp)
```



Exercise 28 *What happens if you replace* `geom_point` *with* `geom_line`*?*

Exercise 29 *And what happens if you add both geoms to the* `gp` *object?*

The available geoms are documented at http://docs.ggplot2.org/current/.

7.2 Windows

By default plots are printed to the Plots window in the bottom right pane of RStudio. To create a new graphics window use the `windows()` function, where by default the width and height are both 7 inches. If working with the Mac or Linux Operating systems use the `quartz()` or `X11()` function, respectively.

The most recent ggplot object to have been created or modified or plotted can be saved in the working directory using the `ggsave` function. For example to save it as a 4 by 4 inch 600 dots per inch (dpi) Portable Network Graphics (png) file called trees type `ggsave("trees.png",width=4,height=4,dpi=600)`. 600 dpi png files are recommended for inclusion in word documents.

If the number of open windows becomes unwieldy the command `graphics.off()` can be used to close all the graphics windows.

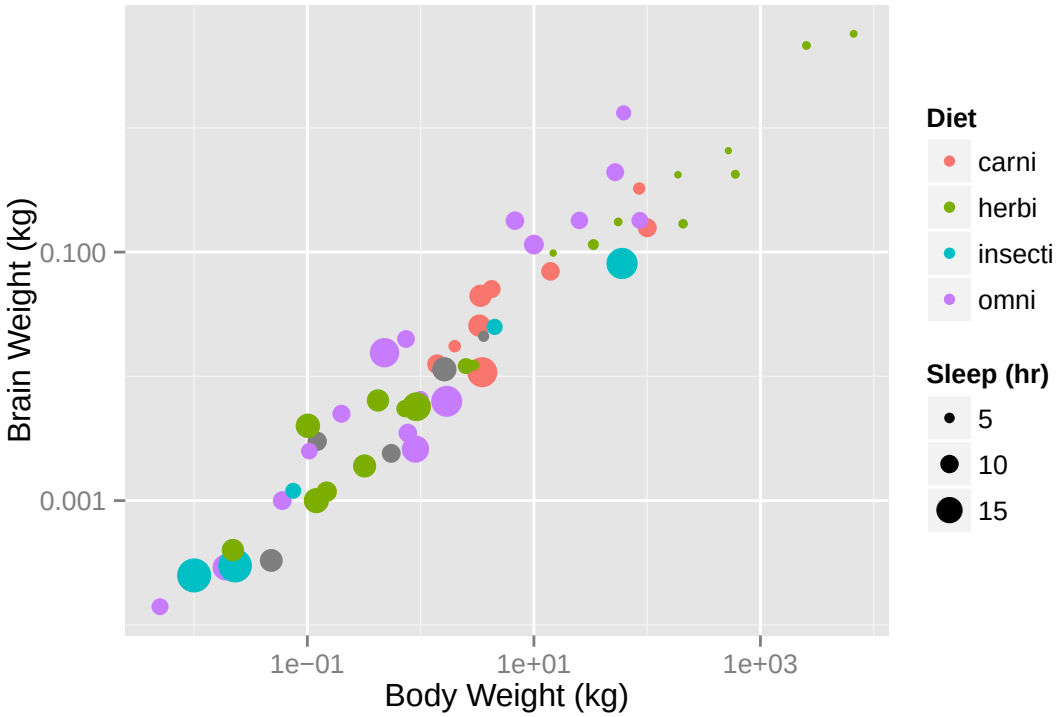
7.3 Scales

Whereas geoms define the method for representing relationships between data, *scales* control the mapping from data to visual properties such as colour, shape, position and size. These visual properties are referred to as aesthetics.

For example consider the `msleep` dataset in the ggplot2 library.

```
gp <- ggplot(data = msleep, aes(x = bodywt, y = brainwt, size = sleep_total,
    colour = vore))
gp <- gp + geom_point()
gp <- gp + scale_x_continuous(name = "Body Weight (kg)", trans = "log10")
```

```
gp <- gp + scale_y_continuous(name = "Brain Weight (kg)", trans = "log10")
gp <- gp + scale_size_continuous(name = "Sleep (hr)")
gp <- gp + scale_color_discrete(name = "Diet")
gp
```



The above code overides the default positional scales for the x and y data with `log10` scales and provides meaningful names. The following code replaces the default discrete color scale with manual values where the color is matched to the diet type.

```
gp <- gp + scale_colour_manual(name = "Diet", values = c(carni = "red",
    herbi = "green3", omni = "brown", insecti = "black"))
```

Exercise 30 *Create a new script called* `ToothGrowth.R` *and produce a plot of the* `ToothGrowth` *data for inclusion in a word report.*

The following ggplot2 functions might be helpful.

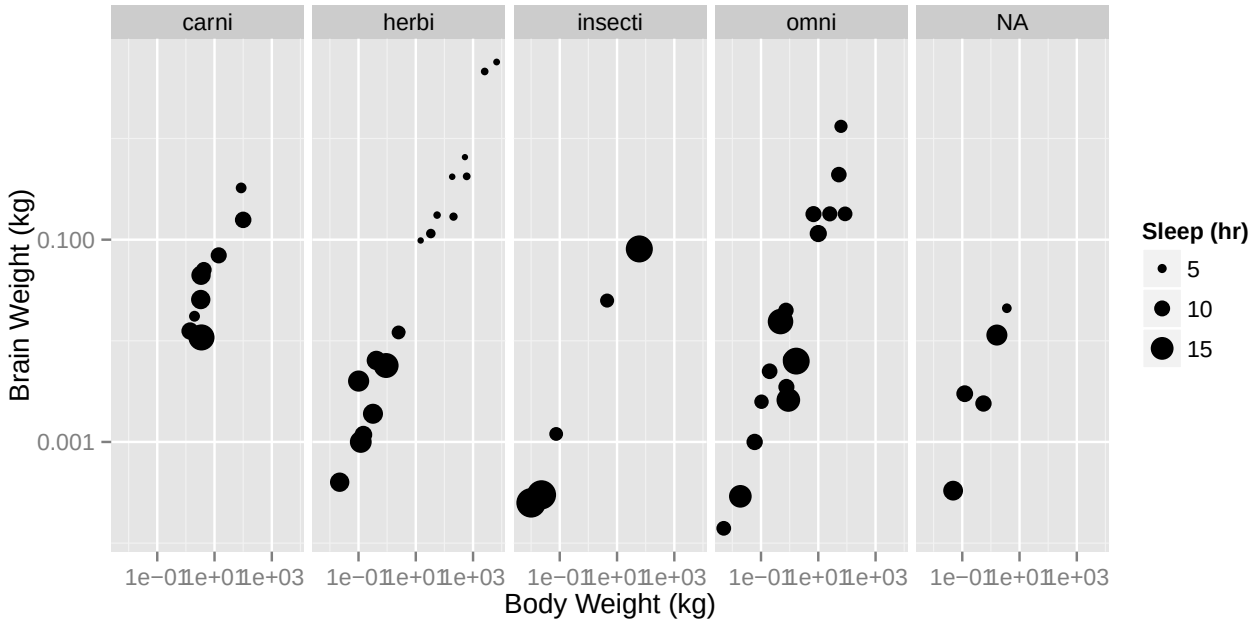
```
geom_jitter(position = position_jitter(width = 0.1))
expand_limits(x = c(0, 2.5))
```

7.4 Facets

One of the most powerful features of the ggplot2 package is its ability to *facet* plots. As an example consider the following plot. What does it suggest to you about the relationship between diet and sleep?

```
gp <- ggplot(data = msleep, aes(x = bodywt, y = brainwt, size = sleep_total))
gp <- gp + facet_grid(. ~ vore)
gp <- gp + geom_point()
gp <- gp + scale_x_continuous(name = "Body Weight (kg)", trans = "log10")
```

```
gp <- gp + scale_y_continuous(name = "Brain Weight (kg)", trans = "log10")
gp <- gp + scale_size_continuous(name = "Sleep (hr)")
print(gp)
```



Exercise 31 *Modify your* `ToothGrowth.R` *script so that it produces a second plot facetted by* `supp`*.*

7.5 Themes

The appearance of non-data elements in a ggplot plot is controlled by the theme system. To see the settings for the current theme type `theme_get()`. To globally change to the black and white theme use the following code:

```
theme_set(theme_bw())
```

Alternatively theme parameters can be set for specific ggplot objects using the `theme()` function. The following code modifies the theme for the current object so that grid lines are not plotted

```
gp <- gp + theme(panel.grid.major = element_blank(), panel.grid.minor = element_blank())
```

Exercise 32 *Alter your* `ToothGrowth.R` *script so that it produces a third plot using the black and white theme without grid lines.*

8 Linear Models

8.1 Linear regression

The basic linear regression model can be expressed as

$$y_i = \alpha + \beta x_i + \epsilon_i$$

where α is the intercept and β is the slope and the error terms (ϵ_i) are independent and normally distributed with equal variance.

The following code fits the basic linear regression model where `Volume` is the response and `Girth` is the predictor for the `trees` data set and prints a summary of the model.

```
mod <- lm(Volume ~ Girth, data = trees)
summary(mod)
```

```
##
## Call:
## lm(formula = Volume ~ Girth, data = trees)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -8.065 -3.107  0.152  3.495  9.587
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -36.943      3.365   -11.0  7.6e-12 ***
## Girth          5.066      0.247    20.5  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 4.25 on 29 degrees of freedom
## Multiple R-squared:  0.935,  Adjusted R-squared:  0.933
## F-statistic:  419 on 1 and 29 DF,  p-value: <2e-16
```

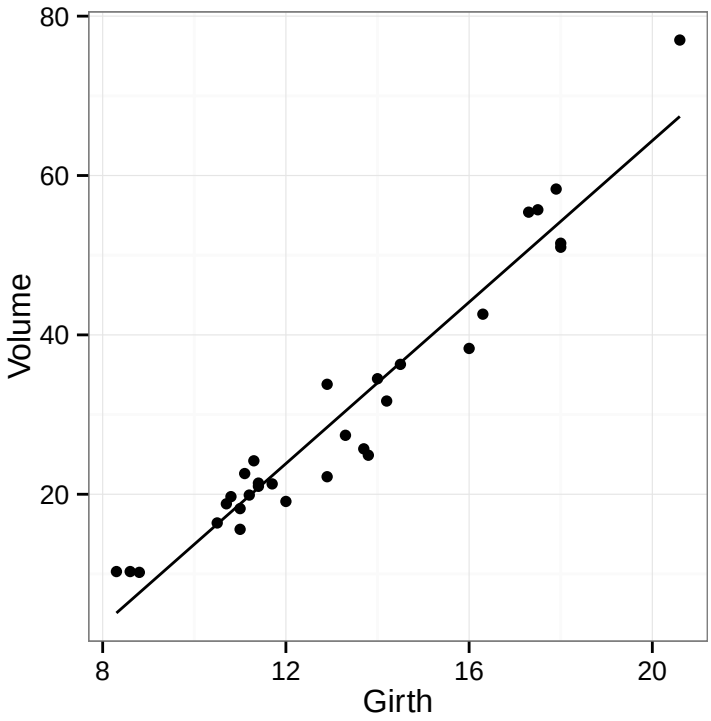
The model sumary indicates (among other things) that the intercept is -36.9 and the slope is 5.1.

8.2 Fitted values

A general approach for plotting the fitted values for any model is to generate the predicted values for a new data set that covers the range of values of interest and then add them to the plot. New data sets can be easily generated using the `new_data` function of the `datalist` package.

```
library(datalist)
newdata <- datalist::new_data(trees, "Girth")
newdata$Volume <- predict(mod, newdata = newdata)

gp <- ggplot(data = trees, aes(x = Girth, y = Volume))
gp <- gp + geom_point()
gp <- gp + geom_line(data = newdata)
print(gp)
```

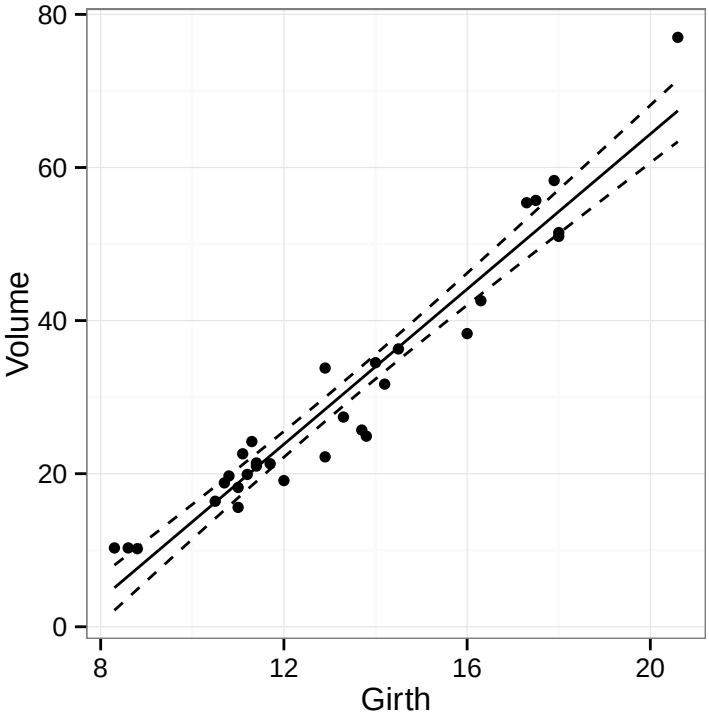


Exercise 33 *Step through the above code line by line and document what each line is doing.*

8.3 Confidence intervals

95% confidence intervals can added to the plot using the same approach.

```
pred <- data.frame(predict(mod, newdata, interval = "conf"))
newdata <- cbind(newdata, pred)
gp <- gp + geom_line(data = newdata, aes(y = lwr), linetype = "dashed")
gp <- gp + geom_line(data = newdata, aes(y = upr), linetype = "dashed")
print(gp)
```



8.4 Prediction intervals

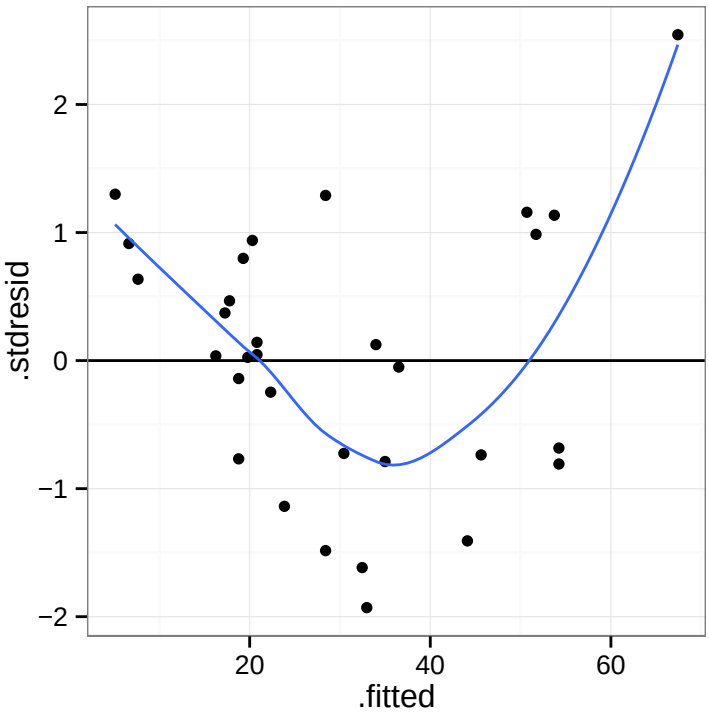
Prediction intervals can be calculated by setting the `interval` argument in the `predict` function to be `"pred"`. Roughly speaking, confidence intervals represent the uncertainty surrounding the underlying relationship whereas prediction intervals represent the uncertainty surrounding new individual observations.

Exercise 34 *Modify your* `trees.R` *script so that it fits a linear model to* `Volume` *against* `Girth` *and plots the observed data with confidence and prediction intervals.*

8.5 Model Fit

A linear regression model is only valid if its residuals are consistent with the assumed error structure. A diagnostic plot can be produced using the following code.

```
qplot(.fitted, .stdresid, data = mod) + geom_hline(yintercept = 0) + geom_smooth(se = FALSE)
```



Exercise 35 *What does the previous diagnostic plot suggest to you?*

The previous code works because the `fortify` function has been defined for `lm` objects. For further examples of diagnostic plots see http://docs.ggplot2.org/current/fortify.lm.html.

The relationship between `Volume` and `Girth` is expected to be allometric because the cross-sectional area at an given point scales to the square of the girth (circumference).

Exercise 36 *Try fitting an allometric relationship by `log` transforming `Volume` and `Girth` and then using the same basic linear regression model. Does the diagnostic plot suggest an improvement in the model?*

8.6 ANCOVA

The basic ANCOVA (analysis of covariance) model includes one categorical and one continous predictor variable without interactions. It can be expressed algebraically as follows

$$y_{ij} = \alpha_i + \beta x_j + \epsilon_{ij}$$

where α_i is the intercept for the i_{th} group mean and β is the slope and the error terms (ϵ_{ij}) are independent and normally distributed with equal variance.

The following code fits the basic ANCOVA model to the `ToothGrowth` data and prints a summary table.

```
mod <- lm(len ~ supp + dose, data = ToothGrowth)
summary(mod)
```

```
##
## Call:
## lm(formula = len ~ supp + dose, data = ToothGrowth)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
```

```
## -6.600 -3.700  0.373  2.116  8.800
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)    9.272      1.282    7.23  1.3e-09 ***
## suppVC        -3.700      1.094   -3.38   0.0013 **
## dose           9.764      0.877   11.14  6.3e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 4.24 on 57 degrees of freedom
## Multiple R-squared:  0.704,  Adjusted R-squared:  0.693
## F-statistic: 67.7 on 2 and 57 DF,  p-value: 8.72e-16
```

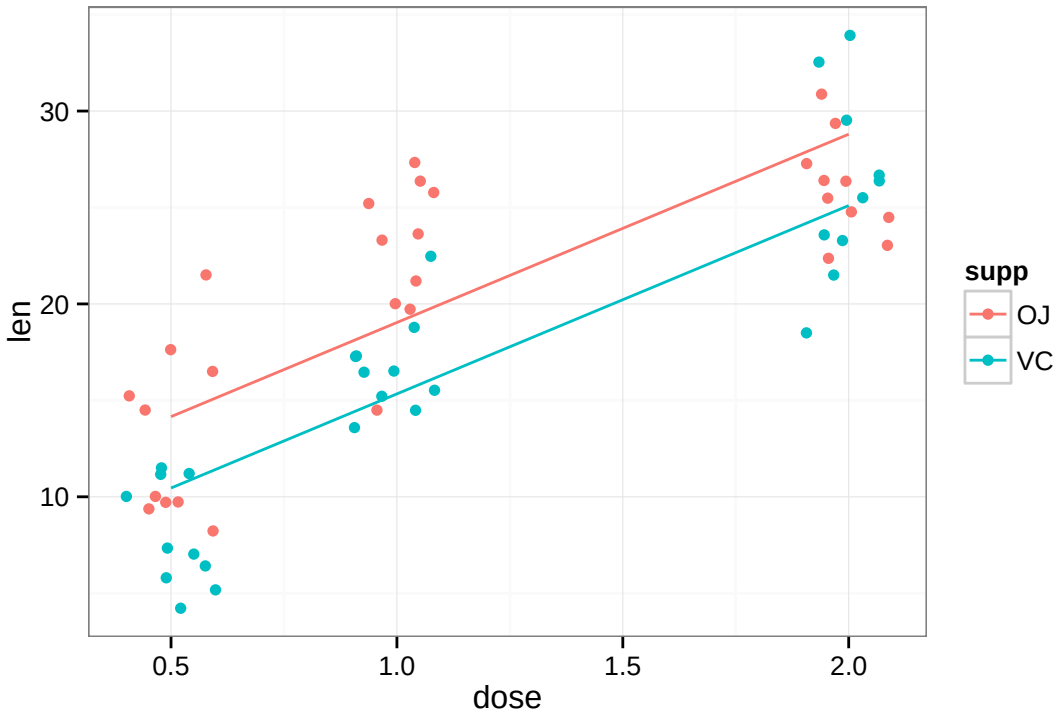
The model's coefficients indicate that the slope of the line is 9.3 and that `VC` is 3.7 less than `OJ`.

Exercise 37 *Are the model's residuals consistent with the assumed error structure?*

The fitted values for both levels of `supp` can be added to the scatterplot of `len` against `dose` using the same general approach as for the `tree` data set.

```
newdata <- datalist::new_data(ToothGrowth, c("dose", "supp"))
newdata$len <- predict(mod, newdata = newdata)

gp <- ggplot(data = ToothGrowth, aes(x = dose, y = len, colour = supp))
gp <- gp + geom_point(position = position_jitter(width = 0.1))
gp <- gp + geom_line(data = newdata, aes(group = supp))
print(gp)
```



Exercise 38 *Modify your script so that it adds the predicted line for both levels of* `supp` *to the scatter plot of the* `ToothGrowth` *data using the previous code.*

The following code fits three additional models corresponding to the ANOVA model with just `supp`, the linear regression model with just `dose` and the ANCOVA model with an interaction between `dose` and `supp`.

```
mod2 <- lm(len ~ supp, data = ToothGrowth)
mod3 <- lm(len ~ dose, data = ToothGrowth)
mod4 <- lm(len ~ dose * supp, data = ToothGrowth)
```

Exercise 39 *Modify your script so that it fits all four competing models and then each model's predictions (along with the raw data) in separate windows.*

Exercise 40 *Which model provides the best fit to the data? Functions you might find useful are* ***anova*** *and* ***AIC****.*

9 Model Formulae and Functions

This section lists the various functions and formulae required to fit a range of linear, generalized linear, generalized additive, and generalized additive mixed models.

```
lm(y~1) # one sample t-test
lm(y~x) # basic linear regression
lm(y~fac) # one-way ANOVA
lm(y~x-1) # basic linear regression through the origin (with no intercept term)
lm(y~x+I(x^2)) # polynomial (quadratic) regression
lm(y~x1+x2) # multiple regression
lm(y~x1+x2+x1:x2) # multiple regression with interaction
lm(y~fac1+fac2) # two-way ANOVA
lm(y~x1+fac2) # ANCOVA
nlme::lme(y~x1,random=~1|fac) # linear mixed model
glm(y~x1,family=binomial) # logistic regression
mgcv::gam(y~s(x),family=poisson) # generalized additive model
mgcv::gamm(y~s(x),random=~1|fac,family=Gamma) # generalized additive mixed model
```

9.1 Additional Analyses

Exercise 41 *Analyse the* ***chickwts*** *data set. To what extent is diet a predictor of body weight? Represent your model fit graphically.*

Exercise 42 *Analyse the* ***msleep*** *data set in the* ***ggplot2*** *package. To what extent are body weight and diet predictors of brain weight? Are carnivores brainier than herbivores?*

10 R Course Cheat Sheet

Operator	Description
`-`	Subtraction. *Usage*: `x - y`
`;`	Separate lines. *Usage*: `x <- 1; y <- 2`
`::`	Specify package of object. *Usage*: `datasets::trees`
`??`	Search help files. *Usage*: `??topic`

Operator	Description
`?`	Help file. *Usage*: `?function_name`
`(`	Bracket. *Usage*: `x*(y+z)`
`*`	Multiplication. *Usage*: `x * y`
`/`	Division. *Usage*: `x / y`
`^`	Power. *Usage*: `x^y`
`+`	Addition. *Usage*: `x + y`
`<-`	Assignment. *Shortcut*: **alt-**. *Usage*: `x <- y`
`$`	Reference column in data.frame. *Useage*: `x$y`
`magrittr::%>%`	Forward pipe operations. *Useage*: `x %>% sum()`

Math Function	Description
`cumsum`	Cumulative sum. *Usage*: `cumsum(x)`
`exp`	Exponential. *Usage*: `exp(x)`
`log`	Logarithm. *Usage*: `log(x, base = 10)`
`mean`	Average. *Usage*: `mean(x, na.rm = TRUE)`
`sqrt`	Square-root. *Usage*: `sqrt(x)`

Vector Function	Description
`as.factor`	Coerce to factor. *Useage*: `as.factor(x)`
`as.numeric`	Coerce to numeric. *Useage*: `as.factor(x)`
`c`	Concatenate. *Usage*: `c(1, -3, 5)`
`length`	Length. *Usage*: `length(seq(2, 5))`
`seq`	Sequence. *Usage*: `seq(1, 4)`

data.frame Function	Description
`cbind`	Combine two data.frames by columns.
`data.frame`	Create data.frame.
`data`	List available data sets.
`datalist::new_data`	Dummy data set.
`dplyr::arrange`	Sort rows.
`dplyr::filter`	Chose a subset of rows based on conditions.
`dplyr::mutate`	Add new columns.
`dplyr::select`	Chose a subset of columns based on names.
`head`	Chose first six rows.

data.frame Function	Description
`na.omit`	Delete missing values.
`read.csv`	Input from csv file.
`tidyr::gather`	Convert from wide to long format
`tidyr::spread`	Convert from long to wide format
`write.csv`	Output as csv file.

Graphics Function	Description
`ggplot2::element_blank`	Blank value for a theme element.
`ggplot2::expand_limits`	Expand scale limits to include specified values.
`ggplot2::facet_grid`	Break plot into facets by variables.
`ggplot2::geom_hline`	Represent values with horizontal lines.
`ggplot2::geom_jitter`	Represent values with points plus random spread.
`ggplot2::geom_line`	Represent values with lines.
`ggplot2::geom_point`	Represent values with points.
`ggplot2::geom_smooth`	Represent values with smoothers.
`ggplot2::ggplot`	Set data.frame and aesthetic mappings for ggplot graphic object.
`ggplot2::ggsave`	Save current plot.
`ggplot2::qplot`	Quick wrapper for ggplot and geom_point.
`ggplot2::scale_color_discrete`	Set discrete color scale attributes.
`ggplot2::scale_color_manual`	Set manual color scale attributes.
`ggplot2::scale_size_continuous`	Set continuous size scale attributes.
`ggplot2::scale_x_continuous`	Set continuous x position scale attributes.
`ggplot2::scale_y_continuous`	Set continuous y position scale attributes.
`ggplot2::theme_get`	Get current theme for graphics.
`ggplot2::theme_set`	Set current theme for graphics.
`ggplot2::theme`	Set theme element for current graphic object.
`graphics.off`	Close all graphics windows.
`windows`	New graphics window. Use `quartz()` or `X11()` for OSX or linux

Model Function	Description
`AIC`	Akaike's Information Criterion for one or more models.
`anova`	Analysis of variance tables for one or more models.
`lm`	Fit linear model. *Useage*: `lm(y ~ x, data = data)`
`predict`	Predict response values for model.

General Function	Description
`class`	Class of object. *Usage*: `class(x)`
`devtools::install_github`	Install package from GitHub.
`getwd`	Get working directory. *Useage*: `getwd()`.
`install.packages`	Install package(s) from CRAN. *Useage*: `install.packages('pkg_name')`
`library`	Load installed package. *Useage*: `library(package_name)`
`ls`	Objects in workspace or package. *Usage*: `ls(); ls(2)`
`print`	Print to console or draw graphics object in window
`rm`	Remove object(s) from workspace. *Usage*: `rm(x)`; `rm(list = ls())`
`search`	Loaded packages. *Useage*: `search()`
`setwd`	Set working directory. *Useage*: `setwd('path_to_dir')`
`summary`	Summary of object. *Useage*: `summary(x)`