

Foundational Statistics - Bi 610 - Spring 2020

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Contents

| | |
|---|-----------|
| 1 Course Overview | 5 |
| 2 Introduction to the course | 7 |
| 2.1 Instructors | 7 |
| 2.2 Course Information | 7 |
| 2.3 Software | 7 |
| 2.4 Inclusion and Accessibility | 7 |
| 3 Course Schedule | 9 |
| 3.1 Weeks 1-2 | 9 |
| 3.2 Week 3 | 9 |
| 3.3 Week 4 | 10 |
| 3.4 Week 5 | 10 |
| 3.5 Week 6 | 10 |
| 3.6 Week 7 | 10 |
| 3.7 Week 8 | 10 |
| 3.8 Week 9 | 11 |
| 3.9 Week 10 | 11 |
| 4 Background material for the course | 13 |
| 4.1 Description of the course | 13 |
| 4.2 Course goals: | 14 |
| 4.3 Introduction to R and RStudio | 14 |
| 5 Organizing and manipulating data files | 17 |
| 5.1 Introduction | 17 |
| 5.2 Navigating file systems from the command line | 18 |
| 5.3 Data file and data file entry dos and don'ts | 24 |
| 5.4 Exercises associated with this chapter: | 25 |
| 5.5 Additional learning resources | 25 |
| 6 An Introduction to the R language | 27 |
| 6.1 Background | 27 |
| 6.2 Why use R? | 27 |

| | | |
|----------|---|-----------|
| 6.3 | Important R terms and definitions | 29 |
| 6.4 | Getting started with R via the RStudio Environment | 30 |
| 6.5 | Exercises associated with this chapter: | 39 |
| 6.6 | Additional learning resources: | 39 |
| 7 | More R Functions, Complex Objects, Basic Plotting, and RMarkdown | 41 |
| 7.1 | Background | 41 |
| 7.2 | More on functions | 41 |
| 7.3 | Indexing vectors | 44 |
| 7.4 | More complex data objects in R | 45 |
| 7.5 | Some brief notes on basic programming in R | 50 |
| 7.6 | Fundamentals of plotting in R | 53 |
| 7.7 | A brief introduction to RMarkdown | 60 |
| 7.8 | Experiment with headers | 61 |
| 7.9 | Exercises associated with this chapter: | 62 |
| 7.10 | Additional learning resources: | 62 |

Chapter 1

Course Overview

This is the complete set of *course materials* for the *Foundational Statistics Course* at the University of Oregon for the Spring of 2020. It is written in **Markdown** so that it can be easily updated.

In this book you will find nearly all the information you will need to complete the course.

Chapter 2

Introduction to the course

This is the complete set of *course materials* for the *Foundational Statistics Course* at the University of Oregon for the Spring of 2020. It is written in **Markdown** so that it can be easily updated.

In this book you will find nearly all the information you will need to complete the course.

2.1 Instructors

Dr. Clay Small, csmall@uoregon.edu

Dr. Bill Cresko, wcresko@uoregon.edu

2.2 Course Information

Virtual Office Hours: T-R 12 to 1:30 (Zoom)

2.3 Software

- Latest version of R
- Latest version of RStudio

2.4 Inclusion and Accessibility

Please tell us your preferred pronouns and/or name, especially if it differs from the class roster. We take seriously our responsibility to create inclusive learning environments. Please notify us if there are aspects of the instruction or design of this course that result in barriers to your participation! You are also encouraged

to contact the Accessible Education Center in 164 Oregon Hall at 541-346-1155 or uoaec@uoregon.edu.

We are committed to making this course an inclusive and respectful learning space. Being respectful includes using preferred pronouns for your classmates. Your classmates come from a diverse set of backgrounds and experiences; please avoid assumptions or stereotypes, and aim for inclusivity. Let us know if there are classroom dynamics that impede your (or someone else's) full engagement.

Because of the COVID-19 pandemic, this course is being delivered entirely remotely. We realized that this situation makes it difficult for some students to interact with the material, for a variety of reasons. We are committed to flexibility during this stressful time and emphasize that we will work with students to overcome difficult barriers as they arise.

Please see this page for more information on campus resources, academic integrity, discrimination, and harassment (and reporting of it).

Chapter 3

Course Schedule

3.1 Weeks 1-2

1. Data organization and management
 - best practices, reproducibility, etc.
2. Basic programming fundamentals for data curation
 - The Unix environment and fundamental commands
 - Formatting and manipulating tabular text files from the terminal
3. Introduction to R and Rstudio
 - Installation/Updates
 - R object types and assignment
4. Practice with R objects
 - vectors, matrices, data frames, etc.
5. Applying core programming fundamentals in R
 - vectorized operations
 - replicate, apply family, ifelse, for loops, etc.

3.2 Week 3

1. Plotting/visualizing data as a means of exploration
 - Different plot types
 - Scale, transformations, etc.
2. Fundamentals of plotting in base R
 - par
 - using palettes, points, sizes, etc. to convey information
 - axes and labels
3. R markdown

3.3 Week 4

1. Population parameters, samples, and sampling distributions
 - Central Limit Theorem and the normal dist.
 - Mean and st. dev.
2. Probability and probability distributions
3. Calculating summary statistics
 - Other common summary statistics (quantiles, etc.)

3.4 Week 5

1. Parameter estimation
 - Simulating data sets with known parameters
 - Revisit probability distributions
2. Uncertainty in estimation
 - Parametric and nonparametric approaches to uncertainty

3.5 Week 6

1. Experimental design
 - lexicon
 - considering sources of variance
 - types of variables (categorical, ordinal, rational)
 - confounding variables
2. Frequentist hypothesis testing
 - error types
 - p-values
 - degrees of freedom
 - statistical power
 - multiple testing problem

3.6 Week 7

1. Comparing means between groups
 - Student's t-test
2. Bootstrapping and randomization to compare means

3.7 Week 8

1. Relationships between quantitative variables
 - correlation and covariance

2. Simple linear regression
 - residuals and least squares
 - fitting linear regression models

3.8 Week 9

1. Analysis of variance
 - Table components and test statistics
2. General linear models in R
 - Model formulae
 - Interpretation of summary output
3. More complex ANOVA frameworks
 - Nested models
 - Factorial models

3.9 Week 10

1. Frequency-based statistical tests
 - Chi-squared tests
 - Contingency tables and tests of independence
2. Brief introduction to generalized linear models (time permitting)
 - logistic regression

Chapter 4

Background material for the course

4.1 Description of the course

This course is an introduction to data management, data visualization, and statistical inference. It is intended for early-stage graduate students with no background in statistics. No prior coursework (undergraduate or graduate) in statistics or programming is assumed. The primary objective of the course is to get students up to speed with respect to organization, manipulation, visualization, and analysis of data, using the R statistical language. The emphasis on application is strong, with the goal of enabling students (after the course) to analyze their own data sets with confidence using reasonable approaches, and, when faced with more difficult analysis problems, to be able to communicate their inference objectives clearly to expert analysts. Students will learn to organize and analyze data sets in the form of RStudio projects, using R Markdown files to reproducibly capture and render code, visualizations, and analyses. In-class exercises will be delivered in the form of pre-formatted R Notebooks, which can be interactively executed by students without having to write all code from scratch.

The course is designed to acquaint students primarily with univariate (single response variable) analysis. Multivariate analysis will be covered in the Advanced Biostatistics 2-course series offered during the Fall and Winter terms. Examples and assignments in class will include data sets primarily from the biological sciences, including studies of morphological and molecular traits, behaviors, ecological questions, and clinical studies. For specific statistical topics covered in class, please see the course goals and tentative schedule below.

4.2 Course goals:

- Properly organize and format primary data and metadata files for analysis
- Learn programming fundamentals of the R statistical language, including objects, functions, iteration, and simulation.
- Make publication-quality data visualizations, including scatterplots, box-plots, frequency distributions, mosaic plots, etc.
- Understand Type I and Type II statistical error, including p-values and power analysis.
- Understand ordinary least-squares regression and linear models in general
- Learn the fundamentals of strong experimental design
- Learn to apply general linear models to basic univariate analysis problems, including Analysis of Variance (ANOVA)
- Learn nonparametric approaches to parameter estimate and statistical inference, including resampling (bootstrapping), permutation, and rank-based analysis.
- Understand how to analyze binary response variables and frequency-based (e.g. contingency table) data sets.

4.3 Introduction to R and RStudio

R is a core computational platform for statistical analysis. It was developed a number of years ago to create an open source environment for advanced computing in statistics and has since become the standard for statistical analysis in the field, replacing commercial packages like SAS and SPSS for the most part. Learning R is an essential part of becoming a scientist who is able to work at the cutting edge of statistical analysis – or even to perform conventional statistical tests (e.g. a t-test) in a standard way. An important part of R is that it is script-based, which makes it easy to create reproducible analysis pipelines, which is an emerging feature of the open data/open analysis movement in science. This is becoming an important component of publication and sharing of research results, so being able to engage fully with this effort is something that all young scientists should do.

RMarkdown is an extra layer placed on top of R that makes it easy to integrate text explanations of what is going on, native R code/scripts, and R output all in one document. The final result can be put into a variety of forms, including webpages, pdf documents, Word documents, etc. Entire books are now written in RMarkdown and its relatives. It is a great way to make quick webpages, like this document, for instance. It is very easy to use and will be the format that I use to distribute your assignments to you and that you will use to turn in your assignments.

R Projects are a simple way of designating a working directory in which to house files related to a given, well, project. Those files might include primary data and metadata files ready for reading into R, .R scripts, Rmarkdown files, and

output such as Rmarkdown-rendered .html files or individual plots, for example. The nice thing about organizing your work with R Projects is that you can keep everything needed to reproduce an analysis in a single directory on your computer. You can open an R Project in RStudio by opening the project's index (.RProj) file, which will automatically set your working directory to that of the project and facilitate loading any saved environments, etc.

In Chapter 6 we will begin working in R and RStudio, but you can get them installed now (in that order) on your computer, if you haven't already. Get the most recent *released* R version by following this link: <https://www.r-project.org/>

We will do our work using Rstudio, which is a powerful and convenient user interface for R, and can be downloaded from here for installation: <https://rstudio.com/products/rstudio/>

4.3.1 Learning resources

There are tons of resources for learning R and RMarkdown on the internet. Here are just a few, but you will no doubt find your own favorites as you become routine R users.

There is an organized group that is dedicated to training in R called DataCamp (<https://www.datacamp.com/>). They provide all of the basics for free. They actually have training for most data science platforms. RStudio provides links for training directly related to R and RMarkdown here: <https://www.rstudio.com/online-learning/>

There are also many, many R training videos on YouTube. Most of them are very well meaning but may not be as in-depth as you want.

You can also go the old "paper" manual route by reading the materials provided by R itself: <https://cran.r-project.org/doc/manuals/r-release/R-intro.pdf>

In reality, if you want to do almost anything in R, simply type in what you are interested in doing into Google and include "in R" and a whole bunch of links telling you exactly what to do will magically appear. Most of them appear as discussions on websites like StackOverflow and Stats.StackExchange. In that case, the first thing that you see is the question—usually someone doing it just a bit wrong—so you should scroll down to see the right way to do it in the answers. It is really an amazing resource that will speed you along in nearly every form of analysis that you are interested in.

Please do not hesitate to contact us if you have questions or run into obstacles. The point of this class is to learn by doing, but our aim is that the doing should involve reasonable first efforts supplemented with help if needed. Also, many of your classmates have some experience with R, writing code, or statistics in general, so they are an excellent resource as well!

Chapter 5

Organizing and manipulating data files

5.1 Introduction

Many of you will already be familiar with data file organization, editing, and formatting for analysis. If so, much of the following material may be review. If not, some of the following guidelines and tools should prove to be quite useful. In biology, and many other fields, primary data are routinely stored as “flat” text files. The exact formatting depends on the type of data, of course, but often we are working with text files organized into rows and columns. Rows can naturally be defined by lines in a file, and columns can be defined by separators (also called delimiters) such as spaces, tabs, or commas, to name a few commonly used ones. Fortunately there are some very powerful and simple-to-use (with a little practice) tools that can be invoked directly from a computer’s command line, or included in written “scripts” that your computer’s operating system can interpret upon you running them. These command line tools are now nearly ubiquitous on all personal computer platforms. Computers running a LINUX operating system allow direct access to these tools via the command line, as does the macOS operating system of Apple computers via the Terminal. Computers running Microsoft Windows 10 now also facilitate use of these conventional “UNIX tools” through a Windows Subsystem for Linux.

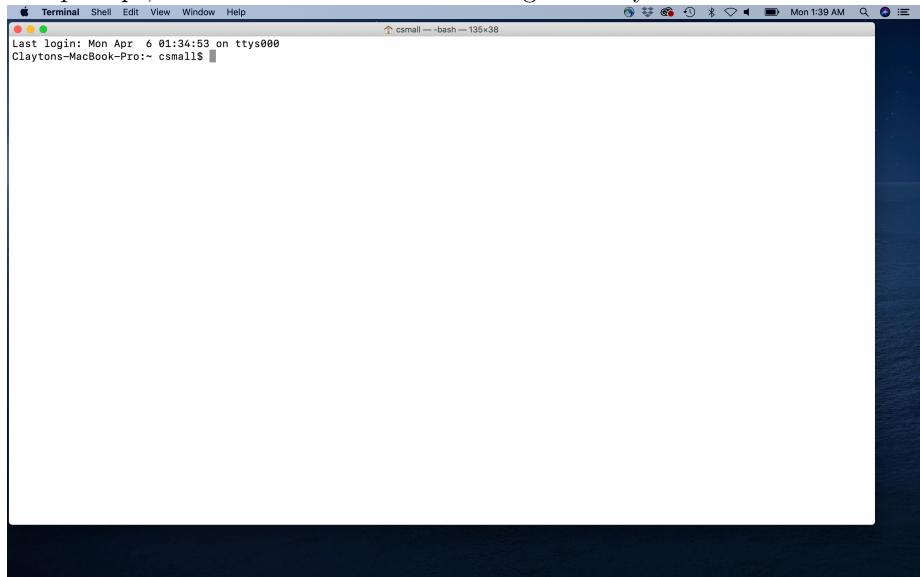
In the following sections, we provide a *very brief* introduction to using some of these tools in order to organize your data files, parse them for information, and perform some basic text manipulations. Mastering these activities is not necessary for this course (in fact, many of the text manipulation tasks can be done in R!), but if you learn to adopt at least some of these skills you will become a better, more organized analyst, and it will help you become comfortable with the command line and programming in general.

5.2 Navigating file systems from the command line

5.2.1 Access to the command line

The first step to using command line tools is to get access to the command line! On Mac and Linux systems you can simply do this by finding and opening the `Terminal` application. On Windows 10 systems, you'll have to install a Linux Bash Shell if you haven't already. To do this you will need to follow the instructions here: <https://itsfoss.com/install-bash-on-windows/> When you get to the point of choosing the Linux distribution to install, I recommend Ubuntu.

At this point you should have command line access through a terminal prompt, which should look something like my Mac Terminal below:



You are now ready to navigate and explore files simply by typing!

5.2.2 Navigating directories and files

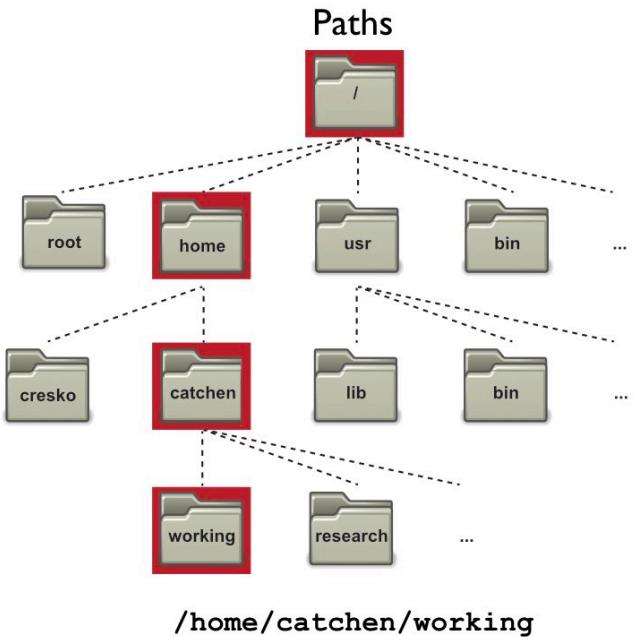
When you are at the command line, just think of your computer as you would if you were navigating using a graphical application (e.g. Mac Finder or Windows Explorer). You are always in a directory in your file system, and you can move to any other directory by typing the appropriate command and destination, then hitting Enter.

The first crucial UNIX command to learn is `pwd`. This command stands for “print working directory,” and it will literally print the path of the directory you are currently in.

Another important command is `ls`. This lists the files and directories (by default) in your working directory. If you specify a different directory, it will list the files and/or directories there. Most UNIX commands (and indeed command-line programs in general), can be run with options. One way to invoke the `and` option is to type a “flag” along with the command. In the case of `ls`, we can type `ls -l`, for example, which will print the output line-by-line. We can also add another flag: `ls -lh` (equivalent to `ls -l -h`), which will print items line-by-line but also make sure the item sizes are “human readable.” If you ever have questions about how to use UNIX program, including the flags and other options, you can type `man program_name` and a wonderful help manual will appear. To exit and return to the command prompt, just hit “q”. These `man` pages are extremely useful and should be your first go-to if you need information for a particular command. Please use these regularly!

The command `cd` will change your location from the current directory to another directory. Like many other programs (UNIX and otherwise) require you to input directory and file locations, with `cd` you can specify your desired location using either the *absolute* or *relative* path. An absolute path is the full “address” of a directory or file, starting from the root of your file system. An example of an absolute path to a directory in my file system is `/Users/csmall/Dropbox/sculpin_project/images/`. Regardless of where my current working directory is in my file system, I can change to this `images/` directory using `cd` and the full path. I can also use a relative path, which is a sort of “shortcut,” to specify the location of a directory or file. Let’s say I am in `/Users/csmall/Dropbox/BiostatsFound_S2020/` and I want to get to the `images/` directory above. I could type `cd ../sculpin_project/images`, which uses a relative path to take me “up” one directory (as denoted by `..`) into `Dropbox/` and back “down” into `sculpin_project/images`. In fact, `..` is a special file in every directory that just means “the directory above.” The special file `.` is the current directory. And to mention one final useful designation for navigation shortcuts, you can use the `~` to denote your home directory.

The schematic below should help you visualize how to think about file system



navigation from the command line:

And for another example, take a look at this series of navigation commands from

```

Last login: Mon Apr  6 01:34:53 on ttys000
Claytons-MacBook-Pro:~ csmall$ pwd
/Users/csmall
Claytons-MacBook-Pro:~ csmall$ ls -l
total 0
drwxr-x-- 3 csmall  staff   96 Sep 23  2019 Applications
drwxrwxr-x@ 4 csmall  staff  128 Apr  4 10:34 Creative Cloud Files
drwxr-----@ 8 csmall  staff  256 Apr  6 01:40 Desktop
drwxr-----@ 40 csmall  staff  1472 Mar 26 08:00 Documents
drwxr-x--@ 144 csmall  staff  3888 Apr  4 18:35 Downloads
drwxr-x--@ 8 csmall  staff  240 Apr  5 10:40 Library
drwxr-xr-x@ 27 csmall  staff  864 Apr  5 19:40 Genius 2020.1 Data
drwxr-----@ 72 csmall  staff  2304 Jan 27 18:34 Library
drwxr-----@ 4 csmall  staff  128 Dec 19 08:43 Movies
drwxr-----@ 5 csmall  staff  160 Dec 19 08:43 Music
drwxr-----@ 6 csmall  staff  192 Dec 18 11:47 Pictures
drwxr-xr-x+ 4 csmall  staff  128 Jul 29  2019 Public
drwxr-xr-x@ 451 csmall  staff  14432 Oct  1  2019 git
drwxr-xr-x@ 7 csmall  staff  224 Apr  5 20:34 github_repos
drwxr-xr-x@ 8 csmall  staff  256 Jul 27  2018 1gv
drwxr-xr-x@ 1 csmall  staff  64 Mar 22 12:18 juicebox/
Claytons-MacBook-Pro:~ csmall$ cd juicebox/
Claytons-MacBook-Pro: juicebox csmall$ pwd
/Users/csmall/juicebox
Claytons-MacBook-Pro: juicebox csmall$ cd ..
Claytons-MacBook-Pro:~ csmall$ pwd
/Users/csmall
Claytons-MacBook-Pro:~ csmall$ cd Dropbox/sculpin_project/images
Claytons-MacBook-Pro:images csmall$ pwd
/Users/csmall/Dropbox/sculpin_project/images
Claytons-MacBook-Pro:images csmall$ cd ../../..
Claytons-MacBook-Pro:~ csmall$ pwd
/Users/csmall
Claytons-MacBook-Pro:~ csmall$ ls -lh /Users/csmall/Dropbox/sculpin_project/images
total 0
-rw-r--r--@ 1 csmall  staff  1,9M Feb 23 2018 Cplexus_lab_2018.JPG
Claytons-MacBook-Pro:~ csmall$ █

```

my terminal and see if you can follow along:

If you want to create a new directory, you can use the `mkdir` command, including the desired name of the new directory. By default this will create the directory in your current working directory, but you can use absolute or relative paths to instead write the directory somewhere else. If you want to delete an empty

directory, `rmdir` is the appropriate command.

Now let's briefly cover some UNIX commands that are useful for managing files. Some of these apply to directories as well, which I will point out as we go. The command `touch` can be used to create a new, empty file, which you can add to using a plain text editor. Examples of popular plain text editors with advanced user interfaces are BBEdit and Atom. You can also use command line text editors, such as `nano`, `emacs`, and `vim`. Most UNIX/LINUX systems have `nano` installed by default. To copy or change the name and/or location of a file (or directory), use `cp` and `mv` commands, respectively. Note that by using absolute or relative paths, you can specify where you want the file or directory to end up. Be especially careful with these, however, because you will overwrite any existing file or directory if you specify the same name and location. Another command you should be extremely cautious with is `rm`, which removes (permanently deletes) a file. `rm -r` can be used to delete a non-empty directory AND all of its contents.

In many cases you will want to look at files, or parts of them at least, from the command line. `cat` will print the entire contents of a file, but can also be used to combine ("concatenate") multiple files in a line-wise manner. `less` and `more` will display specific lines of a file (starting with the first ones), with single- or multi-line "scrolling," respectively, activated using the return or down-arrow keys. To leave the display, you need to hit the "q" key. `head` and `tail` will display the first or last, respectively, n lines of the file, where n is provided as a flag (e.g. `head -200 file.tsv`). The "word count" command `wc` can quantify elements of a text file in various ways, but one common application is `wc -l`, which counts the number of lines in a file.

An aside: If you are working from the command line and want to terminate a process (say you accidentally start a task that will take way too long), press Ctrl-C.

5.2.2.1 A quick review of important UNIX commands for navigation and viewing

`pwd` - prints working directory

`ls` - lists contents of a directory

`cd` - changes the working directory

`mkdir` - creates a new directory

`rmdir` - deletes an empty directory

`touch` - creates an empty file

`cp` - copies a file or directory

`mv` - changes the name of a file or directory

rm - deletes a file, or a directory and everything inside with **-r**
cat - prints the entire file to the terminal, or concatenates and prints multiple files
less - displays the first lines of a file, with scrolling line-by-line
head - prints the first 10 lines (default) of a file
tail - prints the last 10 lines (default) of a file
wc -l - prints the number of lines in a file

5.2.3 Useful UNIX commands for file manipulation

In many cases you will want to search for specific characters or combinations of characters, and do various things with that information. Maybe you want to isolate the lines of a file that contain the query, or perhaps you want to count how many lines contain the query. The tool **grep** is extremely useful in this regard. We don't have time for a comprehensive dive into the utilities of **grep**, but a few common applications are worth mentioning. Character patterns we search for using **grep** may or may not involve special characters that are not interpreted literally. Here we will discuss just a few common cases of **grep** searches and the special characters involved. Some examples of these special characters include **^** (beginning of a line), **\$** (end of a line), **.** (any single character except a newline), ***** (zero or more instances of the preceding character), and **\s** (any whitespace). The standard syntax for **grep** from the command line is **grep "expression" filename**. So, if you wanted to return all of the lines in the data file **zfish_data.tsv** (assuming it is in the current directory) that begin with "embryo_10", you could try **grep "^embryo_10" zfish_data.tsv**. This search would also (unintentionally) find lines beginning with "embryo_100" or "embryo_101", etc., if they exist. So, you have to be careful, and learning the rules just takes practice. In this case **grep "^embryo_10\s" zfish_data.tsv** would achieve the desired result, assuming that there is a whitespace delimiter between fields ("columns") in the data file. Useful flags for **grep** include **-c** (which counts the number of lines containing the query), **-v** (which returns the lines that *do not* contain the query), and **-n** (which prints the line number for each line containing the query). I encourage you to look at many different **grep** use cases online as your demand for complex searches grows.

The program **sed** has reasonably complex applications, but is commonly used as a sort of "search and replace" tool. The syntax for **sed** use is similar to **grep**, except that the query and replacement expressions are organized (with other information) using slashes. For "search and replace" functionality, the syntax looks like this: **sed 's/query/replacement/flag' filename**. One common option for the "flag" component is "g", meaning "global", which replaces all instances. If no flag designation is made only the first instance in the file is replaced. Building on our toy example from above, **sed 's/^embryo_/_larva_/g' zfish_data.tsv** would perform a global

replacement and print the output to the terminal. To change the contents in the original file on the fly, including `sed -i` would do the trick, but is riskier than redirecting the output to a new file.

`cut` is quite straightforward, and can be used to isolate individual fields (think of them like “columns”) from a text file, provided the fields are consistently separated by a delimiter on each line. So, if I had a comma-separated file and I just wanted the first two columns I could type `cut -f1,2 -d"\t" filename`. Note that if you don’t specify a delimiter using the `-d` flag, then it is assumed to be tab-delimited. If you want to bring together fields in separate files, `join` can be used to accomplish this. The two files should have equivalent rows, however, for this action to work properly.

If you want to sort text files alphanumerically, in a field-wise fashion, `sort` is quite useful. If a file contains a single field, minimal specification is required, aside from tuning numerical sorting. For example, if you want to sort numerically, use the `-n` flag, and if you want to sort from largest to smallest, add the `-r` flag. If you want to sort a multi-field file based on just one field, you can use the “key” flag. For instance, if you have a tab-delimited file and want to sort by the second field in reverse numerical order, `sort -k2,2 -nr filename.tsv` would give you the desired result. Finally, if you want to eliminate lines with the same value for a given field, you can use the `-u` “unique” flag.

The UNIX program `awk` is an extremely powerful tool, and can itself be used essentially as a mini programming language. We will not get into the myriad uses of `awk` here, but the reference at the bottom of the chapter is a great resource if you want to learn more. `awk` is extremely efficient at parsing and capturing text files in a column-wise manner, with the ability to also evaluate logical statements applied to rows. The structure of `awk` commands is more complex than that of other UNIX programs we have discussed, but it is still very intuitive. One unique feature is that `awk` contains its own internal functions, which are typed inside curly braces. The “print” function can be used to extract fields, much like `cut`. For instance, `awk -F: '{print $1,$6}' filename.tsv` would print the first and sixth field from `filename.tsv`, assuming a “:” delimiter. With `awk`, fields are specified using the `$` character. If you want also to select only specific rows from a set of columns (like those with a certain value), you can incorporate logical operators. In the above example if we had wanted fields 1 and 6, but only those rows with a value of at least 610 in field 4, we could type the following `awk -F: '$4 >= 610 {print $1,$6}' filename.tsv`. Again, this is just scratching the surface with `awk`, which boasts a great deal of potential for your text file manipulation needs.

5.2.3.1 A quick review of key UNIX commands for text file searching and manipulation

`grep` - searches a file for characters and character combinations

`sed` - stream edits characters and character combinations

`cut` - isolates specific fields (“columns”) from a file using a delimiter

`join` - combines fields (“columns”) from multiple files with equivalent rows

`sort` - orders the rows in a file based on one or more fields

`awk` - flexibly parses, evaluates, and selectively prints row- and column-wise

5.2.4 A quick word on pipes and carrots

One very convenient feature of UNIX commands is that you can control the flow of input and output from one command to another using the `|` (“pipe”) character. For instance, I may want to search an entire file for rows that begin with “fish-1”, and then replace the `-` with `_`. To do this I could do something like `cat file.tsv | grep "fish-1" | sed 's/fish-1/fish_1/g'` This, of course, would print the output to the terminal, but I could actually capture that output into a file using the `>` character. `cat filename | grep "fish-1" | sed 's/fish-1/fish_1/g' > ./newfile.tsv` would write this new file to my current working directory. Furthermore, if you want to append lines of text to an existing file, the “double sideways right-pointing carrot” character `>>` can be used.

The above lessons on UNIX commands for file manipulation truly just scratch the surface of what can be accomplished at the command line and in “shell scripts.” You certainly will have further questions and be hungry for more, but we simply don’t have time during this course. But to work on your UNIX skills for now, check out `Ex1_Uncx_Intro.html` (on Canvas). We need to move on to R now, but at the bottom of this chapter are some UNIX command resources I have found to be especially useful.

5.3 Data file and data file entry dos and don’ts

Do store a copy of your data in a nonproprietary format, such as plain ASCII text (aka a flat file). This is especially important if you are using tools (like UNIX commands) to parse and manipulate the files. Formats like Microsoft Excel are not acceptable as input for many analysis tools, and not everyone has access to proprietary software.

Do leave an un-edited copy of an original data file, even when main analyses require an edited version.

Do use descriptive names for your data files and variables, and use them consistently!

Do maintain effective metadata about the data.

Do add new observations to a data file as rows.

Do add new variables to a data file as columns.

Don't include multiple data types in the same column.

Don't use non-alphanumeric characters (other than the underscore) in file or directory names.

Don't use spaces, tabs, commas, colons, semicolons, or other characters commonly used as field (column) delimiters in names of individual data entries. For example, don't use something like `March 8` as a value for date in a data set.

Don't copy and paste data directly from rich-text-formatted files (like Microsoft Word) into primary data files.

5.4 Exercises associated with this chapter:

- Exercise 1 (file: `Ex1_Unix_Intro.html`)

5.5 Additional learning resources

- <http://mally.stanford.edu/~sr/computing/basic-unix.html> - A nice “cheat sheet”
- http://korflab.ucdavis.edu/Unix_and_Perl/ - Outstanding tutorial by Keith Bradnam and Ian Korf
- <https://www.datacamp.com/courses/introduction-to-shell-for-data-science> - DataCamp tutorial
- <https://www.gnu.org/software/gawk/manual/gawk.html> - A comprehensive guide to `awk`

Chapter 6

An Introduction to the R language

6.1 Background

R is a computer programming language and environment especially useful for graphic visualization and statistical analysis of data. It is an offshoot of a language developed in 1976 at Bell Laboratories called S. R is an interpreted language, meaning that every time code is run it must be translated to machine language by the R interpreter, as opposed to being compiled prior to running. R is the premier computational platform for statistical analysis thanks to its GNU open-source status and countless packages contributed by diverse members of the scientific community.

6.2 Why use R?

- Good general scripting tool for statistics and mathematics
- Powerful and flexible and free
- Runs on all computer platforms
- New packages released all the time
- Superb data management & graphics capabilities
- Reproducibility - can keep your scripts to see exactly what was done
- Can embed your R analyses in dynamic, polished files using R markdown
- You can write your own functions
- Lots of online help available
- Can use a nice IDE such as RStudio

Object R is an object oriented language and everything in R is an object. For example, a single number is an object, a variable is an object, output is an object, a data set is an object that is itself a collection of objects, etc.

Vector A collection of one or more *objects* of the same type (e.g. all numbers or all characters etc).

Function A set of instructions carried out on one or more objects. Functions are typically used to perform specific and common tasks that would otherwise require many instructions. For example, the *function* `mean()` is used to calculate the arithmetic mean of the values in a given *numeric vector*. Functions consist of a name followed by parentheses containing either a set of *parameters* (expressed as *arguments*) or left empty.

Parameter The kind of information that can be passed to a function. For example, the `mean()` *function* declares a single required parameter (a valid object for which the mean is to be calculated is a compulsory) as well as a number of optional parameters that facilitate finer control over the function.

Argument The specific information passed to a function to determine how the function should perform its task. Arguments are expressions (in the form of `name=value`) given between the parentheses that follow the name of the function. For example, the `mean()` function requires at least one argument - either the name of an object that contains the values from which the mean is to be generated or a vector of values.

Figure 6.1: Alt text

6.3 Important R terms and definitions

From Logan, M. 2010. *Biostatistical Design and Analysis Using R*

Operators are symbols in programming that have a specific meaning

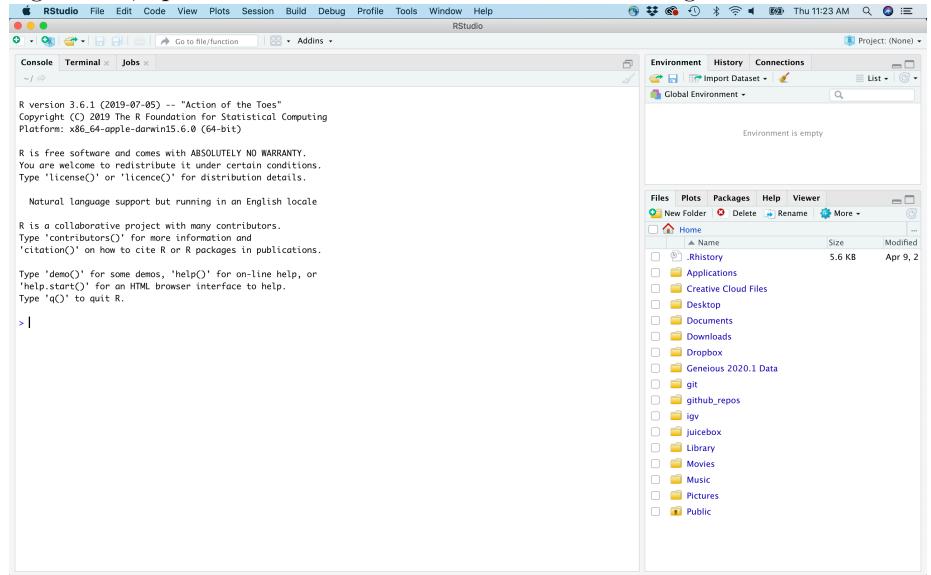
| Operator | Description |
|-----------------|--|
| [[| indexing |
| :: | name space |
| \$ | component |
| ^ | exponentiation (evaluated right to left) |
| - + | sign (unary) |
| : | sequence |
| %special% | special operators (e.g. %/%, %%) |
| * \ | multiplication, division |
| + - | addition and subtraction |
| < > <= >= == != | ordering and comparison |
| ! | logical negation (not) |
| & && | logical AND |
| | logical OR |
| ~ | formula |
| -> ->> | assignment (left to right) |
| = | argument assignment (right to left) |
| <- <<- | assignment (right to left) |
| ? | help |

Figure 6.2: Alt text

From Logan, M. 2010. *Biostatistical Design and Analysis Using R*

6.4 Getting started with R via the RStudio Environment

To begin working with R, open RStudio. You should first see something that

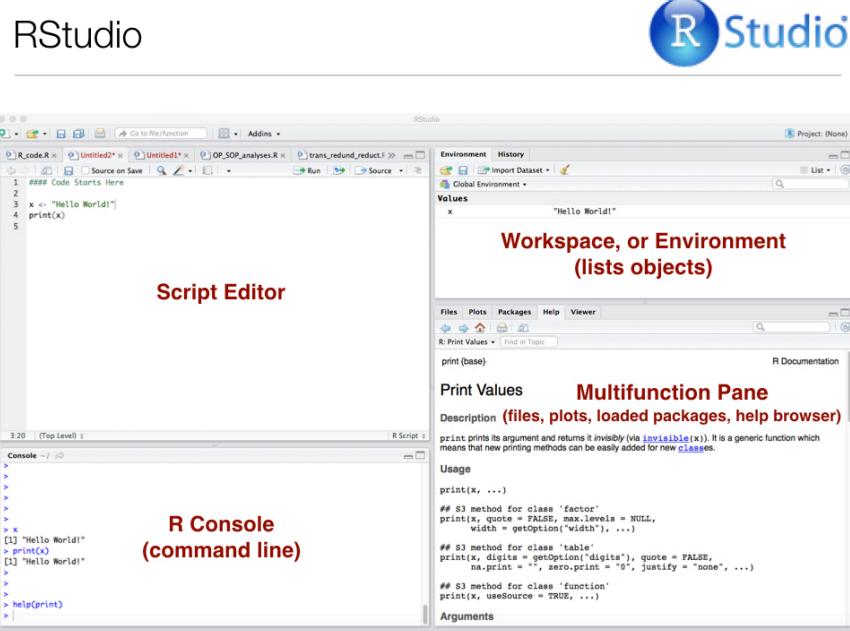


looks like this:

To open a new script editor (where you will keep track of your code and notes), go to File > New File > R Script. Note that there are other options for file types, which we will be using in the future. For now, though, we want a plain script, which when saved will have the extension .R.

It is easy to run code directly from the script editor. For single lines of code, simply make sure your cursor is on that line, and hit Ctrl-Enter. For multiple lines, highlight the block of code you want to run and hit Ctrl-Enter.

Now your display should look something like below (but without the red pane la-



bels, of course):

Note that you can also type commands directly from the command line using the R Console (lower left pane), and the R interpreter will run them when you press Enter.

Any objects you define, and a summary of their values, will appear in the upper right pane, and the lower right pane differs in appearance depending on instructions you provide to R Studio. For instance, if you produce a plot, it will appear there by default. Another extremely important feature of R functions (we'll get to them in a bit) is the help file. Recall from Chapter 5 our discussion of `man` pages for UNIX programs. Help files the equivalent for R functions. They contain almost everything you need to know about a given function, and most of them even include an example at the bottom. These help files will appear in the lower right RStudio pane when you call them, for example when you run `help(function_name)` at the R Console.

6.4.1 R Programming Basics

For the code examples below, it might be useful for you to start your own RStudio session, open a new .R file and type/run code while reading.

- Commands can be submitted through the terminal, console or scripts
- In your scripts, anything that follows # symbol (aka hash) is just for humans
- Notice on these slides I'm evaluating the code chunks and showing output

- The output is shown here after the two # symbols and the number of output items is in []
- Also notice that R follows the normal priority of mathematical evaluation

4*4

```
## [1] 16
(4+3*2^2)
```

```
## [1] 16
```

6.4.1.1 A note on R Markdown

This format provides a much better way to embed code and output, in an easily readable, reproducible manner. We will dive into R Markdown next week, so for now just be aware that it exists.

- http://kbroman.org/knitr_knutshell/pages/Rmarkdown.html
- You can insert R chunks into Rmarkdown documents

6.4.1.2 Assigning Variables

- To “store” information for later use, like the arithmetic operation above, we can assign variables in R.
- Variables are assigned values using the `<-` operator.
- Variable names must begin with a letter, and should not contain spaces or R operators (see above) but other than that, just about anything goes.
- Do keep in mind that R is case sensitive.

```
x <- 2
x * 3
```

```
## [1] 6
```

```
y <- x * 3
```

```
y - 2
```

```
## [1] 4
```

These do not work

```
3y <- 3
3*y <- 3
```

6.4.1.3 Arithmetic operations with functions

- Arithmetic operations can be used with functions as well as numbers.
- Try the following, and then your own.

```
x+2
x^2
log(x) + log(x+1)
```

- Note that the last of these - `log()` - is a built in function of R, and therefore the argument for the function (in this case “x” or “x+1”) needs to be put in parentheses.
- These parentheses will be important, and we’ll come back to them later when we add other arguments after the object in the parentheses.
- The outcome of calculations can be assigned to new variables as well, and the results can be checked using the `print()` function.

```
y <- 67
print(y)

## [1] 67

x <- 124
z <- (x*y)^2
print(z)

## [1] 69022864
```

6.4.1.4 Strings

- Assignments and operations can be performed on characters as well.
- Note that characters need to be set off by quotation marks to differentiate them from numeric objects.
- The `c(function)` stands for ‘concatenate’.
- Note that we are using the same variable names as we did previously, which means that we’re overwriting our previous assignment.
- A good general rule is to use new names for each variable, and make them short but still descriptive

```
x <- "I Love"
print (x)

## [1] "I Love"

y <- "Biostatistics"
print (y)

## [1] "Biostatistics"

z <- c(x,y)
print (z)
```

```
## [1] "I Love"           "Biostatistics"
```

The variable z is now a vector of character objects.

6.4.1.5 Factors

- Sometimes we would like to treat character objects as if they were units for subsequent calculations.
- These are called factors, and we can redefine our character object as one of class factor.
- This might seem a bit strange, but it's important for statistical analyses where we might want to calculate the mean or variance for two different treatments. In that case the two different treatments would be coded as two different “levels” of a factor we designate in our metadata. This will become clear when we get into hypothesis testing in R.

```
z_factor <- as.factor(z)
print(z_factor)
class(z_factor)
```

Note that factor levels are reported alphabetically. I used the `class()` function to ask R what type of object “z_factor” is. `class()` is one of the most important tools at your disposal. Often times you can debug your code simply by changing the class of an object. Because functions are written to work with specific classes, changing the class of a given object is crucial in many cases.

6.4.1.6 Vectors

- In general R thinks in terms of vectors (a list of characters factors or numerical values) and it will benefit any R user to try to write programs with that in mind.
- R operations, and therefore functions, are vectorized.
- This means an operation or function will be performed for each element in a vector.
- Vectors can be assigned directly using the ‘c()’ function and then entering the exact values.

```
x <- c(2,3,4,2,1,2,4,5,10,8,9)
print(x)
```

```
## [1] 2 3 4 2 1 2 4 5 10 8 9
x_plus <- x+1
print(x_plus)
```

```
## [1] 3 4 5 3 2 3 5 6 11 9 10
```

- Creating vectors of new data by entering it by hand can be a drag.
- However, it is also very easy to use functions such as `seq()` and `sample()`.
- Try the examples below. Can you figure out what the three arguments in the parentheses mean?
- Within reason, try varying the arguments to see what happens

```

seq_1 <- seq(0.0, 10.0, by = 0.1)
print(seq_1)

## [1] 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
## [16] 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9
## [31] 3.0 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0 4.1 4.2 4.3 4.4
## [46] 4.5 4.6 4.7 4.8 4.9 5.0 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9
## [61] 6.0 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 7.0 7.1 7.2 7.3 7.4
## [76] 7.5 7.6 7.7 7.8 7.9 8.0 8.1 8.2 8.3 8.4 8.5 8.6 8.7 8.8 8.9
## [91] 9.0 9.1 9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9 10.0

seq_2 <- seq(10.0, 0.0, by = -0.1)
print(seq_2)

## [1] 10.0 9.9 9.8 9.7 9.6 9.5 9.4 9.3 9.2 9.1 9.0 8.9 8.8 8.7 8.6
## [16] 8.5 8.4 8.3 8.2 8.1 8.0 7.9 7.8 7.7 7.6 7.5 7.4 7.3 7.2 7.1
## [31] 7.0 6.9 6.8 6.7 6.6 6.5 6.4 6.3 6.2 6.1 6.0 5.9 5.8 5.7 5.6
## [46] 5.5 5.4 5.3 5.2 5.1 5.0 4.9 4.8 4.7 4.6 4.5 4.4 4.3 4.2 4.1
## [61] 4.0 3.9 3.8 3.7 3.6 3.5 3.4 3.3 3.2 3.1 3.0 2.9 2.8 2.7 2.6
## [76] 2.5 2.4 2.3 2.2 2.1 2.0 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1
## [91] 1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0

seq_square <- (seq_2)*(seq_2)
print(seq_square)

## [1] 100.00 98.01 96.04 94.09 92.16 90.25 88.36 86.49 84.64 82.81
## [11] 81.00 79.21 77.44 75.69 73.96 72.25 70.56 68.89 67.24 65.61
## [21] 64.00 62.41 60.84 59.29 57.76 56.25 54.76 53.29 51.84 50.41
## [31] 49.00 47.61 46.24 44.89 43.56 42.25 40.96 39.69 38.44 37.21
## [41] 36.00 34.81 33.64 32.49 31.36 30.25 29.16 28.09 27.04 26.01
## [51] 25.00 24.01 23.04 22.09 21.16 20.25 19.36 18.49 17.64 16.81
## [61] 16.00 15.21 14.44 13.69 12.96 12.25 11.56 10.89 10.24 9.61
## [71] 9.00 8.41 7.84 7.29 6.76 6.25 5.76 5.29 4.84 4.41
## [81] 4.00 3.61 3.24 2.89 2.56 2.25 1.96 1.69 1.44 1.21
## [91] 1.00 0.81 0.64 0.49 0.36 0.25 0.16 0.09 0.04 0.01
## [101] 0.00

seq_square_new <- (seq_2)^2
print(seq_square_new)

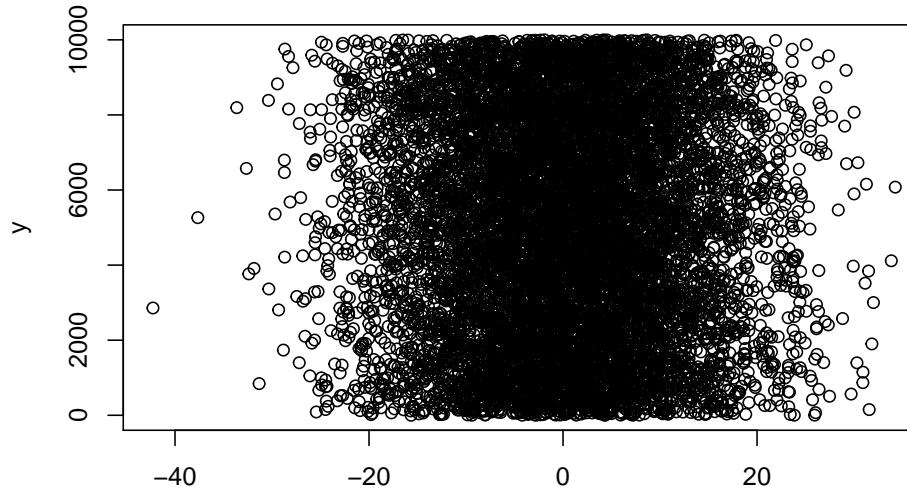
## [1] 100.00 98.01 96.04 94.09 92.16 90.25 88.36 86.49 84.64 82.81

```

```
## [11] 81.00 79.21 77.44 75.69 73.96 72.25 70.56 68.89 67.24 65.61
## [21] 64.00 62.41 60.84 59.29 57.76 56.25 54.76 53.29 51.84 50.41
## [31] 49.00 47.61 46.24 44.89 43.56 42.25 40.96 39.69 38.44 37.21
## [41] 36.00 34.81 33.64 32.49 31.36 30.25 29.16 28.09 27.04 26.01
## [51] 25.00 24.01 23.04 22.09 21.16 20.25 19.36 18.49 17.64 16.81
## [61] 16.00 15.21 14.44 13.69 12.96 12.25 11.56 10.89 10.24 9.61
## [71] 9.00 8.41 7.84 7.29 6.76 6.25 5.76 5.29 4.84 4.41
## [81] 4.00 3.61 3.24 2.89 2.56 2.25 1.96 1.69 1.44 1.21
## [91] 1.00 0.81 0.64 0.49 0.36 0.25 0.16 0.09 0.04 0.01
## [101] 0.00
```

- Here is a way to create your own data sets that are random samples.
- Again, on your own, play around with the arguments in the parentheses to see what happens.

```
x <- rnorm (10000, 0, 10)
y <- sample (1:10000, 10000, replace = T)
xy <- cbind(x,y)
plot(x,y)
```



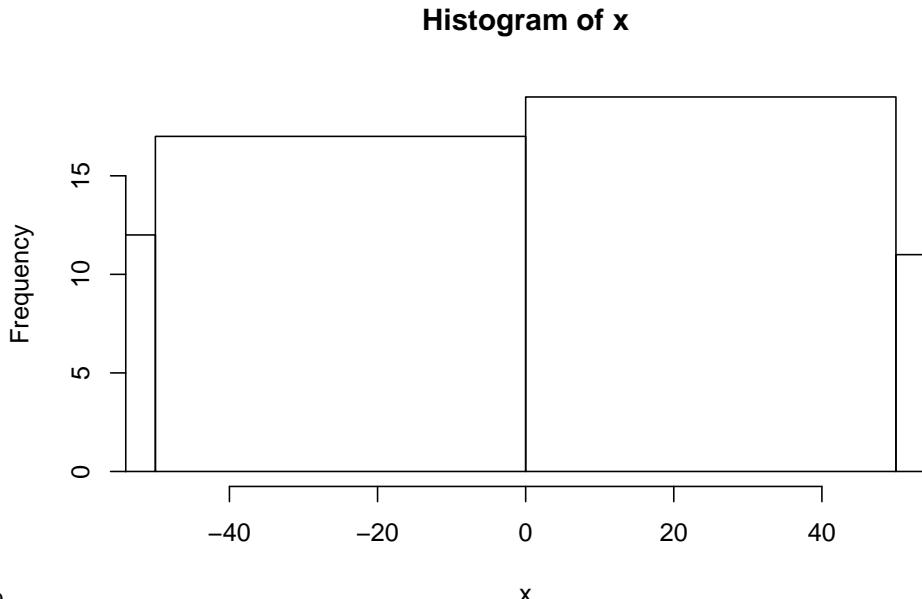
from distributions 1-1.bb

- You've probably figured out that "y" from the last example is a draw of numbers with equal probability (what we call a flat, or uniform distribution).
- What if you want to draw from a defined probability distribution, like the normal distribution?
- Again, play around with the arguments in the parentheses to see what happens.

```
x <- rnorm(100, 0, 100)
print (x)
```

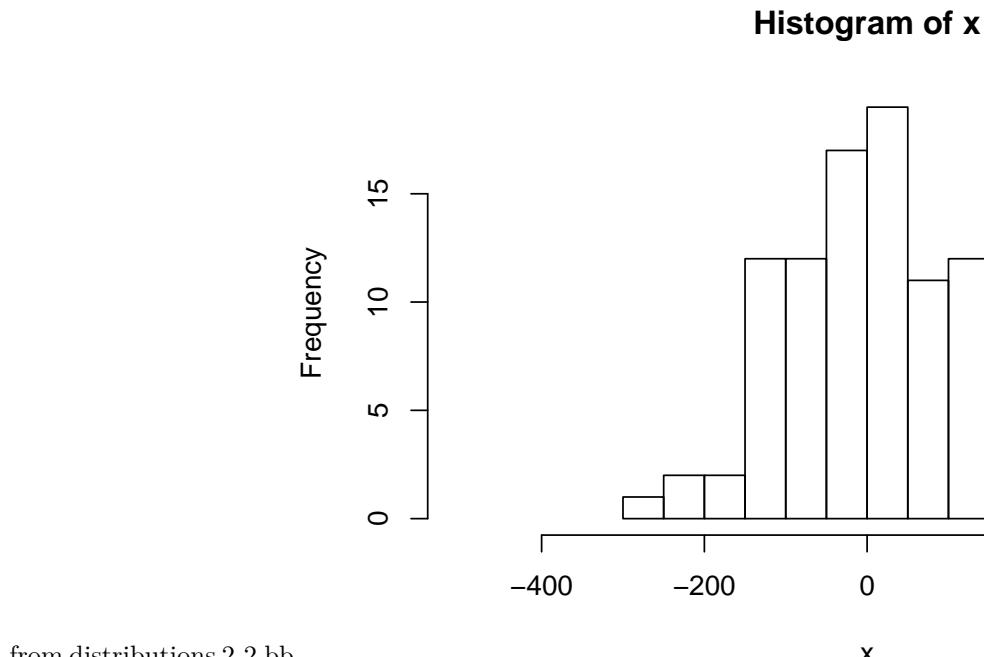
```
## [1] 151.6253376 61.4491546 -101.2273315 -36.4167184 20.9546360
## [6] 49.7479827 124.4586469 85.2667920 34.3207485 64.0841631
## [11] -72.9346097 -22.7366729 -0.1940761 -261.5592573 38.3398461
## [16] 117.4703986 155.4074906 54.0642015 -241.1690891 -5.2591731
## [21] 125.2066296 -88.0526361 30.5564379 38.1836204 25.8460324
## [26] 183.2226328 -130.9675001 -169.6844518 -23.4818771 -7.8957591
## [31] -56.9563600 -145.6200350 108.9253905 106.1174824 35.5578525
## [36] -62.4442141 47.7071453 -105.3214641 64.5432149 138.7378265
## [41] -41.0994345 35.7084069 -5.7955199 -107.9345640 -78.1587436
## [46] 136.8157345 -24.1229416 23.9543780 158.2036725 -141.7687017
## [51] -28.1602197 173.4236959 -96.7606934 -143.0933201 113.4298557
## [56] 52.8402860 33.5927839 12.5271322 208.7985487 278.2796770
## [61] -49.0290720 26.6166432 -10.5347618 -35.1882400 141.0702531
## [66] 61.8747644 -76.2120553 126.0627941 61.8327910 -90.4532729
## [71] -125.1321953 -109.5867921 116.7964207 -6.1924235 65.3464859
## [76] 230.6699083 -182.2410965 -79.2745295 45.2407916 198.7500070
## [81] 50.5875433 -208.7598598 159.4834695 164.3723365 -134.3170363
## [86] 16.9837007 -86.8701030 -8.2594203 89.5801083 -136.1875106
## [91] 28.6984757 -46.3979982 10.0864558 41.6677033 -42.1931638
## [96] -119.1738562 147.0814166 200.0535118 -95.1464831 -84.2382407
```

```
hist(x, xlim = c(-50,50))
```



from distributions 2-1.bb

```
hist(x, xlim = c(-500,500))
```



from distributions 2-2.bb

Can you figure out what the three rnorm() arguments represent?

6.4.1.7 Basic Summary Statistics

We will get into the details regarding summary statistics later, but for now, check out several of the R functions that calculate them.

```
mean(x)
median(x)
var(x)
log(x)
ln(x)
sqrt(x)
sum(x)
length(x)
sample(x, replace = T)
```

- Notice that the last function (`sample`) has an argument (`replace=T`)
- Arguments simply modify or direct the function in some way
- There are many arguments for each function, some of which are defaults

6.4.1.8 Getting help to understand functions

- Getting help on any function is very easy - just type a question mark and the name of the function.
- There are functions for just about anything within R and it is easy enough to write your own functions if none already exist to do what you want to do.
- In general, function calls have a simple structure: a function name, a set of parentheses and an optional set of arguments you assign parameters to and send to the function.
- Help pages exist for all functions that, at a minimum, explain what parameters exist for the function.
- Help can be accessed a few ways - try them :

```
- help(mean)
- ?mean
- example(mean)
- help.search("mean")
- apropos("mean")
- args(mean)
```

6.5 Exercises associated with this chapter:

- Exercise 2 (**rtutorial_1** in **foundstats** R package)

6.6 Additional learning resources:

- Logan, M. 2010. Biostatistical Design and Analysis Using R. - A great intro to R for statistical analysis
- <http://library.open.oregonstate.edu/computationalbiology/> - O'Neil, S.T. 2017. A Primer for Computational Biology

Chapter 7

More R Functions, Complex Objects, Basic Plotting, and RMarkdown

7.1 Background

In this chapter we will cover a variety of topics, all of which will help you build your R programming skills and make you capable of dealing with data sets using R. We will explore additional base R functions that are extremely useful for generating and manipulating vectors, combining vectors into multidimensional R objects, and working with those objects. We will also cover base R plotting functions to get you started with making your own publication-quality plots. Finally, we will touch on the RMarkdown file format, how to write those files in RStudio, and how to render the .Rmd file into polished, readable .html documents.

7.2 More on functions

In the last chapter we touched on functions in R, gave a few examples of commonly used functions, and covered how to learn more about a function using the `help()` function. As mentioned, functions and their use follow a basic structure. To call functions we type their name and include a set of parameters expressed as arguments, which specify what we want them to do, inside parentheses `()`. For example, to successfully call the function `mean()`, we need, at minimum, to supply a vector of numeric values. That vector can be an object we have already assigned in our environment, or it can be the outcome of another function called within the `mean()` function. Below are these two alternatives.

```
z <- c(10, 20, 30)
mean(z)

## [1] 20
mean(c(10, 20, 30))

## [1] 20
```

The second alternative illustrates the power of “nesting” functions within R. You don’t need to perform tasks by defining a bunch of intermediate objects and calling functions in piecemeal manner. In many cases it is much more efficient to nest functions within one another, as long as it doesn’t jeopardize the functionality or readability of your code.

Base R includes dozens of useful functions that will become part of your regular arsenal. We have already mentioned several of these and discussed how to discover and learn more about them. As you become a more advanced R user, and in particular as you begin performing tasks and analyses more specific to your field of study, you will need to use functions that are not included in the base R library. Fortunately, there are thousands of functions distributed in the form of R “packages,” which you can easily install on your system. Packages especially easy to find and use are those distributed via the Comprehensive R Archive Network (CRAN): <https://cran.r-project.org/web/packages/index.html>. If you find a specific function or set of functions you are interested in trying out, for instance after a Google search of your problem, you can download and install the package those functions belong to by running the following command from your R Console:

```
install.packages("name_of_package")
```

Note that the name of the package has to be spelled correctly (and R is case sensitive), and that the name of the package should be in quotation marks. You will get a series of messages printed to the Console, and finally either a confirmation of installation or error message. Once you have installed a package successfully, you do not need to re-run the `install.packages()` function. If you want to check whether a package has already been installed, and look at the details of that installation, you can always run the following from the Console:

```
installed.packages("name_of_package")
```

To actually use the functions from an installed package, you have to “load” that package into your current working environment. To do that we use the `library()` function:

```
library(name_of_package)
```

Note that you do not include quotation marks around the package name for the `library()` function. Unlike package installation, you will need to invoke

`library()` every time you start a new R session to load the package and its functions.

It is also possible, and quite straightforward, to write your own R functions, which you can define within your `.R` or `.Rmd` scripts for convenient usage. If you get the point at which you want to distribute your own functions in the form of a package, that is possible too. Later during this course we will get a little experience in writing simple R functions. Writing more involved functions and publishing packages, however, are topics for a more advanced R course.

7.2.1 More base R functions useful for working with vectors

Below are annotated lists of base R functions commonly used to work with vectors. We will not take the time here to give specific examples for each function, because their usage is quite straightforward and you will get plenty of practice with them in associated exercises. You can also practice using the `help()` function if you have specific questions.

The following functions provide information about vectors:

- `head()`: returns the first elements of an object (like a vector or data frame)
- `tail()`: returns the last elements of an object (like a vector or data frame)
- `length()`: returns the number of elements in a vector
- `class()`: returns the class of elements in a vector (e.g. “character”, “numeric”, “factor”, etc.)

The following functions can modify or generate vectors in structured ways:

- `sort()`: returns a sorted vector from an original vector of numeric values
- `seq()`: returns a “series” of numeric values beginning at one value and ending at another, while also specifying the size of increments/decrements between values
- `rep()`: returns a vector of identical elements, repeated a specified number of times

```
rep(1, 5)

## [1] 1 1 1 1 1

rep("one", 5)

## [1] "one" "one" "one" "one" "one"
```

Note that `seq()` and `rep()` can be repeated and/or combined in various ways, in some cases using `c()`, to generate vectors in a multitude of patterned ways.

The following functions can generate vectors of random values, randomly shuffle vectors, or generate vectors of values drawn from defined probability distributions:

- `sample()`: randomly selects and returns elements from a vector (“shuffles” a vector when size argument is set to original vector size and replace argument is set to “FALSE”)
- `rnorm()`: randomly draws values from a theoretical normal distribution
- `rbinom()`: randomly draws values from a theoretical binomial distribution
- `set.seed()`: sets R’s random number generator seed so that operations with stochastic properties can be reproduced

The following functions can change the class of elements in a particular vector:

- `as.numeric()`: changes the class of objects in a vector to “numeric”.
- `as.factor()`: changes the class of objects in a vector to “factor”.
- `as.character()`: changes the class of objects in a vector to “character”.

The `as.xxx` family of R functions is especially useful if you need to convert the class of a particular object for a given function to use the object properly.

7.3 Indexing vectors

Now that we are quite familiar with different ways for generating vectors, let’s discuss how we isolate specific elements from those vectors. This process is called “indexing,” and in R simple numeric (or “positional”) indexing is intuitively based on integers, starting from “1”. We use the square braces for numeric indexing in R: `[]`. For example if we want to index the first element in a vector, we simply type `[1]` after the vector. Indexing can be performed on a defined vector, or on the fly using the immediate output of a function call.

```
## Using our vector z from above
z[1]

## [1] 10
## On the fly using output from the c() function
c(10, 20, 30)[1]

## [1] 10
```

To isolate a series of consecutive elements from a vector, we simply use the `:` character. For example, if we want to index the first (or last) 4 elements from the vector below we could do this, respectively:

```
c(10, 20, 30, 40, 50, 100, 200)[1:4]
## [1] 10 20 30 40
c(10, 20, 30, 40, 50, 100, 200)[4:7]
## [1] 40 50 100 200
```

For indexing discontinuous elements, we can use our old friend, the `c()` function inside of the square braces. So, if we want to index the first 3 and the 5th elements:

```
c(10, 20, 30, 40, 50, 100, 200)[c(1:3, 5)]
## [1] 10 20 30 50
```

Finally, we can use the `-` character to index all elements of a vector, “minus” other elements. When excluding even consecutive elements, however, we have to include `c()`. For instance, if we want all **except** the first 2 elements, we could do:

```
c(10, 20, 30, 40, 50, 100, 200)[-c(1:2)]
## [1] 30 40 50 100 200
```

7.4 More complex data objects in R

Vectors are extremely important object types in R, for the reasons and examples we have already discussed. Other types of objects in R are also important, and necessary to learn about to do meaningful and efficient work. These other types of objects are more complex than vectors, but they can, in many cases, be composed of vectors.

7.4.1 lists

Lists in R are aggregates of different objects, and those objects can be a mixed variety of types. For example, a list could be an aggregate of 3 different vectors, even if those vectors are different lengths and contain elements of a different class. We can generate lists using the `list()` function.

```
vec1 <- c(10, 20, 30, 40, 50, 100, 200)
vec2 <- c("happy", "sad", "grumpy")
vec3 <- factor(c("high", "low"))

mylist <- list(vec1, vec2, vec3)

print(mylist)

## [[1]]
```

```

## [1] 10 20 30 40 50 100 200
##
## [[2]]
## [1] "happy"   "sad"      "grumpy"
##
## [[3]]
## [1] high low
## Levels: high low
class(mylist)

## [1] "list"
str(mylist)

## List of 3
## $ : num [1:7] 10 20 30 40 50 100 200
## $ : chr [1:3] "happy" "sad" "grumpy"
## $ : Factor w/ 2 levels "high","low": 1 2

```

Let's take note of a few things from the output above. First, notice that each of the three vectors in `mylist` has a numeric (positional) index. Unlike individual vectors, however, primary elements of lists are indexed by double square braces `[]`. So, if we want to index the `vec2` element of `mylist`, we type:

```
mylist[[2]]
```

```
#> [1] "happy"   "sad"      "grumpy"
```

Taking it one step further, if we want to index the 2nd element of the `vec2` element of `mylist`, we type:

```
mylist[[2]][2]
```

```
#> [1] "sad"
```

The other things we should note from our exploration of `mylist` above is that 1. It has a class when we call the `class()` function, and 2. We see a nice breakdown of the 3 components that make up `mylist` when we call the `str()` function. `str()`, which is short for “structure,” is an especially useful function for trying to understand the organization of complex objects in R.

7.4.2 data frames

There is a special class of list we very often work with in R called a “data frame.” You can think of data frames as an especially useful organizing structure for data sets. Data frames are lists of vectors, but the vectors have to be the same length. Also, the vectors (officially known as “columns”) in data frames have names we refer to as “column names,” and the rows also have names. For the types of analysis we will be dealing with in this course, it helps to organize our data so

that variables in our study correspond to columns and observations correspond to rows. Let's explore some practical details regarding the generation and use of data frames.

7.4.2.1 creating data frames in R

We can generate data frames manually, like we did with the list `mylist` above. Here, for example, we can set up three variables (habitat, temp and elevation) as vectors.

```
habitat <- factor(c("mixed", "wet", "wet", "wet", "dry", "dry", "dry", "mixed"))
temp <- c(3.4, 3.4, 8.4, 3, 5.6, 8.1, 8.3, 4.5)
elevation <- c(0, 9.2, 3.8, 5, 5.6, 4.1, 7.1, 5.3)
```

Then we can use the `data.frame()` function to incorporate the vectors into columns of the data frame.

```
mydata <- data.frame(habitat, temp, elevation)
row.names(mydata) <- c("Reedy Lake", "Pearcadale", "Warneet", "Cranbourne",
                      "Lysterfield", "Red Hill", "Devilbend", "Olinda")
```

Note above that we used a function called `row.names` to assign row names to `mydata`. The function `colnames()` does the same, but for column names.

7.4.2.2 working with pre-loaded base R data frames.

There are a few data frames that are available to work with whenever you begin an R session. These can be a great way to practice plotting and analysis, and in fact many examples written to accompany R functions include these data frames to promote reproducibility and convenience. Two of these pre-loaded data frames that are especially popular are `mtcars` and `iris`.

```
head(mtcars)

##          mpg cyl disp  hp drat    wt  qsec vs am gear carb
## Mazda RX4     21.0   6 160 110 3.90 2.620 16.46  0  1    4    4
## Mazda RX4 Wag 21.0   6 160 110 3.90 2.875 17.02  0  1    4    4
## Datsun 710    22.8   4 108  93 3.85 2.320 18.61  1  1    4    1
## Hornet 4 Drive 21.4   6 258 110 3.08 3.215 19.44  1  0    3    1
## Hornet Sportabout 18.7   8 360 175 3.15 3.440 17.02  0  0    3    2
## Valiant       18.1   6 225 105 2.76 3.460 20.22  1  0    3    1

head(iris)

## Sepal.Length Sepal.Width Petal.Length Petal.Width Species
## 1          5.1         3.5         1.4         0.2  setosa
## 2          4.9         3.0         1.4         0.2  setosa
## 3          4.7         3.2         1.3         0.2  setosa
## 4          4.6         3.1         1.5         0.2  setosa
```

```
## 5      5.0      3.6      1.4      0.2  setosa
## 6      5.4      3.9      1.7      0.4  setosa
```

7.4.2.3 reading in data frames in R

A strength of R is being able to import data from an external source. For example, if you have a comma- or tab- separated text file (like the UNIX-friendly formats we discussed previously), it can be easily read into R, by default as a data frame. One function for accomplishing this is `read.table()`, although functions like `read.delim()` can be similarly applied. Two important arguments for `read.table()` are “header” and “row.names”, which indicate that there is a header row (with column names) and row label column (with row names), respectively. You also need to supply the file path and name in quotation marks (no path necessary if the file is in the current working directory), and what character is used as the field (column) delimiter. Here is an example:

```
YourFile <- read.table('yourfile.csv', header=T, row.names=1, sep=',')
YourFile <- read.table('yourfile.txt', header=T, row.names=1, sep='\t')
```

7.4.2.4 exporting data frames in R

If you ever want to save a data frame in a format that you can work with outside of R, the `write.table()` function does pretty much the opposite of its “read” counterpart.

```
write.table(YourFile, "yourfile.csv", quote=F, row.names=T, sep=",")
write.table(YourFile, "yourfile.txt", quote=F, row.names=T, sep="\t")
```

7.4.2.5 indexing data frames

Indexing data frames can be achieved in two different ways. We can use numeric (positional) indexing as in the case of vectors and lists (see above). With a data frame, we can index any subset of it using two pieces of information: row coordinates and column coordinates. To accomplish this we use single square braces `[,]`, in which the row coordinate(s) are typed first, followed by a comma, followed by the column coordinate(s). If we want to index all rows or all columns, we just leave the space to the left or right of the comma blank, respectively. Here are some examples for indexing subsets of the `iris` data frame.

```
## The first row, with all columns
iris[1,]

##   Sepal.Length Sepal.Width Petal.Length Petal.Width Species
## 1          5.1       3.5        1.4       0.2  setosa

## The first 5 rows and the first 2 columns
iris[1:5,1:2]

##   Sepal.Length Sepal.Width
```

```
## 1      5.1      3.5
## 2      4.9      3.0
## 3      4.7      3.2
## 4      4.6      3.1
## 5      5.0      3.6
```

With data frames, we can also use the column names to index subsets. To do this we use the `$` character after the name of the data frame, followed by the name of the column we want to index. Again, below is a demonstration using `iris`. Indexing using column names is perhaps the most useful when defining statistical models, a topic we will reach later in the course.

```
## The first 5 rows of the first column
iris$Sepal.Length[1:5]
```

```
## [1] 5.1 4.9 4.7 4.6 5.0
```

7.4.3 matrices

Matrices in R are somewhat similar to data frames, but mixed classes among columns are not permitted, and rows and columns are only positionally indexed as opposed to having names. Positional indexing for matrices, not surprisingly, follows the `[rownumber, columnnumber]` convention, similar to data frames. A matrix can be generated using the `matrix()` function, as demonstrated below.

```
## Populate a 3x3 matrix with values 1 to 9
matrix(1:9, nrow=3, ncol=3)
```

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

7.4.4 A few additional base R functions for working with complex R objects

To add to your foundational knowledge of R functions, below are a few more functions especially useful for working with objects like data frames and matrices.

- `dim()`: returns the number of rows and columns of a data frame or matrix
- `View()`: opens up a GUI “viewer” for visual inspection of data frames (not recommended for large data frames)
- `cbind()`: combines columns into a single object, which can be used to define or build data frames or matrices
- `rbind()`: combines rows into a single object, which can be used to define or build data frames or matrices

- `t()`: transposes a data frame or matrix, such that rows become columns, and columns become rows

7.5 Some brief notes on basic programming in R

At some point during your development as an R user you will want to programmatically manipulate R objects in an iterative, repeatable manner to automate tasks like plotting, simulations, and analysis. This use of the R language is especially relevant if you want to write your own functions. Here we touch on a few tools and approaches that will open the door to more powerful programming in R. These are skills that are great to practice and learn, but at a fairly foundational level for now. More advanced programming training in R is beyond the scope of this course.

7.5.1 conditional statements with `ifelse()`

One fundamental structural component of computer programming languages is the idea of conditional statements, which often take the form of “if/else” evaluation and execution. The idea is that we can write an algorithm to evaluate a particular statement using a logical operator, and if that statement is true have the program do one thing, but if the statement is false, have it do something else.” In R we can write these statements with a structure similar to other languages, but we can also use the single R function `ifelse()` to accomplish the same thing. The `ifelse()` function is very easy to use. The first argument is the logical evaluation, the second argument is the action to take if that statement is true, and the third argument is the action to take if false. It is also possible to nest multiple `ifelse()` function calls within one another, if multiple evaluations need to be performed with different outcomes. Below is a simple example for using `ifelse()` to generate a vector of values (“colors”), based on another vector.

```
## First define a character vector
char_vec <- c(rep("treatment",5), rep("control",3), rep("treatment", 4), rep("control"
print(char_vec)

## [1] "treatment" "treatment" "treatment" "treatment" "treatment" "control"
## [7] "control"    "control"    "treatment"   "treatment"   "treatment"   "treatment"
## [13] "control"    "control"    "control"     "control"     "control"     "control"

## Generate a vector that stores the color "red" for "treatment" and "blue" for "control"
col_vec <- ifelse(char_vec=="treatment", "red", "blue")
print(col_vec)

## [1] "red"   "red"   "red"   "red"   "red"   "blue"  "blue"  "blue"  "blue"  "red"
## [11] "red"  "red"  "blue"  "blue"  "blue"  "blue"  "blue"  "blue"
```

7.5.2 `replicate()`, `tapply()`, and `apply()`

In some cases we want to repeat a given process over and over again. For example, maybe we want to simulate the sampling process and generate 100 random samples of 100 values from a normal distribution. Fortunately, the R function `replicate()` makes this very easy.

In the example below, we “shuffle” the order of the integers 1 through 10 five times using `replicate()`:

```
replicate(5, sample(1:10, size=10, replace=FALSE))
```

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

Note that the first argument is the number of total iterations we want to reproduce, and that the function returns a matrix as output.

The `replicate()` function belongs to a group of functions referred to informally as the “apply” family. Another commonly used function from this group is `tapply()`, which allows you to apply a function to one vector (for example a numeric vector in a data frame), in a group-wise manner based on one or more factor vectors that correspond to the numeric vector. In other words, if we want to find the maximum value of variable x for each level of factor y in a data frame, we could use `tapply()` to do so. Below is an example, again using the `iris` data frame.

```
## Find the maximum petal length for each species in the iris data frame
tapply(iris$Petal.Length, iris$Species, max)

##      setosa versicolor  virginica
##        1.9       5.1       6.9
```

Note that the first argument is the numerical column, and the second is a factor column. The third is the function we wish to apply, in this case to each species separately.

Another, similar function from this family is simply called `apply()`, and it can be used to apply a function to either all rows (with the MARGIN argument set to 1) or all columns (with the MARGIN argument set to 2) in a data frame or matrix. This is especially useful for calculating summary statistics for what we

call the “margins” of data in tables.

7.5.3 for loops in R

Another fundamental concept in computer programming is the “for loop,” which is an algorithmic strategy for iteratively performing a task according to a pre-defined counter or loop variable, then terminating when the “loop” is evaluated as complete. For example, we may want to perform a specific calculation again and again for successive elements of an R object (like a data frame), and build a vector that successively stores the calculation for each iteration of the “loop.” We will not devote much time to for loops in R here, because the “apply” group of functions can accomplish many of the tasks you would write a for loop to perform, with much greater speed. If you do find a need for including a for loop in your future R programming, however, the commented example below illustrates an efficient framework in which “pre-allocation” of an output vector maximizes for loop speed despite some of R’s.

```
## Calculate mpg/cyl and mpg/wt, for every row in mtcars and if the second is at least

## first pre-allocate our new data frame, which contains NAs initially
newdf <- data.frame(rep(NA, length(mtcars$mpg)), rep(NA, length(mtcars$mpg)))

## then write the for loop to do the above task for every row in mtcars
for(i in 1:length(mtcars$mpg)) {
  newdf[i,1] <- (mtcars$mpg[i]/mtcars$wt[i])/(mtcars$mpg[i]/mtcars$cyl[i])
  newdf[i,2] <- ifelse(newdf[i,1]>=2, "Yes", "No")
}
print(newdf)

##      rep.NA..length.mtcars.mpg.. rep.NA..length.mtcars.mpg...1
## 1              2.290076          Yes
## 2              2.086957          Yes
## 3              1.724138          No
## 4              1.866252          No
## 5              2.325581          Yes
## 6              1.734104          No
## 7              2.240896          Yes
## 8              1.253918          No
## 9              1.269841          No
## 10             1.744186          No
## 11             1.744186          No
## 12             1.965602          No
## 13             2.144772          Yes
## 14             2.116402          Yes
## 15             1.523810          No
## 16             1.474926          No
```

```

## 17          1.496726      No
## 18          1.818182      No
## 19          2.476780     Yes
## 20          2.179837     Yes
## 21          1.622718      No
## 22          2.272727     Yes
## 23          2.328967     Yes
## 24          2.083333     Yes
## 25          2.080624     Yes
## 26          2.067183     Yes
## 27          1.869159      No
## 28          2.643754     Yes
## 29          2.523659     Yes
## 30          2.166065     Yes
## 31          2.240896     Yes
## 32          1.438849      No

```

In the case above, we used the length of the `mtcars` data frame (number of rows) to build a pre-allocated (filled with NAs) data frame of the correct size. Then, we also used the values 1 through that length to set up our “counter” in the for loop. The loop stops after tasks have been completed for `i=32`, which corresponds to the final row in `mtcars`. As mentioned, it’s probably better to rely on the other convenient R functions above for iterative processes, but pre-allocation of output objects is the way to go if you do need to rely on a for loop.

7.6 Fundamentals of plotting in R

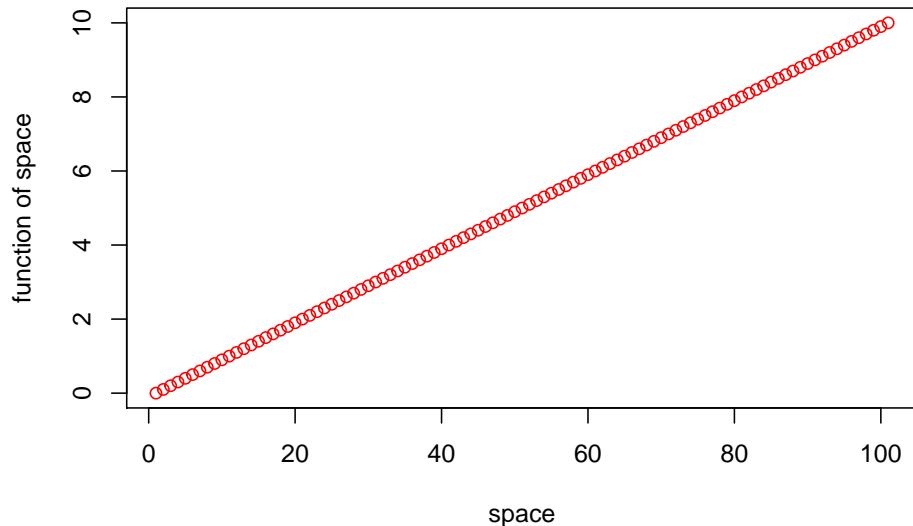
The world of plotting in R is incredibly diverse, and there are entire courses dedicated to data visualization using R. Here we will very briefly cover a few of the most useful plotting functions and strategies using base R. This should be enough of an introduction to get you jump started, but you will no doubt discover more appealing and finely tuned strategies to apply in your future as an R user. For example, some people will find that the highly flexible, customizable package `ggplot2` and its plotting functions are preferable over base R. I encourage you to explore tools like this on your own, once you feel comfortable with R in general. We will also introduce plot- and visualization-related lessons throughout the remainder of the course, as they pertain to the analysis topic at hand.

7.6.1 Basic plotting with `plot()`

One “high level” plotting function in base R is simply called `plot()`. This function can accomplish many, many plotting goals, so we will start with it. Below, we start by calling `plot()` on a single vector that we have generated.

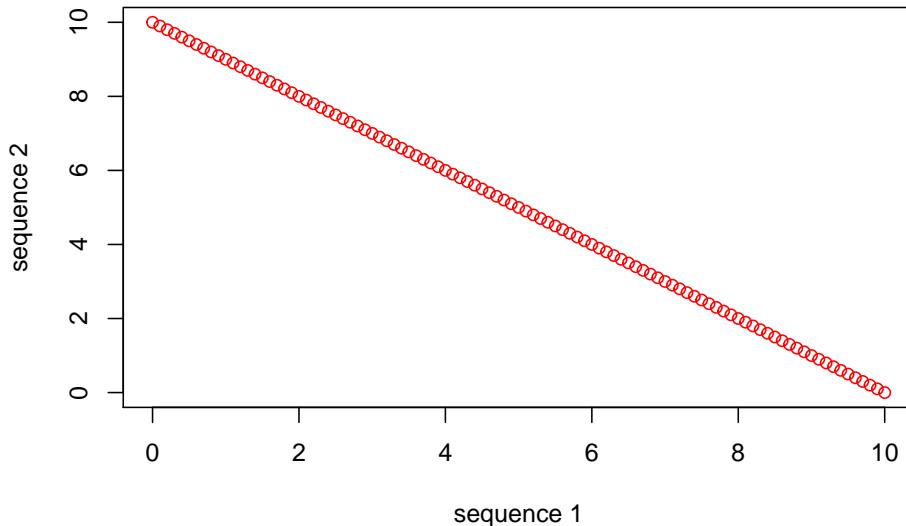
Spend a little time examining the code, and the arguments passed to `plot()` in this example.

```
seq_1 <- seq(0.0, 10.0, by = 0.1)
plot(seq_1, xlab="space", ylab ="function of space", type = "p", col = "red")
```



We only supplied the one vector (`seq_1`) to `plot()` in this case, which resulted in the function just defining the x-axis values as the numeric positions (1 to 101) of `seq_1`. Also, this style of plot is known as a “scatterplot.” There is usually more “scatter,” for example when plotting two variables that not perfectly related. With `plot()`, we usually want to examine the relationship between two different variables, like below:

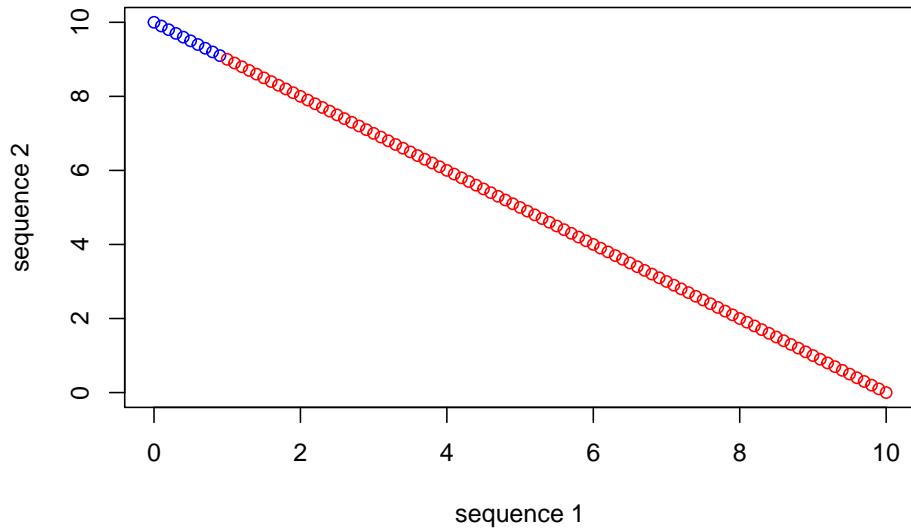
```
seq_1 <- seq(0.0, 10.0, by = 0.1)
seq_2 <- seq(10.0, 0.0, by = -0.1)
plot(seq_1, seq_2, xlab="sequence 1", ylab ="sequence 2", type = "p", col = "red")
```



In this example, `plot()` takes the first argument as the x-axis variable, and the second argument as the y-axis variable. You can also use the `~` to specify variables, but in this case the y-axis variable comes first (`y ~ x`). Also note the other arguments, which are usually named pretty intuitively. Note the axis label arguments, the type of object plotted (“p” stands for “points”), and the color of the plotted objects. There are many possible arguments, and many are actually set by another function called `par()`, that `plot()` calls on internally. One great resource for understanding plotting function arguments is the help menu for `par()`. I promise, if you become familiar with the `par()` documentation, you will quickly ascend the ranks of plotting prowess, and it will save you many frustrating moments in the future! I encourage you to study the `plot()` and `par()` documentation and practice using some of the other arguments that are especially useful, including “main”, “xlim”, “ylim”, and “cex”, for example.

The nice thing about graphical parameters is that, like many things in R, they are vectorized. So, if we want to use different symbols (look into the “pch” argument), colors (“col”), or sizes (look at “cex”) of points for different observations in something like a data frame, we can supply those in the form of a vector! Taking the example above, if we want to plot the first 10 observations as blue, and the remaining observations as red, we can supply a vector of “blues” and “reds” in the appropriate order to `plot()`.

```
seq_1 <- seq(0.0, 10.0, by = 0.1)
seq_2 <- seq(10.0, 0.0, by = -0.1)
plot(seq_1, seq_2, xlab="sequence 1", ylab ="sequence 2", type = "p",
     col = c(rep("blue", 10), rep("red", 91)))
```

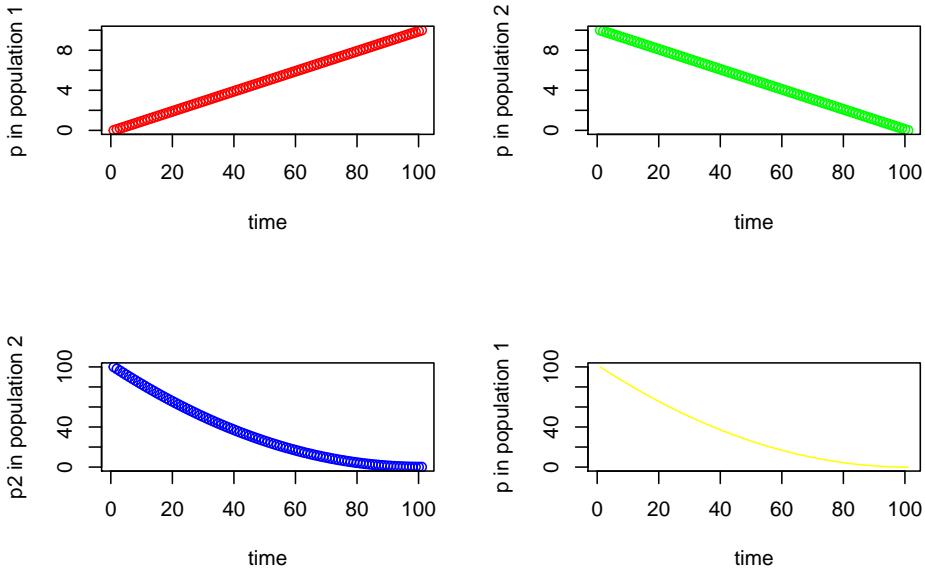


You can see how this would be a nice way to differentiate among observation types in your data set, and produce an information-rich, single plot, as opposed to producing many plots that highlight single variables.

Sometimes we want to include multiple plots, as different panels, in the same figure. Fortunately this is made easy by the `mfrow` argument within `par()`. You simply set the dimensions, denoted by number of rows and number of columns in parentheses, before calling `plot()` repeatedly.

```
seq_square <- (seq_2)*(seq_2)
seq_square_new <- (seq_2)^2

par(mfrow=c(2,2))
plot (seq_1, xlab="time", ylab ="p in population 1", type = "p", col = 'red')
plot (seq_2, xlab="time", ylab ="p in population 2", type = "p", col = 'green')
plot (seq_square, xlab="time", ylab ="p2 in population 2", type = "p", col = 'blue')
plot (seq_square_new, xlab="time", ylab ="p in population 1", type = "l", col = 'yellow')
```

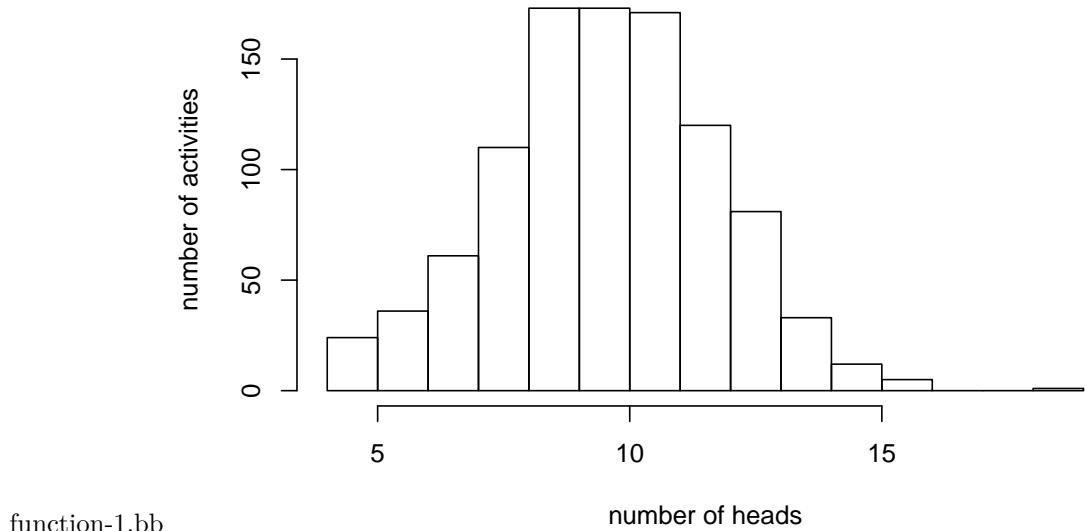


7.6.2 Histograms using `hist()`

We will talk more about frequency distributions and histograms later in the course, but for now it is a good idea to become familiar with one way to plot them. If we have a quantitative variable, like height, and we want to know what the distribution among individuals looks like, we can use a histogram. The function `hist()` will help us with this task. To illustrate, below we will sample values from a binomial distribution. Don't worry about what this means now, as we will return to it later, but the scenario is intuitive. Let's say we flip a coin 20 times and record the number of "heads" as "successes," and let's further say that we perform this "20 coin flips" activity 1000 times. And let's assume that our coin is "fair," such that the probability of getting heads on any given flip is 0.5. We can simulate this process using the `rbinom()` function and plot the results using `hist()`.

```
hist(rbinom(n=1000, size=20, prob=0.5), xlab="number of heads", ylab="number of activities",
     main="Freq. Dist. of Coin Flip Successes")
```

Freq. Dist. of Coin Flip Successes



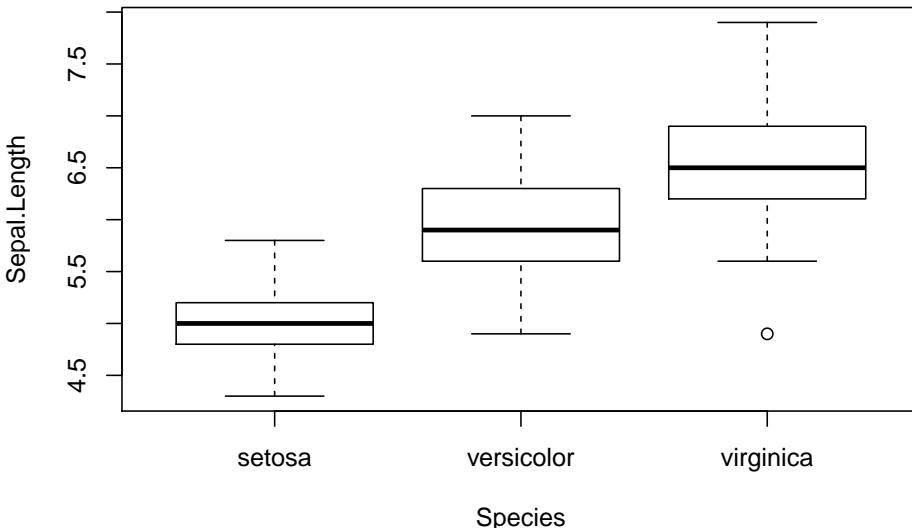
Note that, as expected, our most frequent observation is that we get 10 heads out of 20 flips.

7.6.3 Boxplots using `boxplot()`

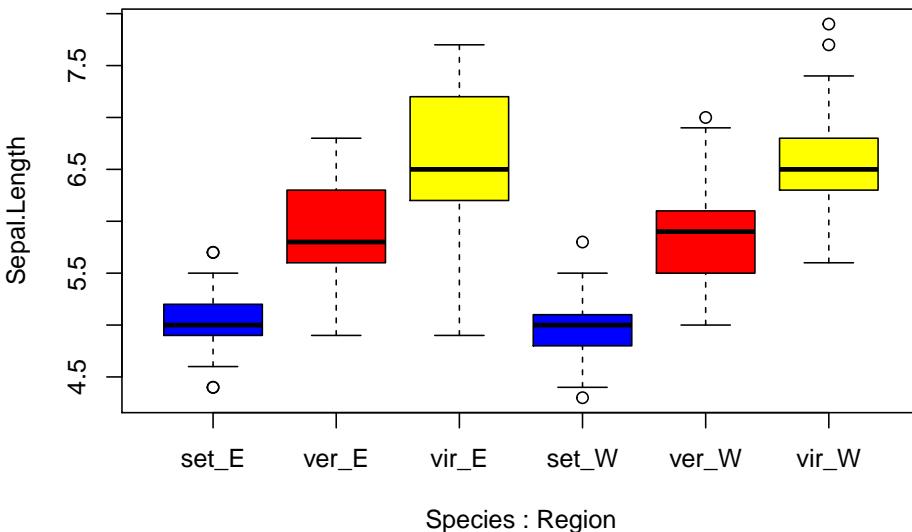
In many cases we want to summarize the distribution of a quantitative variable using “quartiles” (we’ll cover these in depth later), and perhaps we want to do this separately for different observation types in our data set. A boxplot (or “box and whisker plot,” depending on how it is drawn), depicts the 1st, 2nd (median), and 3rd quartile for a vector of numeric values using a box. “Whiskers” are often added to define “fences” beyond which are putative “outliers.” The `boxplot()` function of base R is convenient to use, particularly when your data set is organized in a data frame. Below is a series of simple examples to illustrate the utility of `boxplot()`

```
## make a modified version of the iris data frame, which includes a "Region" factor
new_iris <- iris
new_iris$Region <- as.factor(rep(c(rep("West", 5), rep("East", 5)), 15))

## make a boxplot of Sepal.Length that plots individual boxes for the separate Species
boxplot(Sepal.Length ~ Species, data=new_iris)
```



```
## make a boxplot of Sepal.Length that shows all 6 combinations of factor levels from Species and
boxplot(Sepal.Length ~ Species*Region, col=c("blue", "red", "yellow", "blue", "red", "yellow"),
        data=new_iris, names=c("set_E", "ver_E", "vir_E", "set_W", "ver_W", "vir_W"))
```



Above you can see that by using the `*` character between the factors “Species” and “Region” in our plotting formula `boxplot()` produces a box for each factor level combination. Also, for `boxplot()` note that the “`col`” argument refers to the boxes themselves, so if we supply a vector of 6 colors, those will be applied to the boxes in order from left to right. Speaking of colors, an almost limitless array of colors can be specified in R plotting functions. Furthermore, colors can be coded using their names, or hexadecimal RGB specification. For a thorough

treatment and great resources regarding colors in R, I recommend visiting the links at the bottom of the chapter.

7.7 A brief introduction to RMarkdown

RMarkdown is a language that is distinct from R, but that incorporates R code “chunks,” which can be displayed and run if desired in the final, knitted output. The output can be knitted to a variety of file formats, such as `.html`, `.pdf`, or even Microsoft Word. For this course we will get into the habit of knitting to `.html`, which is the least buggy and error-prone in my experience. In the short section below, we will go over the simple steps required to write and knit your first `.Rmd` file, including the basic style elements of the language and some essential R chunk settings.

To get started using RMarkdown, you first need to make sure that you install the package `rmarkdown` from your Console, using `install.packages()`. Then, assuming you have an RStudio session running, click on File -> New File -> R Markdown. This will open a window in which you will type the name of your new file and the author’s (your) name. A new file in your RStudio script editor pane (the upper left one) should appear. There will be a templated header, along with some other templated code, which you can modify based on your preferences. You may want to get rid of the pdf output line at the top for now, as we will knit to `.html` for this course. Knitting to `.pdf` requires some additional software installation, which we don’t have time to troubleshoot during this course. In any case, let’s now cover some basic formatting code and code “chunk” types.

Below I will provide the code you would type in your own RMarkdown file, followed by what it looks like rendered in this Bookdown document, which is built using a collection of RMarkdown files itself!

7.7.1 RMarkdown formatting basics

You can include “nested” headers (like the one directly above) by using `#` symbols. For example this:

```
## Experiment with headers

### Try a third-level header

#### Or a fourth-level header
```

Renders as this:

7.8 Experiment with headers

7.8.1 Try a third-level header

7.8.1.1 Or a fourth-level header

Text can be rendered in bold, italics, or both like this:

```
Text can easilly be *italicized* or **bolded** or ***both***
```

Which renders as this:

Text can easilly be *italicized* or **bolded** or ***both***

Links can be included like this:

```
Here is a useful link: [Rmd intro by RStudio] (https://rmarkdown.rstudio.com/articles\_intro.html)
```

```
Here is another: [R Markdown cheat sheet] (https://rmarkdown.rstudio.com/lesson-15.html)
```

Which render like this:

Here is a useful link: Rmd intro by RStudio

Here is another: R Markdown cheat sheet

For many more details on RMarkdown format and coding, I highly recommend the above links.

7.8.2 RMarkdown code chunk options

Code chunks in RMarkdown exist to show R code, run the code, or both. In every RMarkdown file you write, you will demarcate code chunks with three “ticks” at the top of the chuck followed immediately by the chunk options in curly braces, on the same line, and another three ticks (on their own line) below the chunk of code. This is what a coded chunk looks like:

```
```{r, eval = TRUE, echo = TRUE}
seq(1, 10, 1)
```
```

Which renders like this:

```
seq(1, 10, 1)
```

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

Note that in the above example the R code will be both run (“evaluated”) and displayed (“echoed”) in the knitted .html file. If we want to suppress either or both of those from being rendered, we just set the chunk options to “FALSE”.

When your RMarkdown file is completed, save any final changes, and click on the “Knit” icon in the toolbar, or click File -> Knit Document. Assuming there are

no errors in your code, the rendered `.html` file should load in a new window for inspection, and the file should be saved in the same location as your `.Rmd` file. This has been a minimal treatment of **RMarkdown**, but it should be enough guidance to get you started writing your own **RMarkdown** scripts. Please consult the aforementioned **RMarkdown** resources for additional instruction, examples, and help.

7.9 Exercises associated with this chapter:

- Exercise 2 (`rtutorial_1` in `foundstats` R package)
- Exercise 3 (`rtutorial_2` in `foundstats` R package)

7.10 Additional learning resources:

- Logan, M. 2010. Biostatistical Design and Analysis Using R. - A great intro to R for statistical analysis
- <http://library.open.oregonstate.edu/computationalbiology/> - O'Neil, S.T. 2017. A Primer for Computational Biology
- <http://www.stat.columbia.edu/~tzheng/files/Rcolor.pdf> - A nice `.pdf` menu for many R colors
- https://www.stat.ubc.ca/~jenny/STAT545A/block14_colors.html - A good introduction to colors in R
- <https://medialab.github.io/iwanthue/> - A cool automated color palette selection tool
- https://rmarkdown.rstudio.com/articles_intro.html - **RStudio** guide to **RMarkdown**
- <https://rmarkdown.rstudio.com/lesson-15.html> - **RMarkdown** “cheat sheet”