

TRES Tidyverse Tutorial

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Outline

This is the readable version of the TRES tidyverse tutorial. A convenient PDF version can be downloaded by clicking the PDF document icon in the header bar.

About

The TRES tidyverse tutorial is an online workshop on how to use the tidyverse, a set of packages in the R computing language designed at making data handling and plotting easier.

This tutorial will take the form of a one hour per week video stream via Google Meet, every Friday morning at 10.00 (Groningen time) starting from the 29th of May, 2020 and lasting for a couple of weeks (depending on the number of topics we want to cover, but there should be at least 5).

PhD students from outside our department are welcome to attend.

Schedule

Topic	Package	Instructor	Date*
Reading data and string manipulation	readr, stringr, glue	Pratik	29/05/20
Data and reshaping	tibble, tidyr	Raphael	05/06/20
Manipulating data	dplyr	Theo	12/06/20
Working with lists and iteration	purrr	Pratik	19/06/20
Plotting	ggplot2	Raphael	26/06/20
Regular expressions	regex	Richel	03/07/20
Programming with the tidyverse	rlang	Pratik	10/07/20

100 Possible extras

- 101 • Reproducibility and package-making (with e.g. usethis)
- 102
- 103 • Embedding C++ code with Rcpp

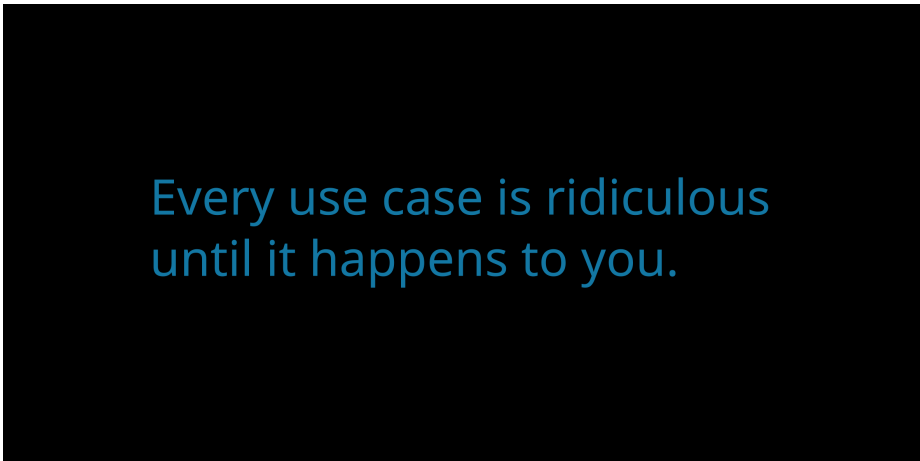
104 Join

105 Join the Slack by clicking this link (Slack account required).

106 *Tentative dates.

Chapter 1

Reading files and string manipulation



Every use case is ridiculous
until it happens to you.

Load the packages for the day.

```
library(readr)
library(stringr)
library(glue)
```

1.1 Data import and export with readr

Data in the wild with which ecologists and evolutionary biologists deal is most often in the form of a text file, usually with the extensions `.csv` or `.txt`. Often, such data has to be written to file from within R. `readr` contains a number of

116 functions to help with reading and writing text files.

117 1.1.1 Reading data

118 Reading in a csv file with `readr` is done with the `read_csv` function, a faster
119 alternative to the base R `read.csv`. Here, `read_csv` is applied to the `mtcars`
120 example.

```
# get the filepath of the example
some_example = readr_example("mtcars.csv")

# read the file in
some_example = read_csv(some_example)

head(some_example)
#> # A tibble: 6 x 11
#>   mpg   cyl  disp    hp  drat    wt   qsec    vs  am  gear  carb
#>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1  21     6   160   110  3.9   2.62  16.5     0    1     4     4
#> 2  21     6   160   110  3.9   2.88  17.0     0    1     4     4
#> 3 22.8     4   108    93  3.85  2.32  18.6     1    1     4     1
#> 4 21.4     6   258   110  3.08  3.22  19.4     1    0     3     1
#> 5 18.7     8   360   175  3.15  3.44  17.0     0    0     3     2
#> 6 18.1     6   225   105  2.76  3.46  20.2     1    0     3     1
```

121 The `read_csv2` function is useful when dealing with files where the separator
122 between columns is a semicolon `;`, and where the decimal point is represented
123 by a comma `,`.

124 Other variants include:

- 125 • `read_tsv` for tab-separated files, and
- 126 • `read_delim`, a general case which allows the separator to be specified
127 manually.

128 `readr` import function will attempt to guess the column type from the first N
129 lines in the data. This N can be set using the function argument `guess_max`.
130 The `n_max` argument sets the number of rows to read, while the `skip` argument
131 sets the number of rows to be skipped before reading data.

132 By default, the column names are taken from the first row of the data, but they
133 can be manually specified by passing a character vector to `col_names`.

134 There are some other arguments to the data import functions, but the defaults
135 usually *just work*.

1.1.2 Writing data

Writing data uses the `write_*` family of functions, with implementations for `csv`, `csv2` etc. (represented by the asterisk), mirroring the import functions discussed above. `write_*` functions offer the `append` argument, which allow a data frame to be added to an existing file.

These functions are not covered here.

1.1.3 Reading and writing lines

Sometimes, there is text output generated in R which needs to be written to file, but is not in the form of a dataframe. A good example is model outputs. It is good practice to save model output as a text file, and add it to version control. Similarly, it may be necessary to import such text, either for display to screen, or to extract data.

This can be done using the `readr` functions `read_lines` and `write_lines`. Consider the model summary from a simple linear model.

```
# get the model
model = lm(mpg ~ wt, data = mtcars)
```

The model summary can be written to file. When writing lines to file, BE AWARE OF THE DIFFERENCES BETWEEN UNIX AND WINDOWS line separators. Usually, this causes no trouble.

```
# capture the model summary output
model_output = capture.output(summary(model))
```

```
# save it to file
write_lines(x = model_output,
  path = "model_output.txt")
```

This model output can be read back in for display, and each line of the model output is an element in a character vector.

```
# read in the model output and display
model_output = read_lines("model_output.txt")

# use cat to show the model output as it would be on screen
cat(model_output, sep = "\n")
#>
#> Call:
#> lm(formula = mpg ~ wt, data = mtcars)
#>
#> Residuals:
#>      Min       1Q   Median       3Q      Max
#> -4.543  -2.365  -0.125   1.410   6.873
#>
```

```

#> Coefficients:
#>               Estimate Std. Error t value Pr(>|t|)
#> (Intercept)   37.285      1.878    19.86 < 2e-16 ***
#> wt           -5.344      0.559    -9.56 1.3e-10 ***
#> ---
#> Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
#>
#> Residual standard error: 3.05 on 30 degrees of freedom
#> Multiple R-squared:  0.753,    Adjusted R-squared:  0.745
#> F-statistic: 91.4 on 1 and 30 DF,  p-value: 1.29e-10

```

These few functions demonstrate the most common uses of `readr`, but most other use cases for text data can be handled using different function arguments, including reading data off the web, unzipping compressed files before reading, and specifying the column types to control for type conversion errors.

Excel files

Finally, data is often shared or stored by well meaning people in the form of Microsoft Excel sheets. Indeed, Excel (especially when synced regularly to remote storage) is a good way of noting down observational data in the field. The `readxl` package allows importing from Excel files, including reading in specific sheets.

1.2 String manipulation with `stringr`

`stringr` is the tidyverse package for string manipulation, and exists in an interesting symbiosis with the `stringi` package. For the most part, `stringr` is a wrapper around `stringi`, and is almost always more than sufficient for day-to-day needs.

`stringr` functions begin with `str_`.

1.2.1 Putting strings together

Concatenate two strings with `str_c`, and duplicate strings with `str_dup`. Flatten a list or vector of strings using `str_flatten`.

```

# str_c works like paste(), choose a separator
str_c("this string", "this other string", sep = "_")
#> [1] "this string_this other string"

# str_dup works like rep
str_dup("this string", times = 3)
#> [1] "this stringthis stringthis string"

# str_flatten works on lists and vectors

```

```

str_flatten(string = as.list(letters), collapse = "_")
#> [1] "a_b_c_d_e_f_g_h_i_j_k_l_m_n_o_p_q_r_s_t_u_v_w_x_y_z"
str_flatten(string = letters, collapse = "-")
#> [1] "a-b-c-d-e-f-g-h-i-j-k-l-m-n-o-p-q-r-s-t-u-v-w-x-y-z"

```

174 `str_flatten` is especially useful when displaying the type of an object that
 175 returns a list when `class` is called on it.

```

# get the class of a tibble and display it as a single string
class_tibble = class(tibble::tibble(a = 1))
str_flatten(string = class_tibble, collapse = ", ")
#> [1] "tbl_df, tbl, data.frame"

```

176 1.2.2 Detecting strings

177 Count the frequency of a pattern in a string with `str_count`. Returns an integer.
 178 Detect whether a pattern exists in a string with `str_detect`. Returns a logical
 179 and can be used as a predicate.
 180 Both are vectorised, i.e, automatically applied to a vector of arguments.

```

# there should be 5 a-s here
str_count(string = "ababababa", pattern = "a")
#> [1] 5

# vectorise over the input string
# should return a vector of length 2, with integers 5 and 3
str_count(string = c("ababbababa", "banana"), pattern = "a")
#> [1] 5 3

# vectorise over the pattern to count both a-s and b-s
str_count(string = "ababababa", pattern = c("a", "b"))
#> [1] 5 4

```

181 Vectorising over both string and pattern works as expected.

```

# vectorise over both string and pattern
# counts a-s in first input, and b-s in the second
str_count(string = c("ababababa", "banana"),
          pattern = c("a", "b"))
#> [1] 5 1

# provide a longer pattern vector to search for both a-s
# and b-s in both inputs
str_count(string = c("ababababa", "banana"),
          pattern = c("a", "b",
                      "b", "a"))
#> [1] 5 1 4 3

```

182 **str_locate** locates the search pattern in a string, and returns the start and
 183 end as a two column matrix.

```
# the behaviour of both str_locate and str_locate_all is
# to find the first match by default
str_locate(string = "banana", pattern = "ana")
#>      start end
#> [1,]      2  4

# str_detect detects a sequence in a string
str_detect(string = "Bananageddon is coming!",
           pattern = "na")
#> [1] TRUE

# str_detect is also vectorised and returns a two-element logical vector
str_detect(string = "Bananageddon is coming!",
           pattern = c("na", "don"))
#> [1] TRUE TRUE

# use any or all to convert a multi-element logical to a single logical
# here we ask if either of the patterns is detected
any(str_detect(string = "Bananageddon is coming!",
               pattern = c("na", "don")))
#> [1] TRUE
```

184 Detect whether a string starts or ends with a pattern. Also vectorised. Both
 185 have a **negate** argument, which returns the negative, i.e., returns FALSE if the
 186 search pattern is detected.

```
# taken straight from the examples, because they suffice
fruit <- c("apple", "banana", "pear", "pineapple")
# str_detect looks at the first character
str_starts(fruit, "p")
#> [1] FALSE FALSE TRUE TRUE

# str_ends looks at the last character
str_ends(fruit, "e")
#> [1] TRUE FALSE FALSE TRUE

# an example of negate = TRUE
str_ends(fruit, "e", negate = TRUE)
#> [1] FALSE TRUE TRUE FALSE
```

187 **str_subset** [WHICH IS NOT RELATED TO **str_sub**] helps with subsetting a
 188 character vector based on a **str_detect** predicate. In the example, all elements
 189 containing “banana” are subset.

190 **str_which** has the same logic except that it returns the vector position and not
 191 the elements.

```

# should return a subset vector containing the first two elements
str_subset(c("banana",
             "bananageddon is coming",
             "applegeddon is not real"),
           pattern = "banana")
#> [1] "banana"                "bananageddon is coming"

# returns an integer vector
str_which(c("banana",
            "bananageddon is coming",
            "applegeddon is not real"),
          pattern = "banana")
#> [1] 1 2

```

1.2.3 Matching strings

`str_match` returns all positive matches of the pattern in the string. The return type is a list, with one element per search pattern.

A simple case is shown below where the search pattern is the phrase “banana”.

```

str_match(string = c("banana",
                     "bananageddon",
                     "bananas are bad"),
          pattern = "banana")
#>      [,1]
#> [1,] "banana"
#> [2,] "banana"
#> [3,] "banana"

```

The search pattern can be extended to look for multiple subsets of the search pattern. Consider searching for dates and times.

Here, the search pattern is a **regex** pattern that looks for a set of four digits (`\\d{4}`) and a month name (`\\w+`) separated by a hyphen. There’s much more to be explored in dealing with dates and times in `lubridate`, another **tidyverse** package.

The return type is a list, each element is a character matrix where the first column is the string subset matching the full search pattern, and then as many columns as there are parts to the search pattern. The parts of interest in the search pattern are indicated by wrapping them in parentheses. For example, in the case below, wrapping `[-.]` in parentheses will turn it into a distinct part of the search pattern.

```

# first with [-.] treated simply as a separator
str_match(string = c("1970-somemonth-01",
                     "1990-anothermonth-01",
                     "2010-thismonth-01"),

```

```

        pattern = "\\d{4}][-.](\\w+)"
#>      [,1]      [,2]      [,3]
#> [1,] "1970-somemonth" "1970" "somemonth"
#> [2,] "1990-anothermonth" "1990" "anothermonth"
#> [3,] "2010-thismonth" "2010" "thismonth"

# then with [-.] actively searched for
str_match(string = c("1970-somemonth-01",
                     "1990-anothermonth-01",
                     "2010-thismonth-01"),
          pattern = "\\d{4}([-.])(\\w+)"
#>      [,1]      [,2]      [,3] [,4]
#> [1,] "1970-somemonth" "1970" "-" "somemonth"
#> [2,] "1990-anothermonth" "1990" "-" "anothermonth"
#> [3,] "2010-thismonth" "2010" "-" "thismonth"

```

208 Multiple possible matches are dealt with using `str_match_all`. An example
 209 case is uncertainty in date-time in raw data, where the date has been entered
 210 as 1970-somemonth-01 or 1970/anothermonth/01.

211 The return type is a list, with one element per input string. Each element is a
 212 character matrix, where each row is one possible match, and each column after
 213 the first (the full match) corresponds to the parts of the search pattern.

```

# first with a single date entry
str_match_all(string = c("1970-somemonth-01 or maybe 1990/anothermonth/01"),
              pattern = "\\d{4}[\\-\\/](\\w+)"
#> [[1]]
#>      [,1]      [,2]      [,3]
#> [1,] "1970-somemonth" "1970" "somemonth"
#> [2,] "1990/anothermonth" "1990" "anothermonth"

# then with multiple date entries
str_match_all(string = c("1970-somemonth-01 or maybe 1990/anothermonth/01",
                        "1990-somemonth-01 or maybe 2001/anothermonth/01"),
              pattern = "\\d{4}[\\-\\/](\\w+)"
#> [[1]]
#>      [,1]      [,2]      [,3]
#> [1,] "1970-somemonth" "1970" "somemonth"
#> [2,] "1990/anothermonth" "1990" "anothermonth"
#>
#> [[2]]
#>      [,1]      [,2]      [,3]
#> [1,] "1990-somemonth" "1990" "somemonth"
#> [2,] "2001/anothermonth" "2001" "anothermonth"

```


214 1.2.4 Simpler pattern extraction

215 The full functionality of `str_match_*` can be boiled down to the most com-
 216 mon use case, extracting one or more full matches of the search pattern using
 217 `str_extract` and `str_extract_all` respectively.

218 `str_extract` returns a character vector with the same length as the input string
 219 vector, while `str_extract_all` returns a list, with a character vector whose
 220 elements are the matches.

```
# extracting the first full match using str_extract
str_extract(string = c("1970-somemonth-01 or maybe 1990/anothermonth/01",
                        "1990-somemonth-01 or maybe 2001/anothermonth/01"),
             pattern = "(\\d{4})[\\-\\/]([a-z]+)")
#> [1] "1970-somemonth" "1990-somemonth"

# extracting all full matches using str_extract_all
str_extract_all(string = c("1970-somemonth-01 or maybe 1990/anothermonth/01",
                           "1990-somemonth-01 or maybe 2001/anothermonth/01"),
                 pattern = "(\\d{4})[\\-\\/]([a-z]+)")
#> [[1]]
#> [1] "1970-somemonth" "1990/anothermonth"
#>
#> [[2]]
#> [1] "1990-somemonth" "2001/anothermonth"
```

221 1.2.5 Breaking strings apart

222 `str_split`, `str_sub`, In the above date-time example, when reading filenames
 223 from a path, or when working sequences separated by a known pattern generally,
 224 `str_split` can help separate elements of interest.

225 The return type is a list similar to `str_match`.

```
# split on either a hyphen or a forward slash
str_split(string = c("1970-somemonth-01",
                     "1990/anothermonth/01"),
           pattern = "[\\-\\/]")
#> [[1]]
#> [1] "1970" "somemonth" "01"
#>
#> [[2]]
#> [1] "1990" "anothermonth" "01"
```

226 This can be useful in recovering simulation parameters from a filename, but may
 227 require some knowledge of `regex`.

```
# assume a simulation output file
filename = "sim_param1_0.01_param2_0.05_param3_0.01.ext"
```

```

# not quite there
str_split(filename, pattern = "_")
#> [[1]]
#> [1] "sim"      "param1"    "0.01"      "param2"    "0.05"      "param3"    "0.01.ext"

# not really
str_split(filename,
            pattern = "sim_")
#> [[1]]
#> [1] ""
#> [2] "param1_0.01_param2_0.05_param3_0.01.ext"

# getting there but still needs work
str_split(filename,
            pattern = "(sim_)|_*param\\d{1}|(.ext)")
#> [[1]]
#> [1] ""      ""      "0.01"  "0.05"  "0.01"  ""

```

228 `str_split_fixed` split the string into as many pieces as specified, and can be
 229 especially useful dealing with filepaths.

```

# split on either a hyphen or a forward slash
str_split_fixed(string = "dir_level_1/dir_level_2/file.ext",
                pattern = "/",
                n = 2)
#>      [,1]      [,2]
#> [1,] "dir_level_1" "dir_level_2/file.ext"

```

230 1.2.6 Replacing string elements

231 `str_replace` is intended to replace the search pattern, and can be co-opted
 232 into the task of recovering simulation parameters or other data from regularly
 233 named files. `str_replace_all` works the same way but replaces all matches of
 234 the search pattern.

```

# replace all unwanted characters from this hypothetical filename with spaces
filename = "sim_param1_0.01_param2_0.05_param3_0.01.ext"
str_replace_all(filename,
                pattern = "(sim_)|_*param\\d{1}|(.ext)",
                replacement = " ")
#> [1] " 0.01 0.05 0.01 "

```

235 `str_remove` is a wrapper around `str_replace` where the replacement is set to
 236 `""`. This is not covered here.

237 Having replaced unwanted characters in the filename with spaces, `str_trim`
 238 offers a way to remove leading and trailing whitespaces.

```

# trim whitespaces from this filename after replacing unwanted text
filename = "sim_param1_0.01_param2_0.05_param3_0.01.ext"
filename_with_spaces = str_replace_all(filename,
                                     pattern = "(sim_)|_*param\\d{1}|(.ext)",
                                     replacement = " ")
filename_without_spaces = str_trim(filename_with_spaces)
filename_without_spaces
#> [1] "0.01 0.05 0.01"

# the result can be split on whitespaces to return useful data
str_split(filename_without_spaces, " ")
#> [[1]]
#> [1] "0.01" "0.05" "0.01"

```

239 1.2.7 Subsetting within strings

240 When strings are highly regular, useful data can be extracted from a string using
 241 `str_sub`. In the date-time example, the year is always represented by the first
 242 four characters.

```

# get the year as characters 1 - 4
str_sub(string = c("1970-somemonth-01",
                  "1990-anothermonth-01",
                  "2010-thismonth-01"),
        start = 1, end = 4)
#> [1] "1970" "1990" "2010"

```

243 Similarly, it's possible to extract the last few characters using negative indices.

```

# get the day as characters -2 to -1
str_sub(string = c("1970-somemonth-01",
                  "1990-anothermonth-21",
                  "2010-thismonth-31"),
        start = -2, end = -1)
#> [1] "01" "21" "31"

```

244 Finally, it's also possible to replace characters within a string based on the
 245 position. This requires using the assignment operator `<-`.

```

# replace all days in these dates to 01
date_times = c("1970-somemonth-25",
               "1990-anothermonth-21",
               "2010-thismonth-31")

# a strictly necessary use of the assignment operator
str_sub(date_times,
        start = -2, end = -1) <- "01"

```

```
date_times
#> [1] "1970-somemonth-01" "1990-anothermonth-01" "2010-thismonth-01"
```

246 1.2.8 Padding and truncating strings

247 Strings included in filenames or plots are often of unequal lengths, especially
 248 when they represent numbers. `str_pad` can pad strings with suitable characters
 249 to maintain equal length filenames, with which it is easier to work.

```
# pad so all values have three digits
str_pad(string = c("1", "10", "100"),
        width = 3,
        side = "left",
        pad = "0")
#> [1] "001" "010" "100"
```

250 Strings can also be truncated if they are too long.

```
str_trunc(string = c("bananas are great and wonderful
                      and more stuff about bananas and
                      it really goes on about bananas"),
          width = 27,
          side = "right", ellipsis = "etc. etc.")
#> [1] "bananas are great etc. etc."
```

251 1.2.9 Stringr aspects not covered here

252 Some `stringr` functions are not covered here. These include:

- 253 • `str_wrap` (of dubious use),
- 254 • `str_interp`, `str_glue*` (better to use `glue`; see below),
- 255 • `str_sort`, `str_order` (used in sorting a character vector),
- 256 • `str_to_case*` (case conversion), and
- 257 • `str_view*` (a graphical view of search pattern matches).
- 258 • `word`, `boundary` etc. The use of `word` is covered below.

259 `stringi`, of which `stringr` is a wrapper, offers a lot more flexibility and control.

260 1.3 String interpolation with glue

261 The idea behind string interpolation is to procedurally generate new complex
 262 strings from pre-existing data.

263 `glue` is as simple as the example shown.

```
# print that each car name is a car model
cars = rownames(head(mtcars))
glue('The {cars} is a car model')
#> The Mazda RX4 is a car model
#> The Mazda RX4 Wag is a car model
#> The Datsun 710 is a car model
#> The Hornet 4 Drive is a car model
#> The Hornet Sportabout is a car model
#> The Valiant is a car model
```

264 This creates and prints a vector of car names stating each is a car model.

265 The related `glue_data` is even more useful in printing from a dataframe. In
 266 this example, it can quickly generate command line arguments or filenames.

```
# use dataframes for now
parameter_combinations = data.frame(param1 = letters[1:5],
                                     param2 = 1:5)

# for command line arguments or to start multiple job scripts on the cluster
glue_data(parameter_combinations,
           'simulation-name {param1} {param2}')
#> simulation-name a 1
#> simulation-name b 2
#> simulation-name c 3
#> simulation-name d 4
#> simulation-name e 5

# for filenames
glue_data(parameter_combinations,
           'sim_data_param1_{param1}_param2_{param2}.ext')
#> sim_data_param1_a_param2_1.ext
#> sim_data_param1_b_param2_2.ext
#> sim_data_param1_c_param2_3.ext
#> sim_data_param1_d_param2_4.ext
#> sim_data_param1_e_param2_5.ext
```

267 Finally, the convenient `glue_sql` and `glue_data_sql` are used to safely write
 268 SQL queries where variables from data are appropriately quoted. This is not
 269 covered here, but it is good to know it exists.

270 `glue` has some more functions — `glue_safe`, `glue_collapse`, and `glue_col`,
 271 but these are infrequently used. Their functionality can be found on the `glue`
 272 github page.

1.4 Strings in ggplot

`ggplot` has two `geoms` (wait for the `ggplot` tutorial to understand more about `geoms`) that work with text: `geom_text` and `geom_label`. These `geoms` allow text to be pasted on to the main body of a plot.

Often, these may overlap when the data are closely spaced. The package `ggrepel` offers another `geom`, `geom_text_repel` (and the related `geom_label_repel`) that help arrange text on a plot so it doesn't overlap with other features. This is *not perfect*, but it works more often than not.

More examples can be found on the `ggrepel` website.

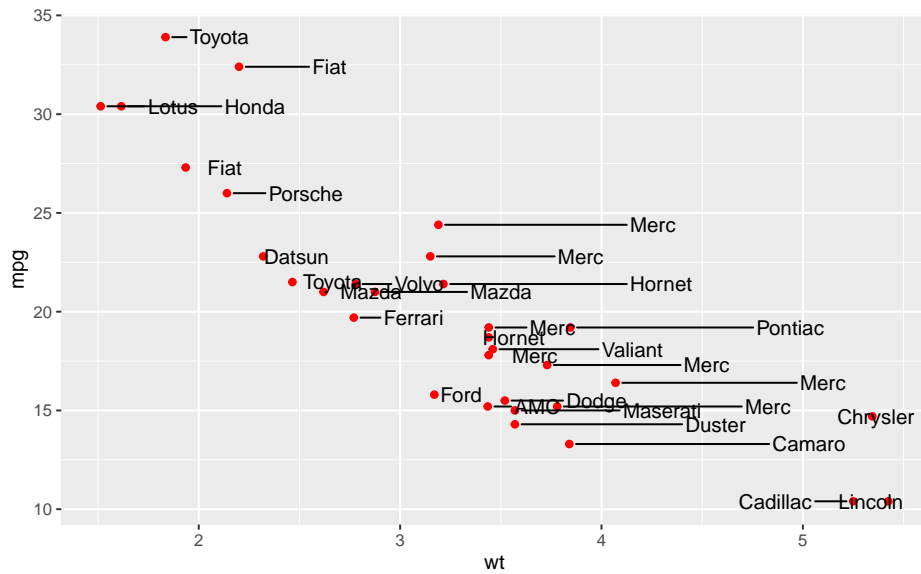
Here, the arguments to `geom_text_repel` are taken both from the `mtcars` data (position), as well as from the car brands extracted using the `stringr::word` (labels), which tries to separate strings based on a regular pattern.

The details of `ggplot` are covered in a later tutorial.

```
library(ggplot2)
library(ggrepel)

# prepare car labels using word function
car_labels = word(rownames(mtcars))

ggplot(mtcars,
  aes(x = wt, y = mpg,
    label = rownames(mtcars)))+
  geom_point(colour = "red")+
  geom_text_repel(aes(label = car_labels),
    direction = "x",
    nudge_x = 0.2,
    box.padding = 0.5,
    point.padding = 0.5)
```



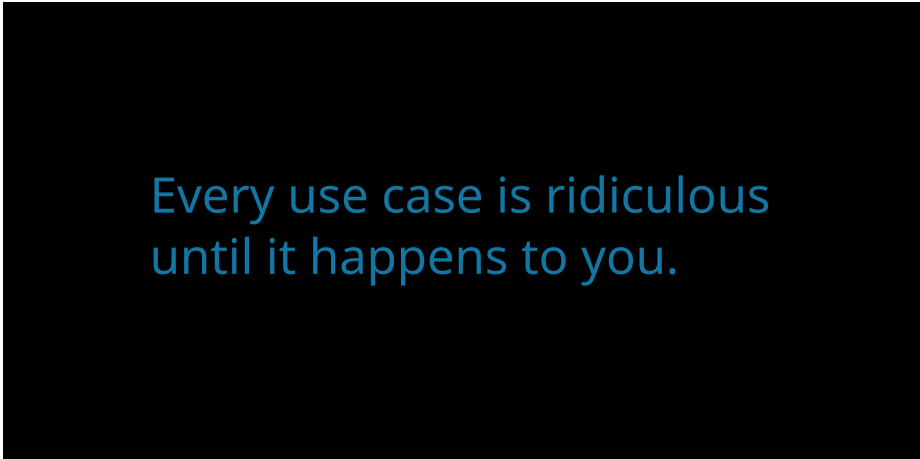
287

288 This is not a good looking plot, because it breaks other rules of plot design,
 289 such as whether this sort of plot should be made at all. Labels and text need
 290 to be applied sparingly, for example drawing attention or adding information to
 291 outliers.

Chapter 2

Reshaping data tables in the tidyverse, and other things

Raphael Scherrer



Every use case is ridiculous
until it happens to you.

```
library(tibble)  
library(tidyr)
```

In this chapter we will learn what *tidy* means in the context of the tidyverse, and how to reshape our data into a tidy format using the `tidyr` package. But first, let us take a detour and introduce the `tibble`.

2.1 The new data frame: tibble

The `tibble` is the recommended class to use to store tabular data in the tidyverse. Consider it as the operational unit of any data science pipeline. For most practical purposes, a `tibble` is basically a `data.frame`.

```
# Make a data frame
data.frame(who = c("Pratik", "Theo", "Raph"), chapt = c("1, 4", "3", "2, 5"))
#>      who chapt
#> 1 Pratik 1, 4
#> 2 Theo   3
#> 3 Raph  2, 5

# Or an equivalent tibble
tibble(who = c("Pratik", "Theo", "Raph"), chapt = c("1, 4", "3", "2, 5"))
#> # A tibble: 3 x 2
#>   who    chapt
#>   <chr> <chr>
#> 1 Pratik 1, 4
#> 2 Theo   3
#> 3 Raph  2, 5
```

The difference between `tibble` and `data.frame` is in its display and in the way it is subsetting, among others. Most functions working with `data.frame` will work with `tibble` and vice versa. Use the `as*` family of functions to switch back and forth between the two if needed, using e.g. `as.data.frame` or `as_tibble`.

In terms of display, the tibble has the advantage of showing the class of each column: `chr` for `character`, `fct` for `factor`, `int` for `integer`, `dbl` for `numeric` and `lgl` for `logical`, just to name the main atomic classes. This may be more important than you think, because many hard-to-find bugs in R are due to wrong variable types and/or cryptic type conversions. This especially happens with `factor` and `character`, which can cause quite some confusion. More about this in the extra section at the end of this chapter!

Note that you can build a tibble by rows rather than by columns with `tribble`:

```
tribble(
  ~who, ~chapt,
  "Pratik", "1, 4",
  "Theo", "3",
  "Raph", "2, 5"
)
#> # A tibble: 3 x 2
#>   who    chapt
#>   <chr> <chr>
#> 1 Pratik 1, 4
#> 2 Theo   3
```

```
#> 3 Raph 2, 5
```

317 As a rule of thumb, try to convert your tables to tibbles whenever you can,
 318 especially when the original table is *not* a data frame. For example, the prin-
 319 cipal component analysis function `prcomp` outputs a **matrix** of coordinates in
 320 principal component-space.

```
# Perform a PCA on mtcars
pca_scores <- prcomp(mtcars)$x
head(pca_scores) # looks like a data frame or a tibble...
#>      PC1    PC2    PC3    PC4    PC5    PC6    PC7    PC8
#> Mazda RX4      -79.60  2.13 -2.15 -2.707 -0.702 -0.3149 -0.09870 -0.0779
#> Mazda RX4 Wag  -79.60  2.15 -2.22 -2.178 -0.884 -0.4534 -0.00355 -0.0957
#> Datsun 710      -133.89 -5.06 -2.14  0.346  1.106  1.1730  0.00576  0.1362
#> Hornet 4 Drive    8.52 44.99  1.23  0.827  0.424 -0.0579 -0.02431  0.2212
#> Hornet Sportabout 128.69 30.82  3.34 -0.521  0.737 -0.3329  0.10630 -0.0530
#> Valiant        -23.22 35.11 -3.26  1.401  0.803 -0.0884  0.23895  0.4239
#>      PC9    PC10    PC11
#> Mazda RX4      -0.200 -0.2901  0.106
#> Mazda RX4 Wag  -0.353 -0.1928  0.107
#> Datsun 710      -0.198  0.0763  0.267
#> Hornet 4 Drive   0.356 -0.0906  0.209
#> Hornet Sportabout 0.153 -0.1886 -0.109
#> Valiant         0.101 -0.0377  0.276
class(pca_scores) # but is actually a matrix
#> [1] "matrix"

# Convert to tibble
as_tibble(pca_scores)
#> # A tibble: 32 x 11
#>      PC1    PC2    PC3    PC4    PC5    PC6    PC7    PC8    PC9    PC10
#>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1  -79.6  2.13 -2.15 -2.71 -0.702 -0.315 -0.0987 -0.0779 -0.200 -0.290
#> 2  -79.6  2.15 -2.22 -2.18 -0.884 -0.453 -0.00355 -0.0957 -0.353 -0.193
#> 3 -134.  -5.06 -2.14  0.346  1.11  1.17  0.00576  0.136 -0.198  0.0763
#> 4   8.52 45.0  1.23  0.827  0.424 -0.0579 -0.0243  0.221  0.356 -0.0906
#> 5  129.  30.8  3.34 -0.521  0.737 -0.333  0.106 -0.0530  0.153 -0.189
#> 6  -23.2 35.1 -3.26  1.40  0.803 -0.0884  0.239  0.424  0.101 -0.0377
#> # ... with 26 more rows, and 1 more variable: PC11 <dbl>
```

321 This is important because a **matrix** can contain only one type of values (e.g. only
 322 **numeric** or **character**), while **tibble** (and **data.frame**) allow you to have
 323 columns of different types.

324 So, in the tidyverse we are going to work with tibbles, got it. But what does
 325 “tidy” mean exactly?

2.2 The concept of tidy data

When it comes to putting data into tables, there are many ways one could organize a dataset. The *tidy* format is one such format. According to the formal definition, a table is tidy if each column is a variable and each row is an observation. In practice, however, I found that this is not a very operational definition, especially in ecology and evolution where we often record multiple variables per individual. So, let's dig in with an example.

Say we have a dataset of several morphometrics measured on Darwin's finches in the Galapagos islands. Let's first get this dataset.

```
# We first simulate random data
beak_lengths <- rnorm(100, mean = 5, sd = 0.1)
beak_widths <- rnorm(100, mean = 2, sd = 0.1)
body_weights <- rgamma(100, shape = 10, rate = 1)
islands <- rep(c("Isabela", "Santa Cruz"), each = 50)

# Assemble into a tibble
data <- tibble(
  id = 1:100,
  body_weight = body_weights,
  beak_length = beak_lengths,
  beak_width = beak_widths,
  island = islands
)

# Snapshot
data
#> # A tibble: 100 x 5
#>   id body_weight beak_length beak_width island
#>   <int>      <dbl>      <dbl>      <dbl> <chr>
#> 1     1      10.8        4.94      1.94 Isabela
#> 2     2      15.4        5.02      2.00 Isabela
#> 3     3      15.0        4.92      1.91 Isabela
#> 4     4       8.51        5.16      2.02 Isabela
#> 5     5      14.9        5.03      1.93 Isabela
#> 6     6       8.41        4.92      2.18 Isabela
#> # ... with 94 more rows
```

Here, we pretend to have measured `beak_length`, `beak_width` and `body_weight` on 100 birds, 50 of them from Isabela and 50 of them from Santa Cruz. In this tibble, each row is an individual bird. This is probably the way most scientists would record their data in the field. However, a single bird is not an “observation” in the sense used in the tidyverse. Our dataset is not tidy but *messy*.

The tidy equivalent of this dataset would be:

```

data <- pivot_longer(
  data,
  cols = c("body_weight", "beak_length", "beak_width"),
  names_to = "variable"
)
data
#> # A tibble: 300 x 4
#>   id island variable    value
#>   <int> <chr>   <chr>    <dbl>
#> 1     1  Isabela body_weight 10.8
#> 2     1  Isabela beak_length  4.94
#> 3     1  Isabela beak_width  1.94
#> 4     2  Isabela body_weight 15.4
#> 5     2  Isabela beak_length  5.02
#> 6     2  Isabela beak_width  2.00
#> # ... with 294 more rows

```

where each *measurement* (and not each *individual*) is now the unit of observation (the rows). The `pivot_longer` function is the easiest way to get to this format. It belongs to the `tidyr` package, which we'll cover in a minute.

As you can see our tibble now has three times as many rows and fewer columns. This format is rather unintuitive and not optimal for display. However, it provides a very standardized and consistent way of organizing data that will be understood (and expected) by pretty much all functions in the tidyverse. This makes the tidyverse tools work well together and reduces the time you would otherwise spend reformatting your data from one tool to the next.

That does not mean that the *messy* format is useless though. There may be use-cases where you need to switch back and forth between formats. For this reason I prefer referring to these formats using their other names: *long* (tidy) versus *wide* (messy). For example, matrix operations work much faster on wide data, and the wide format arguably looks nicer for display. Luckily the `tidyr` package gives us the tools to reshape our data as needed, as we shall see shortly.

Another common example of wide-or-long dilemma is when dealing with *contingency tables*. This would be our case, for example, if we asked how many observations we have for each morphometric and each island. We use `table` (from base R) to get the answer:

```

# Make a contingency table
ctg <- with(data, table(island, variable))
ctg
#>           variable
#> island  beak_length beak_width body_weight
#> Isabela           50          50          50
#> Santa Cruz        50          50          50

```

A variety of statistical tests can be used on contingency tables such as Fisher's

361 exact test, the chi-square test or the binomial test. Contingency tables are in
 362 the wide format by construction, but they too can be pivoted to the long format,
 363 and the tidyverse manipulation tools will expect you to do so. Actually, `tibble`
 364 knows that very well and does it by default if you convert your `table` into a
 365 `tibble`:

```
# Contingency table is pivoted to the long-format automatically
as_tibble(ctg)
#> # A tibble: 6 x 3
#>   island      variable      n
#>   <chr>      <chr>    <int>
#> 1 Isabela    beak_length    50
#> 2 Santa Cruz beak_length    50
#> 3 Isabela    beak_width     50
#> 4 Santa Cruz beak_width     50
#> 5 Isabela    body_weight    50
#> 6 Santa Cruz body_weight    50
```

Summary: Tidy or not tidy

To sum up, the definition of what is tidy and what is not is somewhat subjective. Tables can be in long or wide format, and depending on the complexity of a dataset, there may even be some intermediate states. To be clear, the tidyverse does not only accept long tables, and wide tables may sometimes be the way to go. This is very use-case specific. Have a clear idea of what you want to do with your data (what tidyverse tools you will use), and use that to figure which format makes more sense. And remember, `tidyr` is here to easily do the switching for you.

366 2.3 Reshaping with `tidyr`

367 The `tidyr` package implements tools to easily switch between layouts and also
 368 perform a few other reshaping operations. Old school R users will be famil-
 369 iar with the `reshape` and `reshape2` packages, of which `tidyr` is the tidyverse
 370 equivalent. Beware that `tidyr` is about playing with the general *layout* of the
 371 dataset, while *operations* and *transformations* of the data are within the scope
 372 of the `dplyr` and `purrr` packages. All these packages work hand-in-hand really
 373 well, and analysis pipelines usually involve all of them. But today, we focus
 374 on the first member of this holy trinity, which is often the first one you'll need
 375 because you will want to reshape your data before doing other things. So, please
 376 hold your non-layout-related questions for the next chapters.

2.3.1 Pivoting

Pivoting a dataset between the long and wide layout is the main purpose of **tidyr** (check out the package's logo). We already saw the **pivot_longer** function above. This function converts a table from wide to long format. Similarly, there is a **pivot_wider** function that does exactly the opposite and takes you back to the wide format:

```

pivot_wider(
  data,
  names_from = "variable",
  values_from = "value",
  id_cols = c("id", "island")
)
#> # A tibble: 100 x 5
#>   id island body_weight beak_length beak_width
#>   <int> <chr>      <dbl>      <dbl>      <dbl>
#> 1     1  Isabela      10.8        4.94        1.94
#> 2     2  Isabela      15.4        5.02        2.00
#> 3     3  Isabela      15.0        4.92        1.91
#> 4     4  Isabela       8.51        5.16        2.02
#> 5     5  Isabela      14.9        5.03        1.93
#> 6     6  Isabela       8.41        4.92        2.18
#> # ... with 94 more rows

```

The order of the columns is not exactly as it was, but this should not matter in a data analysis pipeline where you should access columns by their names. It is straightforward to change the order of the columns, but this is more within the scope of the **dplyr** package.

If you are familiar with earlier versions of the tidyverse, **pivot_longer** and **pivot_wider** are the respective equivalents of **gather** and **spread**, which are now deprecated.

There are a few other reshaping operations from **tidyr** that are worth knowing.

2.3.2 Handling missing values

Say we have some missing measurements in the column “value” of our finch dataset:

```

# We replace 100 random observations by NAs
ii <- sample(nrow(data), 100)
data$value[ii] <- NA
data
#> # A tibble: 300 x 4
#>   id island variable value
#>   <int> <chr>   <chr>    <dbl>
#> 1     1  Isabela body_weight 10.8

```

```
#> 2      1 Isabela beak_length NA
#> 3      1 Isabela beak_width  NA
#> 4      2 Isabela body_weight NA
#> 5      2 Isabela beak_length 5.02
#> 6      2 Isabela beak_width  NA
#> # ... with 294 more rows
```

394 We could get rid of the rows that have missing values using `drop_na`:

```
drop_na(data, value)
#> # A tibble: 200 x 4
#>       id island variable    value
#>   <int> <chr>   <chr>    <dbl>
#> 1      1 Isabela body_weight 10.8
#> 2      2 Isabela beak_length 5.02
#> 3      3 Isabela body_weight 15.0
#> 4      3 Isabela beak_length 4.92
#> 5      4 Isabela body_weight 8.51
#> 6      4 Isabela beak_width 2.02
#> # ... with 194 more rows
```

395 Else, we could replace the NAs with some user-defined value:

```
replace_na(data, replace = list(value = -999))
#> # A tibble: 300 x 4
#>       id island variable    value
#>   <int> <chr>   <chr>    <dbl>
#> 1      1 Isabela body_weight 10.8
#> 2      1 Isabela beak_length -999
#> 3      1 Isabela beak_width -999
#> 4      2 Isabela body_weight -999
#> 5      2 Isabela beak_length 5.02
#> 6      2 Isabela beak_width -999
#> # ... with 294 more rows
```

396 where the `replace` argument takes a named list, and the names should refer to
397 the columns to apply the replacement to.

398 We could also replace NAs with the most recent non-NA values:

```
fill(data, value)
#> # A tibble: 300 x 4
#>       id island variable    value
#>   <int> <chr>   <chr>    <dbl>
#> 1      1 Isabela body_weight 10.8
#> 2      1 Isabela beak_length 10.8
#> 3      1 Isabela beak_width 10.8
#> 4      2 Isabela body_weight 10.8
#> 5      2 Isabela beak_length 5.02
```



```
#> 6      2 Isabela beak_width  5.02
#> # ... with 294 more rows
```

Note that most functions in the tidyverse take a tibble as their first argument, and columns to which to apply the functions are usually passed as “objects” rather than character strings. In the above example, we passed the `value` column as `value`, not `"value"`. These column-objects are called by the tidyverse functions *in the context* of the data (the tibble) they belong to.

2.3.3 Splitting and combining cells

The `tidyr` package offers tools to split and combine columns. This is a nice extension to the string manipulations we saw last week in the `stringr` tutorial.

Say we want to add the specific dates when we took measurements on our birds (we would normally do this using `dplyr` but for now we will stick to the old way):

```
# Sample random dates for each observation
data$day <- sample(30, nrow(data), replace = TRUE)
data$month <- sample(12, nrow(data), replace = TRUE)
data$year <- sample(2019:2020, nrow(data), replace = TRUE)
data
#> # A tibble: 300 x 7
#>       id island variable    value  day month  year
#>   <int> <chr>   <chr>    <dbl> <int> <int> <int>
#> 1     1  Isabela body_weight 10.8     8     7  2020
#> 2     1  Isabela beak_length NA      19     7  2019
#> 3     1  Isabela beak_width  NA     17    12  2019
#> 4     2  Isabela body_weight NA      20    12  2020
#> 5     2  Isabela beak_length 5.02    21    10  2020
#> 6     2  Isabela beak_width  NA     23     2  2020
#> # ... with 294 more rows
```

We could combine the `day`, `month` and `year` columns into a single `date` column, with a dash as a separator, using `unite`:

```
data <- unite(data, day, month, year, col = "date", sep = "-")
data
#> # A tibble: 300 x 5
#>       id island variable    value date
#>   <int> <chr>   <chr>    <dbl> <chr>
#> 1     1  Isabela body_weight 10.8 8-7-2020
#> 2     1  Isabela beak_length NA   19-7-2019
#> 3     1  Isabela beak_width  NA   17-12-2019
#> 4     2  Isabela body_weight NA   20-12-2020
#> 5     2  Isabela beak_length 5.02 21-10-2020
#> 6     2  Isabela beak_width  NA   23-2-2020
```

```
#> # ... with 294 more rows
```

Of course, we can revert back to the previous dataset by splitting the `date` column with `separate`.

```
separate(data, date, into = c("day", "month", "year"))
#> # A tibble: 300 x 7
#>   id island variable    value day month year
#>   <int> <chr>   <chr>      <dbl> <chr> <chr> <chr>
#> 1     1  Isabela body_weight  10.8   8     7   2020
#> 2     1  Isabela beak_length  NA    19     7   2019
#> 3     1  Isabela beak_width   NA    17    12   2019
#> 4     2  Isabela body_weight  NA    20    12   2020
#> 5     2  Isabela beak_length  5.02  21    10   2020
#> 6     2  Isabela beak_width   NA    23     2   2020
#> # ... with 294 more rows
```

But note that the `day`, `month` and `year` columns are now of class `character` and not `integer` anymore. This is because they result from the splitting of `date`, which itself was a `character` column.

You can also separate a single column into multiple *rows* using `separate_rows`:

```
separate_rows(data, date)
#> # A tibble: 900 x 5
#>   id island variable    value date
#>   <int> <chr>   <chr>      <dbl> <chr>
#> 1     1  Isabela body_weight  10.8  8
#> 2     1  Isabela body_weight  10.8  7
#> 3     1  Isabela body_weight  10.8 2020
#> 4     1  Isabela beak_length  NA    19
#> 5     1  Isabela beak_length  NA     7
#> 6     1  Isabela beak_length  NA    2019
#> # ... with 894 more rows
```

2.3.4 Expanding tables using combinations

Instead of getting rid of rows with NAs, we may want to add rows with NAs, for example, for combinations of parameters that we did not measure.

```
data <- separate(data, date, into = c("day", "month", "year"))
to_rm <- with(data, island == "Santa Cruz" & year == "2020")
data <- data[!to_rm,]
tail(data)
#> # A tibble: 6 x 7
#>   id island variable    value day month year
#>   <int> <chr>   <chr>      <dbl> <chr> <chr> <chr>
#> 1    98 Santa Cruz beak_length  4.94  22    12   2019
#> 2    98 Santa Cruz beak_width   1.90   9     1   2019
```

```
#> 3 99 Santa Cruz body_weight 15.0 16 7 2019
#> 4 99 Santa Cruz beak_length NA 26 10 2019
#> 5 99 Santa Cruz beak_width 2.04 30 7 2019
#> 6 100 Santa Cruz beak_width NA 23 3 2019
```

421 We could generate a tibble with all combinations of island, morphometric and
422 year using `expand_grid`:

```
expand_grid(
  island = c("Isabela", "Santa Cruz"),
  year = c("2019", "2020")
)
#> # A tibble: 4 x 2
#>   island year
#>   <chr>   <chr>
#> 1 Isabela 2019
#> 2 Isabela 2020
#> 3 Santa Cruz 2019
#> 4 Santa Cruz 2020
```

423 If we already have a tibble to work from that contains the variables to combine,
424 we can use `expand` on that tibble:

```
expand(data, island, year)
#> # A tibble: 4 x 2
#>   island year
#>   <chr>   <chr>
#> 1 Isabela 2019
#> 2 Isabela 2020
#> 3 Santa Cruz 2019
#> 4 Santa Cruz 2020
```

425 As you can see, we get all the combinations of the variables of interest, even
426 those that are missing. But sometimes you might be interested in variables
427 that are *nested* within each other and not *crossed*. For example, say we have
428 measured birds at different locations within each island:

```
nrow_Isabela <- with(data, length(which(island == "Isabela")))
nrow_SantaCruz <- with(data, length(which(island == "Santa Cruz")))
sites_Isabela <- sample(c("A", "B"), size = nrow_Isabela, replace = TRUE)
sites_SantaCruz <- sample(c("C", "D"), size = nrow_SantaCruz, replace = TRUE)
sites <- c(sites_Isabela, sites_SantaCruz)
data$site <- sites
data
#> # A tibble: 232 x 8
#>   id island variable value day month year site
#>   <int> <chr>   <chr>     <dbl> <chr> <chr> <chr> <chr>
#> 1     1 1 Isabela body_weight 10.8 8 7 2020 A
#> 2     1 1 Isabela beak_length NA 19 7 2019 B
```

```
#> 3      1 Isabela beak_width NA      17      12      2019 B
#> 4      2 Isabela body_weight NA      20      12      2020 A
#> 5      2 Isabela beak_length 5.02 21      10      2020 A
#> 6      2 Isabela beak_width NA      23      2      2020 A
#> # ... with 226 more rows
```

Of course, if sites A and B are on Isabela, they cannot be on Santa Cruz, where we have sites C and D instead. It would not make sense to **expand** assuming that **island** and **site** are crossed, instead, they are nested. We can therefore expand using the **nesting** function:

```
expand(data, nesting(island, site, year))
#> # A tibble: 6 x 3
#>   island      site year
#>   <chr>      <chr> <chr>
#> 1 Isabela      A    2019
#> 2 Isabela      A    2020
#> 3 Isabela      B    2019
#> 4 Isabela      B    2020
#> 5 Santa Cruz C    2019
#> 6 Santa Cruz D    2019
```

But now the missing data for Santa Cruz in 2020 are not accounted for because **expand** thinks the **year** is also nested within island. To get back the missing combination, we use **crossing**, the complement of **nesting**:

```
expand(data, crossing(nesting(island, site), year)) # both can be used together
#> # A tibble: 8 x 3
#>   island      site year
#>   <chr>      <chr> <chr>
#> 1 Isabela      A    2019
#> 2 Isabela      A    2020
#> 3 Isabela      B    2019
#> 4 Isabela      B    2020
#> 5 Santa Cruz C    2019
#> 6 Santa Cruz C    2020
#> # ... with 2 more rows
```

Here, we specify that **site** is nested within **island** and these two are crossed with **year**. Easy!

But wait a minute. These combinations are all very good, but our measurements have disappeared! We can get them back by levelling up to the **complete** function instead of using **expand**:

```
tail(complete(data, crossing(nesting(island, site), year)))
#> # A tibble: 6 x 8
#>   island      site year      id variable      value day  month
#>   <chr>      <chr> <chr> <int> <chr>      <dbl> <chr> <chr>
```

```
#> 1 Santa Cruz D      2019      95 beak_width NA      13      10
#> 2 Santa Cruz D      2019      98 beak_length 4.94 22      12
#> 3 Santa Cruz D      2019      99 body_weight 15.0 16      7
#> 4 Santa Cruz D      2019      99 beak_length NA      26      10
#> 5 Santa Cruz D      2019      99 beak_width 2.04 30      7
#> 6 Santa Cruz D      2020      NA <NA>      NA      <NA> <NA>
# the last row has been added, full of NAs
```

441 which nicely keeps the rest of the columns in the tibble and just adds the missing
442 combinations.

443 2.3.5 Nesting

444 The `tidyr` package has yet another feature that makes the tidyverse very pow-
445 erful: the `nest` function. However, it makes little sense without combining it
446 with the functions in the `purrr` package, so we will not cover it in this chapter
447 but rather in the `purrr` chapter.

448 2.3.6 What else can be tidied up?

449 2.3.6.1 Model output with broom

450 Check out the `broom` package and its `tidy` function to tidy up messy linear
451 model output, e.g.

```
library(broom)
fit <- lm(mpg ~ cyl, mtcars)
summary(fit)
#>
#> Call:
#> lm(formula = mpg ~ cyl, data = mtcars)
#>
#> Residuals:
#>      Min       1Q   Median       3Q      Max
#> -4.981 -2.119  0.222  1.072  7.519
#>
#> Coefficients:
#>              Estimate Std. Error t value Pr(>|t|)
#> (Intercept)   37.885      2.074   18.27 < 2e-16 ***
#> cyl           -2.876      0.322   -8.92  6.1e-10 ***
#> ---
#> Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
#>
#> Residual standard error: 3.21 on 30 degrees of freedom
#> Multiple R-squared:  0.726,      Adjusted R-squared:  0.717
#> F-statistic: 79.6 on 1 and 30 DF,  p-value: 6.11e-10
tidy(fit) # returns a tibble
```

```
#> # A tibble: 2 x 5
#>   term          estimate std.error statistic  p.value
#>   <chr>          <dbl>     <dbl>     <dbl>    <dbl>
#> 1 (Intercept)    37.9       2.07      18.3 8.37e-18
#> 2 cyl          -2.88      0.322     -8.92 6.11e-10
```

452 The **broom** package is just one package among a series of packages together
 453 known as **tidymodels** that deal with statistical models according to the tidyverse
 454 philosophy, and those include machine learning models.

455 2.3.6.2 Graphs with **tidygraph**

456 For some datasets, sometimes there is no trivial and intuitive way to store them
 457 into a table. This is the case, for example, for data underlying graphs (as in
 458 networks), which contain information about relations between entities. What
 459 is the unit of observation in a network? A node? An edge between two nodes?
 460 Nodes and edges in a network may each have node- or edge-specific variables
 461 mapped to them, and both may be equally valid units of observation. The
 462 **tidygraph** package has tools to store graph-data in a tidyverse-friendly object,
 463 consisting of two tibbles: one for node-specific information, the other for edge-
 464 specific information. This package goes hand in hand with the **ggraph**, that
 465 makes plotting networks compatible with the grammar of graphics.

466 2.3.6.3 Trees with **tidytree**

467 Phylogenetic trees are a special type of graphs suffering from the same issue,
 468 i.e. of being non-trivial to store in a table. The **tidytree** package and its
 469 companion **treeio** offer an interface to convert tree-like objects (from most
 470 format used by other packages and software) into a tidyverse-friendly format.
 471 Again, the point is that the rest of the tidyverse can be used to wrangle or plot
 472 this type of data in the same way as one would do with regular tabular data.
 473 For plotting a **tidytree** with the grammar of graphics, see **ggtree**.

474 2.4 Extra: factors and the **forcats** package

```
library(forcats)
```

475 Categorical variables can be stored in R as character strings in **character** or
 476 **factor** objects. A **factor** looks like a **character**, but it actually is an **integer**
 477 vector, where each **integer** is mapped to a **character** label. With this respect
 478 it is sort of an enhanced version of **character**. For example,

```
my_char_vec <- c("Pratik", "Theo", "Raph")
my_char_vec
#> [1] "Pratik" "Theo"   "Raph"
```

479 is a **character** vector, recognizable to its double quotes, while

```
my_fact_vec <- factor(my_char_vec) # as.factor would work too
my_fact_vec
#> [1] Pratik Theo Raph
#> Levels: Pratik Raph Theo
```

480 is a **factor**, of which the *labels* are displayed. The *levels* of the factor are the
 481 unique values that appear in the vector. If I added an extra occurrence of my
 482 name:

```
factor(c(my_char_vec, "Raph"))
#> [1] Pratik Theo Raph Raph
#> Levels: Pratik Raph Theo
```

483 we would still have the the same levels. Note that the levels are returned as a
 484 **character** vector in alphabetical order by the **levels** function:

```
levels(my_fact_vec)
#> [1] "Pratik" "Raph" "Theo"
```

485 Why does it matter? Well, most operations on categorical variables can be
 486 performed on **character** or **factor** objects, so it does not matter so much
 487 which one you use for your own data. However, some functions in R require
 488 you to provide categorical variables in one specific format, and others may even
 489 implicitly convert your variables. In **ggplot2** for example, character vectors
 490 are converted into factors by default. So, it is always good to remember the
 491 differences and what type your variables are.

492 But this is a tidyverse tutorial, so I would like to introduce here the package
 493 **forcats**, which offers tools to manipulate factors. First of all, most tools from
 494 **stringr** *will work* on factors. The **forcats** functions expand the string manip-
 495 ulation toolbox with factor-specific utilities. Similar in philosophy to **stringr**
 496 where functions started with **str_**, in **forcats** most functions start with **fct_**.

497 I see two main ways **forcats** can come handy in the kind of data most people
 498 deal with: playing with the order of the levels of a factor and playing with the
 499 levels themselves. We will show here a few examples, but the full breadth of
 500 factor manipulations can be found online or in the excellent **forcats** cheatsheet.

501 2.4.1 Change the order of the levels

502 One example use-case where you would want to change the order of the levels
 503 of a factor is when plotting. Your categorical variable, for example, may not be
 504 plotted in the order you want. If we plot the distribution of each variable across
 505 islands, we get

```
# Make the plotting code a function so we can re-use it without copying and pasting
my_plot <- function(data) {

  # We do not cover the ggplot functions in this chapter, this is just to
  # illustrate our use-case, wait until chapter 5!
```

```

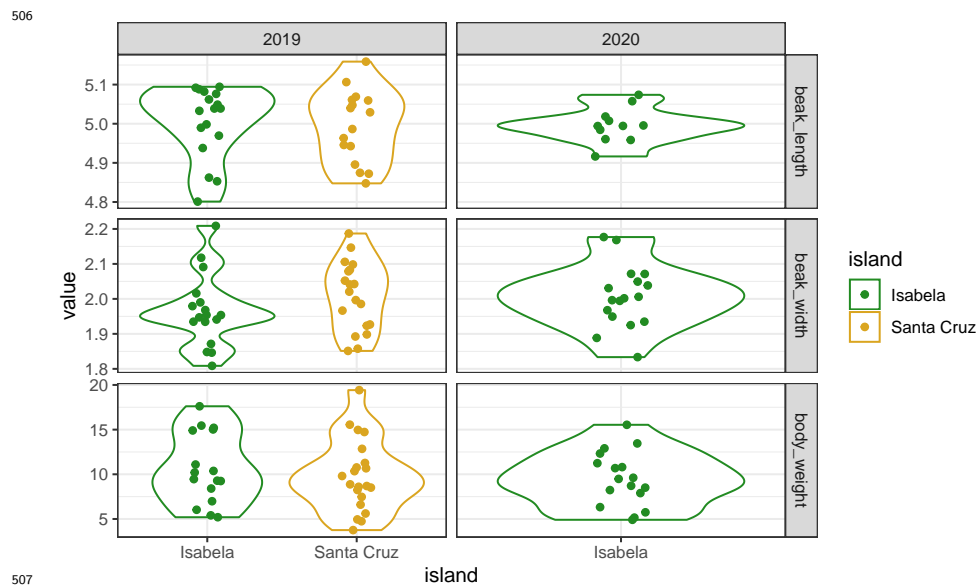
library(ggplot2)
ggplot(data, aes(x = island, y = value, color = island)) +
  geom_violin() +
  geom_jitter(width = 0.1) +
  facet_grid(variable ~ year, scales = "free") +
  theme_bw() +
  scale_color_manual(values = c("forestgreen", "goldenrod"))
}

```

```

my_plot(data)
# Remember that data are missing from Santa Cruz in 2020

```



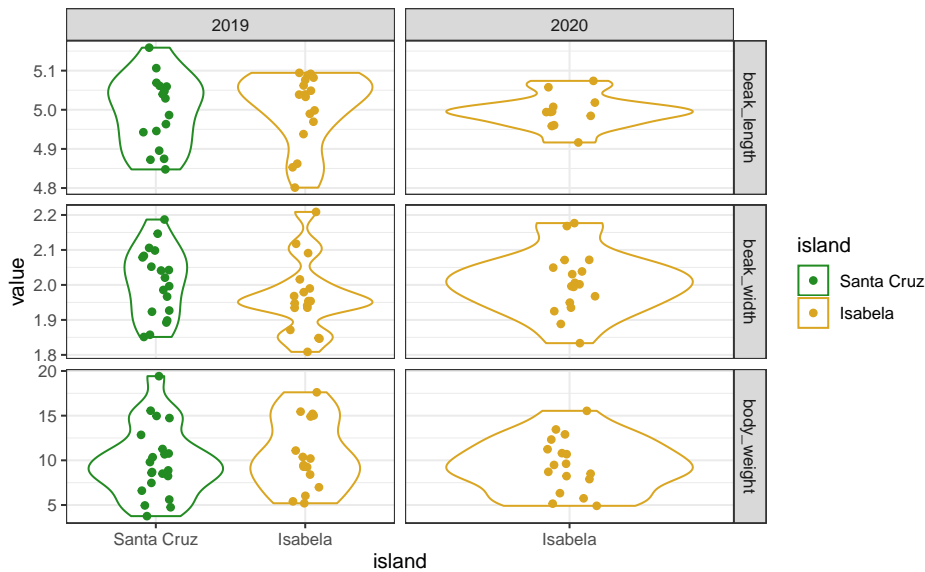
508 Here, the islands (horizontal axis) and the variables (the facets) are displayed
 509 in alphabetical order. When making a figure you may want to customize these
 510 orders in such a way that your message is optimally conveyed by your figure,
 511 and this may involve playing with the order of levels.

512 Use `fct_relevel` to manually change the order of the levels:

```

data$island <- as.factor(data$island) # turn this column into a factor
data$island <- fct_relevel(data$island, c("Santa Cruz", "Isabela"))
my_plot(data) # order of islands has changed!

```

514

515 Beware that reordering a factor *does not change* the order of the items within
 516 the vector, only the order of the *levels*. So, it does not introduce any mismatch
 517 between the `island` column and the other columns! It only matters when the
 518 levels are called, for example, in a `ggplot`. As you can see:

```
data$island[1:10]
#> [1] Isabela Isabela Isabela Isabela Isabela Isabela Isabela Isabela Isabela Isabela
#> [10] Isabela
#> Levels: Santa Cruz Isabela
fct_relevel(data$island, c("Isabela", "Santa Cruz"))[1:10] # same thing, different levels
#> [1] Isabela Isabela Isabela Isabela Isabela Isabela Isabela Isabela Isabela Isabela
#> [10] Isabela
#> Levels: Isabela Santa Cruz
```

519 Alternatively, use `fct_inorder` to set the order of the levels to the order in
 520 which they appear:

```
data$variable <- as.factor(data$variable)
levels(data$variable)
#> [1] "beak_length" "beak_width" "body_weight"
levels(fct_inorder(data$variable))
#> [1] "body_weight" "beak_length" "beak_width"
```

521 or `fct_rev` to reverse the order of the levels:

```
levels(fct_rev(data$island)) # back in the alphabetical order
#> [1] "Isabela" "Santa Cruz"
```

522 Other variants exist to do more complex reordering, all present in the forcats
 523 cheatsheet, for example: * `fct_infreq` to re-order according to the frequency

of each level (how many observation on each island?) * `fct_shift` to shift the order of all levels by a certain rank (in a circular way so that the last one becomes the first one or vice versa) * `fct_shuffle` if you want your levels in random order * `fct_reorder`, which reorders based on an associated variable (see `fct_reorder2` for even more complex relationship between the factor and the associated variable)

2.4.2 Change the levels themselves

Changing the levels of a factor will change the labels in the actual vector. It is similar to performing a string substitution in `stringr`. One can change the levels of a factor using `fct_recode`:

```
fct_recode(
  my_fact_vec,
  "Pratik Gupte" = "Pratik",
  "Theo Pannetier" = "Theo",
  "Raphael Scherrer" = "Raph"
)
#> [1] Pratik Gupte      Theo Pannetier    Raphael Scherrer
#> Levels: Pratik Gupte Raphael Scherrer Theo Pannetier
```

or collapse factor levels together using `fct_collapse`:

```
fct_collapse(my_fact_vec, EU = c("Theo", "Raph"), NonEU = "Pratik")
#> [1] NonEU EU      EU
#> Levels: NonEU EU
```

Again, we do not provide an exhaustive list of `forcats` functions here but the most usual ones, to give a glimpse of many things that one can do with factors. So, if you are dealing with factors, remember that `forcats` may have handy tools for you. Among others: * `fct_anon` to “anonymize”, i.e. replace the levels by random integers * `fct_lump` to collapse levels together based on their frequency (e.g. the two most frequent levels together)

2.4.3 Dropping levels

If you use factors in your tibble and get rid of one level, for any reason, the factor will usually remember the old levels, which may cause some problems when applying functions to your data.

```
data <- data[data$island == "Santa Cruz",] # keep only one island
unique(data$island) # Isabela is gone from the labels
#> [1] Santa Cruz
#> Levels: Santa Cruz Isabela
levels(data$island) # but not from the levels
#> [1] "Santa Cruz" "Isabela"
```

545 Use `droplevels` (from base R) to make sure you get rid of levels that are not
546 in your data anymore:

```
data <- droplevels(data)
levels(data$island)
#> [1] "Santa Cruz"
```

547 Fortunately, most functions within the tidyverse will not complain about missing
548 levels, and will automatically get rid of those inexistant levels for you. But
549 because factors are such common causes of bugs, keep this in mind!

550 Note that this is equivalent to doing:

```
data$island <- fct_drop(data$island)
```

551 2.4.4 Other things

552 Among other things you can use in `forcats`: * `fct_count` to get the frequency
553 of each level * `fct_c` to combine factors together

554 2.4.5 Take home message for forcats

555 Use this package to manipulate your factors. Do you need factors? Or are
556 character vectors enough? That is your call, and may depend on the kind of
557 analyses you want to do and what they require. We saw here that for plotting,
558 having factors can allow you to do quite some tweaking of the display. If you
559 encounter a situation where the order of encoding of your character vector starts
560 to matter, then maybe converting into a factor would make your life easier. And
561 if you do so, remember that lots of tools to perform all kinds of manipulation
562 are available to you with both `stringr` and `forcats`.

563 2.5 External resources

564 Find lots of additional info by looking up the following links:

- 565 • The `readr/tibble/tidyr` and `forcats` cheatsheets.
- 566 • This link on the concept of tidy data
- 567 • The `tibble`, `tidyr` and `forcats` websites
- 568 • The `broom`, `tidymodels`, `tidygraph` and `tidytree` websites

Chapter 3

Data manipulation with dplyr

```
# load the tidyverse
library(tidyverse)
```

3.1 Introduction

3.1.1 Foreword on dplyr

dplyr is tasked with performing all sorts of transformations on a dataset.

The structure of **dplyr** revolves around a set of functions, the so-called **verbs**, that share a common syntax and logic, and are meant to work with one another in chained operations. Chained operations are performed with the pipe operator (`%>%`), that will be introduced in section 3.2.2.

The basic syntax is `verb(data, variable)`, where **data** is a data frame and **variable** is the name of one or more columns containing a set of values for each observation.

There are 5 main verbs, which names already hint at what they do: `rename()`, `select()`, `filter()`, `mutate()`, and `summarise()`. I'm going to introduce each of them (and a couple more) through the following sections.

3.1.2 Example data

Through this tutorial, we will be using mammal trait data from the Phylacine database. Let's have a peek at what it contains.

```
phylacine <- read_csv("data/phylacine_traits.csv")
phylacine
```

```

#> # A tibble: 5,831 x 24
#>   Binomial.1.2 Order.1.2 Family.1.2 Genus.1.2 Species.1.2 Terrestrial Marine
#>   <chr>         <chr>         <chr>         <chr>         <chr>         <dbl> <dbl>
#> 1 Abditomys_l~ Rodentia Muridae Abditomys latidens      1      0
#> 2 Abeomelomys~ Rodentia Muridae Abeomelo~ sevia      1      0
#> 3 Abrawayaomy~ Rodentia Cricetidae Abrawaya~ ruschii      1      0
#> 4 Abrocoma_be~ Rodentia Abrocomid~ Abrocoma bennettii      1      0
#> 5 Abrocoma_bo~ Rodentia Abrocomid~ Abrocoma boliviensis      1      0
#> 6 Abrocoma_bu~ Rodentia Abrocomid~ Abrocoma budini      1      0
#> # ... with 5,825 more rows, and 17 more variables: Freshwater <dbl>,
#> #   Aerial <dbl>, Life.Habit.Method <chr>, Life.Habit.Source <chr>,
#> #   Mass.g <dbl>, Mass.Method <chr>, Mass.Source <chr>, Mass.Comparison <chr>,
#> #   Mass.Comparison.Source <chr>, Island.Endemicity <chr>,
#> #   IUCN.Status.1.2 <chr>, Added.IUCN.Status.1.2 <chr>, Diet.Plant <dbl>,
#> #   Diet.Vertebrate <dbl>, Diet.Invertebrate <dbl>, Diet.Method <chr>,
#> #   Diet.Source <chr>

```

588 `readr` automatically loads the data in a `tibble`, as we have seen in chapter 1
 589 and 2. Calling the `tibble` gives a nice preview of what it contains. We have data
 590 for 5,831 mammal species, and the variables contain information on taxonomy,
 591 (broad) habitat, mass, IUCN status, and diet.

592 If you remember Section 1.2 on tidy data, you may see that this data isn't
 593 exactly tidy. In fact, some columns are in wide (and messy) format, like the
 594 "habitat" (terrestrial, marine, etc.) and diet columns.

595 `dplyr` actually does not require your data to be strictly tidy. If you feel that
 596 your data satisfies the definition "one observation per row, one variable per
 597 column", that's probably good enough.

598 I use a `tibble` here, but `dplyr` works equally well on base data frames. In fact,
 599 `dplyr` is built for `data.frame` objects, and tibbles are data frames. Therefore,
 600 tibbles are mortal.

601 3.2 Working with existing variables

602 3.2.1 Renaming variables with `rename()`

603 The variable names in the phylacine dataset are descriptive, but quite unpracti-
 604 cal. Typing `Binomial.1.2.` is cumbersome and subject to typos (in fact, I just
 605 made one). `binomial` would be much simpler to use.

606 Changing names is straightforward with `rename()`.

```

rename(.data = phylacine, "binomial" = Binomial.1.2)
#> # A tibble: 5,831 x 24
#>   binomial Order.1.2 Family.1.2 Genus.1.2 Species.1.2 Terrestrial Marine
#>   <chr>         <chr>         <chr>         <chr>         <chr>         <dbl> <dbl>

```

```
#> 1 Abditom~ Rodentia Muridae Abditomys latidens 1 0
#> 2 Abeomel~ Rodentia Muridae Abeomelo~ sevia 1 0
#> 3 Abraway~ Rodentia Cricetidae Abrawaya~ ruschii 1 0
#> 4 Abrocom~ Rodentia Abrocomid~ Abrocoma bennettii 1 0
#> 5 Abrocom~ Rodentia Abrocomid~ Abrocoma boliviensis 1 0
#> 6 Abrocom~ Rodentia Abrocomid~ Abrocoma budini 1 0
#> # ... with 5,825 more rows, and 17 more variables: Freshwater <dbl>,
#> # Aerial <dbl>, Life.Habit.Method <chr>, Life.Habit.Source <chr>,
#> # Mass.g <dbl>, Mass.Method <chr>, Mass.Source <chr>, Mass.Comparison <chr>,
#> # Mass.Comparison.Source <chr>, Island.Endemicity <chr>,
#> # IUCN.Status.1.2 <chr>, Added.IUCN.Status.1.2 <chr>, Diet.Plant <dbl>,
#> # Diet.Vertebrate <dbl>, Diet.Invertebrate <dbl>, Diet.Method <chr>,
#> # Diet.Source <chr>
```

607 The first argument is always `.data`, the data table you want to apply change
 608 to. Note how columns are referred to. Once the data table as been passed as an
 609 argument, there is no need to refer to it directly anymore, `dplyr` understands
 610 that you're dealing with variables inside that data frame. So drop that `data$var`,
 611 `data[, "var"]`, and forget the very existence of `attach()` / `detach()`.

612 You can refer to variables names either with strings or directly as objects,
 613 whether you're reading or creating them:

```
rename(
  phylacine,
  # this works
  binomial = Binomial.1.2
)
rename(
  phylacine,
  # this works too!
  binomial = "Binomial.1.2"
)
rename(
  phylacine,
  # guess what
  "binomial" = "Binomial.1.2"
)
```

614 I have applied similar changes to all variables in the dataset. Here is what the
 615 new names look like:

```
616 #> # A tibble: 5,831 x 24
617 #>   binomial order family genus species terrestrial marine freshwater aerial
618 #>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
619 #> 1 Abditom~ Rode~ Murid~ Abdi~ latide~          1 0              0 0
620 #> 2 Abeomel~ Rode~ Murid~ Abeo~ sevia          1 0              0 0
621 #> 3 Abraway~ Rode~ Crice~ Abra~ ruschii          1 0              0 0
```

```

622 #> 4 Abrocom~ Rode~ Abroc~ Abro~ bennet~          1      0      0      0
623 #> 5 Abrocom~ Rode~ Abroc~ Abro~ bolivi~          1      0      0      0
624 #> 6 Abrocom~ Rode~ Abroc~ Abro~ budini          1      0      0      0
625 #> # ... with 5,825 more rows, and 15 more variables: life_habit_method <chr>,
626 #> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
627 #> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
628 #> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
629 #> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
630 #> #   diet_method <chr>, diet_source <chr>

```

631 3.2.2 The pipe operator %>%

632 If you have already come across pieces of code using the tidyverse, chances are
 633 that you have seen this odd symbol. While the pipe is not strictly-speaking a
 634 part of the tidyverse (it comes from its own package, *magrittr*), it is imported
 635 along with each package and widely used in conjunction with its functions. What
 636 does it do? Consider the following example with `rename()`:

```

phylacine2 <- readr::read_csv("data/phylacine_traits.csv")
# regular syntax
rename(phylacine2, "binomial" = "Binomial.1.2")
#> # A tibble: 5,831 x 24
#>   binomial Order.1.2 Family.1.2 Genus.1.2 Species.1.2 Terrestrial Marine
#>   <chr>      <chr>      <chr>      <chr>      <chr>      <dbl>  <dbl>
#> 1 Abditom~ Rodentia Muridae Abditomys latidens          1      0
#> 2 Abeomel~ Rodentia Muridae Abeomelo~ sevia          1      0
#> 3 Abraway~ Rodentia Cricetidae Abrawaya~ ruschii          1      0
#> 4 Abrocom~ Rodentia Abrocomid~ Abrocoma bennettii          1      0
#> 5 Abrocom~ Rodentia Abrocomid~ Abrocoma boliviensis          1      0
#> 6 Abrocom~ Rodentia Abrocomid~ Abrocoma budini          1      0
#> # ... with 5,825 more rows, and 17 more variables: Freshwater <dbl>,
#> #   Aerial <dbl>, Life.Habit.Method <chr>, Life.Habit.Source <chr>,
#> #   Mass.g <dbl>, Mass.Method <chr>, Mass.Source <chr>, Mass.Comparison <chr>,
#> #   Mass.Comparison.Source <chr>, Island.Endemicity <chr>,
#> #   IUCN.Status.1.2 <chr>, Added.IUCN.Status.1.2 <chr>, Diet.Plant <dbl>,
#> #   Diet.Vertibrate <dbl>, Diet.Invertebrate <dbl>, Diet.Method <chr>,
#> #   Diet.Source <chr>
# alternative syntax with the pipe operator
phylacine2 %>% rename("binomial" = "Binomial.1.2")
#> # A tibble: 5,831 x 24
#>   binomial Order.1.2 Family.1.2 Genus.1.2 Species.1.2 Terrestrial Marine
#>   <chr>      <chr>      <chr>      <chr>      <chr>      <dbl>  <dbl>
#> 1 Abditom~ Rodentia Muridae Abditomys latidens          1      0
#> 2 Abeomel~ Rodentia Muridae Abeomelo~ sevia          1      0
#> 3 Abraway~ Rodentia Cricetidae Abrawaya~ ruschii          1      0
#> 4 Abrocom~ Rodentia Abrocomid~ Abrocoma bennettii          1      0

```



```
#> 5 Abrocom~ Rodentia Abrocomid~ Abrocoma boliviensis      1      0
#> 6 Abrocom~ Rodentia Abrocomid~ Abrocoma budini          1      0
#> # ... with 5,825 more rows, and 17 more variables: Freshwater <dbl>,
#> #   Aerial <dbl>, Life.Habit.Method <chr>, Life.Habit.Source <chr>,
#> #   Mass.g <dbl>, Mass.Method <chr>, Mass.Source <chr>, Mass.Comparison <chr>,
#> #   Mass.Comparison.Source <chr>, Island.Endemicity <chr>,
#> #   IUCN.Status.1.2 <chr>, Added.IUCN.Status.1.2 <chr>, Diet.Plant <dbl>,
#> #   Diet.Vertebrate <dbl>, Diet.Invertebrate <dbl>, Diet.Method <chr>,
#> #   Diet.Source <chr>
```

637 Got it? The pipe takes the object on its left-side and silently feeds it to the
 638 *first* argument of the function on its right-side. It could be read as “take x,
 639 then do...”. The reason for using the pipe is because it makes code syntax
 640 closer to the syntax of a sentence, and therefore, easier and faster for your brain
 641 to process (and write!) the code. In particular, the pipe enables easy chains
 642 of operations, where you apply something to an object, then apply something
 643 else to the outcome, and so on... Through the later sections, you will see some
 644 examples of chained operations with `dplyr` functions, but for that I first need
 645 to introduce a couple more verbs.

646 Using the pipe can be quite unsettling at first, because you are not used to
 647 think in this way. But if you push a bit for it, I promise it will make things
 648 a lot easier (and it’s quite addictive!). To avoid typing the tedious symbols,
 649 `magrittr` installs a shortcut for you in RStudio. Use **Ctrl + Shift + M** on
 650 Windows, and **Cmd + Shift + M** on MacOS.

651 Finally I should emphasize that the use of the pipe isn’t limited to the tidyverse,
 652 but extends to almost all R functions. Remember that by default the piped value
 653 is always matched to the first argument of the following function

```
5 %>% rep(3)
#> [1] 5 5 5
"meow" %>% cat()
#> meow
```

654 If you need to pass the left-hand side to an argument other than the first, you
 655 can use the dot place-holder `..`

```
"meow" %>% cat("cats", "go")
#> meow cats go
```

656 Because of its syntax, most base R operators are not compatible with the pipe
 657 (but this is very rarely needed). If needed, `magrittr` introduces alternative
 658 functions for operators.

659 Subsetting operators can be piped, with the dot place-holder.

```
# 5 %>% * 3 # no, won't work
# 5 %>% .* 3 # neither
5 %>% magrittr::multiply_by(3) # yes
```

```
#> [1] 15
```

```
# subsetting
```

```
list("monkey see", "monkey_do") %>% .[[2]]
```

```
#> [1] "monkey_do"
```

```
phylacine %>% .$binomial %>% head()
```

```
#> [1] "Abditomys_latidens" "Abeomelomys_sevia" "Abrawayaomys_ruschi"
```

```
#> [4] "Abrocoma_bennettii" "Abrocoma_boliviensis" "Abrocoma_budini"
```

Because subsetting in this way is particularly hideous, `dplyr` delivers a function to extract values from a single variable. In only works on tables, though.

```
phylacine %>% pull(binomial) %>% head()
```

```
#> [1] "Abditomys_latidens" "Abeomelomys_sevia" "Abrawayaomys_ruschi"
```

```
#> [4] "Abrocoma_bennettii" "Abrocoma_boliviensis" "Abrocoma_budini"
```

3.2.3 Select variables with `select()`

To extract a set of variables (i.e. columns), use the conveniently-named `select()`. The basic syntax is the same as `rename()`: pass your data as the first argument, then call the variables to select, quoted or not.

```
# Single variable
```

```
phylacine %>% select(binomial)
```

```
#> # A tibble: 5,831 x 1
```

```
#>   binomial
```

```
#>   <chr>
```

```
#> 1 Abditomys_latidens
```

```
#> 2 Abeomelomys_sevia
```

```
#> 3 Abrawayaomys_ruschi
```

```
#> 4 Abrocoma_bennettii
```

```
#> 5 Abrocoma_boliviensis
```

```
#> 6 Abrocoma_budini
```

```
#> # ... with 5,825 more rows
```

```
# A set of variables
```

```
phylacine %>% select(genus, "species", mass_g)
```

```
#> # A tibble: 5,831 x 3
```

```
#>   genus      species      mass_g
```

```
#>   <chr>      <chr>      <dbl>
```

```
#> 1 Abditomys  latidens      269
```

```
#> 2 Abeomelomys sevia        52
```

```
#> 3 Abrawayaomys ruschi       63
```

```
#> 4 Abrocoma   bennettii     250
```

```
#> 5 Abrocoma   boliviensis   158
```

```
#> 6 Abrocoma   budini       361.
```

```
#> # ... with 5,825 more rows
```

```
# A range of contiguous variables
```

```

phylacine %>% select(family:terrestrial)
#> # A tibble: 5,831 x 4
#>   family      genus      species      terrestrial
#>   <chr>      <chr>      <chr>      <dbl>
#> 1 Muridae    Abditomys    latidens      1
#> 2 Muridae    Abeomelomys  sevia          1
#> 3 Cricetidae Abrawayaomys ruschii        1
#> 4 Abrocomidae Abrocoma    bennettii      1
#> 5 Abrocomidae Abrocoma    boliviensis    1
#> 6 Abrocomidae Abrocoma    budini          1
#> # ... with 5,825 more rows

```

666 You can select by variable numbers. This is not recommended, as prone to
667 errors, especially if you change the variable order.

```

phylacine %>% select(2)
#> # A tibble: 5,831 x 1
#>   order
#>   <chr>
#> 1 Rodentia
#> 2 Rodentia
#> 3 Rodentia
#> 4 Rodentia
#> 5 Rodentia
#> 6 Rodentia
#> # ... with 5,825 more rows

```

668 `select()` can also be used to *exclude* variables:

```

phylacine %>% select(-binomial)
#> # A tibble: 5,831 x 23
#>   order family genus species terrestrial marine freshwater aerial
#>   <chr> <chr> <chr> <chr>      <dbl> <dbl>      <dbl> <dbl>
#> 1 Rode~ Murid~ Abdi~ latide~      1     0          0     0
#> 2 Rode~ Murid~ Abeo~ sevia      1     0          0     0
#> 3 Rode~ Crice~ Abra~ ruschii    1     0          0     0
#> 4 Rode~ Abroc~ Abro~ bennet~    1     0          0     0
#> 5 Rode~ Abroc~ Abro~ bolivi~    1     0          0     0
#> 6 Rode~ Abroc~ Abro~ budini     1     0          0     0
#> # ... with 5,825 more rows, and 15 more variables: life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
phylacine %>% select(-(binomial:species))
#> # A tibble: 5,831 x 19
#>   terrestrial marine freshwater aerial life_habit_meth~ life_habit_sour~ mass_g

```

```
#>           <dbl> <dbl>           <dbl> <dbl> <chr>           <chr>           <dbl>
#> 1             1      0             0      0 Reported      IUCN. 2016. IUC~    269
#> 2             1      0             0      0 Reported      IUCN. 2016. IUC~    52
#> 3             1      0             0      0 Reported      IUCN. 2016. IUC~    63
#> 4             1      0             0      0 Reported      IUCN. 2016. IUC~   250
#> 5             1      0             0      0 Reported      IUCN. 2016. IUC~   158
#> 6             1      0             0      0 Reported      IUCN. 2016. IUC~   361.
#> # ... with 5,825 more rows, and 12 more variables: mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
```

669 `select()` and `rename()` are pretty similar, and in fact, `select()` can also
 670 rename variables along the way:

```
phylacine %>% select("linnaeus" = binomial)
#> # A tibble: 5,831 x 1
#>   linnaeus
#>   <chr>
#> 1 Abditomys_latidens
#> 2 Abeomelomys_sevia
#> 3 Abrawayaomys_ruschii
#> 4 Abrocoma_bennettii
#> 5 Abrocoma_boliviensis
#> 6 Abrocoma_budini
#> # ... with 5,825 more rows
```

671 And you can mix all of that at once:

```
phylacine %>% select(
  "fam" = family,
  genus:freshwater,
  -terrestrial
)
#> # A tibble: 5,831 x 5
#>   fam      genus      species      marine freshwater
#>   <chr>    <chr>    <chr>    <dbl>    <dbl>
#> 1 Muridae Abditomys latidens      0      0
#> 2 Muridae Abeomelomys sevia      0      0
#> 3 Cricetidae Abrawayaomys ruschii      0      0
#> 4 Abrocomidae Abrocoma bennettii      0      0
#> 5 Abrocomidae Abrocoma boliviensis      0      0
#> 6 Abrocomidae Abrocoma budini      0      0
#> # ... with 5,825 more rows
```

672 3.2.4 Select variables with helpers

673 The Rstudio team just released `dplyr` 1.0.0, and along with it, some nice
 674 helper functions to ease the selection of a set of variables. I give three examples
 675 here, and encourage you to look at the documentation (`?select()`) to find out
 676 more.

```

phylacine %>% select(where(is.numeric))
#> # A tibble: 5,831 x 8
#>   terrestrial marine freshwater aerial mass_g diet_plant diet_vertbrate
#>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1     1     0     0     0  269     100     0
#> 2     1     0     0     0   52      78      3
#> 3     1     0     0     0   63      88      1
#> 4     1     0     0     0  250     100     0
#> 5     1     0     0     0  158     100     0
#> 6     1     0     0     0  361.     100     0
#> # ... with 5,825 more rows, and 1 more variable: diet_invertebrate <dbl>
phylacine %>% select(contains("mass") | contains("diet"))
#> # A tibble: 5,831 x 10
#>   mass_g mass_method mass_source mass_comparison mass_comparison~ diet_plant
#>   <dbl> <chr> <chr> <chr> <chr> <dbl>
#> 1  269 Reported Smith, F. ~ <NA> <NA> 100
#> 2   52 Reported Smith, F. ~ <NA> <NA> 78
#> 3   63 Reported Smith, F. ~ <NA> <NA> 88
#> 4  250 Reported Smith, F. ~ <NA> <NA> 100
#> 5  158 Reported Smith, F. ~ <NA> <NA> 100
#> 6  361. Assumed is~ Journal of~ Abrocoma_ciner~ Journal of Mamm~ 100
#> # ... with 5,825 more rows, and 4 more variables: diet_vertbrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>

habitats <- c("terrestrial", "marine", "arboreal", "fossorial", "freshwater")
phylacine %>% select(any_of(habitats))
#> # A tibble: 5,831 x 3
#>   terrestrial marine freshwater
#>   <dbl> <dbl> <dbl>
#> 1     1     0     0
#> 2     1     0     0
#> 3     1     0     0
#> 4     1     0     0
#> 5     1     0     0
#> 6     1     0     0
#> # ... with 5,825 more rows

```

677 3.2.5 Rearranging variable order with relocate()

678 The order of variables seldom matters in `dplyr`, but due to popular demand,
 679 `dplyr` now has a dedicated verb to rearrange the order of variables. The syntax
 680 is identical to `rename()`, `select()`.

```

phylacine %>% relocate(mass_g, .before = binomial)
#> # A tibble: 5,831 x 24
#>   mass_g binomial order family genus species terrestrial marine freshwater
#>   <dbl> <chr>    <chr> <chr> <chr> <chr>          <dbl>  <dbl>        <dbl>
#> 1   269  Abditom~ Rode~ Murid~ Abdi~ latide~         1      0          0
#> 2    52  Abeomel~ Rode~ Murid~ Abeo~ sevia         1      0          0
#> 3    63  Abraway~ Rode~ Crice~ Abra~ ruschii        1      0          0
#> 4   250  Abrocom~ Rode~ Abroc~ Abro~ bennet~        1      0          0
#> 5   158  Abrocom~ Rode~ Abroc~ Abro~ bolivi~        1      0          0
#> 6   361  Abrocom~ Rode~ Abroc~ Abro~ budini         1      0          0
#> # ... with 5,825 more rows, and 15 more variables: aerial <dbl>,
#> #   life_habit_method <chr>, life_habit_source <chr>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
phylacine %>% relocate(starts_with("diet"), .after = species)
#> # A tibble: 5,831 x 24
#>   binomial order family genus species diet_plant diet_vertibrate
#>   <chr>    <chr> <chr> <chr> <chr>          <dbl>          <dbl>
#> 1  Abditom~ Rode~ Murid~ Abdi~ latide~        100            0
#> 2  Abeomel~ Rode~ Murid~ Abeo~ sevia          78            3
#> 3  Abraway~ Rode~ Crice~ Abra~ ruschii         88            1
#> 4  Abrocom~ Rode~ Abroc~ Abro~ bennet~        100            0
#> 5  Abrocom~ Rode~ Abroc~ Abro~ bolivi~        100            0
#> 6  Abrocom~ Rode~ Abroc~ Abro~ budini         100            0
#> # ... with 5,825 more rows, and 17 more variables: diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>, terrestrial <dbl>, marine <dbl>,
#> #   freshwater <dbl>, aerial <dbl>, life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>

```

681 3.3 Working with observations

682 3.3.1 Ordering rows by value - arrange()

683 `arrange()` sorts rows in the data by **ascending** value for a given variable. Use
 684 the wrapper `desc()` to sort by descending values instead.

```

# Smallest mammals
phylacine %>%
  arrange(mass_g) %>%
  select(binomial, mass_g)
#> # A tibble: 5,831 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Sorex_yukonicus    1.6
#> 2 Crocidura_levicula 1.8
#> 3 Suncus_remyi      1.8
#> 4 Crocidura_lusitania 2
#> 5 Kerivoula_minuta  2.1
#> 6 Suncus_etruscus    2.1
#> # ... with 5,825 more rows

# Largest mammals
phylacine %>%
  arrange(desc(mass_g)) %>%
  select(binomial, mass_g)
#> # A tibble: 5,831 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Balaenoptera_musculus 190000000
#> 2 Balaena_mysticetus   100000000
#> 3 Balaenoptera_physalus 70000000
#> 4 Caperea_marginata    32000000
#> 5 Megaptera_novaeangliae 30000000
#> 6 Eschrichtius_robustus 28500000
#> # ... with 5,825 more rows

# Extra variables are used to sort ties in the first variable
phylacine %>%
  arrange(mass_g, desc(binomial)) %>%
  select(binomial, mass_g)
#> # A tibble: 5,831 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Sorex_yukonicus    1.6
#> 2 Suncus_remyi      1.8
#> 3 Crocidura_levicula 1.8
#> 4 Crocidura_lusitania 2
#> 5 Suncus_etruscus    2.1
#> 6 Kerivoula_minuta  2.1
#> # ... with 5,825 more rows

```

685 *Important:* NA values, if present, are always ordered at the end!

686 **3.3.2 Subset rows by position - slice()**687 Use `slice()` and its variants to extract particular rows.

```

phylacine %>% slice(3) # third row
#> # A tibble: 1 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Abraway~ Rode~ Crice~ Abra~ ruschii          1      0              0      0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>
phylacine %>% slice(5, 1, 2) # fifth, first and second row
#> # A tibble: 3 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Abrocom~ Rode~ Abroc~ Abro~ bolivi~          1      0              0      0
#> 2 Abditom~ Rode~ Murid~ Abdi~ latide~          1      0              0      0
#> 3 Abeomel~ Rode~ Murid~ Abeo~ sevia          1      0              0      0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>
phylacine %>% slice(rep(3, 2)) # duplicate the third row
#> # A tibble: 2 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Abraway~ Rode~ Crice~ Abra~ ruschii          1      0              0      0
#> 2 Abraway~ Rode~ Crice~ Abra~ ruschii          1      0              0      0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>
phylacine %>% slice(-c(2:5830)) # exclude all but first and last row
#> # A tibble: 2 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Abditom~ Rode~ Murid~ Abdi~ latide~          1      0              0      0
#> 2 Zyzomys~ Rode~ Murid~ Zyzo~ woodwa~          1      0              0      0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,

```



```
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>

phylacine %>% slice_tail(n = 3) # last three rows
#> # A tibble: 3 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl>  <dbl>          <dbl>  <dbl>
#> 1 Zyzomys~ Rode~ Murid~ Zyzo~ palata~          1    0              0    0
#> 2 Zyzomys~ Rode~ Murid~ Zyzo~ pedunc~          1    0              0    0
#> 3 Zyzomys~ Rode~ Murid~ Zyzo~ woodwa~          1    0              0    0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>

phylacine %>% slice_max(mass_g) # largest mammal
#> # A tibble: 1 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl>  <dbl>          <dbl>  <dbl>
#> 1 Balaeno~ Ceta~ Balae~ Bala~ muscul~          0    1              0    0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>
```

688 You can also sample random rows in the data:

```
phylacine %>% slice_sample() # a random row
#> # A tibble: 1 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl>  <dbl>          <dbl>  <dbl>
#> 1 Crocidu~ Euli~ Soric~ Croc~ levicu~          1    0              0    0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>

# bootstrap
phylacine %>% slice_sample(n = 5831, replace = TRUE)
#> # A tibble: 5,831 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl>  <dbl>          <dbl>  <dbl>
#> 1 Rhinol~ Chir~ Rhino~ Rhin~ adami          0    0              0    1
#> 2 Hylomys~ Euli~ Erina~ Hylo~ megal~          1    0              0    0
#> 3 Sciurus~ Rode~ Sciur~ Sciu~ yucata~          1    0              0    0
```

```
#> 4 Emballo~ Chir~ Embal~ Emba~ alecto      0      0      0      1
#> 5 Pteralo~ Chir~ Ptero~ Pter~ taki      0      0      0      1
#> 6 Lasiorh~ Dipr~ Vomba~ Lasi~ latifr~      1      0      0      0
#> # ... with 5,825 more rows, and 15 more variables: life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
```

689 3.3.3 Subsetting rows by value with filter()

690 `filter()` does a similar job as `slice()`, but extract rows that satisfy a set of
 691 conditions. The conditions are supplied much the same way as you would do
 692 for an `if` statement.

693 Along with `mutate()` (next section), this is probably the function you are going
 694 to use the most.

695 For example, I might want to extract mammals above a given mass:

```
# megafauna
phylacine %>%
  filter(mass_g > 1e5) %>% # 100 kg
  select(binomial, mass_g)
#> # A tibble: 302 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Ailuropoda_melanoleuca 108400
#> 2 Alcelaphus_buselaphus 171002.
#> 3 Alces_alces      356998
#> 4 Archaeoindris_fontoynonti 160000
#> 5 Arctocephalus_forsteri 101250
#> 6 Arctocephalus_pusillus 178500
#> # ... with 296 more rows

# non-extinct megafauna
phylacine %>%
  filter(mass_g > 1e5, iucn_status != "EP") %>%
  select(binomial, mass_g, iucn_status)
#> # A tibble: 178 x 3
#>   binomial      mass_g iucn_status
#>   <chr>      <dbl> <chr>
#> 1 Ailuropoda_melanoleuca 108400 VU
#> 2 Alcelaphus_buselaphus 171002. LC
#> 3 Alces_alces      356998 LC
#> 4 Arctocephalus_forsteri 101250 LC
```

```
#> 5 Arctocephalus_pusillus 178500 LC
#> 6 Arctocephalus_townsendi 105000 LC
#> # ... with 172 more rows
```

696 Are there any flying mammals that aren't bats?

```
phylacine %>%
  filter(aerial == 1, order != "Chiroptera")
#> # A tibble: 0 x 24
#> # ... with 24 variables: binomial <chr>, order <chr>, family <chr>,
#> #   genus <chr>, species <chr>, terrestrial <dbl>, marine <dbl>,
#> #   freshwater <dbl>, aerial <dbl>, life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
# no :(
```

697 Are humans included in the table?

```
phylacine %>% filter(binomial == "Homo_sapiens")
#> # A tibble: 1 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Homo_sa~ Prim~ Homin~ Homo sapiens          1      0              0      0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>
```

698 filter() can be used to deal with NAs:

```
phylacine %>%
  filter(!is.na(mass_comparison))
#> # A tibble: 754 x 24
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Abrocom~ Rode~ Abroc~ Abro~ budini          1      0              0      0
#> 2 Abrocom~ Rode~ Abroc~ Abro~ famati~          1      0              0      0
#> 3 Abrocom~ Rode~ Abroc~ Abro~ shista~          1      0              0      0
#> 4 Abrocom~ Rode~ Abroc~ Abro~ uspall~          1      0              0      0
#> 5 Abrocom~ Rode~ Abroc~ Abro~ vaccar~          1      0              0      0
#> 6 Acerodo~ Chir~ Ptero~ Acer~ humilis          0      0              0      1
#> # ... with 748 more rows, and 15 more variables: life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
```

```
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
```

699 Tip: `dplyr` introduces the useful function `between()` that does exactly what
700 the name implies

```
between(1:5, 2, 4)
#> [1] FALSE TRUE TRUE TRUE FALSE

# Mesofauna
phylacine %>%
  filter(mass_g > 1e3, mass_g < 1e5) %>%
  select(binomial, mass_g)
#> # A tibble: 1,126 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Acerodon_jubatus    1075
#> 2 Acinonyx_jubatus   46700
#> 3 Acratocnus_odontrigonus 22990
#> 4 Acratocnus_ye      21310
#> 5 Addax_nasomaculatus  70000.
#> 6 Aepyceros_melampus   52500.
#> # ... with 1,120 more rows

# same thing
phylacine %>%
  filter(mass_g %>% between(1e3, 1e5)) %>%
  select(binomial, mass_g)
#> # A tibble: 1,148 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Acerodon_jubatus    1075
#> 2 Acinonyx_jubatus   46700
#> 3 Acratocnus_odontrigonus 22990
#> 4 Acratocnus_ye      21310
#> 5 Addax_nasomaculatus  70000.
#> 6 Aepyceros_melampus   52500.
#> # ... with 1,142 more rows
```

701 Note that you can pipe operations inside function arguments as in the last line
702 above (arguments are expressions, after all!).

703 3.4 Making new variables

704 3.4.1 Create new variables with `mutate()`

705 Very often in data analysis, you will want to create new variables, or edit existing
706 ones. This is done easily through `mutate()`. For example, consider the diet data:

```
diet <- phylacine %>%
  select(
    binomial,
    contains("diet") & !contains(c("method", "source"))
  )
diet
#> # A tibble: 5,831 x 4
#>   binomial      diet_plant diet_vertibrate diet_invertebrate
#>   <chr>          <dbl>          <dbl>          <dbl>
#> 1 Abditomys_latidens      100            0            0
#> 2 Abeomelomys_sevia       78            3           19
#> 3 Abrawayaomys_ruschii    88            1           11
#> 4 Abrocoma_bennettii     100            0            0
#> 5 Abrocoma_boliviensis   100            0            0
#> 6 Abrocoma_budini        100            0            0
#> # ... with 5,825 more rows
```

707 These three variables show the percentage of each category of food that make
708 the diet of that species. They should sum to 100, unless the authors made a
709 typo or other entry error. To assert this, I'm going to create a new variable,
710 `total_diet`.

```
diet <- diet %>% mutate(
  "total_diet" = diet_vertibrate + diet_invertebrate + diet_plant
)
diet
#> # A tibble: 5,831 x 5
#>   binomial      diet_plant diet_vertibrate diet_invertebrate total_diet
#>   <chr>          <dbl>          <dbl>          <dbl>          <dbl>
#> 1 Abditomys_latidens      100            0            0           100
#> 2 Abeomelomys_sevia       78            3           19           100
#> 3 Abrawayaomys_ruschii    88            1           11           100
#> 4 Abrocoma_bennettii     100            0            0           100
#> 5 Abrocoma_boliviensis   100            0            0           100
#> 6 Abrocoma_budini        100            0            0           100
#> # ... with 5,825 more rows

all(diet$total_diet == 100)
#> [1] TRUE
# cool and good
```

711 `mutate()` adds a variable to the table, and keeps all other variables. Sometimes
 712 you may want to just keep the new variable, and drop the other ones. That's the
 713 job of `mutate()`'s twin sibling, `transmute()`. For example, I want to combine
 714 `diet_invertebrate` and `diet_vertibrate` together:

```
diet %>%
  transmute(
    "diet_animal" = diet_invertebrate + diet_vertibrate
  )
#> # A tibble: 5,831 x 1
#>   diet_animal
#>       <dbl>
#> 1           0
#> 2          22
#> 3          12
#> 4           0
#> 5           0
#> 6           0
#> # ... with 5,825 more rows
```

715 You may want to keep some variables and drop others. You could pipe
 716 `mutate()` and `select()` to do so, or you could just pass the variables to keep
 717 to `transmute()`.

```
diet %>%
  transmute(
    "diet_animal" = diet_invertebrate + diet_vertibrate,
    diet_plant
  )
#> # A tibble: 5,831 x 2
#>   diet_animal diet_plant
#>       <dbl>    <dbl>
#> 1           0       100
#> 2          22        78
#> 3          12        88
#> 4           0       100
#> 5           0       100
#> 6           0       100
#> # ... with 5,825 more rows
```

718 You can also refer to variables you're creating to derive new variables from them
 719 as part of the same operation, this is not an issue.

```
diet %>%
  transmute(
    "diet_animal" = diet_invertebrate + diet_vertibrate,
    diet_plant,
    "total_diet" = diet_animal + diet_plant
  )
```

```
)
#> # A tibble: 5,831 x 3
#>   diet_animal diet_plant total_diet
#>   <dbl>      <dbl>      <dbl>
#> 1         0         100         100
#> 2        22         78         100
#> 3        12         88         100
#> 4         0         100         100
#> 5         0         100         100
#> 6         0         100         100
#> # ... with 5,825 more rows
```

720 Sometimes, you may need to perform an operation based on the row number (I
721 don't have a good example in mind). `tibble` has a built-in function to do just
722 that:

```
phylacine %>%
  select(binomial) %>%
  tibble::rownames_to_column(var = "row_nb")
#> # A tibble: 5,831 x 2
#>   row_nb binomial
#>   <chr>   <chr>
#> 1 1      Abditomys_latidens
#> 2 2      Abeomelomys_sevia
#> 3 3      Abrawayaomys_ruschii
#> 4 4      Abrocoma_bennettii
#> 5 5      Abrocoma_boliviensis
#> 6 6      Abrocoma_budini
#> # ... with 5,825 more rows
```

723 3.4.2 Summarise observations with `summarise()`

724 `mutate()` applies operations to all observations in a table. By contrast,
725 `summarise()` applies operations to *groups* of observations, and returns, er,
726 summaries. The default grouping unit is the entire table:

```
phylacine %>%
  summarise(
    "nb_species" = n(), # counts observations
    "nb_terrestrial" = sum(terrestrial),
    "nb_marine" = sum(marine),
    "nb_freshwater" = sum(freshwater),
    "nb_aerial" = sum(aerial),
    "mean_mass_g" = mean(mass_g)
  )
#> # A tibble: 1 x 6
#>   nb_species nb_terrestrial nb_marine nb_freshwater nb_aerial mean_mass_g
```

```
#>      <int>      <dbl>      <dbl>      <dbl>      <dbl>      <dbl>
#> 1      5831      4575      135      156      1162      156882.
```

727 Above you can see that bats account for a large portion of mammal species
 728 diversity (`nb_aerial`). How much exactly? Just as with `mutate()`, you can
 729 perform operations on the variables you just created, in the same statement:

```
phylacine %>%
  summarise(
    "nb_species" = n(),
    "nb_aerial" = sum(aerial), # bats
    "prop_aerial" = nb_aerial / nb_species
  )
#> # A tibble: 1 x 3
#>   nb_species nb_aerial prop_aerial
#>   <int>      <dbl>      <dbl>
#> 1      5831      1162      0.199
```

730 One fifth!

731 If the british spelling bothers you, `summarize()` exists and is strictly equivalent.

732 Here's a simple trick with logical (TRUE / FALSE) variables. Their sum is the
 733 count of observations that evaluate to TRUE (because TRUE is taken as 1 and
 734 FALSE as 0) and their mean is the proportion of TRUE observations. This can be
 735 exploited to count the number of observations that satisfy a condition:

```
phylacine %>%
  summarise(
    "nb_species" = n(),
    "nb_megaafauna" = sum(mass_g > 100000),
    "p_megaafauna" = mean(mass_g > 100000)
  )
#> # A tibble: 1 x 3
#>   nb_species nb_megaafauna p_megaafauna
#>   <int>      <int>      <dbl>
#> 1      5831        302      0.0518
```

736 There are more summaries that just means and counts (see `?summarise()` for
 737 some helpful functions). In fact, `summarise` can use any function or expression
 738 that evaluates to a single value or a *vector* of values. This includes base R `max()`,
 739 `quantiles`, etc.

740 `mutate()` and `transmute()` can compute summaries as well, but they will return
 741 the summary once for each observation, in a new column.

```
phylacine %>%
  mutate("nb_species" = n()) %>%
  select(binomial, nb_species)
#> # A tibble: 5,831 x 2
```



```
#>   binomial      nb_species
#>   <chr>      <int>
#> 1 Abditomys_latidens      5831
#> 2 Abeomelomys_sevia      5831
#> 3 Abrawayaomys_ruschii    5831
#> 4 Abrocoma_bennettii      5831
#> 5 Abrocoma_boliviensis    5831
#> 6 Abrocoma_budini         5831
#> # ... with 5,825 more rows
```

742 3.4.3 Grouping observations by variables

743 In most cases you don't want to run summary operations on the entire set of
 744 observations, but instead on observations that share a common value, i.e. groups.
 745 For example, I want to run the summary displayed above, but for each Order
 746 of mammals.

747 `distinct()` extracts all the unique values of a variable

```
phylacine %>% distinct(order)
#> # A tibble: 29 x 1
#>   order
#>   <chr>
#> 1 Rodentia
#> 2 Chiroptera
#> 3 Carnivora
#> 4 Pilosa
#> 5 Diprotodontia
#> 6 Cetartiodactyla
#> # ... with 23 more rows
```

748 I could work my way with what we have already seen, filtering observations
 749 (`filter(order == "Rodentia")`) and then piping the output to `summarise()`,
 750 and do it again for each Order. But that would be tedious.

751 Instead, I can use `group_by()` to pool observations by order.

```
phylacine %>%
  group_by(order)
#> # A tibble: 5,831 x 24
#> # Groups:   order [29]
#>   binomial order family genus species terrestrial marine freshwater aerial
#>   <chr>    <chr> <chr>  <chr> <chr>      <dbl>  <dbl>      <dbl>  <dbl>
#> 1 Abditom~ Rode~ Murid~ Abdi~ latide~      1      0          0      0
#> 2 Abeomel~ Rode~ Murid~ Abeo~ sevia      1      0          0      0
#> 3 Abraway~ Rode~ Crice~ Abra~ ruschii    1      0          0      0
#> 4 Abrocom~ Rode~ Abroc~ Abro~ bennet~    1      0          0      0
#> 5 Abrocom~ Rode~ Abroc~ Abro~ bolivi~    1      0          0      0
```

```
#> 6 Abrocom~ Rode~ Abroc~ Abro~ budini          1          0          0          0
#> # ... with 5,825 more rows, and 15 more variables: life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>
```

At first glance, nothing has changed, apart from an extra line of information in the output that tells me the observations have been grouped. But now here's what happen if I run the same `summarise()` statement on an ungrouped and a grouped table

```
phylacine %>%
  summarise(
    "n_species" = n(),
    "mean_mass_g" = mean(mass_g)
  )
#> # A tibble: 1 x 2
#>   n_species mean_mass_g
#>   <int>      <dbl>
#> 1     5831    156882.

phylacine %>%
  group_by(order) %>%
  summarise(
    "n_species" = n(),
    "mean_mass_g" = mean(mass_g)
  )
#> # A tibble: 29 x 3
#>   order          n_species mean_mass_g
#>   <chr>          <int>      <dbl>
#> 1 Afrosoricida         57         306.
#> 2 Carnivora           313       47905.
#> 3 Cetartiodactyla      392    1854811.
#> 4 Chiroptera          1162         49.1
#> 5 Cingulata            39    235529.
#> 6 Dasyuromorphia        74         748.
#> # ... with 23 more rows
```

I get one value for each group.

Observations can be grouped by multiple variables, which will output a summary for every unique combination of groups.

```
phylacine %>%
  group_by(order, iucn_status) %>%
  summarise(
```

```

    "n_species" = n()
  )
#> # A tibble: 138 x 3
#> # Groups:   order [29]
#>   order      iucn_status n_species
#>   <chr>      <chr>      <int>
#> 1 Afrosoricida CR          1
#> 2 Afrosoricida DD          4
#> 3 Afrosoricida EN          7
#> 4 Afrosoricida EP          2
#> 5 Afrosoricida LC         32
#> 6 Afrosoricida NT          3
#> # ... with 132 more rows

```

759 Whenever you call `summarise()`, the last level of grouping is dropped. Note
 760 how in the output table above, observations are still grouped by order, and no
 761 longer by IUCN status. If I summarise observations again:

```

phylacine %>%
  group_by(order, iucn_status) %>%
  summarise(
    "n_species" = n()
  ) %>%
  summarise(
    "n_species_2" = n()
  )
#> # A tibble: 29 x 2
#>   order      n_species_2
#>   <chr>      <int>
#> 1 Afrosoricida          7
#> 2 Carnivora             8
#> 3 Cetartiodactyla       9
#> 4 Chiroptera            8
#> 5 Cingulata             5
#> 6 Dasyuromorphia        7
#> # ... with 23 more rows

```

762 I get the summary across orders, and the table is no longer grouped at all. This
 763 is useful to consider if you need to work on summaries across different levels of
 764 the data.

765 For example, I would like to know how the species in each order are distributed
 766 between the different levels of threat in the IUCN classification. To get these
 767 proportions, I need to first get the count of each number of species in a level of
 768 threat inside an order, and divide that by the number of species in that order.

```

phylacine %>%
  group_by(order, iucn_status) %>%

```

```

summarise("n_order_iucn" = n()) %>%
# grouping by iucn_status silently dropped
mutate(
  "n_order" = sum(n_order_iucn),
  "p_iucn" = n_order_iucn / n_order
)
#> # A tibble: 138 x 5
#> # Groups:   order [29]
#>   order      iucn_status n_order_iucn n_order p_iucn
#>   <chr>      <chr>          <int>   <int>  <dbl>
#> 1 Afrosoricida CR              1      57 0.0175
#> 2 Afrosoricida DD              4      57 0.0702
#> 3 Afrosoricida EN              7      57 0.123
#> 4 Afrosoricida EP              2      57 0.0351
#> 5 Afrosoricida LC             32      57 0.561
#> 6 Afrosoricida NT              3      57 0.0526
#> # ... with 132 more rows

```

769 10.2% of Carnivores are Endangered ("EN").

770 3.4.4 Grouped data and other dplyr verbs

771 Grouping does not only affect the behaviour of `summarise`, but under circum-
772 stances, other verbs can (and will!) perform operations by groups.

```

# Species with a higher mass than the mammal mean
phylacine %>%
  select("binomial", "mass_g") %>%
  filter(mass_g > mean(mass_g, na.rm = TRUE))
#> # A tibble: 234 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Alcelaphus_buselaphus 171002.
#> 2 Alces_alces          356998
#> 3 Archaeoindris_fontoynonti 160000
#> 4 Arctocephalus_pusillus 178500
#> 5 Arctodus_simus        709500
#> 6 Balaena_mysticetus    100000000
#> # ... with 228 more rows

# Species with a higher mass than the mean in their order
phylacine %>%
  group_by(order) %>%
  select("binomial", "mass_g") %>%
  filter(mass_g > mean(mass_g, na.rm = TRUE))
#> # A tibble: 890 x 3
#> # Groups:   order [27]

```

```

#>   order      binomial      mass_g
#>   <chr>      <chr>      <dbl>
#> 1 Chiroptera Acerodon_celebensis    390
#> 2 Chiroptera Acerodon_humilis      600.
#> 3 Chiroptera Acerodon_jubatus    1075
#> 4 Chiroptera Acerodon_leucotis    513.
#> 5 Chiroptera Acerodon_mackloti    470.
#> 6 Rodentia  Aeretes_melanopterus    732.
#> # ... with 884 more rows

# Largest mammal
phylacine %>%
  select(binomial, mass_g) %>%
  slice_max(mass_g)
#> # A tibble: 1 x 2
#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Balaenoptera_musculus 190000000
# Largest species in each order
phylacine %>%
  group_by(order) %>%
  select(binomial, mass_g) %>%
  slice_max(mass_g)
#> # A tibble: 30 x 3
#> # Groups:   order [29]
#>   order      binomial      mass_g
#>   <chr>      <chr>      <dbl>
#> 1 Afrosoricida Plesiorycteropus_madagascariensis    13220
#> 2 Carnivora    Mirounga_leonina      1600000
#> 3 Cetartiodactyla Balaenoptera_musculus    190000000
#> 4 Chiroptera    Acerodon_jubatus      1075
#> 5 Cingulata    Glyptodon_clavipes    2000000
#> 6 Dasyuromorphia Thylacinus_cynocephalus    30000
#> # ... with 24 more rows

```

773 To avoid grouped operations, you can simply drop grouping with `ungroup()`.

774 3.5 Working with multiple tables

775 3.5.1 Binding tables

776 `dplyr` introduces `bind_rows()` and `bind_cols()`, which are equivalent to base
 777 R `rbind()` and `cbind()`, with a few extra feature. They are faster, and can
 778 bind many tables at once, and bind data frames with vectors or lists.

779 `bind_rows()` has an option to pass a variable specifying which dataset each
 780 observation originates from.

```

porpoises <- phylacine %>%
  filter(family == "Phocoenidae") %>%
  select(binomial, iucn_status)
echidnas <- phylacine %>%
  filter(family == "Tachyglossidae") %>%
  select(binomial, iucn_status)

bind_rows(
  "porpoise" = porpoises,
  "echidna" = echidnas,
  .id = "kind"
)
#> # A tibble: 13 x 3
#>   kind    binomial    iucn_status
#>   <chr>    <chr>        <chr>
#> 1 porpoise Neophocaena_asiaeorientalis VU
#> 2 porpoise Neophocaena_phocaenoides VU
#> 3 porpoise Phocoena_dioptrica DD
#> 4 porpoise Phocoena_phocoena LC
#> 5 porpoise Phocoena_sinus CR
#> 6 porpoise Phocoena_spinipinnis DD
#> # ... with 7 more rows

```

3.5.2 Combining variables of two tables with mutating joins

Mutating joins are tailored to combine tables that share a set of observations but have different variables.

As an example, let's split the phylacine dataset in two smaller datasets, one containing information on diet and one on the dominant habitat.

```

diet <- phylacine %>%
  select(binomial, diet_plant:diet_invertebrate) %>%
  slice(1:5)
diet
#> # A tibble: 5 x 4
#>   binomial    diet_plant diet_vertibrate diet_invertebrate
#>   <chr>        <dbl>         <dbl>         <dbl>
#> 1 Abditomys_latidens    100             0             0
#> 2 Abeomelomys_sevia     78              3            19
#> 3 Abrawayaomys_ruschii   88              1            11
#> 4 Abrocoma_bennettii    100             0             0
#> 5 Abrocoma_boliviensis  100             0             0

life_habit <- phylacine %>% select(binomial, terrestrial:aerial) %>%
  slice(1:3, 6:7)

```

```

life_habit
#> # A tibble: 5 x 5
#>   binomial      terrestrial marine freshwater aerial
#>   <chr>          <dbl>   <dbl>         <dbl>   <dbl>
#> 1 Abditomys_latidens      1     0           0     0
#> 2 Abeomelomys_sevia      1     0           0     0
#> 3 Abrawayaomys_ruschi      1     0           0     0
#> 4 Abrocoma_budini        1     0           0     0
#> 5 Abrocoma_cinerea        1     0           0     0

```

787 The two datasets each contain 5 species, the first three are shared, and the two
 788 last differ between the two.

```

intersect(diet$binomial, life_habit$binomial)
#> [1] "Abitomys_latidens" "Abeomelomys_sevia" "Abrawayaomys_ruschi"
setdiff(diet$binomial, life_habit$binomial)
#> [1] "Abrocoma_bennettii" "Abrocoma_boliviensis"

```

789 To use mutate-joins, both tables need to have a **key**, a variable that identifies
 790 each observation. Here, that would be `binomial`, the species names. If
 791 your table doesn't have such a key and the rows between the tables match
 792 one another, remember you can create a row number variable easily with
 793 `tibble::column_to_rownames()`.

```

inner_join(diet, life_habit, by = "binomial")
#> # A tibble: 3 x 8
#>   binomial diet_plant diet_vertibrate diet_invertebra~ terrestrial marine
#>   <chr>      <dbl>         <dbl>         <dbl>         <dbl>   <dbl>
#> 1 Abditom~    100           0           0           1     0
#> 2 Abeomel~    78           3          19           1     0
#> 3 Abraway~    88           1          11           1     0
#> # ... with 2 more variables: freshwater <dbl>, aerial <dbl>

```

794 `inner_join` combined the variables, and dropped the observations that weren't
 795 matched between the two tables. There are three other variations of mutating
 796 joins, differing in what they do with unmatching variables.

```

left_join(diet, life_habit, by = "binomial")
#> # A tibble: 5 x 8
#>   binomial diet_plant diet_vertibrate diet_invertebra~ terrestrial marine
#>   <chr>      <dbl>         <dbl>         <dbl>         <dbl>   <dbl>
#> 1 Abditom~    100           0           0           1     0
#> 2 Abeomel~    78           3          19           1     0
#> 3 Abraway~    88           1          11           1     0
#> 4 Abrocom~   100           0           0          NA     NA
#> 5 Abrocom~   100           0           0          NA     NA
#> # ... with 2 more variables: freshwater <dbl>, aerial <dbl>
right_join(diet, life_habit, by = "binomial")
#> # A tibble: 5 x 8

```

```

#>   binomial diet_plant diet_vertibrate diet_invertebra~ terrestrial marine
#>   <chr>         <dbl>             <dbl>             <dbl>         <dbl> <dbl>
#> 1 Abditom~      100                0                0                1      0
#> 2 Abeomel~      78                3                19               1      0
#> 3 Abraway~      88                1                11               1      0
#> 4 Abrocom~      NA                NA                NA                1      0
#> 5 Abrocom~      NA                NA                NA                1      0
#> # ... with 2 more variables: freshwater <dbl>, aerial <dbl>
full_join(diet, life_habit, by = "binomial")
#> # A tibble: 7 x 8
#>   binomial diet_plant diet_vertibrate diet_invertebra~ terrestrial marine
#>   <chr>         <dbl>             <dbl>             <dbl>         <dbl> <dbl>
#> 1 Abditom~      100                0                0                1      0
#> 2 Abeomel~      78                3                19               1      0
#> 3 Abraway~      88                1                11               1      0
#> 4 Abrocom~      100                0                0                NA     NA
#> 5 Abrocom~      100                0                0                NA     NA
#> 6 Abrocom~      NA                NA                NA                1      0
#> # ... with 1 more row, and 2 more variables: freshwater <dbl>, aerial <dbl>

semi_join(diet, life_habit, by = "binomial")
#> # A tibble: 3 x 4
#>   binomial diet_plant diet_vertibrate diet_invertebrate
#>   <chr>         <dbl>             <dbl>             <dbl>
#> 1 Abditomys_latidens      100                0                0
#> 2 Abeomelomys_sevia       78                3                19
#> 3 Abrawayaomys_ruschii    88                1                11
anti_join(diet, life_habit, by = "binomial")
#> # A tibble: 2 x 4
#>   binomial diet_plant diet_vertibrate diet_invertebrate
#>   <chr>         <dbl>             <dbl>             <dbl>
#> 1 Abrocoma_bennettii      100                0                0
#> 2 Abrocoma_boliviensis    100                0                0

```

3.5.3 Filtering matching observations between two tables with filtering joins

So-called filtering joins return row from the first table that are matched (or not, for `anti_join()`) in the second.

```

semi_join(diet, life_habit, by = "binomial")
#> # A tibble: 3 x 4
#>   binomial diet_plant diet_vertibrate diet_invertebrate
#>   <chr>         <dbl>             <dbl>             <dbl>
#> 1 Abditomys_latidens      100                0                0
#> 2 Abeomelomys_sevia       78                3                19

```



```
#> 3 Abrawayaomys_ruschi      88      1      11
anti_join(diet, life_habit, by = "binomial")
#> # A tibble: 2 x 4
#>   binomial      diet_plant diet_vertibrate diet_invertebrate
#>   <chr>      <dbl>      <dbl>      <dbl>
#> 1 Abrocoma_bennettii      100      0      0
#> 2 Abrocoma_boliviensis    100      0      0
```


801 Chapter 4

802 Working with lists and 803 iteration



Every use case is ridiculous
until it happens to you.

804

```
# load the tidyverse  
library(tidyverse)
```

805 4.1 List columns with `tidyr`

806 4.1.1 Nesting data

807 It may become necessary to indicate the groups of a tibble in a somewhat more
808 explicit way than simply using `dplyr::group_by`. `tidyr` offers the option to
809 create nested tibbles, that is, to store complex objects in the columns of a tibble.
810 This includes other tibbles, as well as model objects and plots.

811 NB: Nesting data is done using `tidyr::nest`, which is different from the simi-
 812 larly named `tidyr::nesting`.

813 The example below shows how *Phylacine* data can be converted into a nested
 814 tibble.

```
# get phylacine data
data = read_csv("data/phylacine_traits.csv")
data = data %>%
  `colnames`<-`(str_to_lower(colnames(.))) %>%
  `colnames`<-`(str_remove(colnames(.), "(.1.2)")) %>%
  `colnames`<-`(str_replace_all(colnames(.), "\\.", "_"))

# nest phylacine by order
nested_data = data %>%
  group_by(order) %>%
  nest()

nested_data
#> # A tibble: 29 x 2
#> # Groups:   order [29]
#>   order      data
#>   <chr>      <list>
#> 1 Rodentia   <tibble [2,306 x 23]>
#> 2 Chiroptera <tibble [1,162 x 23]>
#> 3 Carnivora  <tibble [313 x 23]>
#> 4 Pilosa     <tibble [34 x 23]>
#> 5 Diprotodontia <tibble [183 x 23]>
#> 6 Cetartiodactyla <tibble [392 x 23]>
#> # ... with 23 more rows

# get column class
sapply(nested_data, class)
#>      order      data
#> "character"    "list"
```

815 The data is now a nested data frame. The class of each of its columns is
 816 respectively, a character (order name) and a list (the data of all mammals in
 817 the corresponding order).

818 While `nest` can be used without first grouping the tibble, it's just much easier
 819 to group first.

820 4.1.2 Unnesting data

821 A nested tibble can be converted back into the original, or into a processed form,
 822 using `tidyr::unnest`. The original groups are retained.

```

# use unnest to recover the original data frame
unnest(nested_data, cols = "data") %>%
  head()
#> # A tibble: 6 x 24
#> # Groups:   order [1]
#>   order binomial family genus species terrestrial marine freshwater aerial
#>   <chr> <chr>    <chr> <chr> <chr>          <dbl>  <dbl>        <dbl> <dbl>
#> 1 Rode~ Abditom~ Murid~ Abdi~ latide~      1    0            0    0
#> 2 Rode~ Abeomel~ Murid~ Abeo~ sevia      1    0            0    0
#> 3 Rode~ Abraway~ Crice~ Abra~ ruschii    1    0            0    0
#> 4 Rode~ Abrocom~ Abroc~ Abro~ bennet~    1    0            0    0
#> 5 Rode~ Abrocom~ Abroc~ Abro~ bolivi~    1    0            0    0
#> 6 Rode~ Abrocom~ Abroc~ Abro~ budini    1    0            0    0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>

# unnesting preserves groups
groups(unnest(nested_data, cols = "data"))
#> [[1]]
#> order

```

823 The `unnest_longer` and `unnest_wider` variants of `unnest` are maturing func-
 824 tions, that is, not in their final form. They allow interesting variations on
 825 unnesting — these are shown here but advised against. Unnest the data first,
 826 and then convert it to the form needed.

827 4.1.3 Working with list columns

828 The class of a list column is `list`, and working with list columns (and lists, and
 829 list-like objects such as vectors) makes iteration necessary, since this is one of
 830 the only ways to operate on lists.

831 Two examples are shown below when getting the class and number of rows of
 832 the nested tibbles in the list column.

```

# how many rows in each nested tibble?
for (i in seq_along(nested_data$data[1:10])) {
  print(nrow(nested_data$data[[i]]))
}
#> [1] 2306
#> [1] 1162
#> [1] 313
#> [1] 34
#> [1] 183

```

```

#> [1] 392
#> [1] 460
#> [1] 57
#> [1] 20
#> [1] 465

# what is the class of each element?
lapply(X = nested_data$data[1:3], FUN = class)
#> [[1]]
#> [1] "tbl_df"      "tbl"        "data.frame"
#>
#> [[2]]
#> [1] "tbl_df"      "tbl"        "data.frame"
#>
#> [[3]]
#> [1] "tbl_df"      "tbl"        "data.frame"

```

833 Functionals

834 The second example uses `lapply`, and this is a *functional*. *Functionals* are func-
 835 tions that take another function as one of their arguments. Base R functionals
 836 include the `*apply` family of functions: `apply`, `lapply`, `vapply` and so on.

837 4.2 Iteration with map

838 The `tidyverse` replaces traditional loop-based iteration with *functionals* from
 839 the `purrr` package.

840 Why use purrr

841 A good reason to use `purrr` functionals instead of base R functionals is their
 842 consistent and clear naming, which always indicates how they should be used.
 843 This is explained in the examples below. How `map` is different from `for` and
 844 `lapply` are best explained in the **Advanced R Book**.

845 4.2.1 Basic use of map

846 `map` works very similarly to `lapply`, where `.x` is object on whose elements to
 847 apply the function `.f`.

```

# get the number of rows in data
map(.x = nested_data$data, .f = nrow) %>%
  head()
#> [[1]]
#> [1] 2306
#>

```

```
#> [[2]]
#> [1] 1162
#>
#> [[3]]
#> [1] 313
#>
#> [[4]]
#> [1] 34
#>
#> [[5]]
#> [1] 183
#>
#> [[6]]
#> [1] 392
```

848 `map` works on any list-like object, which includes vectors, and always returns a
 849 list. `map` takes two arguments, the object on which to operate, and the function
 850 to apply to each element.

```
# get the square root of each integer 1 - 10
some_numbers = 1:3
map(some_numbers, sqrt)
#> [[1]]
#> [1] 1
#>
#> [[2]]
#> [1] 1.41
#>
#> [[3]]
#> [1] 1.73
```

851 4.2.2 map variants returning vectors

852 Though `map` always returns a list, it has variants named `map_*` where the suffix
 853 indicates the return type. `map_chr`, `map_dbl`, `map_int`, and `map_lgl` return
 854 character, double (numeric), integer, and logical vectors.

```
# use map_dbl to get the mean mass in each order
map_dbl(nested_data$data, function(df){
  mean(df$mass_g)
})
#> [1] 4.86e+02 4.91e+01 4.79e+04 7.86e+05 4.02e+04 1.85e+06 6.68e+03 3.06e+02
#> [9] 1.61e+02 4.06e+01 7.48e+02 1.45e+03 2.36e+05 3.37e+01 1.74e+02 9.58e+05
#> [17] 9.03e+02 4.70e+06 1.13e+03 2.84e+03 2.23e+01 1.12e+06 1.83e+02 5.94e+05
#> [25] 1.22e+04 9.44e+03 1.65e+06 4.45e+01 5.24e+04

# map_chr will convert the output to a character
```

```

# here we get the most common IUCN status of each order
map_chr(nested_data$data, function(df){

  count(df, iucn_status) %>%
    arrange(-n) %>%
    summarise(common_status = first(iucn_status)) %>%
    pull(common_status)
})
#> [1] "LC" "LC" "LC" "EP" "LC" "LC" "LC" "LC" "LC" "LC" "LC" "LC" "EP" "VU" "LC"
#> [16] "EP" "LC" "EP" "LC" "LC" "NT" "VU" "LC" "EP" "VU" "CR" "EP" "LC" "LC"

# map_lgl returns TRUE/FALSE values
some_numbers = c(NA, 1:3, NA, NaN, Inf, -Inf)
map_lgl(some_numbers, is.na)
#> [1] TRUE FALSE FALSE FALSE TRUE TRUE FALSE FALSE

```

855 4.2.3 map variants returning data frames

856 `map_df` returns data frames, and by default binds dataframes by rows, while
 857 `map_dfr` does this explicitly, and `map_dfc` does returns a dataframe bound by
 858 column.

```

# get the first two rows of each dataframe
map_df(nested_data$data[1:3], head, n = 2)
#> # A tibble: 6 x 23
#>   binomial family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr>          <dbl> <dbl>          <dbl> <dbl>
#> 1 Abditom~ Murid~ Abdi~ latide~          1      0              0      0
#> 2 Abeomel~ Murid~ Abeo~ sevia          1      0              0      0
#> 3 Acerodo~ Ptero~ Acer~ celebe~          0      0              0      1
#> 4 Acerodo~ Ptero~ Acer~ humilis          0      0              0      1
#> 5 Acinony~ Felid~ Acin~ jubatus          1      0              0      0
#> 6 Ailurop~ Ursid~ Ailu~ melano~          1      0              0      0
#> # ... with 15 more variables: life_habit_method <chr>, life_habit_source <chr>,
#> #   mass_g <dbl>, mass_method <chr>, mass_source <chr>, mass_comparison <chr>,
#> #   mass_comparison_source <chr>, island_endemicity <chr>, iucn_status <chr>,
#> #   added_iucn_status <chr>, diet_plant <dbl>, diet_vertibrate <dbl>,
#> #   diet_invertebrate <dbl>, diet_method <chr>, diet_source <chr>

```

859 `map` accepts arguments to the function being mapped, such as in the example
 860 above, where `head()` accepts the argument `n = 2`.

861 `map_dfr` behaves the same as `map_df`.

```

# the same as above but with a pipe
nested_data$data[1:5] %>%
  map_dfr(head, n = 2)
#> # A tibble: 10 x 23

```



```

#>   binomial family genus species terrestrial marine freshwater aerial
#>   <chr>      <chr> <chr> <chr>          <dbl>  <dbl>      <dbl>  <dbl>
#> 1 Abditom~ Murid~ Abdi~ latide~         1      0          0      0
#> 2 Abeomel~ Murid~ Abeo~ sevia          1      0          0      0
#> 3 Acerodo~ Ptero~ Acer~ celebe~         0      0          0      1
#> 4 Acerodo~ Ptero~ Acer~ humilis         0      0          0      1
#> 5 Acinony~ Felid~ Acin~ jubatus         1      0          0      0
#> 6 Ailurop~ Ursid~ Ailu~ melano~         1      0          0      0
#> # ... with 4 more rows, and 15 more variables: life_habit_method <chr>,
#> #   life_habit_source <chr>, mass_g <dbl>, mass_method <chr>,
#> #   mass_source <chr>, mass_comparison <chr>, mass_comparison_source <chr>,
#> #   island_endemicity <chr>, iucn_status <chr>, added_iucn_status <chr>,
#> #   diet_plant <dbl>, diet_vertibrate <dbl>, diet_invertebrate <dbl>,
#> #   diet_method <chr>, diet_source <chr>

```

862 `map_dfc` binds the resulting 3 data frames of two rows each by column, and
 863 automatically repairs the column names, adding a suffix to each duplicate.

864 4.2.4 Working with list columns using map

865 The various `map` versions integrate well with list columns to make syn-
 866 thetic/summary data. In the example, the `dplyr::mutate` function is used to
 867 add three columns to the nested tibble: the number of rows, the mean mileage,
 868 and the name of the first car.

869 In each of these cases, the vectors added are generated using `purrr` functions.

```

# get the number of rows per dataframe, the mean mileage, and the first car
nested_data = nested_data %>%
  mutate(
    # use the int return to get the number of rows
    n_rows = map_int(data, nrow),

    # double return for mean mileage
    mean_mass = map_dbl(data, function(df) {mean(df$mass_g)}),

    # character return to get the heaviest member
    first_animal = map_chr(data, function(df) {
      arrange(df, -mass_g) %>%
        .$binomial %>%
        first()
    })
  )

# examine the output
nested_data
#> # A tibble: 29 x 5

```

```
#> # Groups:   order [29]
#>   order      data      n_rows mean_mass first_animal
#>   <chr>      <list>      <int>    <dbl> <chr>
#> 1 Rodentia   <tibble [2,306 x 23]>  2306    486.  Nechoerus_aesopi
#> 2 Chiroptera <tibble [1,162 x 23]>  1162    49.1  Acerodon_jubatus
#> 3 Carnivora  <tibble [313 x 23]>    313  47905.  Mirounga_leonina
#> 4 Pilosa     <tibble [34 x 23]>     34  785958.  Megatherium_americanum
#> 5 Diprotodontia <tibble [183 x 23]>    183  40202.  Diprotodon_optatum
#> 6 Cetartiodactyla <tibble [392 x 23]>    392 1854811.  Balaenoptera_musculus
#> # ... with 23 more rows
```

870 4.2.5 Selective mapping using map variants

871 `map_at` and `map_if` work like other `*_at` and `*_if` functions. Here, `map_if` is
 872 used to run a linear model only on those tibbles which have sufficient data. The
 873 predicate is specified by `.p`.

874 In this example, the nested tibble is given a new column using `dplyr::mutate`,
 875 where the data to be added is a mixed list.

```
# split data by order number and run an lm only if there are more than 100 rows
nested_data = nest(data, data = -order)
```

```
nested_data = mutate(nested_data,
  model = map_if(.x = data,
    # this is the predicate
    # which elements should be operated on?
    .p = function(x){
      nrow(x) > 100
    },
    # this is the function to use
    # if the predicate is satisfied
    .f = function(x){
      lm(mass_g ~ diet_plant, data = x)
    })
```

```
# check the data structure
```

```
nested_data %>% head()
```

```
#> # A tibble: 6 x 3
```

```
#>   order      data      model
#>   <chr>      <list>      <list>
#> 1 Rodentia   <tibble [2,306 x 23]> <lm>
#> 2 Chiroptera <tibble [1,162 x 23]> <lm>
#> 3 Carnivora  <tibble [313 x 23]>   <lm>
#> 4 Pilosa     <tibble [34 x 23]>    <tibble [34 x 23]>
#> 5 Diprotodontia <tibble [183 x 23]>   <lm>
```

```
#> 6 Cetartiodactyla <tibble [392 x 23]>    <lm>
```

Some elements of the column `model` are tibbles, which have not been operated on because they have fewer than 100 rows (species). The remaining elements are `lm` objects.

4.3 More map variants

`map` also has variants along the axis of how many elements are operated upon. `map2` operates on two vectors or list-like elements, and returns a single list as output, while `pmap` operates on a list of list-like elements. The output has as many elements as the input lists, which must be of the same length.

4.3.1 Mapping over two inputs with `map2`

`map2` has the same variants as `map`, allowing for different return types. Here `map2_int` returns an integer vector.

```
# consider 2 vectors and replicate the simple vector addition using map2
map2_int(.x = 1:5,
         .y = 6:10,
         .f = sum)
#> [1] 7 9 11 13 15
```

`map2` doesn't have `_at` and `_if` variants.

One use case for `map2` is to deal with both a list element and its index, as shown in the example. This may be necessary when the list index is removed in a `split` or `nest`. This can also be done with `imap`, where the index is referred to as `.y`.

```
# make a named list for this example
this_list = list(a = "first letter",
                 b = "second letter")
```

```
# a not particularly useful example
map2(this_list, names(this_list),
     function(x, y) {
       glue::glue('{x} : {y}')
     })
```

```
#> $a
#> first letter : a
#>
#> $b
#> second letter : b
```

```
# imap can also do this
imap(this_list,
```

```

      function(x, .y){
        glue::glue('{x} : {.y}')
      }
#> $a
#> first letter : a
#>
#> $b
#> second letter : b

```

892 4.3.2 Mapping over multiple inputs with pmap

893 pmap instead operates on a list of multiple list-like objects, and also comes with
 894 the same return type variants as map. The example shows both aspects of pmap
 895 using pmap_chr.

```

# operate on three different lists
list_01 = as.list(1:3)
list_02 = as.list(letters[1:3])
list_03 = as.list(rainbow(3))

# print a few statements
pmap_chr(list(list_01, list_02, list_03),
  function(l1, l2, l3){
    glue::glue('number {l1}, letter {l2}, colour {l3}')
  })
#> [1] "number 1, letter a, colour #FF0000FF"
#> [2] "number 2, letter b, colour #00FF00FF"
#> [3] "number 3, letter c, colour #0000FFFF"

```

896 4.4 Combining map variants and tidyverse func- 897 tions

898 The example below shows a relatively complex data manipulation pipeline. Such
 899 pipelines must either be thought through carefully in advance, or checked for
 900 required output on small subsets of data, so as not to consume excessive system
 901 resources.

902 In the pipeline:

- 903 1. The tibble becomes a nested dataframe by order (using `tidyr::nest`),
- 904 2. If there are enough data points (> 100), a linear model of mass \sim plant
 905 diet is fit (using `purrr::map_if`, and `stats::lm`),
- 906 3. The model coefficients are extracted if the model was fit (using
 907 `purrr::map` & `dplyr::case_when`),
- 908 4. The model coefficients are converted to data for plotting (using
 909 `purrr::map`, `tibble::tibble`, & `tidyr::pivot_wider`),

- 910 5. The raw data is plotted along with the model fit, taking the title from the
 911 nested data frame (using `purrr::pmap` & `ggplot2::ggplot`).

```
nested_data <-
  data %>%
  tidyr::nest(data = -order) %>%
  mutate(data,
    model = map_if(.x = data,

      # this is the predicate
      # which elements should be operated on?
      .p = function(x){
        nrow(x) > 100
      },

      # this is the function to use
      # if the predicate is satisfied
      .f = function(x){
        lm(mass_g ~ diet_plant, data = x)
      }) %>%

  mutate(m_coef = map(model,

    # use case when to get model coefficients
    function(x) {
      dplyr::case_when(
        "lm" %in% class(x) ~ {
          list(coef(x))
        },
        TRUE ~ {
          list(c(NA, NA))
        }
      )
    },

    # work on the two element double vector of coefficients
    m_coef = map(m_coef, function(x){
      tibble(coef = unlist(x),
        param = c("intercept", "diet_plant")) %>%
        pivot_wider(names_from = "param",
          values_from = "coef")
    })),

    # work on the raw data and the coefficients
    plot = pmap(list(order, data, m_coef), function(ord, x, y){

      # pay no attention to the ggplot for now
```

```

ggplot2::ggplot()+
  geom_point(data = x,
             aes(diet_plant, mass_g),
             size = 0.1)+
  scale_y_log10()+
  labs(title = glue::glue('order: {ord}'))
})

```

912 4.5 A return to map variants

913 Lists are often nested, that is, a list element may itself be a list. It is possible
 914 to map a function over elements at a specific depth.

915 In the example, `phylacine` is split by `order`, and then by IUCN status, creating
 916 a two-level list, with the second layer operated on.

```

# use map to make a 2 level list
this_list = split(data, data$order) %>%
  map(function(df){ split(df, df$iucn_status) })

# map over the second level to count the number of
# species in each order in each IUCN class
# display only the first element
map_depth(this_list[1], 2, nrow)
#> $Afrosoricida
#> $Afrosoricida$CR
#> [1] 1
#>
#> $Afrosoricida$DD
#> [1] 4
#>
#> $Afrosoricida$EN
#> [1] 7
#>
#> $Afrosoricida$EP
#> [1] 2
#>
#> $Afrosoricida$LC
#> [1] 32
#>
#> $Afrosoricida$NT
#> [1] 3
#>
#> $Afrosoricida$VU
#> [1] 8

```

917 4.5.1 Iteration without a return

918 `map` and its variants have a return type, which is either a list or a vector. How-
 919 ever, it is often necessary to iterate a function over a list-like object for that
 920 function's side effects, such as printing a message to screen, plotting a series of
 921 figures, or saving to file.

922 `walk` is the function for this task. It has only the variants `walk2`, `iwalk`, and
 923 `pwalk`, whose logic is similar to `map2`, `imap`, and `pmap`. In the example, the
 924 function applied to each list element is intended to print a message.

```
this_list = split(data, data$order)

iwalk(this_list,
      function(df, .y){
        print(glue::glue('{nrow(df)} species in order {.y}'))
      })
#> 57 species in order Afrosoricida
#> 313 species in order Carnivora
#> 392 species in order Cetartiodactyla
#> 1162 species in order Chiroptera
#> 39 species in order Cingulata
#> 74 species in order Dasyuromorphia
#> 2 species in order Dermoptera
#> 97 species in order Didelphimorphia
#> 183 species in order Diprotodontia
#> 465 species in order Eulipotyphla
#> 5 species in order Hyracoidea
#> 94 species in order Lagomorpha
#> 3 species in order Litopterna
#> 19 species in order Macroscelidea
#> 1 species in order Microbiotheria
#> 7 species in order Monotremata
#> 2 species in order Notoryctemorphia
#> 3 species in order Notoungulata
#> 7 species in order Paucituberculata
#> 24 species in order Peramelemorphia
#> 29 species in order Perissodactyla
#> 9 species in order Pholidota
#> 34 species in order Pilosa
#> 460 species in order Primates
#> 18 species in order Proboscidea
#> 2306 species in order Rodentia
#> 20 species in order Scandentia
#> 5 species in order Sirenia
#> 1 species in order Tubulidentata
```

925 4.5.2 Modify rather than map

926 When the return type is expected to be the same as the input type, that is, a
 927 list returning a list, or a character vector returning the same, `modify` can help
 928 with keeping strictly to those expectations.

929 In the example, simply adding 2 to each vector element produces an error,
 930 because the output is a `numeric`, or `double`. `modify` helps ensure some type
 931 safety in this way.

```
vec = as.integer(1:10)

tryCatch(
  expr = {

    # this is what we want you to look at

    modify(vec, function(x) { (x + 2) })

  },

  # do not pay attention to this
  error = function(e){
    print(toString(e))
  }
)
#> [1] "Error: Can't coerce element 1 from a double to a integer\n"
```

932 Converting the output to an integer, which was the original input type, serves
 933 as a solution.

```
modify(vec, function(x) { as.integer(x + 2) })
#> [1] 3 4 5 6 7 8 9 10 11 12
```

934 A note on `invoke`

935 `invoke` used to be a wrapper around `do.call`, and can still be found with its
 936 family of functions in `purrr`. It is however retired in favour of functionality
 937 already present in `map` and `rlang::exec`, the latter of which will be covered in
 938 another session.

939 4.6 Other functions for working with lists

940 `purrr` has a number of functions to work with lists, especially lists that are not
 941 nested list-columns in a tibble.

942 4.6.1 Filtering lists

943 Lists can be filtered on any predicate using `keep`, while the special case `compact`
 944 is applied when the empty elements of a list are to be filtered out. `discard` is
 945 the opposite of `keep`, and keeps only elements not satisfying a condition. Again,
 946 the predicate is specified by `.p`.

```
# a list containing numbers
this_list = list(a = 1, b = -1, c = 2, d = NULL, e = NA)

# remove the empty element
# this must be done before using keep on the list
this_list = compact(this_list)

# use discard to remove the NA
this_list = discard(this_list, .p = is.na)

# keep list elements which are positive
keep(this_list, .p = function(x){ x > 0 })
#> $a
#> [1] 1
#>
#> $c
#> [1] 2
```

947 `head_while` is bit of an odd case, which returns all elements of a list-like object
 948 in sequence until the first one fails to satisfy a predicate, specified by `.p`.

```
1:10 %>%
  head_while(.p = function(x) x < 5)
#> [1] 1 2 3 4
```

949 4.6.2 Summarising lists

950 The purrr functions `every`, `some`, `has_element`, `detect`, `detect_index`, and
 951 `vec_depth` help determine whether a list passes a certain logical test or not.
 952 These are seldom used and are not discussed here.

953 4.6.3 Reduction and accumulation

954 `reduce` helps combine elements along a list using a specific function. Consider
 955 the example below where list elements are concatenated into a single vector.

```
this_list = list(a = 1:3, b = 3:4, c = 5:10)

reduce(this_list, c)
#> [1] 1 2 3 3 4 5 6 7 8 9 10
```

956 This can also be applied to data frames. Consider some random samples of
 957 `mtcars`, each with only 5 cars removed. The objective is to find the cars present
 958 in all 10 samples.

959 The way `reduce` works in the example below is to take the first element and find
 960 its intersection with the second, and to take the result and find its intersection
 961 with the third and so on.

```
# sample mtcars
mtcars = as_tibble(mtcars, rownames = "car")

sampled_data = map(1:10, function(x){
  sample_n(mtcars, nrow(mtcars)-5)
})

# get cars which appear in all samples
sampled_data = reduce(sampled_data,
  dplyr::inner_join)
```

962 `accumulate` works very similarly, except it retains the intermediate products.
 963 The first element is retained as is. `accumulate2` and `reduce2` work on two lists,
 964 following the same logic as `map2` etc. Both functions can be used in much more
 965 complex ways than demonstrated here.

```
# make a list
this_list = list(a = 1:3, b = 3:6, c = 5:10, d = c(1,2,5,10,12))

# a multiple accumulate can help
accumulate(this_list, union, .dir = "forward")
#> $a
#> [1] 1 2 3
#>
#> $b
#> [1] 1 2 3 4 5 6
#>
#> $c
#> [1] 1 2 3 4 5 6 7 8 9 10
#>
#> $d
#> [1] 1 2 3 4 5 6 7 8 9 10 12
```

966 4.6.4 Miscellaneous operation

967 `purrr` offers a few more functions to work with lists (or list like objects).
 968 `prepend` works very similarly to `append`, except it adds to the head of a list.
 969 `splice` adds multiple objects together in a list. `splice` will break the existing
 970 list structure of input lists.

971 `flatten` has a similar behaviour, and converts a list of vectors or list of lists to a
 972 single list-like object. `flatten_*` options allow the output type to be specified.

```
this_list = list(a = rep("a", 3),
                 b = rep("b", 4))

this_list
#> $a
#> [1] "a" "a" "a"
#>
#> $b
#> [1] "b" "b" "b" "b"

# use flatten chr to get a character vector
flatten_chr(this_list)
#> [1] "a" "a" "a" "b" "b" "b" "b"
```

973 `transpose` shifts the index order in multi-level lists. This is seen in the example,
 974 where the `iucn_status` goes from being the index of the second level to the index
 975 of the first.

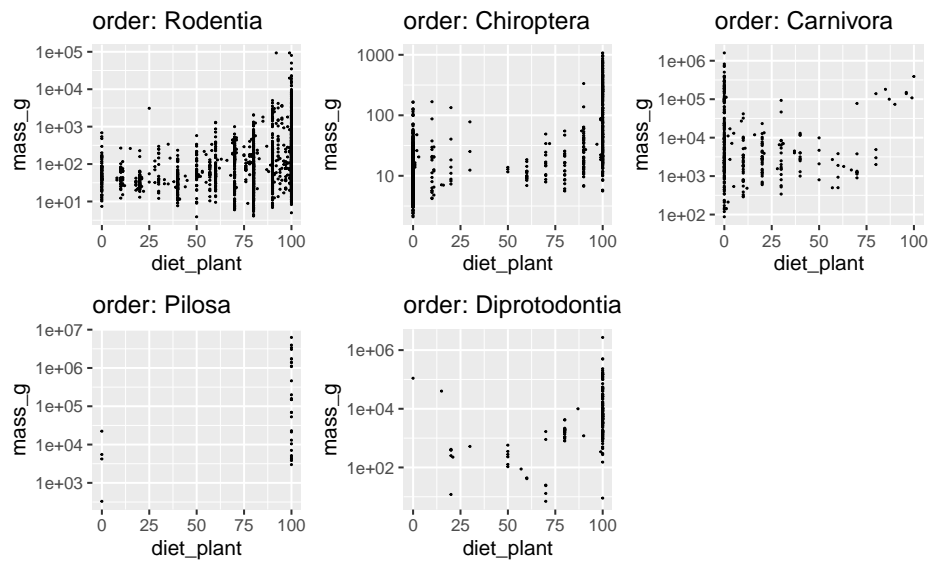
```
this_list = split(data, data$order) %>%
  map(function(df) {split(df, df$iucn_status)})

# from a list of lists where species are divided by order and then
# iucn_status, this is now a list of lists where species are
# divided by status and then order
transpose(this_list[1])
```

976 4.7 Lists of ggplots with patchwork

977 The patchwork library helps compose `ggplots`, which will be properly intro-
 978 duced in the next session. `patchwork` usually works on lists of `ggplots`, which
 979 can come from a standalone list, or from a list column in a nested dataframe.
 980 The example below shows the latter, with the `data` data frame from earlier.

```
# use patchwork on list
patchwork::wrap_plots(nested_data$plot[1:5])
```



Chapter 5

ggplot2 and the grammar of graphics

By Raphael Scherrer, data from Anne-Marie Veenstra-Skirl



Every use case is ridiculous
until it happens to you.

In this tutorial we will learn how to make nice graphics using `ggplot2`, perhaps the most well-known member of the tidyverse. So well-known, in fact, that people often know `ggplot2` before they get to know about the tidyverse. We will first learn about the philosophy behind `ggplot2` and then follow that recipe to build more complex customized plots through some examples.

5.1 Introduction

5.1.1 What is ggplot2 and why use it?

There are many ways of making graphics in base R. For example, `plot` is used for scatterplots, `hist` is used for histograms, `boxplot` is self-explanatory, and `image` can be used for heatmaps. However, those functions are often developed by different people with different logics in mind, which can make them inconsistent with each other, e.g. one has to learn what the arguments of each function are and switching from one type of visualization to another may not be very easy. `ggplot2` is aimed at solving this problem and making plotting *flexible*, allowing to build virtually any graph using a common standard, the *grammar of graphics* (which is what “gg” stands for). By building on a single reference grammar, `ggplot2` fits nicely into the tidyverse, and as part of it, it also follows the same rule as `tidyr`, `dplyr` or `purrr`, making the integration between all those packages very smooth.

5.1.2 What is the grammar of graphics?

The grammar of graphics is a system of rules on how to structure plots such that almost any graph can be made through combinations of a limited set of simpler elements, just as you can make any sentence by combining together letters from an alphabet. `ggplot2` is the implementation of this philosophy in R, and comes with a limited set of *layers*, that you can pick and combine into an impressive variety of graphics, all based on the same syntax. But what are those elements?

Here is the backbone of a ggplot statement (I will from now on use “ggplot” to refer to an object of class `ggplot`, the output of the `ggplot` function and the object that contains our graphic), taken from the book R for Data Science:

```
ggplot(data = <DATA>) +
  <GEOM_FUNCTION>(
    mapping = aes(<MAPPINGS>),
    stat = <STAT>,
    position = <POSITION>
  ) +
  <COORDINATE_FUNCTION> +
  <FACET_FUNCTION>
```

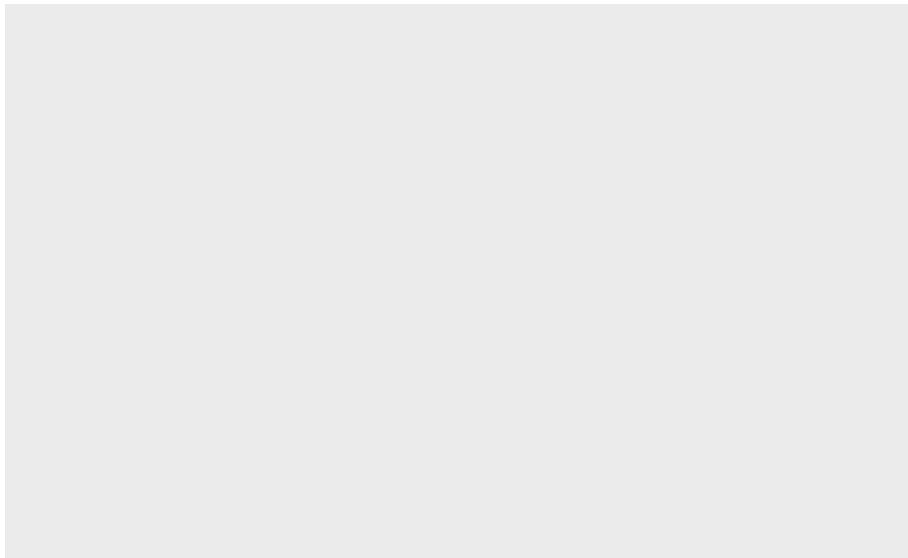
This pseudocode snippet illustrates a fundamental aspect of `ggplot2`, which is that plots are built by *successive* commands, each corresponding to a layer, assembled together using the `+` operator. This might seem less practical than having a whole plot made in a single call to the `plot` function, but it is this modularity that actually gives `ggplot2` its flexibility.

This means that in `ggplot2` you will typically need multiple commands to make a plot. All ggplots are made of at least the two following basic ingredients:

- A call to the `ggplot` function, with the relevant data frame passed to it (this data frame contains our data to plot)
- A `geom` layer, specifying the type of plot to be shown. Variables from the data are mapped onto the graphical properties of this layer, called *aesthetics*.

That means that:

```
library(tidyverse)
ggplot(mtcars)
```



will not show anything. A `ggplot` object is there, but it has no layers yet.

Plots can then be customized with statistical transformations, re-positioning, changes in coordinate system, facetting, and more. We will now go through the different elements.

5.1.3 Quick plot

Note that the `qplot` function, which stands for “quick plot”, will show a plot when called on your dataset. It is a wrapper around `ggplot2` layers that allows to quickly get a visualization, just like using `plot` from base R. However, it is less flexible than combining your `ggplot` yourself, so here we will make sure that you understand how the different layers are assembled.

5.2 But first, the data

In this chapter we will use the data from `bacterial_experiment.csv`, forged by Annie for us to use. This dataset resembles Annie’s experiment where she

created mutator strains of bacteria (that is, bacteria that mutate at a much higher rate than usual) and tracked their growth through time and at different concentrations of an agent supposed to activate the full “mutation potential” of those strains.

```
data <- read_csv("data/bacterial_experiment.csv")
data
#> # A tibble: 310 x 7
#>   strain assay conc ratio time      cfu OD600
#>   <chr>   <chr> <dbl> <dbl> <chr>   <dbl> <dbl>
#> 1 strain 1 test 1      1  8.58 T0      3200000000 0.319
#> 2 strain 1 test 1      1  8.58 T1      1293846908 0.911
#> 3 strain 1 test 1      1  6.11 T0      370110830 0.287
#> 4 strain 1 test 1      1  6.11 T1      1480443320 0.9
#> 5 strain 1 test 1      1 11.8 T0      377928804 0.321
#> 6 strain 1 test 1      1 11.8 T1      1511715216 0.914
#> # ... with 304 more rows
```

The different strains of bacteria were grown in two different **assays**, whose details are irrelevant for the purpose of this tutorial. **cfu** is the number of colony forming units while OD600 is the optical density at 600nm wavelength; both are estimates of bacterial population density. **ratio** represents the ratio in mutants between two time points, T0 and T1 (encoded in **time**).

In this table, the unit of observation is the time point (T0 and T1 are on different rows), therefore the values of **ratio**, which are attributed to each T0-T1 pair, are duplicated to yield one value per time point. To make our life easier with later plotting and to stay within the *tidy* spirit of the tidyverse (where one table should have one unit of observation), we use the tools we have already learnt to make a ratio-wise table:

```
data2 <- data %>%
  pivot_wider(names_from = "time", values_from = c("cfu", "OD600"))
data2
#> # A tibble: 155 x 8
#>   strain assay conc ratio   cfu_T0   cfu_T1 OD600_T0 OD600_T1
#>   <chr>   <chr> <dbl> <dbl>   <dbl>   <dbl>   <dbl>   <dbl>
#> 1 strain 1 test 1      1  8.58 3200000000 1293846908    0.319    0.911
#> 2 strain 1 test 1      1  6.11 370110830 1480443320    0.287    0.9
#> 3 strain 1 test 1      1 11.8 377928804 1511715216    0.321    0.914
#> 4 strain 1 test 1      1  7.78 369871771 1479487084    0.299    0.92
#> 5 strain 1 test 1      5 10.5 3800000000 1505539596    0.295    0.922
#> 6 strain 1 test 1      5  8.29 322488344 1289953376    0.275    0.88
#> # ... with 149 more rows
```


5.3 Geom layers

The `geom` object is the core visual layer of a plot, and it defines the type of plot being made, e.g. `geom_point` will add points, `geom_line` will add lines, etc. There are tons of geoms to pick from, depending on the type of figure you want to make, and new geoms are regularly added in extensions to `ggplot2` (links at the end of this chapter).

All geoms have aesthetics, or graphical parameters, that may be specified. Those include `x` and `y` coordinates, `color`, `transparency`, etc. Some aesthetics are mandatory for some geoms, e.g. `geom_point` needs `x` and `y` coordinates of the points to plot. Other aesthetics are optional, e.g. if `color` is unspecified, all the points will look black. Some geoms even have no mandatory aesthetics, such as `geom_abline`, which will plot a diagonal running through the origin and with slope one if its `intercept` and `slope` are unspecified.

Aesthetics are specified in two ways: (1) variables from the `data` can be mapped to them using the `aes` function, or (2) they can take fixed values.

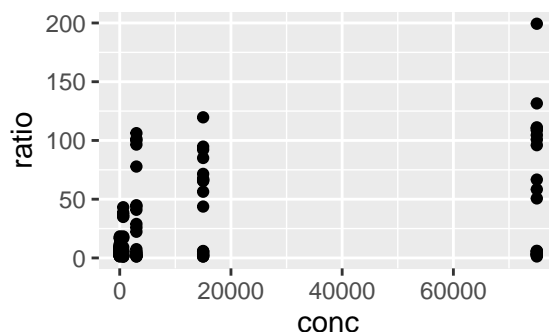
Some of the main aesthetics to know, besides geom-specific coordinates (e.g. `x`, `y`), include: `color`, `fill` (color used to fill surfaces), `group` (used e.g. to plot multiple lines with similar aspect on the same plot), `alpha` (transparency), `size`, `linetype`, `shape`, and `label` (for showing text).

Note that in most functions across the tidyverse both US and UK English can be used, e.g. `colour` is also a valid aesthetics, and `dplyr::summarize` is equivalent to `dplyr::summarise`.

5.3.1 Mapping variables to aesthetics

Variables are mapped to aesthetics using the `aes` function. Here is a basic scatterplot example showing `ratio` against `conc`:

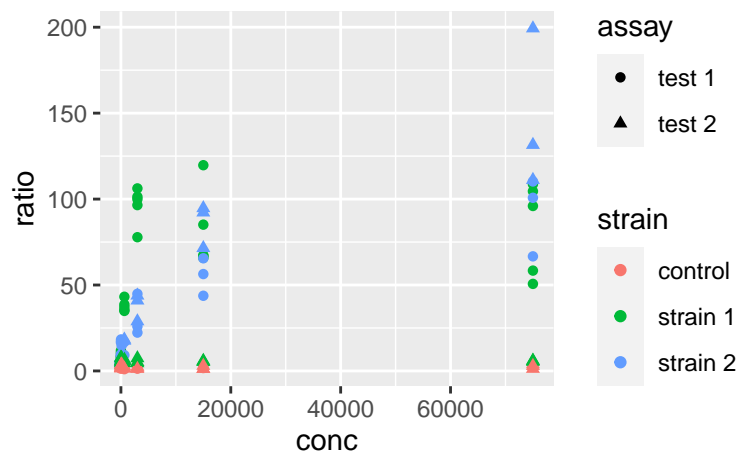
```
ggplot(data2) +  
  geom_point(mapping = aes(x = conc, y = ratio))
```



We can use the other available aesthetics to show more aspects of the data, or to see patterns a bit more clearly. For example, we can color-code the points

1094 based on their strain, and change their shape based on the type of assay:

```
ggplot(data2) +  
  geom_point(mapping = aes(x = conc, y = ratio, color = strain, shape = assay))
```

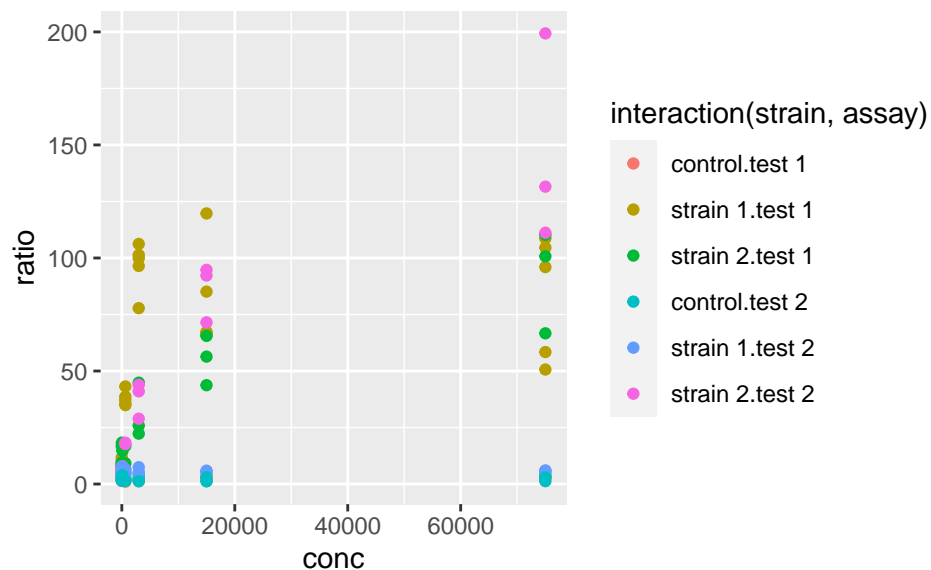


1095

1096 Do you want to map several variables to a single aesthetic? Then **interaction**
1097 from base R can be used within a **ggplot**:

```
ggplot(data2) +  
  geom_point(  
    mapping = aes(x = conc, y = ratio, color = interaction(strain, assay))  
  )
```

1098

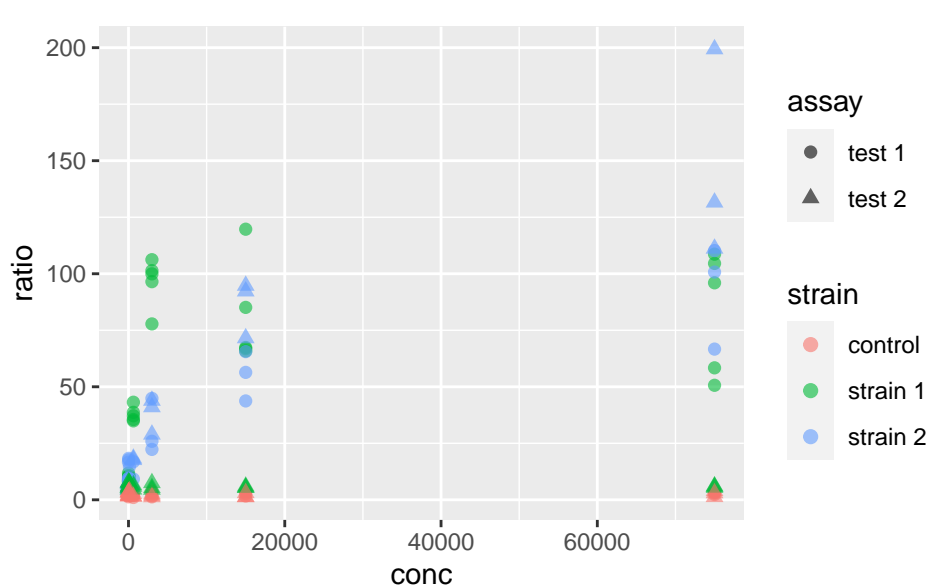


1099

5.3.2 Fixed aesthetics

Fixed graphical parameters (i.e. that are not mapped to a variable) should be added as arguments of the geom *outside* the `aes` command. For example, to make *all* points a little bigger and more transparent, we can use

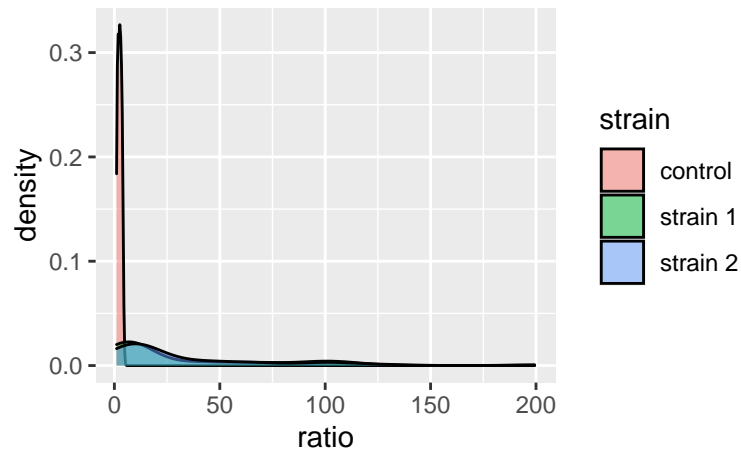
```
ggplot(data2) +
  geom_point(
    mapping = aes(x = conc, y = ratio, color = strain, shape = assay),
    size = 2, alpha = 0.6
  )
```



5.3.3 Statistical transformation

Statistical transformations, or `stat` functions, can be applied to the data within a `geom` call. Actually, statistical transformations are *always* applied within a `geom` call, but most of the time the identity function is used. To illustrate, consider the following plot showing a distribution of `ratio` for different strains:

```
ggplot(data2) +
  geom_density(aes(x = ratio, fill = strain), alpha = 0.5)
```

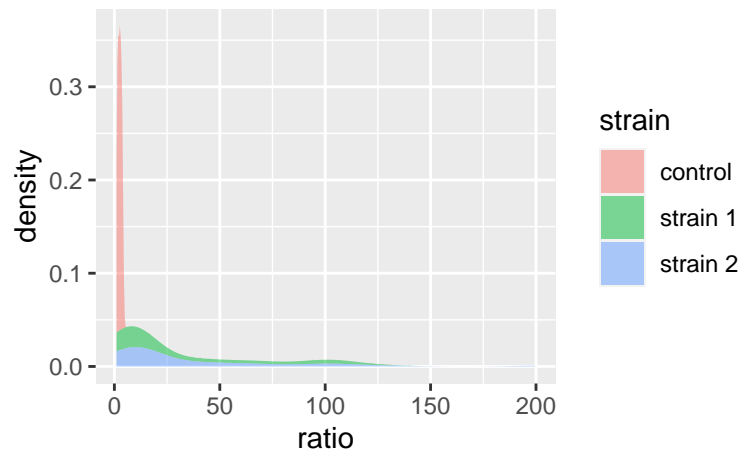


1111

1112 Here, the `density` axis is not part of the original dataset `data2`; it was computed
 1113 from the data, for each value of `ratio`, by using a density-estimation algorithm.
 1114 This shows that `stat_density` (and not `stat_identity`) is the default `stat`
 1115 used in `geom_density`. Every `geom` comes with its default `stat`.

1116 Similarly, `stat` functions can be used in place of `geom` because every `stat` has
 1117 a default `geom` associated to it. So, we can call:

```
ggplot(data2) +  
  stat_density(aes(x = ratio, fill = strain), alpha = 0.5)
```

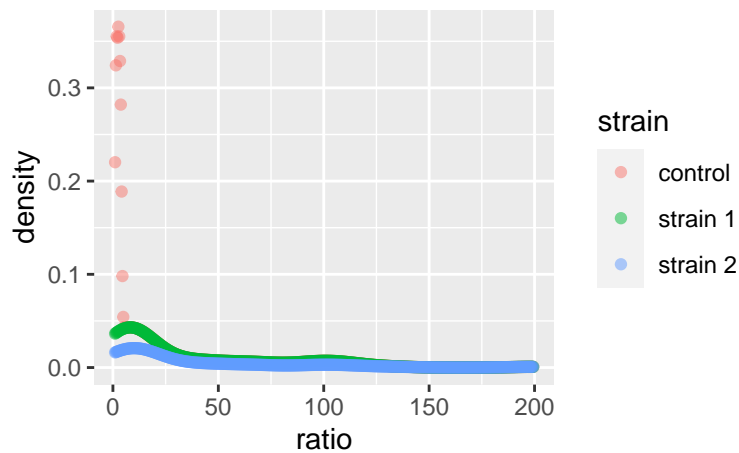


1118

1119 which has `geom_density` as default `geom`.

1120 It is possible to override the default `stat` using the `stat` argument of `geom`,
 1121 and conversely, it is possible to change the default `geom` associated with a given
 1122 `stat`. For example, say we want to plot our densities as points. Then,

```
ggplot(data2) +  
  stat_density(aes(x = ratio, color = strain), alpha = 0.5, geom = "point")
```



1123

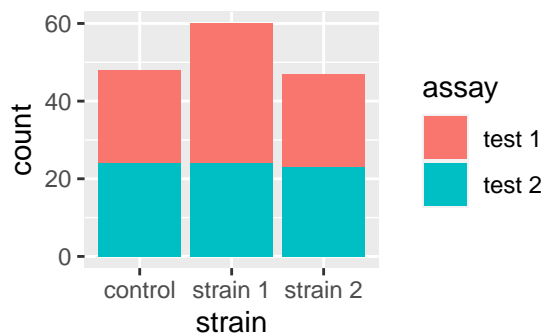
1124 does the job (note that we replaced `fill` with `color` because our points do not
1125 have a surface to fill).

1126 Note that default `geom-stat` combinations are usually well thought of (density
1127 plots are a good example). Therefore, it is often not necessary to play with
1128 stats. It may matter in some specific cases, e.g. when using `geom_bar`, but we
1129 do not cover that here (you can check out the dedicated chapter in R for Data
1130 Science for an example).

1131 5.3.4 Position

1132 The `position` argument of geoms allows to adjust the positioning of the geom's
1133 elements. It has a few variants, but the possibilities depend on the geom used.
1134 We illustrate those available to `geom_bar`. By default, `geom_bar` uses
1135 the `stat_count` statistical transformation, meaning that it will show us the
1136 number of observations into each category of a factor, e.g. `strain`, splitted into
1137 categories of another factor, e.g. `assay`:

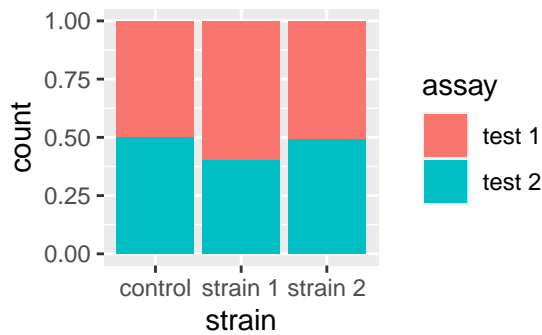
```
ggplot(data2) +  
  geom_bar(aes(x = strain, fill = assay))
```



1138

1139 If we wanted to visualize proportions instead of numbers, we could use the `fill`
 1140 value of the `position` argument:

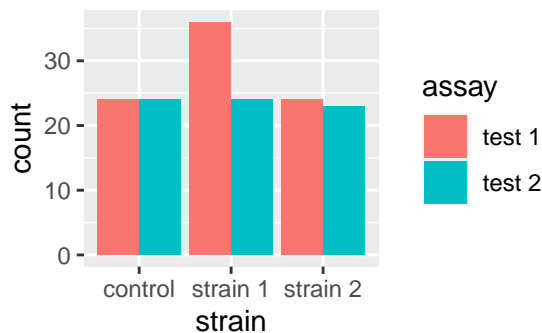
```
ggplot(data2) +  
  geom_bar(aes(x = strain, fill = assay), position = "fill")
```



1141

1142 Alternatively we could use the `dodge` option to show the different categories
 1143 side-by-side:

```
ggplot(data2) +  
  geom_bar(aes(x = strain, fill = assay), position = "dodge")
```



1144

1145 Those are only two examples of what can be done. Just remember that `position`
 1146 exists and look into the documentation of your geom of interest to see what
 1147 position adjustments are available! (Check out `geom_jitter` as a nice wrapper
 1148 around `geom_point` with a `jitter` position adjustment, perfect to overlay with
 1149 boxplots or violin plots.)

1150 5.3.5 Other geoms

1151 The most common geoms you may encounter are:

- 1152 • `geom_point` for scatter plots and `geom_jitter` for the dodged equivalent
- 1153 • `geom_bar` for a barplot
- 1154 • `geom_text` for a scatter plot of labels
- 1155 • `geom_histogram` and `geom_density`, self-explanatory

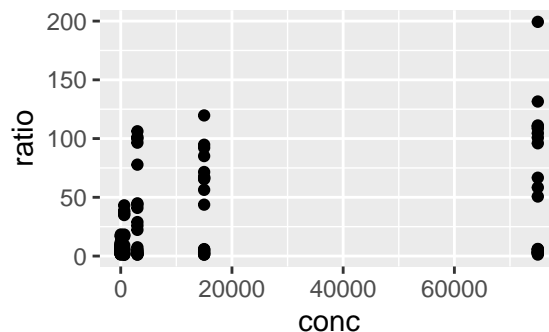
- `geom_boxplot` and `geom_violin`
- `geom_line`, `geom_path` (a line never goes backwards along the x-axis, while a path can) and `geom_smooth` (local regression smoothing)
- `geom_segment`, `geom_hline`, `geom_vline` and `geom_abline` that may come handy as annotations
- `geom_tile` for heatmaps

There are literally tons of geoms and ways to use them. In this tutorial, we emphasize the understanding of the grammar and how to assemble the different ingredients, rather than the ingredients themselves. For this reason, here we are not giving an exhaustive sample of each geom and what they look like. So, keep this list of names in mind as a reminder that whatever plot you want to make, there probably is a `geom` for it. To explore a gallery of examples, check out the R graph gallery.

5.3.6 Extra on aesthetics

It is possible to use the `+` operators, not only to add layers but also to modify previous layers. You might wonder why not to write the layer correctly in the first place. This starts making more sense in cases e.g. where a plot can be modified in different ways. For example, consider this plot:

```
ggplot(data2, aes(x = conc, y = ratio)) +  
  geom_point()
```

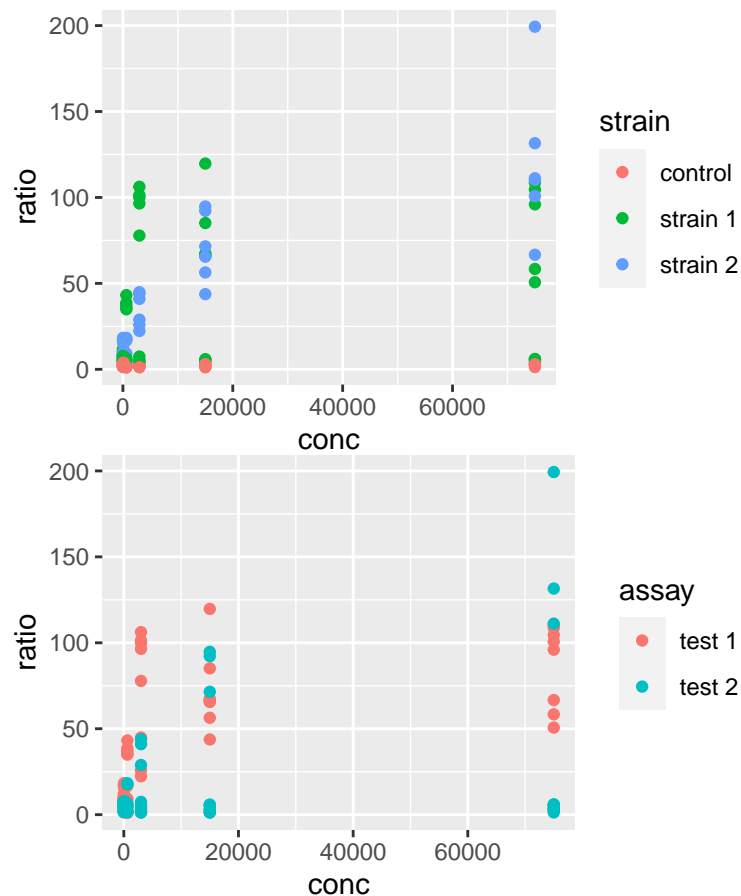


We may want to color-code the points based on `strain` or `assay`, or both, thus requiring two plots building on this single one. An important property of `ggplot` objects is that they can be assigned to variables, e.g.

```
p <- ggplot(data2, aes(x = conc, y = ratio)) +  
  geom_point()
```

Note that we have to call the object `p` for the plot to be displayed. If we just assign the plot to `p`, the plot does not show. We can subsequently add differential aesthetics to different copies of `p`:

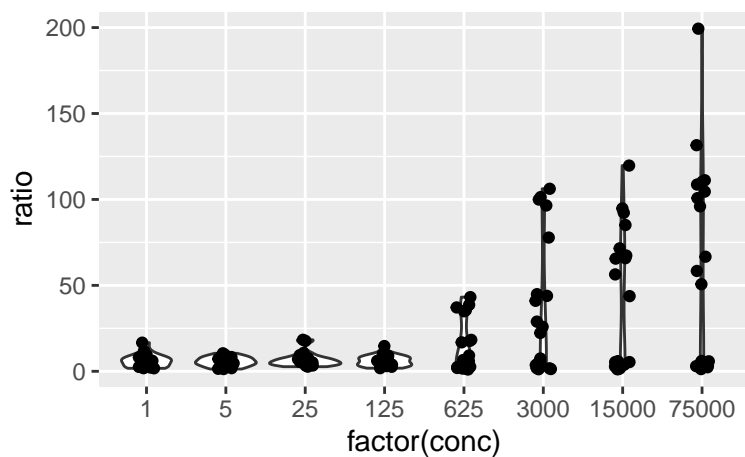
```
p + aes(color = strain)  
p + aes(color = assay)
```



5.3.7 Plot-wide aesthetics and multiple geoms

In the last example, by adding new aesthetics mapping to the `ggplot` using the `+` operator, we did not add these aesthetics *specifically* to the `geom_point` layer, but to all the geoms present in the plot. Similarly, one can pass aesthetic mappings to the `ggplot` command directly, not necessarily with the `geom` statement. This saves some typing when geoms taking the same aesthetics are used, e.g. `geom_violin` and `geom_jitter`:

```
ggplot(data2, aes(x = factor(conc), y = ratio)) +
  geom_violin() +
  geom_jitter(width = 0.1)
# x is made categorical here
```

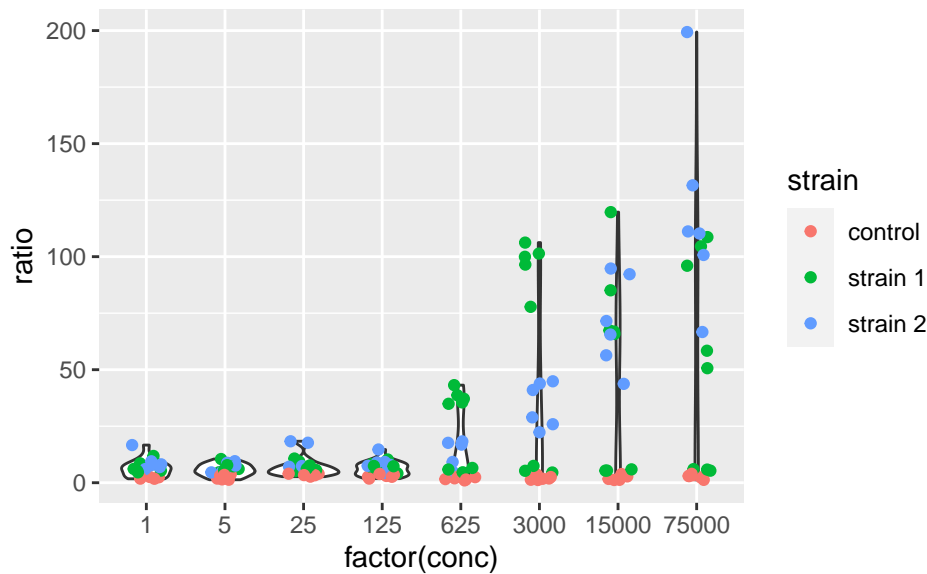



1190

1191 This shows a nice example of multiple geoms combined in a single plot. If,
 1192 however, the aesthetics used in some geoms are geom-specific, better pass them
 1193 to their respective `geom`. For example, if you want to color only the points but
 1194 not the violins, use:

```
ggplot(data2, aes(x = factor(conc), y = ratio)) +  
  geom_violin() +  
  geom_jitter(mapping = aes(color = strain), width = 0.2)
```

1195

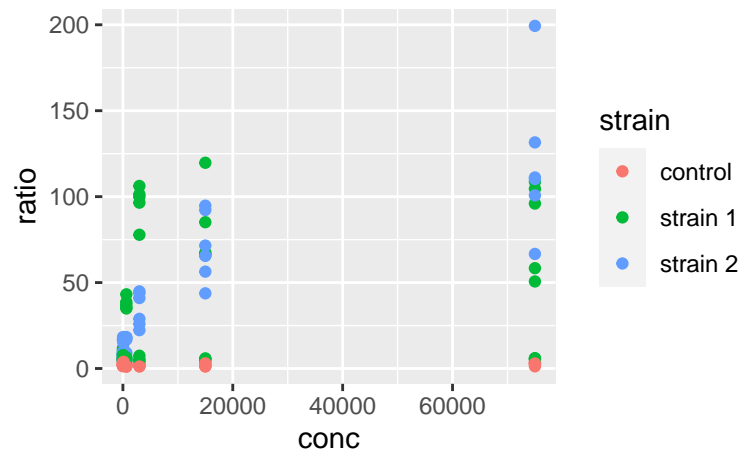


1196

5.3.8 Multiple geoms with different datasets

Just as aesthetics can vary from geom to geom, so do datasets. In other words, the dataset does not have to be passed to the `ggplot` command necessarily, and can be passed to a `geom` instead, for example:

```
ggplot() +
  geom_point(data2, mapping = aes(x = conc, y = ratio, color = strain))
```



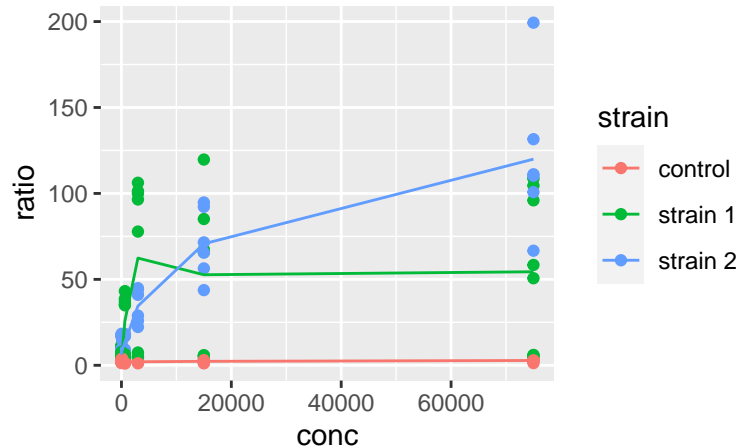
This means that different geoms can be based on different datasets. This allows quite some complexification of the plots and illustrates very well the usefulness of the other packages of the tidyverse. Say, for example, that we want to add to this plot a line going through the means at each value of `conc`. These mean values are not yet present in our dataset, and we need to come up with a mean-wise dataset. `dplyr` is our friend for this task:

```
data3 <- data2 %>%
  group_by(conc, strain) %>%
  summarize(ratio = mean(ratio))
data3
#> # A tibble: 24 x 3
#> # Groups:   conc [8]
#>   conc strain  ratio
#>   <dbl> <chr>   <dbl>
#> 1      1 control    2.21
#> 2      1 strain 1    7.09
#> 3      1 strain 2    9.16
#> 4      5 control    2.50
#> 5      5 strain 1    7.17
#> 6      5 strain 2    6.89
#> # ... with 18 more rows
```

Let us now add an extra layer of information based on this latest, summary

1209 dataset:

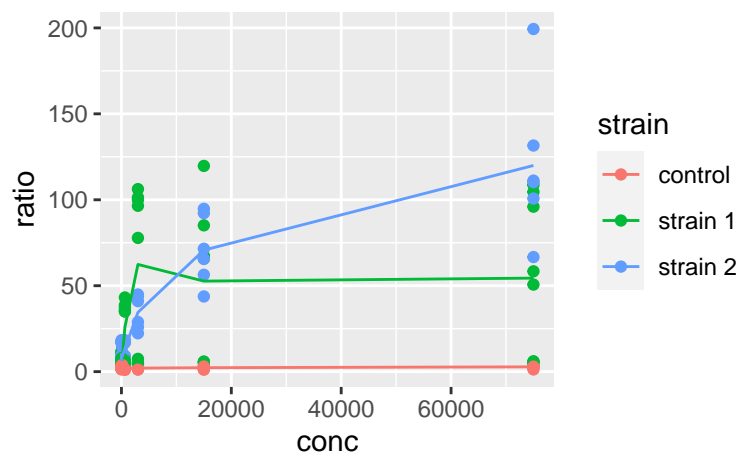
```
ggplot() +
  geom_point(data = data2, mapping = aes(x = conc, y = ratio, color = strain)) +
  geom_line(data = data3, mapping = aes(x = conc, y = ratio, color = strain))
```



1210

1211 Here, we could save some typing by writing:

```
ggplot(data2, mapping = aes(x = conc, y = ratio, color = strain)) +
  geom_point() +
  geom_line(data = data3)
```



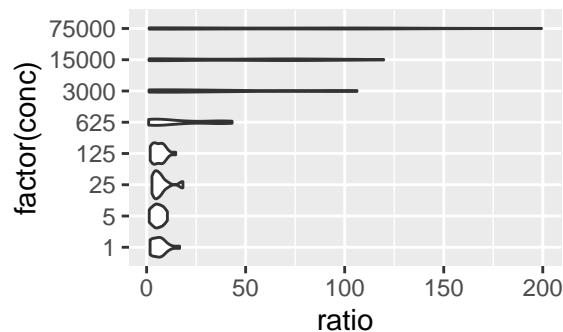
1212

1213 where `geom_line` inherits the same aesthetic mapping as `geom_point`. But then,
 1214 you have to make sure that `data3` contains all the aesthetics that the `ggplot`
 1215 call expects to see in each of its `geoms` (here `x`, `y` and `color`).

5.4 Coordinate-system

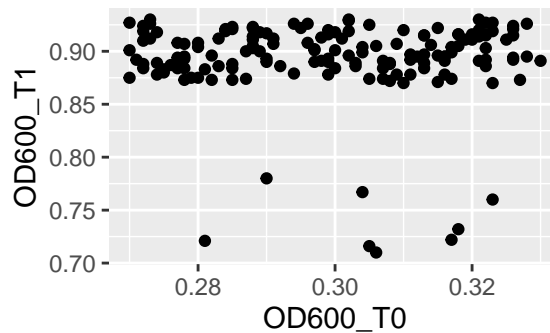
The default way that the plotting window is organized is an orthogonal space with a horizontal x-axis and a vertical y-axis. Use the `coord` commands to deviate from this. For example, `coord_flip` will flip the axes:

```
ggplot(data2, aes(x = factor(conc), y = ratio)) +
  geom_violin() +
  coord_flip()
```



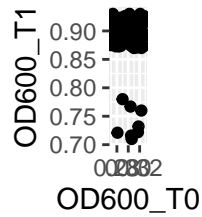
while `coord_fixed` will fix the aspect ratio between the axes, thus showing them on the same scale. For example, the following plot of the optical density between two time points,

```
ggplot(data2, aes(x = OD600_T0, y = OD600_T1)) +
  geom_point()
```



becomes:

```
ggplot(data2, aes(x = OD600_T0, y = OD600_T1)) +
  geom_point() +
  coord_fixed()
```



1226

1227 when both axes are shown on the same scale.

1228 Other coordinate systems exist, depending on the need, including `coord_polar`
 1229 for radial plots or `coord_quickmap`, tailored at latitude-longitude plotting.

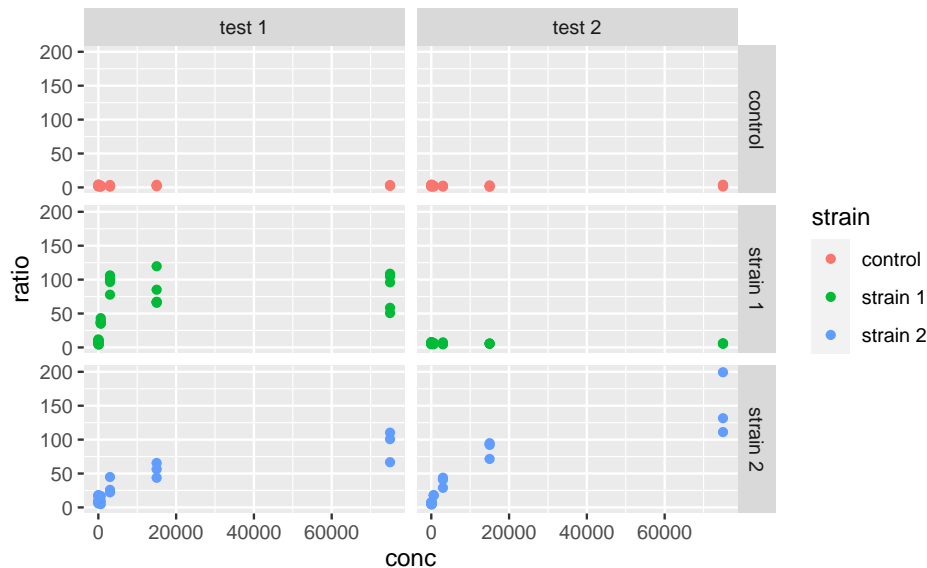
1230 5.5 Facetting

1231 One of the most powerful features of `ggplot2` is its easy way of splitting a plot
 1232 into multiple subplots, or *facets*.

1233 There are two functions for facetting: `facet_grid` and `facet_wrap`.
 1234 `facet_grid` will arrange the plot in rows and columns depending on
 1235 variables that the user defines:

```
ggplot(data2, aes(x = conc, y = ratio, color = strain)) +  
  geom_point() +  
  facet_grid(strain ~ assay)
```

1236



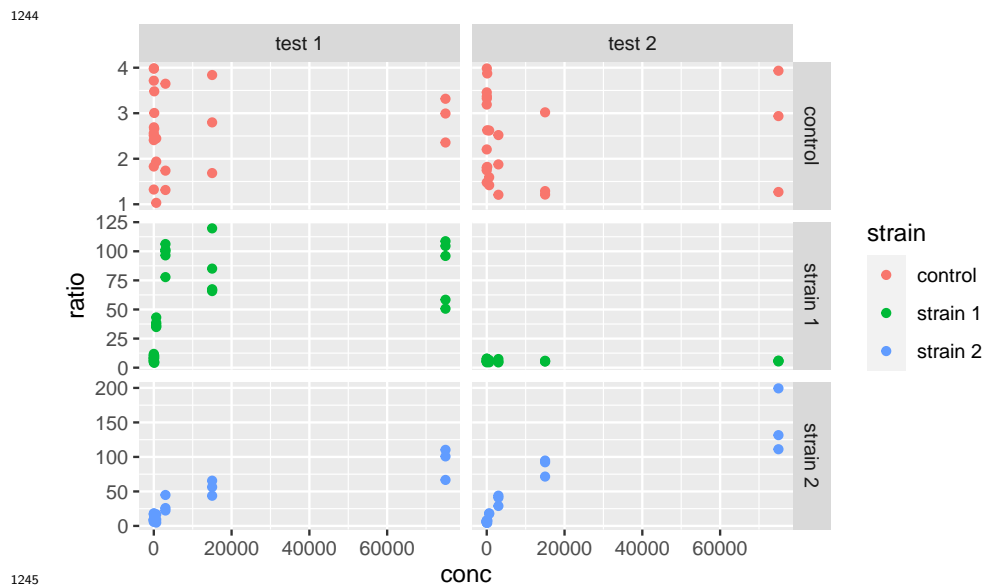
1237

1238 Here the tilde (~) symbolizes a *formula*, a type of expression in R with a left
 1239 and right-hand side, which here are interpreted as variables to use for rows and

columns, respectively. If using only one variable for faceting, use `.` or nothing on the other side of the tilde.

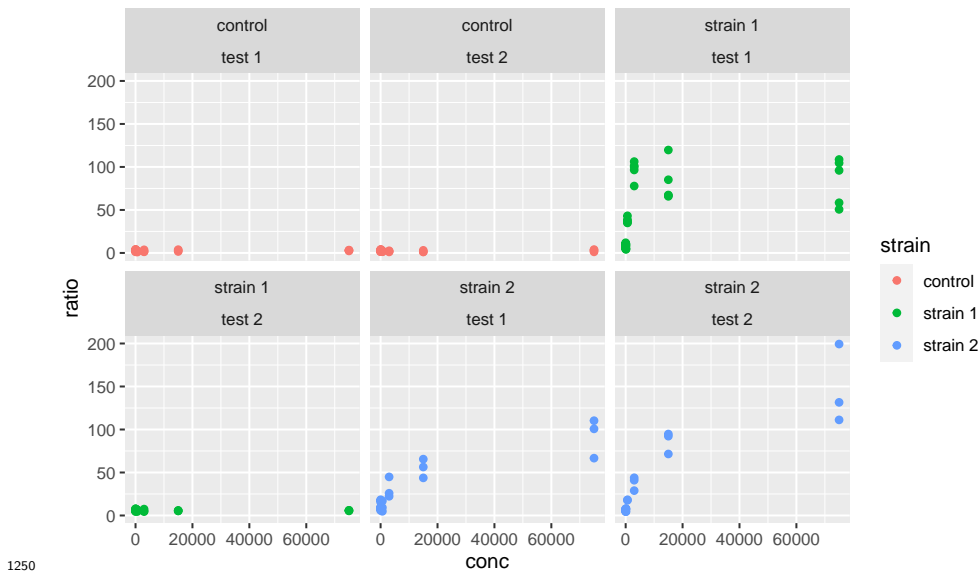
Note that facets are plotted on the same scale. We can use the `scales` argument to allow free scales, for example:

```
ggplot(data2, aes(x = conc, y = ratio, color = strain)) +
  geom_point() +
  facet_grid(strain ~ assay, scales = "free_y")
```



`facet_wrap` is similar to `facet_grid`, except that it does not organize the facets in rows and columns but rather as an array of facets that fill the screen by row, like when filling a matrix with numbers:

```
ggplot(data2, aes(x = conc, y = ratio, color = strain)) +
  geom_point() +
  facet_wrap(strain ~ assay)
```

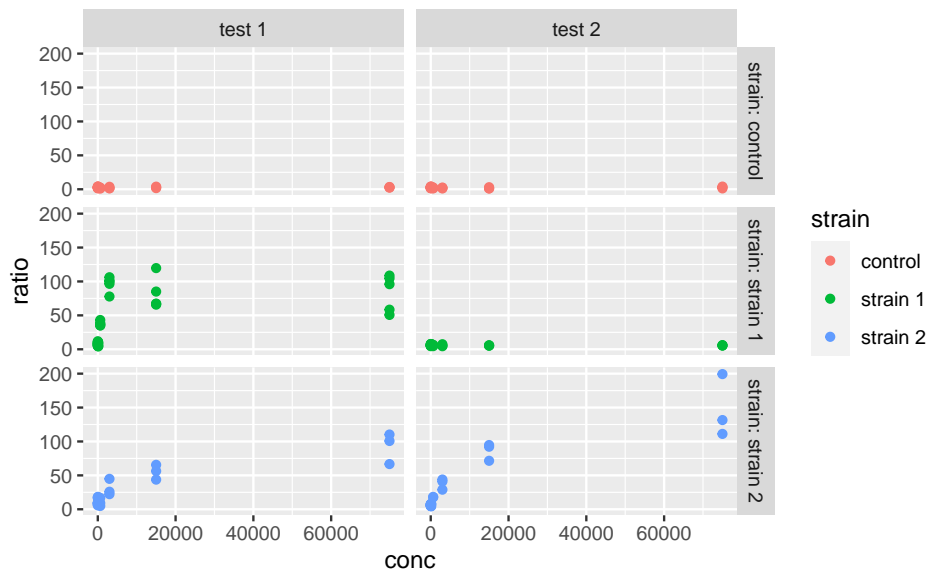


where the position of the variables relative to the `~` becomes irrelevant.

Note that a faceted ggplot is still *one* ggplot, not a combination of ggplots, which we will cover later.

Custom-labelling the strips of the facets is done with the `labeller` argument. The way this is used is a little complicated, but essentially looks like this:

```
ggplot(data2, aes(x = conc, y = ratio, color = strain)) +
  geom_point() +
  facet_grid(strain ~ assay, labeller = labeller(.rows = label_both))
```



Here, the `label_both` function is applied to the variable facetting by row, which is `strain`. `label_both` tells the `labeller` to label the strips with the name of the variable (`strain`) followed by its value, separated by a colon. We will not cover labelling in details here, but keep in mind that the `labeller` argument is what to play with, and that it takes the output of the `labeller` function as input, which itself takes labelling functions, such as `label_both`, as arguments. Other labelling functions include `label_value`, which just shows the value in the strip (that is the default) and `label_parsed`, which is used for showing mathematical expressions in strip labels (e.g. greek letters, exponents etc.). It is possible to provide custom names too. For more information on customizing facet strip labels, visit this link.

Note: I made a package called `ggsim`, yet another extension of `ggplot2` with a few functions coming handy for simulation data. One of the functions, `facetize`, is aimed at making your life easier when labelling the strips of your facets (i.e. not going into the nitty gritty of the `labeller` function), especially when some facets include parsing mathematical expressions. Feel free to install it from GitHub by using:

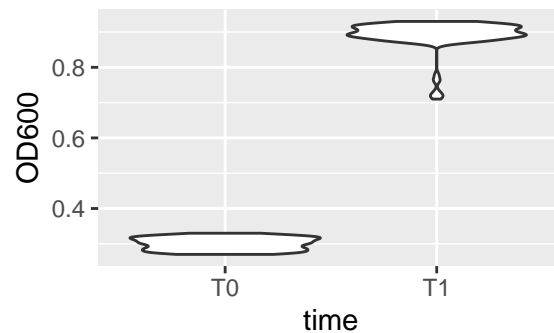
```
devtools::install_github("rscherrer/ggsim")
```

5.6 The right format for the dataset

One question that may come to your mind is: what is the right format of a dataset for use in `ggplot`, especially since it is part of the tidyverse? The answer is: it depends, and this is where the intergration with other tidyverse tools makes our life easier. If, for example, we want to use a variable for facetting or as an aesthetics, it is important to have this variable as a single column.

For example, in the original `data` dataset, we could have compared the optical density between the two time point:

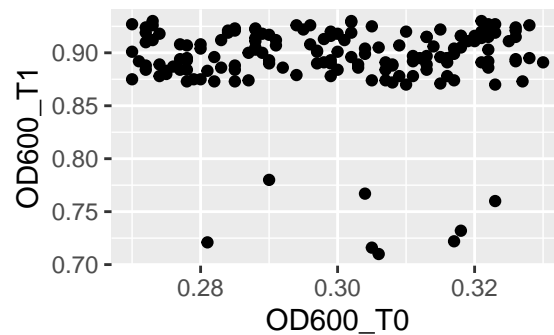
```
ggplot(data, aes(x = time, y = OD600)) +  
  geom_violin()
```



1283

where `time` is both an aesthetic (`x`) and its own column. However, if we want to plot the optical density of time point T1 *versus* that of time point T0, then we need these two time points in separate columns, which is exactly what `OD600_T0` and `OD600_T1`, in the `data2` dataset, are (remember we got those using `tidyr::pivot_wider`):

```
ggplot(data2, aes(x = OD600_T0, y = OD600_T1)) +  
  geom_point()
```



1289

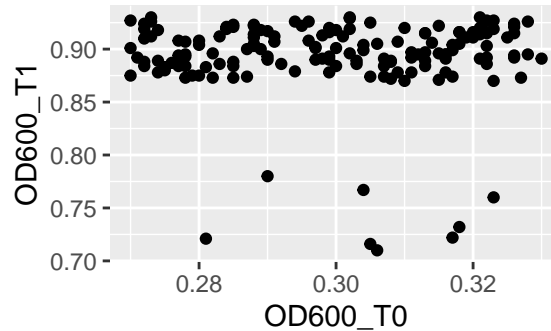
5.7 Plotting as part of a pipeline

1290

What we just saw means that sometimes reformatting of a dataset is needed (e.g. using `pivot_longer` or `pivot_wider` from `tidyr`) to get this one plot done that requires reshaping. If you do not want to spend space storing a reformatted data frame into a whole new object, just to make a single plot, you can use `ggplot` as final part of a tidyverse pipeline. For example, starting from the original data:

1296

```
data %>%
  pivot_wider(names_from = "time", values_from = c("cfu", "OD600")) %>%
  ggplot(aes(x = OD600_T0, y = OD600_T1)) +
  geom_point()
```



1297

1298 Notice the use of the pipe `%>%` to pass the resulting data frame on to the `ggplot`
 1299 command. Because `ggplot` is called with a pipe, its first argument is already
 1300 passed (it is the data frame coming through the pipe), so we only need to pass
 1301 the second argument, i.e. the aesthetics mapping, to the `ggplot` function.

1302 5.8 Customization

1303 Now that we saw everything there is to know about structuring a `ggplot`, it is
 1304 time to learn how to polish it (the easiest and most rewarding part!).

1305 5.8.1 Scales

1306 Every aesthetics can be scaled. This includes specifying what values an aesthet-
 1307 ics can take (e.g. what colors to pick, or what range of transparencies to use),
 1308 possible break points along the legend, or legend titles and labels, among others.
 1309 Use the `scale_*` family of functions for that. There are many such functions,
 1310 because many aesthetics can be modified, but the logic behind their naming is
 1311 always the same:

```
1312 scale_<AESTHETIC>_<TYPE>
```

1313 where `<AESTHETIC>` is replaced by the aesthetic you want to scale (e.g. `color`,
 1314 `size`, `alpha`) and `<TYPE>` is the type of variable that is mapped to this aesthetic
 1315 (common types are `continuous`, `discrete` and `manual`). Some scaling functions
 1316 do not take a `<TYPE>` but just an `<AESTHETIC>` in their name, e.g. `scale_alpha`.

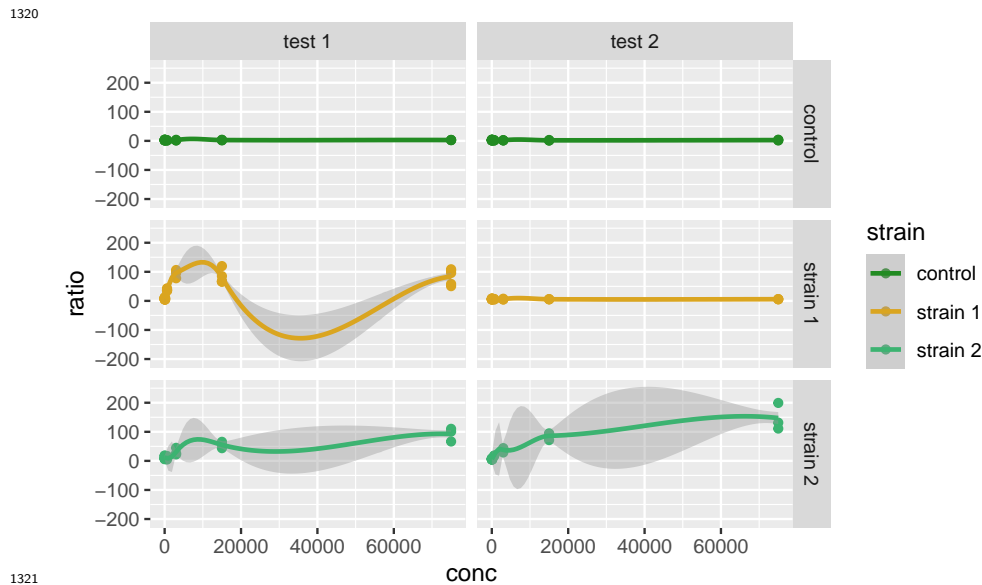
1317 In our example, if we color-code points according to their `strain`, which is a cat-
 1318 egorical variable, we can use `scale_color_manual` (aka `scale_colour_manual`)
 1319 to manually pick the colors we want:

```
ggplot(data2, aes(x = conc, y = ratio, color = strain)) +
  geom_point() +
```

```

geom_smooth() + # just to spice up our use of geoms
facet_grid(strain ~ assay) +
scale_color_manual(values = c("forestgreen", "goldenrod", "mediumseagreen"))

```

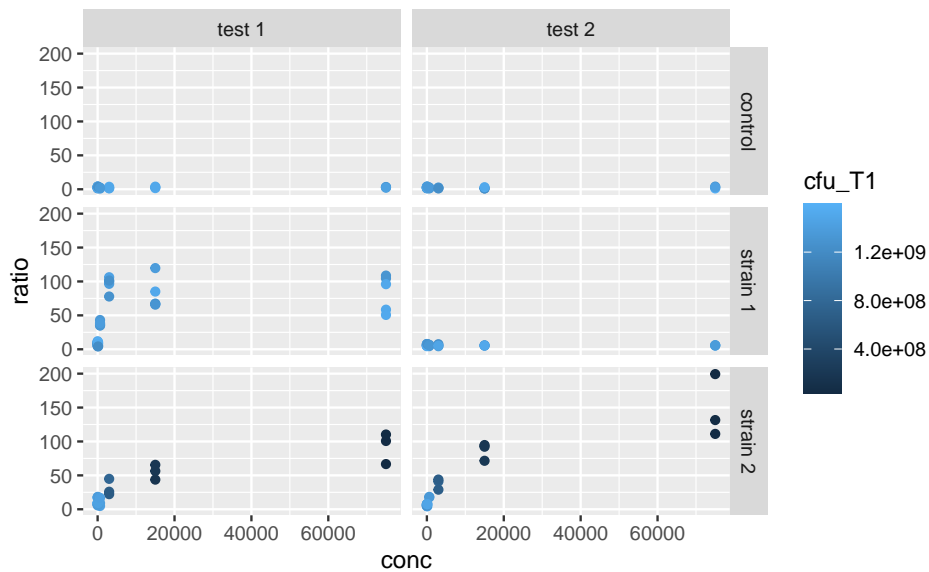


1322 Alternatively, we could color-code the points based on their number of
 1323 CFU at time point T1, `cfu_T1`, which is a continuous variable, using
 1324 `scale_color_continuous`. Without scaling:

```

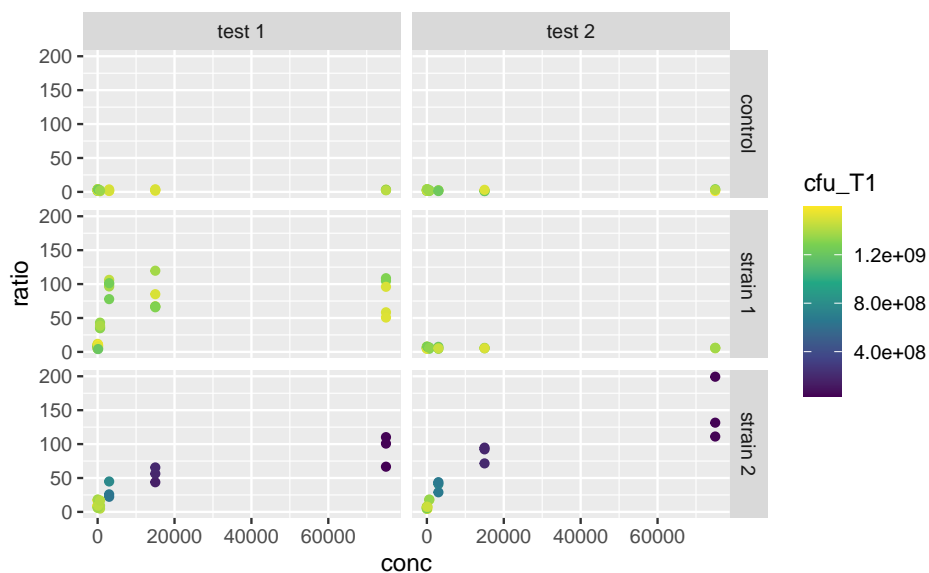
ggplot(data2, aes(x = conc, y = ratio, color = cfu_T1)) +
  geom_point() +
  facet_grid(strain ~ assay)

```



With scaling:

```
ggplot(data2, aes(x = conc, y = ratio, color = cfu_T1)) +
  geom_point() +
  facet_grid(strain ~ assay) +
  scale_color_continuous(type = "viridis")
```

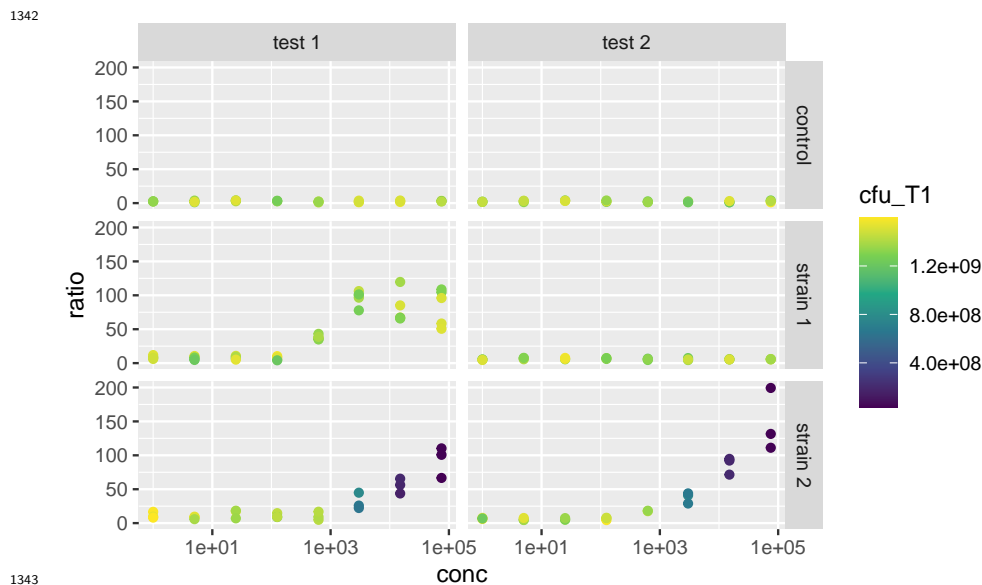


The arguments that are taken by the `scale_` function really depend on the use case, e.g. `scale_color_manual` expects discrete values,

1332 `scale_color_continuous` expects a `type` of built-in continuous color gradient,
 1333 and `scale_color_gradient` expects a `low` and `high` color boundaries (and also
 1334 a mid-gradient color in the case of `scale_color_gradient2`). But the logic
 1335 shown here is similar across many aesthetics, e.g. `scale_alpha_continuous`
 1336 and `scale_size_continuous` work in similar ways, both taking a `range`
 1337 argument. So, lots of scaling functions to play with, of which we do not provide
 1338 an exhaustive list here.

1339 Mandatory aesthetics, such as `x` and `y`, also have their scaling functions. If
 1340 `x` or `y` is continuous, one can e.g. use `scale_x_log10` to show this axis on a
 1341 logarithmic scale, without having to log-transform the data before plotting, e.g.

```
ggplot(data2, aes(x = conc, y = ratio, color = cfu_T1)) +  
  geom_point() +  
  facet_grid(strain ~ assay) +  
  scale_color_continuous(type = "viridis") +  
  scale_x_log10()
```



1344 More on re-scaling legend titles and labels further down.

1345 5.8.2 Labels

1346 The functions `ggtitle`, `xlab`, `ylab` and `labs` allow you to customize the labels
 1347 shown for each aesthetics (remember that the x- and y-axes are aesthetics too),
 1348 and for the main title of the plot. On to a full-fledge example:

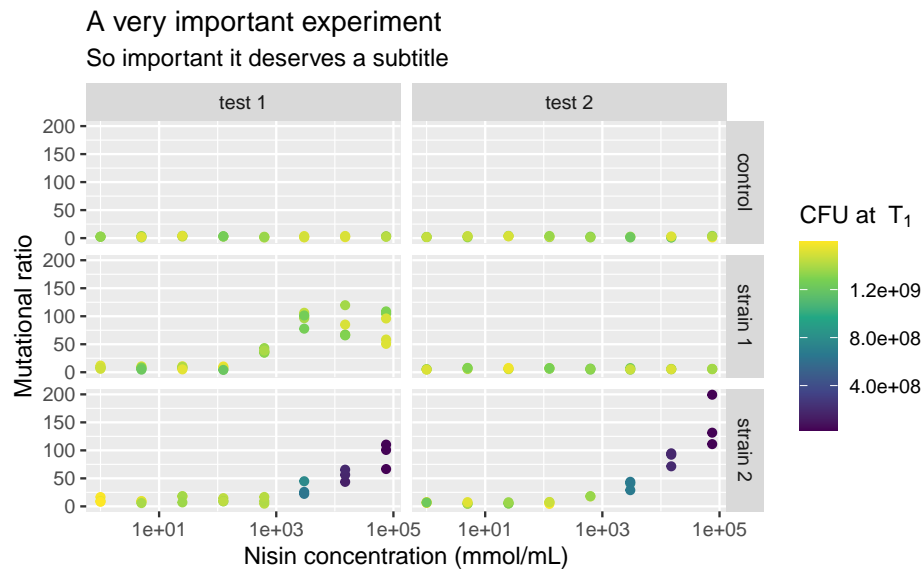
```
p <- ggplot(data2, aes(x = conc, y = ratio, color = cfu_T1)) +  
  geom_point() +
```

```

facet_grid(strain ~ assay) +
scale_color_continuous(type = "viridis") +
scale_x_log10() +
xlab("Nisin concentration (mmol/mL)") +
ylab("Mutational ratio") +
labs(color = parse(text = "'CFU at '~T[1]")) + # plotmath expression
ggtitle(
  "A very important experiment",
  "So important it deserves a subtitle"
)

```

1349



1350

1351 Note that `xlab` and `ylab` are wrappers around `labs`, meaning that we could
 1352 have provided `labs` with `x = ...` and `y = ...` in addition to `color = ...`,
 1353 its arguments just need to take the names of the aesthetics. If you want no
 1354 labels, use e.g. `xlab(NULL)` or `ylab(NULL)`.

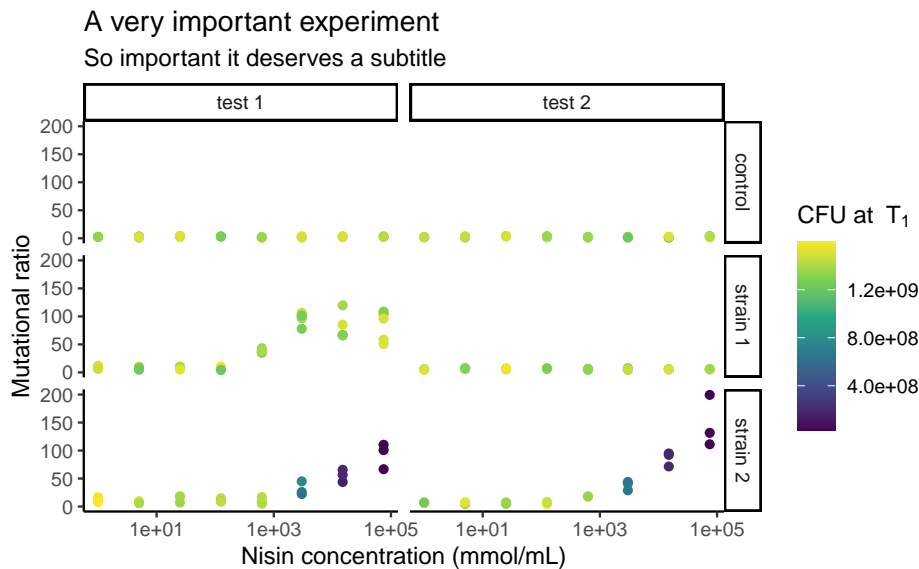
1355 Also notice the use of `parse` to display mathematical notations using the
 1356 `plotmath` syntax. This is not part of the tidyverse though, so it is a story for
 1357 another day, feel free to look it up (type `?bquote`)!

1358 5.8.3 Themes

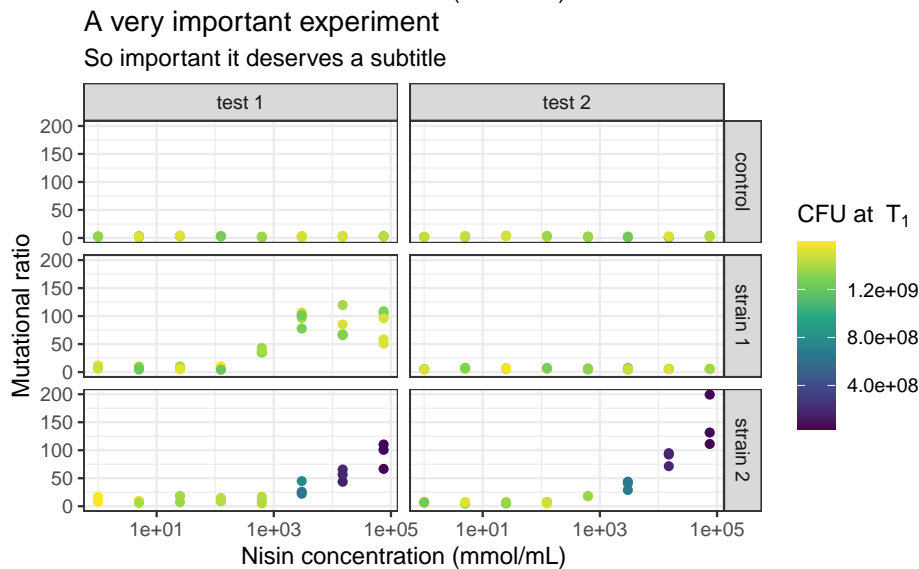
1359 You may be already frustrated that all plots have this same grey default `ggplot2`
 1360 background. Of course, it is possible to change this too by playing with the
 1361 `theme` functions. There are other built-in themes than the default grey one,
 1362 such as `theme_bw` or `theme_classic`:

```
p + theme_classic()
p + theme_bw()
```

1363



1364



1365

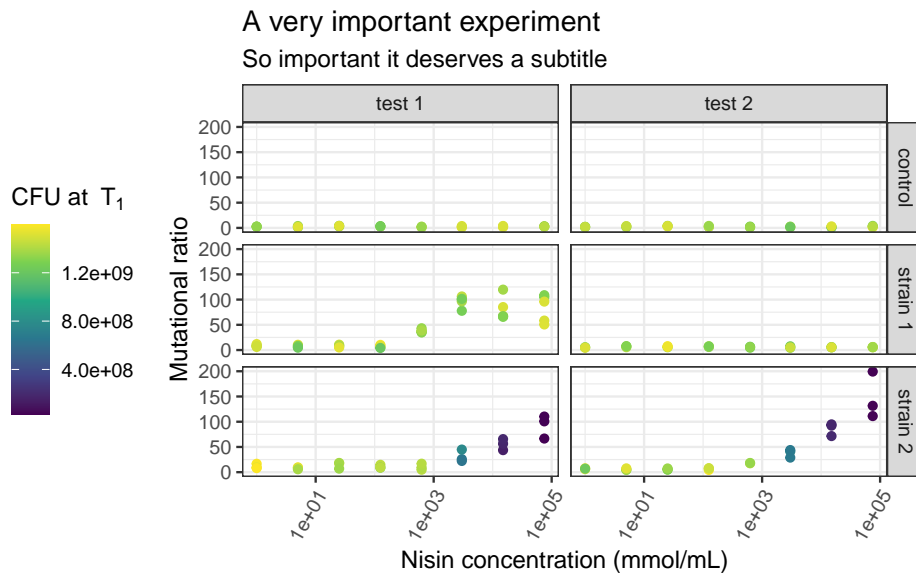
1366 The individual elements of the theme, e.g. the background grid or the color of
 1367 the panel, can be customized using the arguments in the `theme` function. The
 1368 `theme` function can also be used to modify stuff related to the legend or the axes
 1369 of the plots. For example:

```
p <- p +
  theme_bw() +
```

```

theme(
  legend.position = "left",
  axis.text.x = element_text(angle = 60, hjust = 1)
)
p

```



1370

1371 Here, `legend.position` is sort of self-explanatory, but `axis.text.x` is a bit
 1372 more subtle. Some elements of the theme, such as the text of the axes, need
 1373 a series of graphical parameters in order to be modified, and the graphical
 1374 parameters that can be used depend on the type of object those theme elements
 1375 are (are they `text`, `rect` or `line`?). We use the `element_*` family of functions
 1376 to pass those graphical parameters to our theme elements of interest. Here, we
 1377 use `element_text` to transform the `text` on the x-axis by rotating it by an
 1378 `angle` of 60 degrees, and then align each label to the right (`hjust` stands for
 1379 “horizontal justification”). Again, lots of combinations are possible. Explore!

1380 5.8.4 Legend

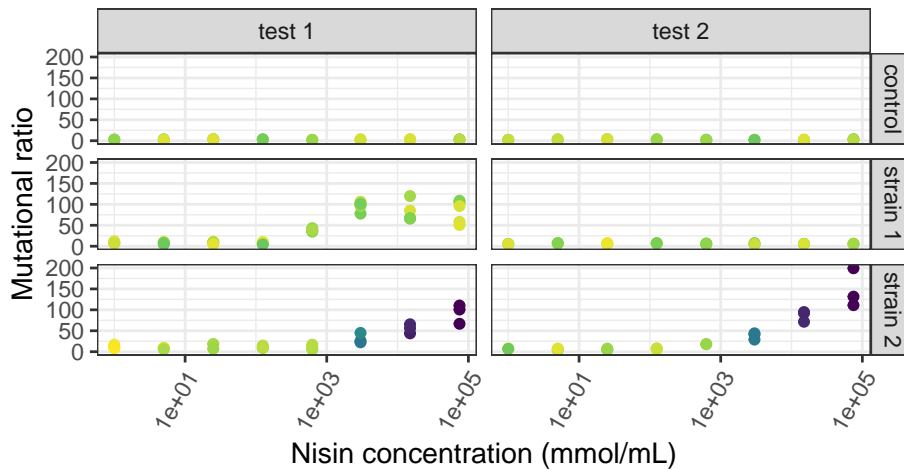
1381 The one thing I Google the most, without a doubt, is “custom legend in ggplot”,
 1382 because I always forget how to choose which legend to show, e.g. if I want to
 1383 display the color legend but not the alpha legend. So here it is: to hide *all* the
 1384 legends, use:

```
p + theme(legend.position = "none")
```

1385

A very important experiment

So important it deserves a subtitle



1386

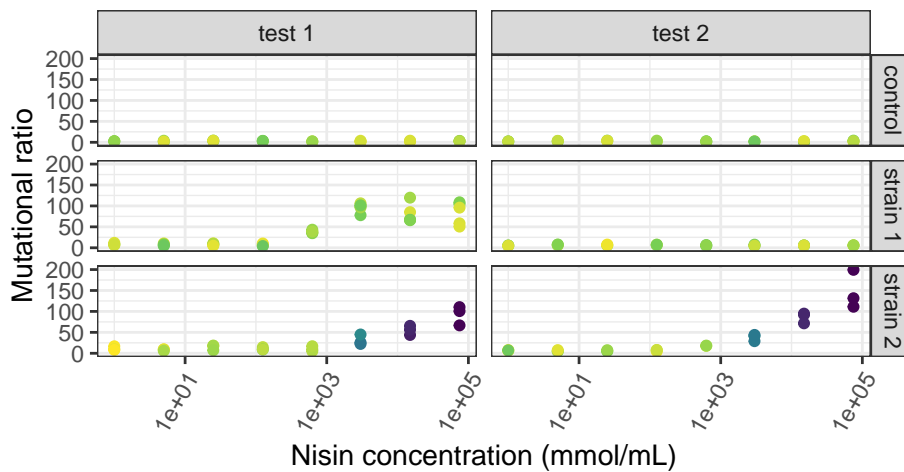
1387 And to selectively hide *some* legends, use `guides`:

```
p + guides(color = FALSE)
```

1388

A very important experiment

So important it deserves a subtitle

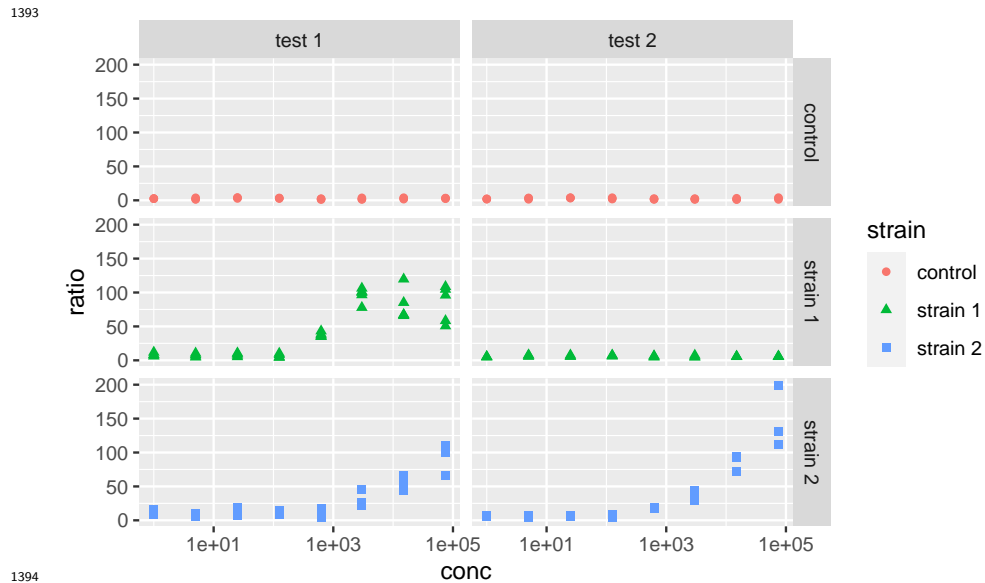


1389

1390 It is also important to remember that `ggplot2` will try to combine legends
 1391 together whenever it can. If the same variable is mapped to two different aes-
 1392 thetics, e.g. shape and color, only one legend will appear:

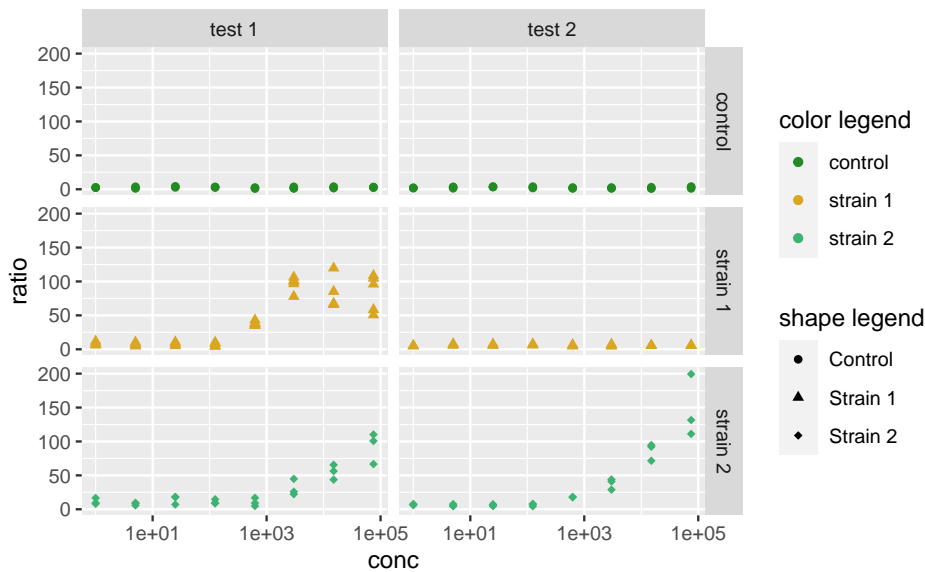
```
ggplot(data2, aes(x = conc, y = ratio, color = strain, shape = strain)) +  
  geom_point() +
```

```
facet_grid(strain ~ assay) +
scale_x_log10()
```



1395 But this behavior can be controlled. You can use the arguments of the `scale_`
 1396 functions to pass custom titles and labels to the legends. And if the legends
 1397 mapping to the same variable have different titles or labels, they will be shown
 1398 separately:

```
ggplot(data2, aes(x = conc, y = ratio, color = strain, shape = strain)) +
  geom_point() +
  facet_grid(strain ~ assay) +
  scale_x_log10() +
  scale_color_manual(
    "color legend", values = c("forestgreen", "goldenrod", "mediumseagreen")
  ) +
  scale_shape_manual(
    "shape legend", values = c(16, 17, 18),
    labels = c("Control", "Strain 1", "Strain 2")
  )
```



Note that you can also use this trick to combine different legends together, by giving them the same titles and labels.

5.9 Combining plots

This was more or less what you need to know to be operational when plotting *single* ggplots. But what if the facetting option is not enough, and you want to combine multiple plots into a single figure? `ggplot2` itself does not do that, but the good news is, there are many packages that do. Those include `patchwork`, `cowplot`, `grid`, `gridExtra`, `egg` or `aplot` (and probably more).

One term that these packages often use is `grob`. A `grob` is a ggplot-like object, such as a `ggplot` but could also be a single text label in the middle of a plotting window. These packages essentially assemble grobs together.

`patchwork` is personally my favorite so I will focus on this one here. It has the advantage to automatically align the frames of the different plots across the different subplots (I found that this is not entirely true when combining `ggtree` objects with other plots, `aplot` is better for this specific case). It also has an excellent, succinct documentation.

Let us look at an example, where we assign the previous plot to `p1` and make a new plot to combine it with, called `p2`:

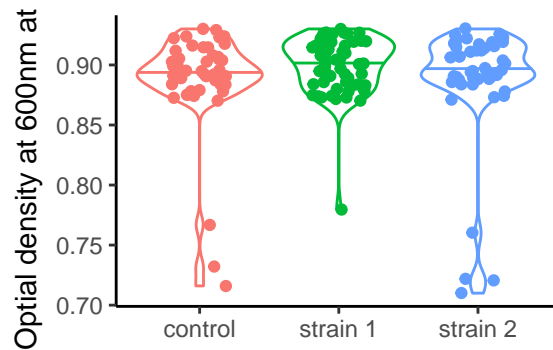
```
p1 <- p
p2 <- ggplot(data2, aes(x = strain, y = OD600_T1, color = strain)) +
  geom_violin(draw_quantiles = 0.5) +
  geom_jitter(width = 0.2) +
  theme_classic() +
```

```

xlab(NULL) +
ylab(parse(text = "'Optial density at 600nm at'~T[1]")) +
theme(legend.position = "none")
p2

```

1419

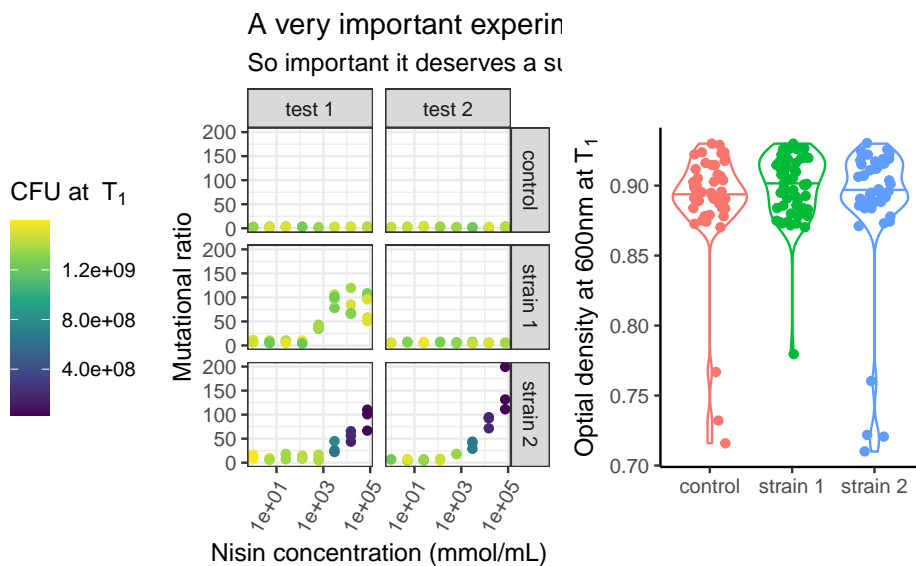
1420 In `patchwork`, we would combine both using:

```

library(patchwork)
p1 + p2

```

1421



1422

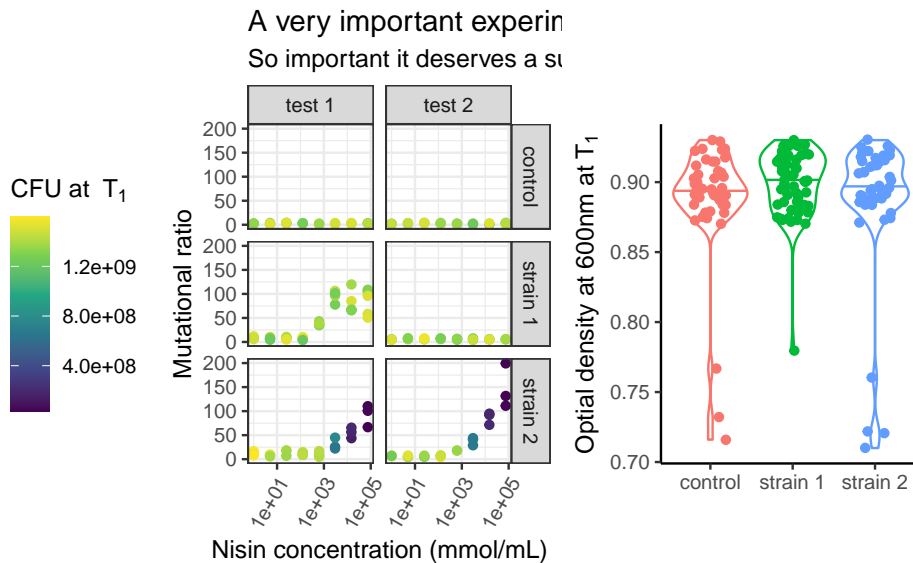
1423 `patchwork` uses operators such as `+`, `/` or `|` to assemble the plots in various
 1424 layouts. It looks simple, but a caveat of this approach is that it may become
 1425 tedious when assembling, e.g. 15 small plots, or plots from a list of unknown
 1426 length. The programmatic equivalent of the above example is:

```

wrap_plots(p1, p2) # or even more programmatic, wrap_plots(list(p1, p2))

```

1427



1428

1429 More customization can be added to the previous combination of plots, such as
 1430 layout specifications, e.g. controlling the position and dimension of the different
 1431 plots, or annotations, e.g. global title, labelling each plot or capturing the leg-
 1432 ends of all the plots and show it as one global legend). But this is a `ggplot2`
 1433 tutorial and we just want you to know that `patchwork` and friends exist, so go
 1434 check them out to know more about what they can do!

1435 5.10 Saving a plot

1436 Last but not least, ggplots have their own saving function: `ggsave` (it also works
 1437 on combinations of ggplots made by `patchwork` or `cowplot`), which guesses the
 1438 extension of your figure (e.g. `.png` or `.pdf`) from the file name you provide. You
 1439 can also give it specific `width`, `height` and `dpi` (resolution) parameter values.

1440 5.11 High throughput plotting workflow

1441 As we mentioned in the part about combining plots, sometimes we want to do
 1442 things many times (in my case I often make 100 times the same figure, just for
 1443 different replicate simulations). Of course we would not copy and paste many
 1444 times the same snippet of code, or write 100 times + to assemble some plots (by
 1445 now we are advanced R users, after all). This is where we can make use, again,
 1446 of the combination of tidyverse tools, and especially `purrr`.

1447 Let us make a function that plots the number of CFU against the optical density,
 1448 faceted by time point (so, that function expects a time point-wise dataset, such
 1449 as `data`):

```

plot_this <- function(data) {
  ggplot(data, aes(x = OD600, y = cfu, color = cfu)) +
    geom_point() +
    facet_grid(. ~ time) +
    theme_classic() +
    scale_color_continuous(type = "viridis") +
    theme(legend.position = "none") +
    xlab(parse(text = "'OD at 600nm at '~T[1]")) +
    ylab("CFU")
}

```

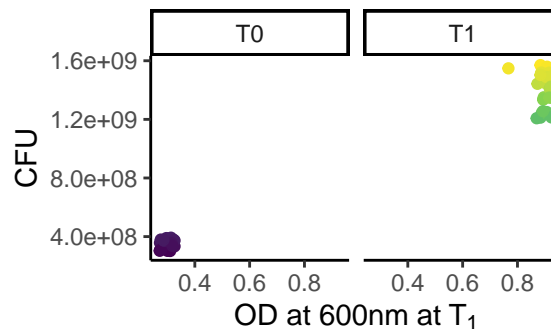
1450 Note that this does not plot anything, it is just a function that will if called on
 1451 a dataset.

1452 The objective is to apply this function to each **strain-assay** combination, thus
 1453 getting *one plot* per combination. We can check that this function works as
 1454 expected for a single combination using our friend **dplyr**:

```

data %>%
  filter(strain == "control", assay == "test 1") %>%
  plot_this()

```



1455

1456 which works because **plot_this** takes a data frame as first argument.

1457 Now that we are happy with our single-plot function, we **tidyr::nest** our
 1458 data frame into all the relevant combinations of **strain** and **assay**, and we
 1459 **purrr::map** through the resulting list-column to produce many ggplots in one
 1460 go:

```

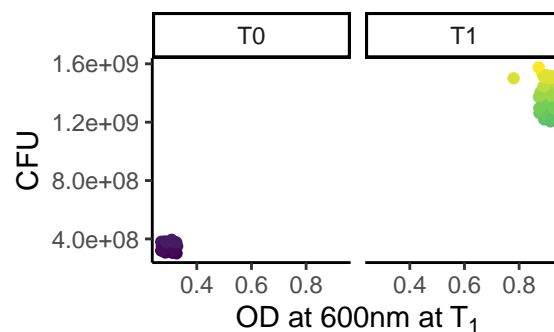
newdata <- data %>%
  group_by(assay, strain) %>%
  nest() %>%
  mutate(fig = map(data, plot_this))
newdata
#> # A tibble: 6 x 4
#> # Groups:   strain, assay [6]
#>   strain assay data      fig

```

```
#>   <chr>   <chr> <list>           <list>
#> 1 strain 1 test 1 <tibble [72 x 5]> <gg>
#> 2 control test 1 <tibble [48 x 5]> <gg>
#> 3 strain 2 test 1 <tibble [48 x 5]> <gg>
#> 4 strain 2 test 2 <tibble [46 x 5]> <gg>
#> 5 strain 1 test 2 <tibble [48 x 5]> <gg>
#> 6 control test 2 <tibble [48 x 5]> <gg>
```

1461 where the new list-column `fig` is a list of `ggplot` objects, that we can check
1462 individually:

```
newdata$fig[[1]]
```



1463

1464 Looks purrrfect.

1465 If you ask yourself why going through this hassle with only two assays and three
1466 strains, just think about a case where you would have hundreds of e.g. simula-
1467 tions, sequences, field sites or study species.

1468 Let us go a bit further. Now we want to combine plots for each `strain` into one
1469 figure per `assay`. We also want to give the resulting combined plot a figure file
1470 name, and save all the figures. There we go:

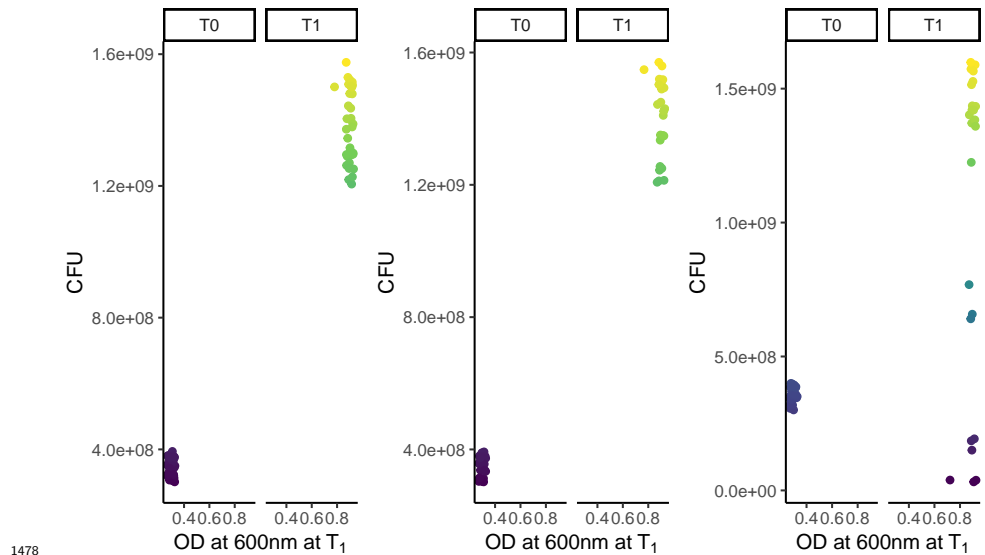
```
newdata <- newdata %>%
  select(-data) %>% # just to clean up a bit
  group_by(assay) %>%
  nest() %>%
  mutate(combifig = map(data, ~ wrap_plots(.x$fig)))
newdata
#> # A tibble: 2 x 3
#> # Groups:   assay [2]
#>   assay data          combifig
#>   <chr> <list>         <list>
#> 1 test 1 <tibble [3 x 2]> <patchwrk>
#> 2 test 2 <tibble [3 x 2]> <patchwrk>
```

1471 Note that we use the *formula*-way of passing functions to `map` (using `~`), which is
1472 more succinct than the *lambda* way (using an anonymous function `function(x)`)

1473 `wrap_plots(x)`), and where `.x` is interpreted as an element of the list we iterate
 1474 through (here the list-column `data`). Please refer to the `purrr` documentation
 1475 for more details.

1476 As we can see, we have created a new list-column `combifig`, filled with
 1477 `patchwork` objects, i.e. combined plots:

```
newdata$combifig[[1]]
```



1479 We could of course further customize the assembly of plots, but we refer the
 1480 reader to the `patchwork` documentation for this.

1481 Last step, preparing file names and saving the figures, using old friends from
 1482 the tidyverse:

```
library(glue)
newdata %>%
  mutate(filename = glue("data/figure_{str_replace(assay, ' ', '_')}.png")) %>%
  mutate(saved = walk2(filename, combifig, ggsave))
#> # A tibble: 2 x 5
#> # Groups:   assay [2]
#>   assay data          combifig filename          saved
#>   <chr> <list>         <list>   <glue>         <glue>
#> 1 test 1 <tibble [3 x 2]> <patchwrk> data/figure_test_1.p~ data/figure_test_1.p~
#> 2 test 2 <tibble [3 x 2]> <patchwrk> data/figure_test_2.p~ data/figure_test_2.p~
```

1483 5.12 Want more?

1484 `ggplot2` is undoubtedly one of the largest chunks of the tidyverse. Here we
 1485 tried to provide a global understanding of how it works, but we could not dig

1486 into all possible functions it has (this would take us days). Hopefully now you
1487 are armed with the necessary knowledge to be able to find the missing pieces
1488 you need.

1489 Some things, however, are missing from **ggplot2**. Fortunately, there are many of
1490 extensions building on **ggplot2** that respect the same grammar. Some of them
1491 implement new geoms (e.g. such as **ggbridges** for ridge-density plots, **ggradar**
1492 for radial plots, or **gghalves** for mixes of geoms), others combine plots together
1493 (examples cited above), offer more complex themes (e.g. **ggnewscale** for multi-
1494 ple scales of the same type to coexist, or **ggdark** for a dark background), deal
1495 with complicated objects that are not trivial to fit in data frames (e.g. **ggtree**
1496 for tree-like objects or **ggraph** for networks), or provide shortcuts to quickly pro-
1497 duce publication-ready figures for common plot layouts and their corresponding
1498 statistical analyses (e.g. **ggpubr**, **ggrapid** or **GGally**). There are even packages
1499 for animated graphics (**gganimate**), interactive plot building (**esquisse**) or 3D
1500 surface plotting (**rayshader**). See the links below!

1501 5.13 References

- 1502 • The **ggplot2** website where you can find links to other resources
- 1503 • The **ggplot2** cheatsheet
- 1504 • The dedicated chapter in R for Data Science
- 1505 • A non-exhaustive list of extensions at this link
- 1506 • The R graph gallery for inspiration
- 1507 • Hadley’s article explaining the grammar of graphics
- 1508 • The **patchwork** documentation
- 1509 • The **ggtree** and **ggraph** packages

Chapter 6

Introduction



1513 ‘Regular expressions’ from <https://xkcd.com/208>

1514 6.1 Goal

1515 In this chapter, you will learn:

- 1516 • How to express your ideas as a regular expression
- 1517 • Verify that you indeed did so

1518 6.2 Why is this important?

1519 Knowing the basics of regular expressions, prevents you having to hand-craft
1520 functions to detect patterns in any text.

1521 Being able to verify your own assumptions allows you to speed up any develop-
1522 ment of any code. It is estimated that 80-90% of all the time, we are debugging
1523 our code. Being good at testing, is the way to become faster.

1524 6.3 Exercise: Spot the pattern

1525 Each line below is or contains a pattern. Observe what your brain does when
1526 interpreting a line. If it thinks: ‘Hey, that’s a [pattern], because [regular expres-
1527 sion]’, you got your answer!

1528 Answer, for each line: (1) what is it? (2) why did you think to?

1529 Lithium-ion batteries play a central role in the world of technology.
1530 But would it be safe to simply orbit the planet?
1531 Your Next Samsung Phone May Not Come With a Charger in the Box
1532 The restrictions would end 90 days after Portland's state of emergency order lifts.
1533 Those cities have limits at 15%.

1534 6.4 Answers: Spot the pattern

1535 Lithium-ion batteries play a central role in the world of technology.

1536 This is a sentence, because it ends with a dot.

1537 But would it be safe to simply orbit the planet?

1538 This is a question, because it ends with a question mark.

1539 Your Next Samsung Phone May Not Come With a Charger in the Box

1540 This is a title, because most words start with an uppercase character.

1541 The restrictions would end 90 days after Portland's state of emergency order lifts.

1542 This is a sentence with a decimal number, because there is a sequence of char-
 1543 acters that consists out of numbers only.

1544 Those cities have limits at 15%.

1545 This is a sentence with a percentage, because there is a sequence of characters
 1546 that consists out of numbers only, with a percentage sign connected to it.

1547 • Texts from <https://slashdot.org>.

1548 6.5 What are regular expressions?

1549 A regular expression ‘is a sequence of characters that define a search pattern’.
 1550 Such a pattern may be a zip code, a date, or any other text of which you can
 1551 say: ‘this is not just text, it is a [something]’.

1552 For example, take a Dutch zip code: 9747 AG. Dutch zip code have four digits,
 1553 a space and then two uppercase alphabet characters.

1554 6.6 Applications

1555 DNA data:

```
1556 >KU215420.1|Felinecoronavirus|Feliscatus|Belgium|2013|Envelope
1557 ATGATGTTTCCTAGGGCATTACTATCATAGATGACCATGGTATGGTTGTTAGTGTCTTC
1558 >KP143511.1|Felinecoronavirus|Feliscatus|UnitedKingdom|2013|Envelope
1559 ATGATGTTTCCTAGGGCATTACTATCATAGACGACCATGGTATGGTTGTTAGTGTCTTC
```

1560 Protein data:

```
1561 >sp|PODTC2|SPIKE_SARS2 Spike glycoprotein OS=Severe acute respiratory syndrome coronavirus 2 OX=2
1562 MFVFLVLLPLVSSQCVNLTTRTQLPPAYTNSFTRGVYYPDKVFRSSVLHSTQDLFLPFFS
1563 >sp|PODTC5|VME1_SARS2 Membrane protein OS=Severe acute respiratory syndrome coronavirus 2 OX=2697
1564 MADSNGTITVEELKKLLEQWNLVIGFLFTWICLLQFAYANRNRFLYIIKLIFLWLLWPV
```

1565 6.7 Multiple in R



1566

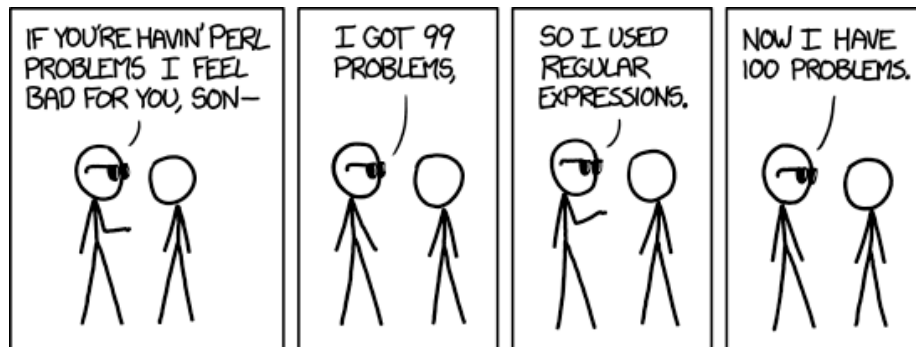
1567 The ‘stringr’ logo. ‘stringr’ is part of the Tidyverse

1568 R functions to work with regular expressions:

```
1569 • stringr::string_  
1570 • egrep  
1571 • gsub
```

```
library(stringr)
```

1572 6.8 Dangers of regexes



1573
1574 'Perl problems', from <https://xkcd.com/1171/>

1575 Regexes have different flavors, such as POSIX and perl.

1576 I define UNIX as 30 definitions of regular expressions living under
1577 one roof.

1578 Donald Knuth. Digital Typography, ch. 33, p. 649 (1999)

1579 We'll have to test!

Chapter 7

Testing



From George Dinwiddie's blog, <http://blog.gdinwiddie.com/2012/>

1584 12/26/tdd-hat/

1585 7.1 Why test?

1586 Testers don't like to break things; they like to dispel the illusion that
1587 things work.

1588 Kaner, Bach, Pettichord

- 1589 • To be sure your code is correct
- 1590 • Spend less time fixing bugs
- 1591 • Unit of communication
- 1592 • Clean software interface

1593 7.2 Our first test

1594 The `testthat` package is the Tidyverse package to write tests.

```
library(testthat)
```

1595 All test functions start with `expect_`, for example:

```
expect_true(1 + 1 == 2)
expect_false("cat" == "dog")
expect_equal(1 + 1, 2)
```


1596

Chapter 8

1597

Detect a full match

1598

Here, we will detect simple patterns using `str_which`.

1599

Tip: run `?str_which` for its documentation.

Detect Matches



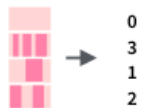
TRUE
TRUE
FALSE
TRUE

str_detect(string, **pattern**) Detect the presence of a pattern match in a string.
`str_detect(fruit, "a")`



1
2
4

str_which(string, **pattern**) Find the indexes of strings that contain a pattern match.
`str_which(fruit, "a")`



0
3
1
2

str_count(string, **pattern**) Count the number of matches in a string.
`str_count(fruit, "a")`



start and
2 4
4 7
NA NA
3 4

str_locate(string, **pattern**) Locate the positions of pattern matches in a string. Also **str_locate_all**. `str_locate(fruit, "a")`

1600

1601

From 'Work with Strings Cheatsheet', <https://rstudio.com/resources/cheatsheets>

1602

1603 8.1 str_which demo

```
fruit <- c("apple", "banana", "pinapple")

expect_equal(
  str_which(fruit, "banana"),
  2
)



expect_equal(
  str_which(fruit, "apple"),
  c(1, 3)
)

expect_equal(
  str_which(fruit, "submarine"),
  integer(0)
)
```

1604 8.2 Example exercise: is_a_one

1605 Write a function called `is_a_one` that detects if a string is one one, using
1606 `str_subset`.

1607 Use the anchors as shown on the cheatsheet to specify that the complete string,
1608 from begin to the end, must consist out of characters

regex	matches
	start of string
	end of string

1610 From ‘Work with Strings Cheatsheet’, [https://rstudio.com/](https://rstudio.com/resources/cheatsheets)
1611 [resources/cheatsheets](https://rstudio.com/resources/cheatsheets)

1612 These tests must pass:

```
1613 expect_true(is_a_one("1"))
1614 expect_false(is_a_one("X"))
1615 expect_false(is_a_one("11"))
1616 expect_false(is_a_one(c("1", "1")))
1617 expect_false(is_a_one(integer(0)))
1618 expect_false(is_a_one(NULL))
1619 expect_false(is_a_one(NA))
```

```
1620 expect_false(is_a_one(Inf))
```

1621 8.2.1 Answer is_a_one

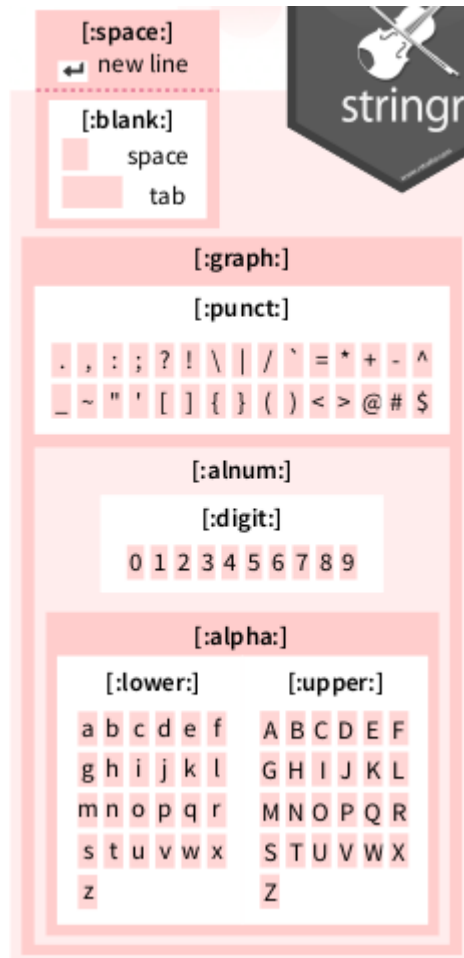
```
is_a_one <- function(text) {  
  length(stringr::str_which(text, "^1$")) == 1  
}
```

```
expect_true(is_a_one("1"))  
expect_false(is_a_one("X"))  
expect_false(is_a_one("11"))  
expect_false(is_a_one(c("1", "1")))  
expect_false(is_a_one(integer(0)))  
expect_false(is_a_one(NULL))  
expect_false(is_a_one(NA))  
expect_false(is_a_one(Inf))
```

1622 8.3 Exercise: is_a_digit

1623 Write a function called `is_a_digit` that detects if a string is one digit.

1624 Use the regex pattern as shown on the cheatsheet to specify a digit:



1625

1626 From 'Work with Strings Cheatsheet', [https://rstudio.com/](https://rstudio.com/resources/cheatsheets)
 1627 resources/cheatsheets

1628 These tests must pass:

```

1629 expect_true(is_a_digit("0"))
1630 expect_true(is_a_digit("1"))
1631 # The other digits
1632 expect_false(is_a_digit(""))
1633 expect_false(is_a_digit("X"))
1634 expect_false(is_a_digit(c("1", "2")))
1635 expect_false(is_a_digit(character(0)))
1636 expect_false(is_a_digit(NULL))
1637 expect_false(is_a_digit(NA))
1638 expect_false(is_a_digit(Inf))

```

1639 **8.3.1 Answer: is_a_digit**

```
is_a_digit <- function(text) {  
  length(stringr::str_which(text, "^[[:digit:]]$")) == 1  
}
```

```
expect_true(is_a_digit("0"))  
expect_true(is_a_digit("1"))  
# The other digits  
expect_false(is_a_digit(""))  
expect_false(is_a_digit("12"))  
expect_false(is_a_digit("X"))  
expect_false(is_a_digit(c("1", "2")))  
expect_false(is_a_digit(character(0)))  
expect_false(is_a_digit(NULL))  
expect_false(is_a_digit(NA))  
expect_false(is_a_digit(Inf))
```

1640 **8.4 Exercise: is_a_word**1641 Write a function called `is_a_word` that detects if a string is a word.

1642 To simplify now, a word is defined as:

- 1643 • Having one or more lowercase characters
- 1644 • Having no dashes, nor numbers

1645 Use the quantifiers as shown on the cheatsheet to specify that one needs one or
1646 more characters:

regexp**a?****a*****a+****a{n}****a{n, }****a{n, m}****matches**

zero or one

zero or more

one or more

exactly **n****n** or morebetween **n** and **m**

1647

1648 From ‘Work with Strings Cheatsheet’, [https://rstudio.com/](https://rstudio.com/resources/cheatsheets)
 1649 resources/cheatsheets

1650 These tests must pass:

```
1651 expect_true(is_a_word("a"))
1652 expect_true(is_a_word("an"))
1653 expect_true(is_a_word("apple"))
1654 expect_false(is_a_word("X"))
1655 expect_false(is_a_word("XX"))
1656 expect_false(is_a_word("Hi"))
1657 expect_false(is_a_word("hI"))
1658 expect_false(is_a_word("hoWdy"))
1659 expect_false(is_a_word(c("an", "apple")))
1660 expect_false(is_a_word(character(0)))
1661 expect_false(is_a_word(NULL))
1662 expect_false(is_a_word(NA))
1663 expect_false(is_a_word(Inf))
```

1664 8.4.1 Answer: is_a_word

```
is_a_word <- function(text) {
  length(stringr::str_which(text, "^[:lower:]+$")) == 1
}

expect_true(is_a_word("a"))
expect_true(is_a_word("an"))
```

```

expect_true(is_a_word("apple"))
expect_false(is_a_word("X"))
expect_false(is_a_word("XX"))
expect_false(is_a_word("Hi"))
expect_false(is_a_word("hI"))
expect_false(is_a_word("hoWdy"))
expect_false(is_a_word(c("an", "apple")))
expect_false(is_a_word(character(0)))
expect_false(is_a_word(NULL))
expect_false(is_a_word(NA))
expect_false(is_a_word(Inf))

```

1665 8.5 Exercise: is_dna_sequence

1666 Write a function called `is_dna_sequence` that detects if a string is a DNA
 1667 sequence.

1668 To simplify now, a DNA sequence is defined as:

- 1669 • There are four characters, one per nucleotides
- 1670 • These characters are uppercase (A, C, G and T)

1671 Use the alternates as shown on the cheatsheet to specify that each character
 1672 must be one of the four nucleotides:

regexp	matches
<code>ab d</code>	or
<code>[abe]</code>	one of
<code>[^abe]</code>	anything but
<code>[a-c]</code>	range

1674 From ‘Work with Strings Cheatsheet’, [https://rstudio.com/](https://rstudio.com/resources/cheatsheets)
 1675 resources/cheatsheets

1676 These tests must pass:

```

1677 expect_true(is_dna_sequence("A"))
1678 expect_true(is_dna_sequence("AC"))
1679 expect_true(is_dna_sequence("ACG"))
1680 expect_true(is_dna_sequence("ACGT"))
1681 expect_false(is_dna_sequence("a"))
1682 expect_false(is_dna_sequence("Ax"))
1683 expect_false(is_dna_sequence("xA"))
1684 expect_false(is_dna_sequence("AxA"))
1685 expect_false(is_dna_sequence(c("A", "CGT")))
1686 expect_false(is_dna_sequence(character(0)))

```

```
1687 expect_false(is_dna_sequence(NULL))
1688 expect_false(is_dna_sequence(NA))
1689 expect_false(is_dna_sequence(Inf))
```

1690 8.5.1 Answer: is_dna_sequence

```
is_dna_sequence <- function(text) {
  length(stringr::str_which(text, "[ACGT]+$")) == 1
}

expect_true(is_dna_sequence("A"))
expect_true(is_dna_sequence("AC"))
expect_true(is_dna_sequence("ACG"))
expect_true(is_dna_sequence("ACGT"))
expect_false(is_dna_sequence("a"))
expect_false(is_dna_sequence("Ax"))
expect_false(is_dna_sequence("xA"))
expect_false(is_dna_sequence("AxA"))
expect_false(is_dna_sequence(c("A", "CGT")))
expect_false(is_dna_sequence(character(0)))
expect_false(is_dna_sequence(NULL))
expect_false(is_dna_sequence(NA))
expect_false(is_dna_sequence(Inf))
```


Chapter 9

Extract a pattern

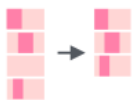
Here, we will extract a pattern using `str_match`.

Tip: run `?str_match` for its documentation.

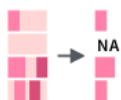
Subset Strings



str_sub(string, start = 1L, end = -1L) Extract substrings from a character vector.
`str_sub(fruit, 1, 3); str_sub(fruit, -2)`



str_subset(string, **pattern**) Return only the strings that contain a pattern match.
`str_subset(fruit, "b")`



str_extract(string, **pattern**) Return the first pattern match found in each string, as a vector. Also **str_extract_all** to return every pattern match.
`str_extract(fruit, "[aeiou]")`



str_match(string, **pattern**) Return the first pattern match found in each string, as a matrix with a column for each () group in pattern. Also **str_match_all**.
`str_match(sentences, "(a|the) ([^]+)")`

From 'Work with Strings Cheatsheet', <https://rstudio.com/resources/cheatsheets>

9.1 Context

Here we will work on a DNA sequence:

```
text <- readr::read_lines("data/virus.fas")
head(text, n = 10)
#> [1] ">KX722530.1/Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2] "ATGATGTTTCCTAGGGCTTTTACTATCATAGATGACCATGGTATGGTTGTAAGCGTCTTC"
#> [3] "TTCTGGCTCCTGTTGATAATTATATTGATATTGTTTTCAATAGCATTGCTAAATGTTATT"
#> [4] "AAGTTATGCATGGTTTGTGCAATCTGGGTAAGACTATTATAGTACTACCTGCACGCCAT"
#> [5] "GCATATGATGCCTACAAGACTTTTATGCAAATTAAGGCATATAATCCCGACGAAGCACTT"
#> [6] "TTGGTTTGA"
#> [7] ">FJ938053.1/Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [8] "ATGATGTTTCCTAGGGCATTTTACTATCATAGATGACCATGGTATGGTTGTCAGCGTCTTC"
#> [9] "TTTTGGCTCCTGTTGATAATTATATTGATATTGTTTTCAATAGCATTGCTAAATGTTATT"
#> [10] "AAGTTATGCATGGTATGTTGCAATTTGGGTAAGACTATTATAGTATTACCTGCACGCCAT"
```

The data encoded in this text:

```
>[DNA sequence number]|[virus name]|[host species name]|[country of host]|[year]|[prot
[DNA sequence]
```

9.2 str_match

`str_match` returns:

- a matrix
- a row per line of text, containing the match or an NA
- a column per submatch (see later)

For example, using a ‘everything’ pattern, we get:

```
matches <- stringr::str_match(text, ".*")
expect_equal(class(matches), "matrix")
expect_equal(nrow(matches), length(text))
expect_equal(ncol(matches), 1)
head(matches)
#> [1]
#> [1,] ">KX722530.1/Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2,] "ATGATGTTTCCTAGGGCTTTTACTATCATAGATGACCATGGTATGGTTGTAAGCGTCTTC"
#> [3,] "TTCTGGCTCCTGTTGATAATTATATTGATATTGTTTTCAATAGCATTGCTAAATGTTATT"
#> [4,] "AAGTTATGCATGGTTTGTGCAATCTGGGTAAGACTATTATAGTACTACCTGCACGCCAT"
#> [5,] "GCATATGATGCCTACAAGACTTTTATGCAAATTAAGGCATATAATCCCGACGAAGCACTT"
#> [6,] "TTGGTTTGA"
```

Using a pattern that is specific for the DNA sequence descriptors, we get NAs:

```
matches <- stringr::str_match(text, ">.*")
expect_equal(class(matches), "matrix")
```

```

expect_equal(nrow(matches), length(text))
expect_equal(ncol(matches), 1)
head(matches, n = 8)
#>      [,1]
#> [1,] ">KX722530.1/Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2,] NA
#> [3,] NA
#> [4,] NA
#> [5,] NA
#> [6,] NA
#> [7,] ">FJ938053.1/Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [8,] NA

```

1710 Using round brackets, the matrix gives one extra column per sub-match. Here,
 1711 we select for all info after the >:

```

matches <- stringr::str_match(text, ">(.*?)")
expect_equal(class(matches), "matrix")
expect_equal(nrow(matches), length(text))
expect_equal(ncol(matches), 2)
head(matches, n = 8)
#>      [,1]
#> [1,] ">KX722530.1/Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2,] NA
#> [3,] NA
#> [4,] NA
#> [5,] NA
#> [6,] NA
#> [7,] ">FJ938053.1/Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [8,] NA
#>      [,2]
#> [1,] "KX722530.1/Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2,] NA
#> [3,] NA
#> [4,] NA
#> [5,] NA
#> [6,] NA
#> [7,] "FJ938053.1/Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [8,] NA

```

1712 Select the second column:

```

matches <- matches[, 2]
expect_equal(class(matches), "character")
expect_equal(length(matches), 180)
head(matches, n = 8)
#> [1] "KX722530.1/Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2] NA

```

```
#> [3] NA
#> [4] NA
#> [5] NA
#> [6] NA
#> [7] "FJ938053.1|Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [8] NA
```

1713 Get rid of the NAs using purrr:

```
matches <- purrr::discard(matches, is.na)
expect_equal(class(matches), "character")
expect_equal(length(matches), 30)
head(matches)
#> [1] "KX722530.1|Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2] "FJ938053.1|Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [3] "GU553362.1|Felinecoronavirus/feline/Netherlands/2007/Envelope"
#> [4] "KP143512.1|Felinecoronavirus/Feliscatus/UnitedKingdom/2013/Envelope"
#> [5] "KU215424.1|Felinecoronavirus/Feliscatus/Belgium/2013/Envelope"
#> [6] "HQ392470.1|Felinecoronavirus/feline/NetherlandsUtrecht/2007/Envelope"
```

1714 All of this in one go:

```
matches <- purrr::discard(
  stringr::str_match(text, ">(.*?)")[, 2],
  is.na
)
expect_equal(length(matches), 30)
head(matches)
#> [1] "KX722530.1|Felinecoronavirus/Feliscatus/Denmark/2015/Envelope"
#> [2] "FJ938053.1|Felinecoronavirus/cat/NetherlandsUtrecht/2007/Envelope"
#> [3] "GU553362.1|Felinecoronavirus/feline/Netherlands/2007/Envelope"
#> [4] "KP143512.1|Felinecoronavirus/Feliscatus/UnitedKingdom/2013/Envelope"
#> [5] "KU215424.1|Felinecoronavirus/Feliscatus/Belgium/2013/Envelope"
#> [6] "HQ392470.1|Felinecoronavirus/feline/NetherlandsUtrecht/2007/Envelope"
```

1715 9.3 Example exercise: extract_dna_sequence_numbers

1716 Extract the DNA sequence numbers.

1717 Hint:

- 1718 • it is the text between > and |Felinecoronavirus.
- 1719 • Use \\| in your regex to indicate you want the pipe character (as a|b is
- 1720 the regex for ‘a or b’)

1721 These tests must pass:

```
1722 expect_equal(30, length(extract_dna_sequence_numbers(text)))
1723 expect_equal("KX722530.1", extract_dna_sequence_numbers(text)[1])
```

1724 `expect_equal("KP143511.1", extract_dna_sequence_numbers(text)[30])`

1725 9.4 Answer: extract_dna_sequence_numbers

```
extract_dna_sequence_numbers <- function(text) {
  purrr::discard(
    stringr::str_match(text, ">(.*?)\\|Felinecoronavirus.*")[, 2],
    is.na
  )
}

expect_equal(30, length(extract_dna_sequence_numbers(text)))
expect_equal("KX722530.1", extract_dna_sequence_numbers(text)[1])
expect_equal("KP143511.1", extract_dna_sequence_numbers(text)[30])
```

1726 The regex ">(.*?)\\|.*" would not work, because the asterisk is *greedy*.

1727 9.5 Example exercise: extract_year

1728 Extract the year the DNA sequence has been obtained. Convert the text to a
1729 number.

1730 Hint: the year is always 4 consecutive numbers, from 1993 to (and including)
1731 2016.

1732 These tests must pass:

```
1733 expect_equal(30, length(extract_year(text)))
1734 expect_equal(2015, extract_year(text)[1])
1735 expect_equal(2013, extract_year(text)[30])
```

1736 9.6 Answer: extract_year

```
extract_year <- function(text) {
  as.numeric(
    purrr::discard(
      stringr::str_match(text, ".*([:digit:]{4}).*")[, 2],
      is.na
    )
  )
}

expect_equal(30, length(extract_year(text)))
expect_equal(2015, extract_year(text)[1])
expect_equal(2013, extract_year(text)[30])
```

1737 Here, the simple regex worked, *because* the asterisk is greedy.

Chapter 10

Other functions

10.1 Mutate

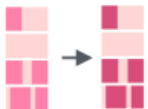
Mutate Strings



str_sub() <- value. Replace substrings by identifying the substrings with `str_sub()` and assigning into the results.
`str_sub(fruit, 1, 3) <- "str"`



str_replace()(string, **pattern**, replacement) Replace the first matched pattern in each string. `str_replace(fruit, "a", "-")`



str_replace_all()(string, **pattern**, replacement) Replace all matched patterns in each string. `str_replace_all(fruit, "a", "-")`

1741

1742 From 'Work with Strings Cheatsheet', [https://rstudio.com/](https://rstudio.com/resources/cheatsheets)
1743 resources/cheatsheets

```
s <- "UnitedKingdom"
t <- stringr::str_replace(
  s,
  "([:upper:][:lower:]+)([:upper:][:lower:]+)",
  "\\1 \\2"
)
expect_equal("United Kingdom", t)
```


Chapter 11

Bigger picture

11.1 Develop in packages

- Also when ‘just’ doing data analysis

11.2 Regex usage beyond R is common

Command-line tools with regular expressions:

- `grep`, `egrep`
- `sed`
- `dir/ls`

11.3 Don’t overdo it



‘Regex Golf’, from <https://xkcd.com/1313/>

Regex golf is a challenge to create the shortest regexes possible.

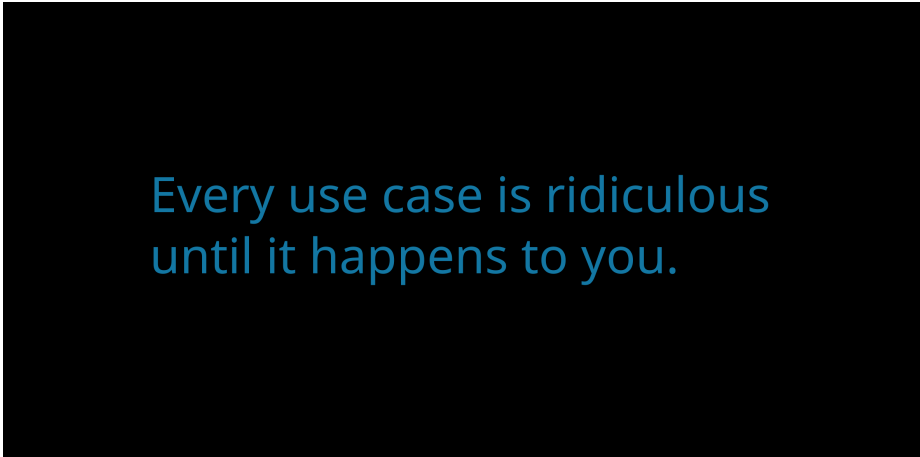
1757 Chapter 12

1758 Resources

- 1759 • RStudio cheatsheets, including the ‘Work with Strings Cheatsheet’

1760 Chapter 13

1761 Programming in the 1762 *tidyverse*



Every use case is ridiculous
until it happens to you.

1763
1764 Load the packages for the day.

```
library(tidyverse)  
library(rlang)
```

1765 A function to look at errors.

```
try_this <- function(ex) {  
  tryCatch(  
    expr = {  
      ex  
    },  
    error = function(e) {
```

```

    print(glue::glue(as.character(e), "\n"))
  }
)
}

```

1766 13.1 An explanation of the problem

1767 13.1.1 What the issue is

1768 Get some data from *Phylacine*, and attempt to select or filter.

```

# read in phylacine data
data = read_csv("data/phylacine_traits.csv")

# regular filtering
small_mammals = data %>%
  filter(Mass.g < 1000)

# filtering on a string
small_mammals_too = data %>%
  filter("Mass.g" < 1000)

```

1769 Examine `small_mammals` and `small_mammals_too` to check whether they are
1770 as expected.

```

# count rows
map_int(list(sm_1 = small_mammals, sm2 = small_mammals_too),
        nrow)
#> sm_1 sm2
#> 4381  0

```

1771 The difference in the number of rows is because `dplyr::filter` could not un-
1772 derstand the string `"Mass.g"` as a variable in the dataframe.

1773 This is because the `tidyverse`, through its `tidyselect` package, makes a dis-
1774 tinction between `"Mass.g"`, and `Mass.g`.

1775 A better explanation of (some of) the theory behind this can be found here:
1776 Programming with `dplyr`.

1777 The same issue arises with functions such as `dplyr::summarise` and
1778 `dplyr::group_by`.

```

# summarise using an unquoted variable
summarise(data,
           mean_mass = mean(Mass.g))
#> # A tibble: 1 x 1
#>   mean_mass
#>   <dbl>
#> 1 156882.

```

```
# this will print a warning
summarise(data,
           mean_mass = mean("Mass.g"))
#> Warning in mean.default("Mass.g"): argument is not numeric or logical: returning
#> NA
#> # A tibble: 1 x 1
#>   mean_mass
#>   <dbl>
#> 1      NA
```

13.1.2 Why the issue is a problem

Consider an analysis pipeline as follows.

data %>% select variables %>% summarise by groups

```
data %>%
  select(Mass.g, Diet.Plant, Order.1.2) %>%
  group_by(Order.1.2) %>%
  summarise_all(.funs = mean) %>%
  head()
#> # A tibble: 6 x 3
#>   Order.1.2      Mass.g Diet.Plant
#>   <chr>          <dbl>    <dbl>
#> 1 Afrosoricida    306.      0.947
#> 2 Carnivora      47905.     14.1
#> 3 Cetartiodactyla 1854811.    76.2
#> 4 Chiroptera       49.1     27.3
#> 5 Cingulata      235529.     43.0
#> 6 Dasyuromorphia   748.      1.09
```

Now consider that this analysis pipeline is repeated many times in your document. Consider also that a well intentioned person has renamed the dataframe columns.

```
data <- data %>%
  `colnames<-`(str_replace_all(colnames(data), "\\.", "_") %>%
               str_to_lower %>%
               str_remove("_1_2"))
```

The group-summarise code above will no longer work.

```
try_this(ex =

  data %>%
    select(Mass.g, Diet.Plant, Order.1.2) %>%
    group_by(Order.1.2) %>%
    summarise_all(.funs = mean) %>%
```

```

      head()
    )
    #> Error: Can't subset columns that don't exist.
    #> x Column `Mass.g` doesn't exist.

```

1786 This illustrates the problem in part: when the columns to be operated upon are
 1787 *unknown to the programmer*, much of basic **tidyverse** code cannot be gener-
 1788 alised to be used with any dataframe.

1789 13.1.3 Passing variables as strings is (also) an issue

1790 The variables to be operated on could be given as strings, perhaps as the ar-
 1791 gument to a function, or as a global variable. This way, a single global vector
 1792 could contain the grouping variables for all further **summarise** procedures.

1793 This runs into the problem identified earlier.

```

# choose some variables
vars_to_select = c("Mass.g", "Diet.Plant")
vars_to_group = c("Order.1.2")

# attempt to select and summarise on group
# the tidyverse will not be pleased
try_this(ex =

  data %>%
    select(vars_to_select) %>% # this works with a warning
    group_by(vars_to_group) %>%
    summarise(mean_mass = mean(Mass.g),
              mean_plant = mean(Diet.Plant))
)
#> Error: Can't subset columns that don't exist.
#> x Columns `Mass.g` and `Diet.Plant` don't exist.

```

1794 In the case of a standard **filter %>% group %>% summarise** pipeline, the func-
 1795 tion's operations are evident. It must filter a dataframe based on a/some col-
 1796 umn(s), and then summarise by groups. The filter to be applied, the variables
 1797 to group by, and the variables to be summarised should be passed as function
 1798 arguments — just how this is to be done is not immediately obvious.

1799 13.2 Flexible selection is easy

1800 Selection often precedes data operations, but is not part of the pipeline dealt
 1801 with further.

1802 This is because **dplyr::select** appears to work on both quoted and unquoted
 1803 variables, but in general some useful **select** helpers such as **dplyr::all_of**
 1804 should be used. These straightforward helper functions significantly expand

1805 `select`'s flexibility and ease of use, and are not covered here. See the `select`
 1806 help for more information.

1807 13.3 A first attempt at a flexible function

1808 The attempt below to write such a function, which gives the mean and confidence
 1809 intervals of groups is likely to fail.

```
# define a ci function
ci <- function(x, ci = 95) {
  qnorm(1 - (1 - ci / 100)/2) * sd(x, na.rm = TRUE) / sqrt(length(x))
}

custom_summary <- function(data, filters, grouping_vars, summary_vars) {

  data %>%
    filter(filters) %>%
    group_by(grouping_vars) %>%
    summarise(mean = mean(summary_vars),
              ci = ci(summary_vars))

}
```

1810 13.3.1 Failure of the first attempt

```
# this is going to fail, so look at the error message
try_this(ex = custom_summary(data,
  filters = list(mass_g > 1000),
  grouping_vars = list(order, family),
  summary_vars = list(diet_plant))
)

#> Error: Problem with `filter()` input `..1`.
#> x object 'mass_g' not found
#> i Input `..1` is `filters`.
```

1811 This function initially failed because `filter` could not find `mass_g` in the
 1812 dataframe. This is because `mass_g` is treated as an independent R object, while
 1813 the function should instead treat it as a variable in a dataframe.

1814 The difference between so-called `data` and `environment` variables is explained
 1815 better at the `rlang` and `tidyeval` websites and tutorials linked at the end of
 1816 this chapter. It is this difference that prevents `filter` from correctly interpreting
 1817 `mass_g`.

13.3.2 Passing arguments as strings doesn't help

The example below tries to get `filter` to work. What could be tried? One option is to attempt passing the filtering process as a string argument, i.e., `"mass_g > 1000"`.

```
# it doesn't matter whether filters is a vector or list
try_this(ex = custom_summary(data,
  filters = c("mass_g > 1000"),
  grouping_vars = list(order, family),
  summary_vars = list(diet_plant))
)

#> Error: Problem with `filter()` input `..1`.
#> x Input `..1` must be a logical vector, not a character.
#> i Input `..1` is `filters`.
```

While this doesn't work, it is on the right track, which is that the `filters` argument needs some extra work beyond changing the type.

13.3.3 None of the other arguments will be successful

`filter` was the first failure, after which it stopped further evaluation, but none of the steps of the custom function would have worked, for the same reason `filter` would not have worked: all the arguments need some work before they can be passed to their respective functions.

13.4 Flexible filtering in a function

The first thing to try is to change how `filter` uses the argument passed to it. Here, the argument `filters` is passed as a character vector, and is set by default to filter out mammals with masses below 1 kg.

The argument could be passed as a list, but the `rlang::parse_exprs` function works on vectors, not lists. The conversion between them is trivial for single level lists with atomic types (`purrr::as_vector`).

A brief detour: Expressions in R

A full explanation of R works under the hood would take a very long time. A working knowledge of how this working can be exploited is usually sufficient to use most of R's functionality.

R expressions are one such. They represent a promise of R code, but without being evaluated. Any string can be parsed (interpreted) as an R expression.

What does `rlang::parse_exprs` do? It interprets a string as an R command. This expression can then be evaluated later. Consider the following, where `a` is assigned the numeric value 3.

```

# a is assigned
a = 3

# parsed but not evaluated
rlang::parse_expr("a + 3")
#> a + 3

# evaluated
rlang::parse_expr("a + 3") %>% eval
#> [1] 6

```

1845 Here, `a + 3` was converted to an expression in the second command, and only
 1846 evaluated in the third.

1847 Unquoting with !!!

1848 R expressions underlie R code. Their evaluation can be forced inside another
 1849 function using the special operators `!!` and `!!!`, for single and multiple R
 1850 expressions respectively.

1851 13.4.1 Flexible filtering using expressions

1852 Consider the case where mammals below 1 kg body mass are to be excluded.
 1853 The `dplyr` code would look like this:

```
1854 filter(data, mass_g > 1000)
```

1855 This fixes both the variable to be filtered by, as well as the cut-off value. This
 1856 can be made flexible for a custom function that allows any kind of filtering.

```

custom_summary = function(data,
                           filters = c("mass_g > 1000")) {

  # THIS IS THE IMPORTANT BIT
  filters = rlang::parse_exprs(filters)

  data %>%
    filter(!!!filters)
}

```

1857 Try this function with single and multiple filters.

```

# mammals above a kilo
custom_summary(data,
               filters = c("mass_g > 1000")) %>%

  select(binomial, mass_g) %>%
  head()
#> # A tibble: 6 x 2

```

```

#>   binomial      mass_g
#>   <chr>      <dbl>
#> 1 Acerodon_jubatus    1075
#> 2 Acinonyx_jubatus   46700
#> 3 Acratocnus_odontrigonus 22990
#> 4 Acratocnus_ye      21310
#> 5 Addax_nasomaculatus 70000.
#> 6 Aepyceros_melampus  52500.

# mammals between 250 and 500 g and which are mostly carnivorous
custom_summary(data,
  filters = c("between(mass_g, 250, 500)",
    "diet_plant < 10")) %>%

  select(binomial, mass_g, diet_plant) %>%

  head()
#> # A tibble: 6 x 3
#>   binomial      mass_g diet_plant
#>   <chr>      <dbl>      <dbl>
#> 1 Chrysospalax_trevelyani  426.        0
#> 2 Cyclopes_didactylus    330.        0
#> 3 Desmana_moschata      383        0
#> 4 Dologale_dybowskii    350        0
#> 5 Hydromys_chrysogaster  480.        0
#> 6 Hyosciurus_heinrichi   296        0

```

1858 The function `filter` correctly processes the string passed to filter the data.

1859 13.5 Flexible grouping in a function

1860 Just as the exact filtering approach can be controlled from a single string vector
 1861 in the example above, the grouping variables can also be stored and passed
 1862 as arguments using the `...` (dots) argument. Dots are a convenient way of
 1863 referring to all unnamed arguments of a function. Here, they are used to accept
 1864 the grouping variables.

1865 13.5.1 Using `...` and ‘forwarding’

```

custom_summary = function(data,
  filters = c("mass_g > 1000"),
  ...) {
  # deal with groups
  grouping_vars = rlang::enquos(...)

  data %>%

```

```

    filter(!!!rlang::parse_exprs(filters)) %>%

    # this is the important bit
    group_by(!!!grouping_vars)
}

```

1866 Try the function again, and check the grouping variables.

```

custom_summary(data,
               filters = c("mass_g > 1000"),
               order, family) %>%

  group_vars()
#> [1] "order" "family"

```

1867 13.5.2 Passing grouping variables as strings

1868 In the previous example, the grouping variables were passed as unquoted vari-
 1869 ables, then `enquo`-ted and parsed, after which they were applied. An alternative
 1870 way of passing arguments to a function is as a string vector, i.e, `grouping_vars`
 1871 `= c("var_a", "var_b")`.

1872 This can be done by interpreting the string vector as R symbols using
 1873 `rlang::syms`. It could also be done by treating them as a full expression using
 1874 the previously covered `rlang::parse_exprs`. However, both methods must use
 1875 an unquoting-splice (`!!!`), i.e., force the evaluation of a list of R expressions.

1876 13.5.3 Using `rlang::syms`

```

custom_summary = function(data,
                          filters = c("mass_g > 1000"),
                          grouping_vars) {
  # deal with groups
  grouping_vars = rlang::syms(grouping_vars)

  data %>%
    filter(!!!rlang::parse_exprs(filters)) %>%

    # this is the important bit
    group_by(!!!grouping_vars)
}

custom_summary(data,
               filters = c("mass_g > 1000"),
               grouping_vars = c("order", "family")
               ) %>%

  summarise(mean_mass = mean(mass_g)) %>%

```

```

head()
#> # A tibble: 6 x 3
#> # Groups:   order [2]
#>   order      family      mean_mass
#>   <chr>      <chr>      <dbl>
#> 1 Afrosoricida Tenrecidae    13220
#> 2 Carnivora    Ailuridae      4900
#> 3 Carnivora    Canidae    10502.
#> 4 Carnivora    Eupleridae    5853.
#> 5 Carnivora    Felidae    52801.
#> 6 Carnivora    Herpestidae   2334.

```

1877 13.5.4 Using rlang::parse_exprs

```

custom_summary = function(data,
                           filters = c("mass_g > 1000"),
                           grouping_vars) {
  # deal with groups
  grouping_vars = rlang::parse_exprs(grouping_vars)

  data %>%
    filter(!!!rlang::parse_exprs(filters)) %>%

    # this is the important bit
    group_by(!!!grouping_vars)
}

custom_summary(data,
               filters = c("mass_g > 1000"),
               grouping_vars = c("family", "iucn_status")
               ) %>%

  summarise(mean_mass = mean(mass_g)) %>%
  head()
#> # A tibble: 6 x 3
#> # Groups:   family [5]
#>   family      iucn_status mean_mass
#>   <chr>      <chr>      <dbl>
#> 1 Ailuridae    EN          4900
#> 2 Anomaluridae DD          1770
#> 3 Antilocapridae EP    40503.
#> 4 Antilocapridae LC    46083.
#> 5 Aotidae      LC          1060
#> 6 Aplodontiidae LC          1004

```

13.6 Flexible summarising in a function

Summarising using string expressions has been around in the `tidyverse` for a very long time, and `summarise_at` is a function most users are familiar with, along with its variants `summarise_if`, `summarise_all`

13.6.1 Using `dplyr::summarise_at`

Simply pass a string vector to the `.vars` argument of `summarise_at`, while passing a list, named or otherwise, of functions to the `.funs` argument.

```
custom_summary = function(data,
                           filters = c("mass_g > 1000"),
                           grouping_vars,
                           summary_vars,
                           summary_funs) {
  # deal with groups
  grouping_vars = rlang::parse_exprs(grouping_vars)

  data %>%
    filter(!!!parse_exprs(filters)) %>%
    group_by(!!!grouping_vars) %>%

    # important bit
    summarise_at(.vars = summary_vars,
                 .funs = summary_funs)
}

custom_summary(data,
               grouping_vars = c("order", "family"),
               summary_vars = "mass_g",
               summary_funs = list(this_is_a_mean = mean, sd))
#> # A tibble: 113 x 4
#> # Groups:   order [24]
#>   order      family  this_is_a_mean  fn1
#>   <chr>      <chr>      <dbl>  <dbl>
#> 1 Afrosoricida Tenrecidae    13220    NA
#> 2 Carnivora    Ailuridae      4900    NA
#> 3 Carnivora    Canidae    10502. 11618.
#> 4 Carnivora    Eupleridae    5853.  6234.
#> 5 Carnivora    Felidae    52801. 88201.
#> 6 Carnivora    Herpestidae   2334.   937.
#> # ... with 107 more rows
```

13.6.2 Using the `across` argument for summary variables

`dplyr` 1.0.0 had `summarise_*` superseded by the `across` argument to `summarise`. This works somewhat differently. The example below shows how the mean of a trait of mammal groups can be found.

This example makes use of embracing using `{{ }}`, where the double curly braces indicate a promise, i.e., an expectation that such a variable will exist in the function environment.

```
custom_summary = function(data,
                           filters = c("mass_g > 1000"),
                           grouping_vars,
                           summary_vars) {
  # deal with groups
  grouping_vars = parse_exprs(grouping_vars)

  data %>%
    filter(!!!parse_exprs(filters)) %>%
    group_by(!!!grouping_vars) %>%

    # important bit
    summarise(across({{ summary_vars }},
                     ~ mean(.)))
}

custom_summary(data,
               grouping_vars = c("order", "family"),
               summary_vars = c(mass_g, diet_plant)) %>%

  head()
#> # A tibble: 6 x 4
#> # Groups:   order [2]
#>   order      family    mass_g diet_plant
#>   <chr>      <chr>      <dbl>    <dbl>
#> 1 Afrosoricida Tenrecidae 13220      4
#> 2 Carnivora    Ailuridae   4900     80
#> 3 Carnivora    Canidae  10502.    15.0
#> 4 Carnivora    Eupleridae  5853.     2.67
#> 5 Carnivora    Felidae   52801.    0.348
#> 6 Carnivora    Herpestidae 2334.     9.86
```

`across` also accepts multiple functions just as `summarise_*` did. This works as follows.

```
# mean and sd
data %>%
  group_by(order, family) %>%
```



```

summarise(across(c(mass_g, diet_plant),
  list(~ mean(.),
        ~ sd(.))
  )
) %>%
head()
#> # A tibble: 6 x 6
#> # Groups:   order [2]
#>   order      family      mass_g_1 mass_g_2 diet_plant_1 diet_plant_2
#>   <chr>      <chr>      <dbl>    <dbl>    <dbl>      <dbl>
#> 1 Afrosoricida Chrysochloridae    60.7     86.6         0         0
#> 2 Afrosoricida Tenrecidae      449.    2197.         1.5        6.83
#> 3 Carnivora    Ailuridae      4900      NA          80         NA
#> 4 Carnivora    Canidae     10268.   11568.        16.0       18.0
#> 5 Carnivora    Eupleridae    3777.    5364.         4.6        6.72
#> 6 Carnivora    Felidae     52801.   88201.        0.348       2.36

```

1894 13.6.3 Summarise multiple variables using ...

1895 Here, the unquoted and unnamed variables passed to the function are captured
 1896 by ... and enquos-ed, i.e. their evaluation is delayed. Then the variables are
 1897 forcibly evaluated within the mean function, and this expression is captured
 1898 using expr. Since there are multiple variables to summarise, these expressions
 1899 are stored as a list.

```

custom_summary = function(data,
  grouping_vars,
  filters,
  ...) {
  # deal with groups
  grouping_vars = rlang::parse_exprs(grouping_vars)

  # deal with summary variables
  summary_vars = rlang::enquos(...)

  # apply the summary function to the variables
  summary_vars <- purrr::map(summary_vars, function(var) {
    rlang::expr(mean(!!var, na.rm = TRUE))
  })

  data %>%
    filter(!!!rlang::parse_exprs(filters)) %>%
    group_by(!!!grouping_vars) %>%

    # important bit
    summarise(!!!summary_vars)

```

```

}

custom_summary(data,
  grouping_vars = c("order", "family"),
  filters = "mass_g > 10",
  mass_g, diet_plant) %>%

  head()
#> # A tibble: 6 x 4
#> # Groups:   order [2]
#>   order      family      `mean(mass_g, na.rm = T)` `mean(diet_plant, na.rm = ~
#>   <chr>      <chr>      <dbl>      <dbl>
#> 1 Afrosorici~ Chrysochlori~      60.7      0
#> 2 Afrosorici~ Tenrecidae      597.      2
#> 3 Carnivora   Ailuridae     4900     80
#> 4 Carnivora   Canidae    10268.    16.0
#> 5 Carnivora   Eupleridae     3777.     4.6
#> 6 Carnivora   Felidae    52801.    0.348

```

1900 **expr and enqu**

1901 **expr** and **enquo** are essentially the same, defusing/quoting (delaying evaluation)
 1902 of R code. **expr** works on expressions supplied by the primary user, while **enquo**
 1903 works on arguments passed to a function. When in doubt, ask whether the
 1904 expression to be quoted has entered the function environment as an argument.
 1905 If yes, use **enquo**, and if not **expr**. The plural forms **enquos** and **exprs** exist for
 1906 multiple arguments.

1907 **13.6.3.1 Correct the names of summary variables**

1908 The example above returns summary variables that are not assigned a name.
 1909 The **enquos** function can assign the name from the variable names, so
 1910 **mean(mass_g)** is returned as **mass_g**. Since it is useful to add a tag to make
 1911 clear what the summary variable is (mean, variance etc.) an extra **glue** step is
 1912 added to assign informative names to the summary variables.

```

custom_summary = function(data,
  grouping_vars,
  filters,
  ...) {
  # deal with groups
  grouping_vars = rlang::parse_exprs(grouping_vars)

  # deal with summary variables
  summary_vars = rlang::enquos(..., .named = TRUE)

  # apply the summary function to the variables

```

```

summary_vars <- purrr::map(summary_vars, function(var) {
  rlang::expr(mean(!!var, na.rm = TRUE))
})

# add a prefix to the summary variables
names(summary_vars) <- glue::glue('mean_{names(summary_vars)}')

data %>%
  filter(!!!rlang::parse_exprs(filters)) %>%
  group_by(!!!grouping_vars) %>%

  # important bit
  summarise(!!!summary_vars)
}

custom_summary(data,
  grouping_vars = c("order", "family"),
  filters = "mass_g > 10",
  mass_g, diet_plant) %>%

  head()
#> # A tibble: 6 x 4
#> # Groups:   order [2]
#>   order      family      mean_mass_g mean_diet_plant
#>   <chr>      <chr>          <dbl>          <dbl>
#> 1 Afrosoricida Chrysochloridae    60.7             0
#> 2 Afrosoricida Tenrecidae      597.             2
#> 3 Carnivora    Ailuridae      4900             80
#> 4 Carnivora    Canidae     10268.           16.0
#> 5 Carnivora    Eupleridae     3777.             4.6
#> 6 Carnivora    Felidae     52801.           0.348

```

1913 13.6.4 Summarise with multiple functions

1914 The final step is to pass multiple summary functions to the summary variables.
 1915 Unlike the earlier example using `summarise(across(vars, funs))`, the goal
 1916 here is to apply one function to each variable.

1917 This is done by passing the functions and the variables on which they should op-
 1918 erate as strings, and using string interpolation via `glue` to construct a coherent
 1919 R expression. This expression is then named and evaluated.

```

custom_summary = function(data,
  grouping_vars,
  filters,
  functions,
  summary_vars) {

```

```

# deal with groups
grouping_vars = parse_exprs(grouping_vars)

# deal with summary variables
# summary_vars = # enquo(..., .named = TRUE)

# apply the summary function to the variables
summary_exprs <- parse_exprs(glue::glue('{functions}({summary_vars}, na.rm = TRUE)'))

# add a prefix to the summary variables
names(summary_exprs) <- glue::glue('{functions}_{summary_vars}')

data %>%
  filter(!!!parse_exprs(filters)) %>%
  group_by(!!!grouping_vars) %>%

  # important bit
  summarise(!!!summary_exprs)
}

custom_summary(data,
  grouping_vars = c("order", "family"),
  filters = "mass_g > 10",
  functions = c("mean", "var"),
  summary_vars = c("mass_g", "diet_plant")) %>%

  head()
#> # A tibble: 6 x 4
#> # Groups:   order [2]
#>   order      family      mean_mass_g var_diet_plant
#>   <chr>      <chr>          <dbl>          <dbl>
#> 1 Afrosoricida Chrysochloridae    60.7            0
#> 2 Afrosoricida Tenrecidae        597.           61.8
#> 3 Carnivora    Ailuridae        4900            NA
#> 4 Carnivora    Canidae        10268.          325.
#> 5 Carnivora    Eupleridae        3777.           45.2
#> 6 Carnivora    Felidae        52801.           5.57

```

13.7 Further resources

1920

1921

1922

1923

1924

- **dplyr**: <https://dplyr.tidyverse.org/index.html>
- Tidy evaluation: Superseded and archived, but still useful <https://tidyeval.tidyverse.org/>
- **rlang**: <https://rlang.r-lib.org/>