

# Lecture materials | granolarr

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# Preface

*Stefano De Sabbata*

This work is licensed under the GNU General Public License v3.0. Contains public sector information licensed under the Open Government Licence v3.0.

This book contains the *lectures* component of granolarr, a repository of reproducible materials to teach geographic information and data science in R. Part of the materials are derived from the lectures for the module GY7702 Practical Programming in R of the MSc in Geographic Information Science at the School of Geography, Geology, and the Environment of the University of Leicester, by Dr Stefano De Sabbata.

This book was created using R, RStudio, RMarkdown, Bookdown, and GitHub.

## Session info

```
sessionInfo()

## R version 4.0.2 (2020-06-22)
## Platform: x86_64-pc-linux-gnu (64-bit)
## Running under: Ubuntu 20.04 LTS
##
## Matrix products: default
## BLAS/LAPACK: /usr/lib/x86_64-linux-gnu/openblas-openmp/libopenblas-r0.3.8.so
##
## locale:
##   [1] LC_CTYPE=en_US.UTF-8        LC_NUMERIC=C
##   [3] LC_TIME=en_US.UTF-8        LC_COLLATE=en_US.UTF-8
##   [5] LC_MONETARY=en_US.UTF-8    LC_MESSAGES=C
##   [7] LC_PAPER=en_US.UTF-8       LC_NAME=C
##   [9] LC_ADDRESS=C               LC_TELEPHONE=C
##  [11] LC_MEASUREMENT=en_US.UTF-8 LC_IDENTIFICATION=C
##
## attached base packages:
```

```
## [1] stats      graphics   grDevices utils      datasets  methods   base
##
## loaded via a namespace (and not attached):
## [1] compiler_4.0.2  magrittr_1.5    bookdown_0.20  htmltools_0.5.0
## [5] tools_4.0.2    yaml_2.2.1     stringi_1.4.6  rmarkdown_2.3
## [9] knitr_1.29     stringr_1.4.0   digest_0.6.25  xfun_0.16
## [13] rlang_0.4.7    evaluate_0.14
```

# Chapter 1

## Introduction to R

### 1.1 About this module

This module will provide you with the fundamental skills in

- basic programming in R
- data wrangling
- data analysis
- reproducibility

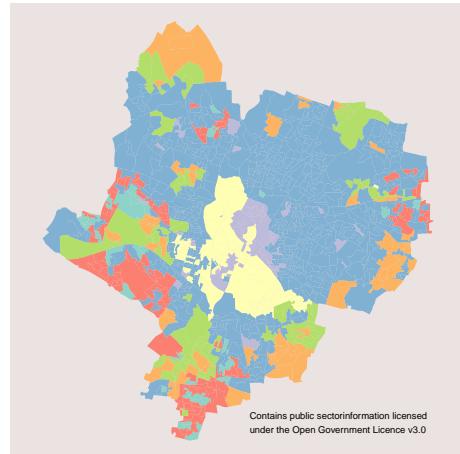
basis for

- *Geospatial Data Analysis*
- *Geospatial Databases and Information Retrieval*

### 1.2 R programming language

One of the most widely used programming languages and an effective tool for (*geospatial*) data science

- data wrangling
- statistical analysis
- machine learning
- data visualisation and maps
- processing spatial data
- geographic information analysis



## 1.3 Schedule

The lectures and practical sessions have been designed to follow the schedule below

- **1 R coding**
  - 100 Introduction
  - 110 R programming
- **2 Data wrangling**
  - 200 Selection and manipulation
  - 210 Table operations
  - 220 Reproducibility
- **3 Data analysis**
  - 300 Exploratory data analysis
  - 310 Comparing data
  - 320 Regression models
- **4 Machine learning**
  - 400 Unsupervised
  - 410 Supervised

## 1.4 Reference books

Suggested reading

- *Programming Skills for Data Science: Start Writing Code to Wrangle, Analyze, and Visualize Data with R* by Michael Freeman and Joel Ross, Addison-Wesley, 2019. See book webpage and repository.
- *R for Data Science* by Garrett Grolemund and Hadley Wickham, O'Reilly Media, 2016. See online book.
- *Discovering Statistics Using R* by Andy Field, Jeremy Miles and Zoë Field, SAGE Publications Ltd, 2012. See book webpage.
- *Machine Learning with R: Expert techniques for predictive modeling* by Brett Lantz, Packt Publishing, 2019. See book webpage.

Further reading

- *The Art of R Programming: A Tour of Statistical Software Design* by Norman Matloff, No Starch Press, 2011. See book webpage

- *An Introduction to R for Spatial Analysis and Mapping* by Chris Brunsdon and Lex Comber, Sage, 2015. See book webpage
- *Geocomputation with R* by Robin Lovelace, Jakub Nowosad, Jannes Muenchow, CRC Press, 2019. See online book.

## 1.5 R

Created in 1992 by Ross Ihaka and Robert Gentleman at the University of Auckland, New Zealand

- Free, open-source implementation of *S*
  - statistical programming language
  - Bell Labs
- Functional programming language
- Supports (and commonly used as) procedural (i.e., imperative) programming
- Object-oriented
- Interpreted (not compiled)

## 1.6 Interpreting values

When values and operations are inputted in the *Console*, the interpreter returns the results of its interpretation of the expression

2

```
## [1] 2
"String value"

## [1] "String value"
# comments are ignored
```

## 1.7 Basic types

R provides three core data types

- numeric
  - both integer and real numbers
- character
  - i.e., text, also called *strings*
- logical
  - TRUE or FALSE

## 1.8 Numeric operators

R provides a series of basic numeric operators

Operator	Meaning	Example	Output
+	Plus	5 + 2	7
-	Minus	5 - 2	3
*	Product	5 * 2	10
/	Division	5 / 2	2.5
%/%	Integer division	5 %/% 2	2
%%	Module	5 %% 2	1
^	Power	5^2	25

```
5 + 2
```

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

## 1.9 Logical operators

R provides a series of basic logical operators to test

Operator	Meaning	Example	Output
==	Equal	5 == 2	FALSE
!=	Not equal	5 != 2	TRUE
> (>=)	Greater (or equal)	5 > 2	TRUE
< (<=)	Less (or equal)	5 <= 2	FALSE
!	Not	!TRUE	FALSE
&	And	TRUE & FALSE	FALSE
	Or	TRUE   FALSE	TRUE

```
5 >= 2
```

```
## [1] TRUE
```

## 1.10 Summary

An introduction to R

- Basic types
- Basic operators

**Next:** Core concepts

- Variables

- Functions
- Libraries



# Chapter 2

## Core concepts

### 2.1 Recap

Prev: An introduction to R

- Basic types
- Basic operators

Now: Core concepts

- Variables
- Functions
- Libraries

### 2.2 Variables

Variables **store data** and can be defined

- using an *identifier* (e.g., `a_variable`)
- on the left of an *assignment operator* `<-`
- followed by the object to be linked to the identifier
- such as a *value* (e.g., `1`)

```
a_variable <- 1
```

The value of the variable can be invoked by simply specifying the **identifier**.

```
a_variable
```

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

## 2.3 Algorithms and functions

An **algorithm** or *effective procedure* is a mechanical rule, or automatic method, or programme for performing some mathematical operation (Cutland, 1980).

A **program** is a specific set of instructions that implement an abstract algorithm.

The definition of an algorithm (and thus a program) can consist of one or more **functions**

- set of instructions that perform a task
- possibly using an input, possibly returning an output value

Programming languages usually provide pre-defined functions that implement common algorithms (e.g., to find the square root of a number or to calculate a linear regression)

## 2.4 Functions

Functions execute complex operations and can be invoked

- specifying the *function name*
- the *arguments* (input values) between simple brackets
  - each *argument* corresponds to a *parameter*
  - sometimes the *parameter* name must be specified

```
sqrt(2)
```

```
## [1] 1.414214
round(1.414214, digits = 2)
```

```
## [1] 1.41
```

## 2.5 Functions and variables

- functions can be used on the right side of `<-`
- variables and functions can be used as *arguments*

```
sqrt_of_two <- sqrt(2)
sqrt_of_two
```

```
## [1] 1.414214
round(sqrt_of_two, digits = 2)
```

```
## [1] 1.41
```

```
round(sqrt(2), digits = 2)
## [1] 1.41
```

## 2.6 Naming

When creating an identifier for a variable or function

- R is a **case sensitive** language
  - UPPER and lower case are not the same
  - `a_variable` is different from `a_VARIABLE`
- names can include
  - alphanumeric symbols
  - `.` and `_`
- names must start with
  - a letter

## 2.7 Libraries

Once a number of related, reusable functions are created

- they can be collected and stored in **libraries** (a.k.a. *packages*)
  - `install.packages` is a function that can be used to install libraries (i.e., downloads it on your computer)
  - `library` is a function that *loads* a library (i.e., makes it available to a script)

Libraries can be of any size and complexity, e.g.:

- `base`: base R functions, including the `sqrt` function above
- `rgdal`: implementation of the GDAL (Geospatial Data Abstraction Library) functionalities

## 2.8 stringr

R provides some basic functions to manipulate strings, but the `stringr` library provides a more consistent and well-defined set

```
library(stringr)

str_length("Leicester")
## [1] 9
str_detect("Leicester", "e")
## [1] TRUE
```

```
str_replace_all("Leicester", "e", "x")
```

```
## [1] "Lxicxstxr"
```

## 2.9 Summary

Core concepts

- Variables
- Functions
- Libraries

Next: Tidyverse

- Tidyverse libraries
- *pipe* operator

# Chapter 3

## Tidyverse

### 3.1 Recap

Prev: Core concepts

- Variables
- Functions
- Libraries

Now: Tidyverse

- Tidyverse libraries
- *pipe* operator

### 3.2 Tidyverse

The Tidyverse was introduced by statistician Hadley Wickham, Chief Scientist at RStudio (worth following him on twitter).

*“The tidyverse is an opinionated collection of R packages designed for data science. All packages share an underlying design philosophy, grammar, and data structures.”* (Tidyverse homepage).

#### Core libraries

- |  |   |
|--|---|
| <ul style="list-style-type: none"><li>• <code>tibble</code></li><li>• <code>tidyverse</code></li><li>• <code>stringr</code></li><li>• <code>dplyr</code></li></ul> | <ul style="list-style-type: none"><li>• <code>readr</code></li><li>• <code>ggplot2</code></li><li>• <code>purrr</code></li><li>• <code>forcats</code></li></ul> |
|--|---|

Also, imports `magrittr`, which plays an important role.

### 3.3 Tidyverse core libraries

The meta-library Tidyverse includes:

- **tibble** is a modern re-imagining of the data frame, keeping what time has proven to be effective, and throwing out what it has not. Tibbles are data.frames that are lazy and surly: they do less and complain more forcing you to confront problems earlier, typically leading to cleaner, more expressive code.
- **tidyr** provides a set of functions that help you get to tidy data. Tidy data is data with a consistent form: in brief, every variable goes in a column, and every column is a variable.
- **stringr** provides a cohesive set of functions designed to make working with strings as easy as possible. It is built on top of stringi, which uses the ICU C library to provide fast, correct implementations of common string manipulations.

### 3.4 Tidyverse core libraries

The meta-library Tidyverse includes:

- **dplyr** provides a grammar of data manipulation, providing a consistent set of verbs that solve the most common data manipulation challenges.
- **readr** provides a fast and friendly way to read rectangular data (like csv, tsv, and fwf). It is designed to flexibly parse many types of data found in the wild, while still cleanly failing when data unexpectedly changes.
- **ggplot2** is a system for declaratively creating graphics, based on The Grammar of Graphics. You provide the data, tell ggplot2 how to map variables to aesthetics, what graphical primitives to use, and it takes care of the details.

### 3.5 Tidyverse core libraries

The meta-library Tidyverse contains the following libraries:

- **purrr** enhances R’s functional programming (FP) toolkit by providing a complete and consistent set of tools for working with functions and vectors. Once you master the basic concepts, purrr allows you to replace many for loops with code that is easier to write and more expressive.
- **forcats** provides a suite of useful tools that solve common problems with factors. R uses factors to handle categorical variables, variables that have a fixed and known set of possible values.

## 3.6 The pipe operator

The Tidyverse (via `magrittr`) also provide a clean and effective way of combining multiple manipulation steps

The pipe operator `%>%`

- takes the result from one function
- and passes it to the next function
- as the **first argument**
- that doesn't need to be included in the code anymore

## 3.7 Pipe example



## 3.8 Pipe example

The two codes below are equivalent

- the first simply invokes the functions
- the second uses the pipe operator `%>%`

```
round(sqrt(2), digits = 2)

## [1] 1.41

library(tidyverse)

sqrt(2) %>%
  round(digits = 2)
```

```
## [1] 1.41
```

### 3.9 Coding style

A *coding style* is a way of writing the code, including

- how variable and functions are named
  - lower case and `_`
- how spaces are used in the code
- which libraries are used

```
# Bad
X<-round(sqrt(2),2)

#Good
sqrt_of_two <- sqrt(2) %>%
  round(digits = 2)
```

Study the Tidyverse Style Guid and use it consistently!

### 3.10 Summary

Tidyverse

- Tidyverse libraries
- *pipe* operator
- Coding style

**Next:** Practical session

- The R programming language
- Interpreting values
- Variables
- Basic types
- Tidyverse
- Coding style

# Chapter 4

## Data types

### 4.1 Recap

Prev: Introduction

- 101 Lecture: Introduction to R
- 102 Lecture: Core concepts
- 103 Lecture: Tidyverse
- 104 Practical session

Now: Data types

- vectors
- factors
- matrices, arrays
- lists

### 4.2 Vectors

**Vectors** are ordered list of values.

- Vectors can be of any data type
  - numeric
  - character
  - logic
- All items in a vector have to be of the same type
- Vectors can be of any length

### 4.3 Defining vectors

A vector variable can be defined using

- an **identifier** (e.g., `a_vector`)
- on the left of an **assignment operator** `<-`
- followed by the object to be linked to the identifier
- in this case, the result returned by the function `c`
- which creates a vector containing the provided elements

```
a_vector <- c("Birmingham", "Derby", "Leicester",
             "Lincoln", "Nottingham", "Wolverhampton")
a_vector

## [1] "Birmingham"      "Derby"           "Leicester"        "Lincoln"
## [5] "Nottingham"     "Wolverhampton"
```

## 4.4 Creating vectors

- the operator `:`
- the function `seq`
- the function `rep`

`4:7`

```
## [1] 4 5 6 7
seq(1, 7, by = 0.5)

## [1] 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
seq(1, 10, length.out = 7)

## [1] 1.0 2.5 4.0 5.5 7.0 8.5 10.0
rep("Ciao", 4)

## [1] "Ciao" "Ciao" "Ciao" "Ciao"
```

## 4.5 Selection

Each element of a vector can be retrieved specifying the related **index** between square brackets, after the identifier of the vector. The first element of the vector has index 1.

`a_vector[3]`

```
## [1] "Leicester"
```

A vector of indexes can be used to retrieve more than one element.

`a_vector[c(5, 3)]`

```
## [1] "Nottingham" "Leicester"
```

## 4.6 Functions on vectors

Functions can be used on a vector variable directly

```
a_numeric_vector <- 1:5
a_numeric_vector + 10

## [1] 11 12 13 14 15
sqrt(a_numeric_vector)

## [1] 1.000000 1.414214 1.732051 2.000000 2.236068
a_numeric_vector >= 3

## [1] FALSE FALSE TRUE TRUE TRUE
```

## 4.7 Any and all

Overall expressions can be tested using the functions:

- **any**, TRUE if any of the elements satisfies the condition
- **all**, TRUE if all of the elements satisfy the condition

```
any(a_numeric_vector >= 3)

## [1] TRUE
all(a_numeric_vector >= 3)

## [1] FALSE
```

## 4.8 Factors

A **factor** is a data type similar to a vector. However, the values contained in a factor can only be selected from a set of **levels**.

```
houses_vector <- c("Bungalow", "Flat", "Flat",
  "Detached", "Flat", "Terrace", "Terrace")
houses_vector

## [1] "Bungalow" "Flat"      "Flat"      "Detached" "Flat"      "Terrace"   "Terrace"
houses_factor <- factor(c("Bungalow", "Flat", "Flat",
  "Detached", "Flat", "Terrace", "Terrace"))
houses_factor

## [1] Bungalow Flat      Flat      Detached Flat      Terrace  Terrace
## Levels: Bungalow Detached Flat Terrace
```

## 4.9 table

The function **table** can be used to obtain a tabulated count for each level.

```
houses_factor <- factor(c("Bungalow", "Flat", "Flat",
  "Detached", "Flat", "Terrace", "Terrace"))
houses_factor

## [1] Bungalow Flat      Flat      Detached Flat      Terrace Terrace
## Levels: Bungalow Detached Flat Terrace

table(houses_factor)

## houses_factor
## Bungalow Detached      Flat  Terrace
##          1           1       3       2
```

## 4.10 Specified levels

A specific set of levels can be specified when creating a factor by providing a **levels** argument.

```
houses_factor_spec <- factor(
  c("People Carrier", "Flat", "Flat", "Hatchback",
    "Flat", "Terrace", "Terrace"),
  levels = c("Bungalow", "Flat", "Detached",
            "Semi", "Terrace"))

table(houses_factor_spec)

## houses_factor_spec
## Bungalow      Flat Detached      Semi  Terrace
##          0           3       0       0       2
```

## 4.11 (Unordered) Factors

In statistics terminology, (unordered) factors are **categorical** (i.e., binary or nominal) variables. Levels are not ordered.

```
income_nominal <- factor(
  c("High", "High", "Low", "Low", "Low",
    "Medium", "Low", "Medium"),
  levels = c("Low", "Medium", "High"))
```

The *greater than* operator is not meaningful on the `income_nominal` factor defined above

```
income_nominal > "Low"
## Warning in Ops.factor(income_nominal, "Low"): '>' not meaningful for factors
## [1] NA NA NA NA NA NA NA NA NA
```

## 4.12 Ordered Factors

In statistics terminology, ordered factors are **ordinal** variables. Levels are ordered.

```
income_ordered <- ordered(
  c("High", "High", "Low", "Low", "Low",
    "Medium", "Low", "Medium"),
  levels = c("Low", "Medium", "High"))

income_ordered > "Low"
## [1] TRUE TRUE FALSE FALSE FALSE TRUE FALSE TRUE
sort(income_ordered)
## [1] Low     Low     Low     Low     Medium Medium High    High
## Levels: Low < Medium < High
```

## 4.13 Matrices

**Matrices** are collections of numerics arranged in a two-dimensional rectangular layout

- the first argument is a vector of values
- the second specifies number of rows and columns
- R offers operators and functions for matrix algebra

```
a_matrix <- matrix(c(3, 5, 7, 4, 3, 1), c(3, 2))
a_matrix
```

```
##      [,1] [,2]
## [1,]    3    4
## [2,]    5    3
## [3,]    7    1
```

## 4.14 Arrays

```

## , , 1
##
Variables of the type array are higher-## [,1] [,2] [,3]
dimensional matrices.## [1,] 1 5 9
• the first argument is a vector con-## [2,] 2 6 10
taining the values## [3,] 3 7 11
• the second argument is a vector## [4,] 4 8 12
specifying the depth of each di-##
mension## , , 2
## [,1] [,2] [,3]
a3dim_array <- array(1:24, dim=c(4, 3, 2))## [1,] 13 17 21
a3dim_array## [2,] 14 18 22
## [3,] 15 19 23
## [4,] 16 20 24

```

## 4.15 Selection

Subsets of matrices (and arrays) can be selected as seen for vectors.

```

a_matrix[2, c(1, 2)]
## [1] 5 3
a3dim_array[c(1, 2), 2, 2]
## [1] 17 18

```

## 4.16 Lists

Variables of the type **list** can contain elements of different types (including vectors and matrices), whereas elements of vectors are all of the same type.

```

employee <- list("Stef", 2015)
employee
## [[1]]
## [1] "Stef"
##
## [[2]]
## [1] 2015
employee[[1]] # Note the double square brackets for selection
## [1] "Stef"

```

## 4.17 Named Lists

In **named lists** each element has a name, and elements can be selected using their name after the symbol \$.

```
employee <- list(employee_name = "Stef", start_year = 2015)
employee

## $employee_name
## [1] "Stef"
##
## $start_year
## [1] 2015

employee$employee_name

## [1] "Stef"
```

## 4.18 Recap

Data types

- Vectors
- Factors
- Matrices, arrays
- Lists

Next: Control structures

- Conditional statements
- Loops



# Chapter 5

## Control structures

### 5.1 Recap

Prev: Data types

- Vectors
- Factors
- Matrices and arrays
- Lists

Now: Control structures

- Conditional statements
- Loops

### 5.2 If

Format: `if (condition) statement`

- *condition*: expression returning a logic value (TRUE or FALSE)
- *statement*: any valid R statement
- *statement* only executed if *condition* is TRUE

```
a_value <- -7
if (a_value < 0) cat("Negative")
```

```
## Negative
a_value <- 8
if (a_value < 0) cat("Negative")
```

### 5.3 Else

Format: `if (condition) statement1 else statement2`

- *condition*: expression returning a logic value (TRUE or FALSE)
- *statement1* and *statement2*: any valid R statements
- *statement1* executed if *condition* is TRUE
- *statement2* executed if *condition* is FALSE

```
a_value <- -7
if (a_value < 0) cat("Negative") else cat("Positive")

## Negative
a_value <- 8
if (a_value < 0) cat("Negative") else cat("Positive")

## Positive
```

### 5.4 Code blocks

**Code blocks** allow to encapsulate **several** statements in a single group

- { and } contain code blocks
- the statements are execute together

```
first_value <- 8
second_value <- 5
if (first_value > second_value) {
  cat("First is greater than second\n")
  difference <- first_value - second_value
  cat("Their difference is ", difference)
}

## First is greater than second
## Their difference is 3
```

### 5.5 Loops

Loops are a fundamental component of (procedural) programming.

There are two main types of loops:

- **conditional** loops are executed as long as a defined condition holds true
  - construct `while`
  - construct `repeat`
- **deterministic** loops are executed a pre-determined number of times
  - construct `for`

## 5.6 While

The *while* construct can be defined using the `while` reserved word, followed by the conditional statement between simple brackets, and a code block. The instructions in the code block are re-executed as long as the result of the evaluation of the conditional statement is TRUE.

```
current_value <- 0

while (current_value < 3) {
  cat("Current value is", current_value, "\n")
  current_value <- current_value + 1
}

## Current value is 0
## Current value is 1
## Current value is 2
```

## 5.7 For

The *for* construct can be defined using the `for` reserved word, followed by the definition of an **iterator**. The iterator is a variable which is temporarily assigned with the current element of a vector, as the construct iterates through all elements of the vector. This definition is followed by a code block, whose instructions are re-executed once for each element of the vector.

```
cities <- c("Derby", "Leicester", "Lincoln", "Nottingham")
for (city in cities) {
  cat("Do you live in", city, "?\n")
}

## Do you live in Derby ?
## Do you live in Leicester ?
## Do you live in Lincoln ?
## Do you live in Nottingham ?
```

## 5.8 For

It is common practice to create a vector of integers on the spot in order to execute a certain sequence of steps a pre-defined number of times.

```
for (i in 1:3) {
  cat("This is execution number", i, ":\n")
  cat("    See you later!\n")
}

## This is execution number 1 :
```

```
##      See you later!
## This is execetuion number 2 :
##      See you later!
## This is execetuion number 3 :
##      See you later!
```

## 5.9 Loops with conditional statements

`3:0`

```
## [1] 3 2 1 0
#Example: countdown!
for (i in 3:0) {
  if (i == 0) {
    cat("Go!\n")
  } else {
    cat(i, "\n")
  }
}

## 3
## 2
## 1
## Go!
```

## 5.10 Summary

Control structures

- Conditional statements
- Loops

**Next:** Functions

- Defining functions
- Scope of a variable

# Chapter 6

## Functions

### 6.1 Summary

Prev: Control structures

- Conditional statements
- Loops

Now: Functions

- Defining functions
- Scope of a variable

### 6.2 Defining functions

A function can be defined

- using an **identifier** (e.g., `add_one`)
- on the left of an **assignment operator** `<-`
- followed by the corpus of the function

```
add_one <- function (input_value) {  
  output_value <- input_value + 1  
  output_value  
}
```

### 6.3 Defining functions

The corpus

- starts with the reserved word `function`

- followed by the **parameter(s)** (e.g., `input_value`) between simple brackets
- and the instruction(s) to be executed in a code block
- the value of the last statement is returned as output

```
add_one <- function (input_value) {
  output_value <- input_value + 1
  output_value
}
```

## 6.4 Defining functions

After being defined

- a function can be invoked by specifying
  - the **identifier**
  - the necessary **parameter(s)**

```
add_one(3)
```

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

```
add_one(1024)
```

```
## [1] 1025
```

## 6.5 More parameters

- A function can be defined as having two or more **parameters**
  - by specifying more than one parameter name (separated by **commas**) in the function definition
- A function always take as input as many values as the number of parameters specified in the definition
  - otherwise an error is generated

```
area_rectangle <- function (height, width) {
  area <- height * width
  area
}
```

```
area_rectangle(3, 2)
```

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

## 6.6 Functions and control structures

Functions can contain both loops and conditional statements

```

factorial <- function (input_value) {
  result <- 1
  for (i in 1:input_value) {
    cat("current:", result, " | i:", i, "\n")
    result <- result * i
  }
  result
}
factorial(3)

## current: 1 | i: 1
## current: 1 | i: 2
## current: 2 | i: 3

## [1] 6

```

## 6.7 Scope

The **scope of a variable** is the part of code in which the variable is “visible”

In R, variables have a **hierarchical** scope:

- a variable defined in a script can be used referred to from within a definition of a function in the same script
- a variable defined within a definition of a function will **not** be referable from outside the definition
- scope does **not** apply to **if** or loop constructs

## 6.8 Example

In the case below

- `x_value` is **global** to the function `times_x`
- `new_value` and `input_value` are **local** to the function `times_x`
  - referring to `new_value` or `input_value` from outside the definition of `times_x` would result in an error

```

x_value <- 10
times_x <- function (input_value) {
  new_value <- input_value * x_value
  new_value
}
times_x(2)

## [1] 20

```

## 6.9 Summary

Functions

- Defining functions
- Scope of a variable

**N**ext: Practical session

- Conditional statements
- Loops
  - While
  - For
- Functions
  - Loading functions from scripts
- Debugging

# Chapter 7

## Data Frames

### 7.1 Recap

Prev: R programming

- 111 Lecture: Data types
- 112 Lecture: Control structures
- 113 Lecture: Functions
- 114 Practical session

Now: Data Frames

- Data Frames
- Tibbles

### 7.2 Lists and named lists

#### List

- can contain elements of different types
  - whereas elements of vectors are all of the same type
- in **named lists**, each element has a name
  - elements can be selected using the operator \$

```
employee <- list(employee_name = "Stef", start_year = 2015)
employee[[1]]
```

```
## [1] "Stef"
employee$employee_name

## [1] "Stef"
```

## 7.3 Data Frames

A **data frame** is equivalent to a *named list* where all elements are *vectors of the same length*.

```
employees <- data.frame(
  EmployeeName = c("Maria", "Pete", "Sarah"),
  Age = c(47, 34, 32),
  Role = c("Professor", "Researcher", "Researcher"))
employees

##   EmployeeName  Age      Role
## 1         Maria  47 Professor
## 2         Pete   34 Researcher
## 3        Sarah  32 Researcher
```

Data frames are the most common way to represent tabular data in R. Matrices and lists can be converted to data frames.

## 7.4 Selection

Selection is similar to vectors and lists.

```
employees[1, 1] # value selection

## [1] "Maria"

employees[1, ] # row selection

##   EmployeeName  Age      Role
## 1         Maria  47 Professor
employees[, 1] # column selection

## [1] "Maria" "Pete"  "Sarah"
```

## 7.5 Selection

Selection is similar to vectors and lists.

```
employees$EmployeeName # column selection, as for named lists

## [1] "Maria" "Pete"  "Sarah"
employees$EmployeeName[1]

## [1] "Maria"
```

## 7.6 Table manipulation

- Values can be assigned to cells
  - using any selection method
  - and the assignment operator `<-`
- New columns can be defined
  - assigning a vector to a new name

```
employees$Age[3] <- 33
employees$Place <- c("Leicester", "Leicester", "Leicester")
employees
```

```
##   EmployeeName Age      Role      Place
## 1         Maria  47 Professor Leicester
## 2        Pete   34 Researcher Leicester
## 3       Sarah   33 Researcher Leicester
```

## 7.7 Column processing

Operations can be performed on columns as they where vectors

```
10 - c(1, 2, 3)

## [1] 9 8 7

# Use Sys.Date to retrieve the current year
current_year <- as.integer(format(Sys.Date(), "%Y"))

# Calculate employee year of birth
employees$Year_of_birth <- current_year - employees$Age
employees

##   EmployeeName Age      Role      Place Year_of_birth
## 1         Maria  47 Professor Leicester        1973
## 2        Pete   34 Researcher Leicester        1986
## 3       Sarah   33 Researcher Leicester        1987
```

## 7.8 tibble

A tibble is a modern reimagining of the data.frame within tidyverse

- they do less
  - don't change column names or types
  - don't do partial matching
- complain more
  - e.g. when referring to a column that does not exist

That forces you to confront problems earlier, typically leading to cleaner, more expressive code.

## 7.9 Summary

Data Frames

- Data Frames
- Tibbles

**Next:** Data selection and filtering

- dplyr
- dplyr::select
- dplyr::filter

# Chapter 8

## Selection and filtering

### 8.1 Recap

Prev: Data Frames

- Data Frames
- Tibbles

Now: Data selection and filtering

- dplyr
- dplyr::select
- dplyr::filter

### 8.2 dplyr

The `dplyr` (pronounced *dee-ply-er*) library is part of `tidyverse` and it offers a grammar for data manipulation

- `select`: select specific columns
- `filter`: select specific rows
- `arrange`: arrange rows in a particular order
- `summarise`: calculate aggregated values (e.g., mean, max, etc)
- `group_by`: group data based on common column values
- `mutate`: add columns
- `join`: merge tables (`tibbles` or `data.frames`)

```
library(tidyverse)
```

## 8.3 Example dataset

The library `nycflights13` contains a dataset storing data about all the flights departed from New York City in 2013

```
library(nycflights13)

nycflights13::flights

## # A tibble: 336,776 x 19
##   year month   day dep_time sched_dep_time dep_delay arr_time
##   <int> <int> <int>     <int>          <int>      <dbl>    <int>
## 1  2013     1     1       517            515        2     830
## 2  2013     1     1       533            529        4     850
## 3  2013     1     1       542            540        2     923
## # ... with 336,773 more rows, and 12 more variables:
## #   sched_arr_time <int>, arr_delay <dbl>, carrier <chr>,
## #   flight <int>, tailnum <chr>, origin <chr>, dest <chr>,
## #   air_time <dbl>, distance <dbl>, hour <dbl>, minute <dbl>,
## #   time_hour <dttm>
```

## 8.4 Selecting table columns

Columns of **data frames** and **tibbles** can be selected

- specifying the column index

```
nycflights13::flights[, c(13, 14)]
```

- specifying the column name

```
nycflights13::flights[, c("origin", "dest")]
```

```
## # A tibble: 336,776 x 2
##   origin dest
##   <chr>  <chr>
## 1 EWR    IAH
## 2 LGA    IAH
## 3 JFK    MIA
## # ... with 336,773 more rows
```

## 8.5 dplyr::select

`select` can be used to specify which columns to retain

```
nycflights13::flights %>%
  dplyr::select(
```

```

    origin, dest, dep_delay, arr_delay, year:day
)

## # A tibble: 336,776 x 7
##   origin dest  dep_delay arr_delay year month   day
##   <chr>  <chr>     <dbl>     <dbl> <int> <int> <int>
## 1 EWR    IAH        2         11  2013     1     1
## 2 LGA    IAH        4         20  2013     1     1
## 3 JFK    MIA        2         33  2013     1     1
## 4 JFK    BQN       -1        -18  2013     1     1
## 5 LGA    ATL       -6        -25  2013     1     1
## # ... with 336,771 more rows

```

## 8.6 dplyr::select

... or whichones to drop, using - in front of the column name

```
nycflights13::flights %>%
  dplyr::select(origin, dest, dep_delay, arr_delay, year:day) %>%
  dplyr::select(-arr_delay)
```

```

## # A tibble: 336,776 x 6
##   origin dest  dep_delay year month   day
##   <chr>  <chr>     <dbl> <int> <int> <int>
## 1 EWR    IAH        2  2013     1     1
## 2 LGA    IAH        4  2013     1     1
## 3 JFK    MIA        2  2013     1     1
## # ... with 336,773 more rows

```

## 8.7 Logical filtering

Conditional statements can be used to filter a vector

- i.e. to retain only certain values
- where the specified value is TRUE

```
a_numeric_vector <- -3:3
a_numeric_vector

## [1] -3 -2 -1  0  1  2  3
a_numeric_vector[c(FALSE, FALSE, FALSE, TRUE, TRUE, TRUE, TRUE)]

## [1] 0 1 2 3
```

## 8.8 Conditional filtering

As a conditional expression results in a logic vector...

```
a_numeric_vector > 0

## [1] FALSE FALSE FALSE FALSE TRUE TRUE TRUE
... conditional expressions can be used for filtering
a_numeric_vector[a_numeric_vector > 0]

## [1] 1 2 3
```

## 8.9 Filtering data frames

The same approach can be applied to **data frames** and **tibbles**

```
nycflights13::flights$month

##      [1] 1 1 1 1 1 1 1 1 1 1 1 1 1 1 ...
nycflights13::flights$month == 11

##      [1] FALSE FALSE FALSE FALSE FALSE FALSE FALSE...
nycflights13::flights[nycflights13::flights$month == 11, ]

## # A tibble: 27,268 x 19
##   year month   day dep_time sched_dep_time
##   <int> <int> <int>    <int>          <int>
## 1  2013     11     1        5         2359
## # ... with 27,267 more rows, and 14 more variables:
## #   dep_delay <dbl>, arr_time <int>,
## #   sched_arr_time <int>, arr_delay <dbl>,
## #   carrier <chr>, flight <int>, tailnum <chr>,
## #   origin <chr>, dest <chr>, air_time <dbl>,
## #   distance <dbl>, hour <dbl>, minute <dbl>,
## #   time_hour <dttm>
```

## 8.10 dplyr::filter

```
nycflights13::flights %>%
  # Flights in November
  dplyr::filter(month == 11)

## # A tibble: 27,268 x 19
##   year month   day dep_time sched_dep_time
##   <int> <int> <int>    <int>          <int>
```

```

## 1 2013 11 1 5 2359
## 2 2013 11 1 35 2250
## 3 2013 11 1 455 500
## # ... with 27,265 more rows, and 14 more variables:
## #   dep_delay <dbl>, arr_time <int>,
## #   sched_arr_time <int>, arr_delay <dbl>,
## #   carrier <chr>, flight <int>, tailnum <chr>,
## #   origin <chr>, dest <chr>, air_time <dbl>,
## #   distance <dbl>, hour <dbl>, minute <dbl>,
## #   time_hour <dttm>

```

## 8.11 Select and filter

```

nycflights13::flights %>%
  # Select the columns you need
  dplyr::select(origin, dest, dep_delay, arr_delay, year:day) %>%
  # Drop arr_delay... because you don't need it after all
  dplyr::select(-arr_delay) %>%
  # Filter in only November flights
  dplyr::filter(month == 11)

## # A tibble: 27,268 x 6
##   origin dest  dep_delay year month day
##   <chr>   <chr>     <dbl> <int> <int> <int>
## 1 JFK    PSE        6  2013    11     1
## 2 JFK    SYR       105 2013    11     1
## 3 EWR    CLT       -5  2013    11     1
## # ... with 27,265 more rows

```

## 8.12 Summary

Data selection and filtering

- dplyr
- dplyr::select
- dplyr::filter

Next: Data manipulation

- dplyr::arrange
- dplyr::summarise
- dplyr::group\_by
- dplyr::mutate



# Chapter 9

## Data manipulation

### 9.1 Recap

Prev: Data selection and filtering

- dplyr
- dplyr::select
- dplyr::filter

Now: Data manipulation

- dplyr::arrange
- dplyr::summarise
- dplyr::group\_by
- dplyr::mutate

### 9.2 Example

```
library(tidyverse)
library(nycflights13)

nov_dep_delays <-
  nycflights13::flights %>%
  dplyr::select(origin, dest, dep_delay, year:day) %>%
  dplyr::filter(month == 11)

nov_dep_delays

## # A tibble: 27,268 x 6
##   origin dest  dep_delay year month   day
##   <chr>   <chr>     <dbl> <int> <int> <int>
```

```
## 1 JFK      PSE          6 2013    11    1
## 2 JFK      SYR          105 2013   11    1
## 3 EWR      CLT          -5 2013   11    1
## # ... with 27,265 more rows
```

### 9.3 dplyr::arrange

Arranges rows in a particular order

- descending orders specified by using - (minus symbol)

```
nov_dep_delays %>%
  dplyr::arrange(
    # Ascending destination name
    dest,
    # Descending delay
    -dep_delay
  )

## # A tibble: 27,268 x 6
##   origin dest  dep_delay year month   day
##   <chr>   <chr>     <dbl> <int> <int>
## 1 JFK     ABQ        25  2013    11    29
## 2 JFK     ABQ        21  2013    11    22
## # ... with 27,266 more rows
```

### 9.4 dplyr::summarise

Calculates aggregated values

- e.g., using functions such as mean, max, etc.

```
nov_dep_delays %>%
  # Need to filter out rows where delay is NA
  dplyr::filter(!is.na(dep_delay)) %>%
  # Create two aggregated columns
  dplyr::summarise(
    avg_dep_delay = mean(dep_delay),
    tot_dep_delay = sum(dep_delay)
  )

## # A tibble: 1 x 2
##   avg_dep_delay tot_dep_delay
##             <dbl>         <dbl>
## 1           5.44       146945
```

## 9.5 dplyr::group\_by

Groups rows based on common values for specified column(s)

- combined with `summarise`, aggregated values per group

```
nov_dep_delays %>%
  # First group by same destination
  dplyr::group_by(dest) %>%
  # Then calculate aggregated value
  dplyr::filter(!is.na(dep_delay)) %>%
  dplyr::summarise(tot_dep_delay = sum(dep_delay))

## # A tibble: 90 x 2
##   dest    tot_dep_delay
##   <chr>      <dbl>
## 1 ABQ        -66
## 2 ALB        636
## # ... with 88 more rows
```

## 9.6 dplyr::tally and dplyr::count

- `dplyr::tally` short-hand for `summarise` with `n`  
– number of rows
- `dplyr::count` short-hand for `group_by` and `tally`  
– number of rows per group

```
nov_dep_delays %>%
  # Count flights by same destination
  dplyr::count(dest)

## # A tibble: 90 x 2
##   dest     n
##   <chr> <int>
## 1 ABQ      30
## 2 ALB      46
## 3 ATL    1384
## # ... with 87 more rows
```

## 9.7 dplyr::mutate

Calculate values for new columns based on current columns

```
nov_dep_delays %>%
  dplyr::mutate(
  # Combine origin and destination into one column
  orig_dest = str_c(origin, dest, sep = "->"),
```

```

# Departure delay in days (rather than minutes)
delay_days = ((dep_delay / 60) /24)
)

## # A tibble: 27,268 x 8
##   origin dest  dep_delay year month   day orig_dest delay_days
##   <chr>   <chr>     <dbl> <int> <int> <chr>           <dbl>
## 1 JFK     PSE        6  2013    11      1 JFK->PSE       0.00417
## 2 JFK     SYR       105  2013    11      1 JFK->SYR       0.0729
## 3 EWR     CLT       -5  2013    11      1 EWR->CLT      -0.00347
## # ... with 27,265 more rows

```

## 9.8 Full pipe example

```

nycflights13::flights %>%
  dplyr::select(
    origin, dest, dep_delay, arr_delay,
    year:day
  ) %>%
  dplyr::select(-arr_delay) %>%
  dplyr::filter(month == 11) %>%
  dplyr::filter(!is.na(dep_delay)) %>%
  dplyr::arrange(dest, -dep_delay) %>%
  dplyr::group_by(dest) %>%
  dplyr::summarise(
    tot_dep_delay = sum(dep_delay)
  ) %>%
  dplyr::mutate(
    tot_dep_delay_days = ((tot_dep_delay / 60) /24)
  )

```

## 9.9 Full pipe example

```

## # A tibble: 90 x 3
##   dest  tot_dep_delay tot_dep_delay_days
##   <chr>     <dbl>           <dbl>
## 1 ABQ        -66          -0.0458
## 2 ALB        636           0.442
## 3 ATL       8184            5.68
## 4 AUS        574            0.399
## 5 AVL        239            0.166
## 6 BDL         80            0.0556
## 7 BGR        437            0.303
## 8 BHM        412            0.286

```

```
## 9 BNA          3943      2.74
## 10 BOS          2968      2.06
## # ... with 80 more rows
```

## 9.10 Summary

Data manipulation

- dplyr::arrange
- dplyr::summarise
- dplyr::group\_by
- dplyr::mutate

Next: Practical session

- Creating R projects
- Creating R scripts
- Data wrangling script



# Chapter 10

## Join operations

### 10.1 Recap

Prev: Selection and manipulation

- Data frames and tibbles
- Data selection and filtering
- Data manipulation

Now: Join operations

- Joining data
- dplyr join functions

### 10.2 Example

```
cities <- data.frame(  
  city_name = c("Barcelona", "London", "Rome", "Los Angeles"),  
  country_name = c("Spain", "UK", "Italy", "US"),  
  city_pop_M = c(1.62, 8.98, 4.34, 3.99)  
)  
  
cities_area <- data.frame(  
  city_name = c("Barcelona", "London", "Rome", "Munich"),  
  city_area_km2 = c(101, 1572, 496, 310)  
)
```

### 10.3 Example

city_name	country_name	city_pop_M
Barcelona	Spain	1.62
London	UK	8.98
Rome	Italy	4.34
Los Angeles	US	3.99

city_name	city_area_km2
Barcelona	101
London	1572
Rome	496
Munich	310

### 10.4 Joining data

Tables can be joined (or ‘merged’)

- information from two tables can be combined
- specifying **column(s) from two tables with common values**
  - usually one with a unique identifier of an entity
- rows having the same value are joined
- depending on parameters
  - a row from one table can be merged with multiple rows from the other table
  - rows with no matching values in the other table can be retained
- `merge` base function or join functions in `dplyr`

## 10.5 Join types



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## 10.6 dplyr joins

dplyr provides a series of join verbs

- **Mutating joins**
  - `inner_join`: inner join
  - `left_join`: left join
  - `right_join`: right join
  - `full_join`: full join
- **Nesting joins**
  - `nest_join`: all rows columns from left table, plus a column of tibbles with matching from right
- **Filtering joins** (keep only columns from left)
  - `semi_join`: rows from left where match with right
  - `anti_join`: rows from left where no match with right

## 10.7 dplyr::full\_join

- `full_join` combines all the available data

```
dplyr::full_join(
  # first argument, left table
  # second argument, right table
  cities, cities_area,
```

```
# specify which column to be matched
by = c("city_name" = "city_name")
)
```

city_name	country_name	city_pop_M	city_area_km2
Barcelona	Spain	1.62	101
London	UK	8.98	1572
Rome	Italy	4.34	496
Los Angeles	US	3.99	NA
Munich	NA	NA	310

## 10.8 Pipes and shorthands

When using (all) join verbs in `dplyr`

```
# using pipe, left table is "coming down the pipe"
cities %>%
  dplyr::full_join(cities_area, by = c("city_name" = "city_name"))

# if no columns specified, columns with the same name are matched
cities %>%
  dplyr::full_join(cities_area)
```

city_name	country_name	city_pop_M	city_area_km2
Barcelona	Spain	1.62	101
London	UK	8.98	1572
Rome	Italy	4.34	496
Los Angeles	US	3.99	NA
Munich	NA	NA	310

## 10.9 dplyr::left\_join

- keeps all the data from the **left** table
  - first argument or “*coming down the pipe*”
- rows from the right table without a match are dropped
  - second argument (or first when using *pipes*)

```
cities %>%
  dplyr::left_join(cities_area)
```

city_name	country_name	city_pop_M	city_area_km2
Barcelona	Spain	1.62	101
London	UK	8.98	1572
Rome	Italy	4.34	496
Los Angeles	US	3.99	NA

## 10.10 dplyr::right\_join

- keeps all the data from the **right** table
  - second argument (or first when using *pipes*)
- rows from the left table without a match are dropped
  - first argument or “*coming down the pipe*”

```
cities %>%
  dplyr::right_join(cities_area)
```

city_name	country_name	city_pop_M	city_area_km2
Barcelona	Spain	1.62	101
London	UK	8.98	1572
Rome	Italy	4.34	496
Munich	NA	NA	310

## 10.11 dplyr::inner\_join

- keeps only rows that have a match in **both** tables
- rows without a match either way are dropped

```
cities %>%
  dplyr::inner_join(cities_area)
```

city_name	country_name	city_pop_M	city_area_km2
Barcelona	Spain	1.62	101
London	UK	8.98	1572
Rome	Italy	4.34	496

## 10.12 dplyr::semi\_join and anti\_join

```
cities %>%
  dplyr::semi_join(cities_area)
```

city_name	country_name	city_pop_M
Barcelona	Spain	1.62
London	UK	8.98
Rome	Italy	4.34

```
cities %>%
  dplyr::anti_join(cities_area)
```

city_name	country_name	city_pop_M
Los Angeles	US	3.99

## 10.13 Summary

Join operations

- Joining data
- dplyr join functions

**Next:** Tidy-up your data

- Wide and long data
- Re-shape data
- Handle missing values

# Chapter 11

## Tidy data

**CONTENT WARNING:** Some of the data used in these slides discuss issues that some people might find distressing: **disease**.

### 11.1 Recap

Prev: Join operations

- Joining data
- dplyr join functions

Now: Tidy-up your data

- Wide and long data
- Re-shape data
- Handle missing values

### 11.2 Long data

Each real-world entity is represented by *multiple rows*

- each one reporting only one of its attributes
- one column indicates which attribute each row represent
- another column is used to report the value

Common approach for temporal series

city	week_ending	cases
Derby	2020-10-03	NA
Leicester	2020-10-03	473
Nottingham	2020-10-03	1701
Derby	2020-10-10	320
Leicester	2020-10-10	616
Nottingham	2020-10-10	NA

### 11.3 Wide data

Each real-world entity is represented by *one single row*

- its attributes are represented through different columns

city	cases_2020_10_03	cases_2020_10_10
Derby	NA	320
Leicester	473	616
Nottingham	1701	NA

- **Long data** can be more flexible
  - new attributes add new rows where necessary
- **Wide data** require more structure
  - new attributes need new column for all entities

### 11.4 Example

```
city_info_long <- data.frame(
  city = c("Derby", "Leicester", "Nottingham",
          "Derby", "Leicester", "Nottingham"),
  week_ending = c("2020-10-03", "2020-10-03", "2020-10-03",
                 "2020-10-10", "2020-10-10", "2020-10-10"),
  cases = c(NA, 473, 1701, 320, 616, NA)
) %>%
  tibble::as_tibble()
```

city	week_ending	cases
Derby	2020-10-03	NA
Leicester	2020-10-03	473
Nottingham	2020-10-03	1701
Derby	2020-10-10	320
Leicester	2020-10-10	616
Nottingham	2020-10-10	NA

### 11.5 tidyverse

The `tidyverse` (pronounced *tidy-er*) library is part of `tidyverse`

Provides a series of functions to “*tidy-up*” your data, including

- re-shape your data
  - `tidyr::pivot_wider`: pivot from long to wide
  - `tidyr::pivot_longer`: pivot from wide to long
- handle missing values
  - `tidyr::drop_na`: remove rows with missing data
  - `tidyr::replace_na`: replace missing data
  - `tidyr::fill`: fill missing data
  - `tidyr::complete`: add missing value combinations

## 11.6 `tidyr::pivot_wider`

Re-shape from **long** to **wide** format

```
city_info_wide <-
  city_info_long %>%
  tidyr::pivot_wider(
    # Column from which to extract new column names
    names_from = week_ending,
    # Column from which to extract values
    values_from = cases
  )
```

city	2020-10-03	2020-10-10
Derby	NA	320
Leicester	473	616
Nottingham	1701	NA

## 11.7 `tidyr::pivot_wider`

It might be useful (or indeed necessary) to **format** the values that will become the names of the new columns

```
city_info_wide <- city_info_long %>% dplyr::mutate(
  # Change "--" to "_" in the string representing the dates
  week_ending = stringr::str_replace_all(week_ending, "--", "_")
) %>%
  tidyr::pivot_wider(
    names_from = week_ending, values_from = cases, # As before
    names_prefix = "cases_" # Add a prefix
) # Apologies for bad coding style, need to fit code in slide :)
```

city	cases_2020_10_03	cases_2020_10_10
Derby	NA	320
Leicester	473	616
Nottingham	1701	NA

## 11.8 tidyr::pivot\_longer

Re-shape from **wide** to **long** format

```
city_info_back_to_long <- city_info_wide %>%
  tidyr::pivot_longer(
    cols = -city, # Pivot all columns, excluding city
    names_to = "week_ending", # Name column for column names
    values_to = "cases" # Name column for values
  ) # Again, not best formatting, sorry _-_'
```

city	week_ending	cases
Derby	cases_2020_10_03	NA
Derby	cases_2020_10_10	320
Leicester	cases_2020_10_03	473
Leicester	cases_2020_10_10	616
Nottingham	cases_2020_10_03	1701
Nottingham	cases_2020_10_10	NA

## 11.9 tidyr::pivot\_longer

It might be useful (or indeed necessary) to **format** the values extracted from the column names

```
city_info_back_to_long <- city_info_wide %>%
  tidyr::pivot_longer(
    # As before
    cols = -city, names_to = "week_ending", values_to = "cases",
    # Remove name prefix
    names_prefix = "cases_",
    # Transform the values that will become column names
    # list of new column names <-> functions to apply
    names_transform = list(
      # Provide a function name or define one
      week_ending = function (x) {
        stringr::str_replace_all(x, "_", "-")
      }
    )
  ) # I usually format my code decently, I promise
```

## 11.10 tidyr::pivot\_longer

... which brings us back exactly where we started.

city	week_ending	cases
Derby	2020-10-03	NA
Derby	2020-10-10	320
Leicester	2020-10-03	473
Leicester	2020-10-10	616
Nottingham	2020-10-03	1701
Nottingham	2020-10-10	NA

## 11.11 tidyverse

The **tidyverse** (pronounced *tidy-er*) library is part of **tidyverse**

Provides a series of functions to “*tidy-up*” your data, including

- re-shape your data
  - `tidyr::pivot_wider`: pivot from long to wide
  - `tidyr::pivot_longer`: pivot from wide to long
- handle missing values
  - `tidyr::drop_na`: remove rows with missing data
  - `tidyr::replace_na`: replace missing data
  - `tidyr::fill`: fill missing data
  - `tidyr::complete`: add missing value combinations

## 11.12 tidyverse::replace\_na

If the data allow for a baseline value, missing values can be replaced

```
city_info_long %>%
  tidyverse::replace_na(
    # List of columns <-> values to replace NA
    list(cases = 0)
  )
```

city	week_ending	cases
Derby	2020-10-03	0
Leicester	2020-10-03	473
Nottingham	2020-10-03	1701
Derby	2020-10-10	320
Leicester	2020-10-10	616
Nottingham	2020-10-10	0

## 11.13 tidyverse::fill

Sometimes it can make sense to **fill** missing values using “*nearby*” values, but **caution**, order and grouping matter!

```
city_info_long %>%
  dplyr::group_by(city) %>%
  dplyr::arrange(week_ending) %>%
  # Columns to fill
  tidyverse::fill(cases)
```

city	week_ending	cases
Derby	2020-10-03	NA
Leicester	2020-10-03	473
Nottingham	2020-10-03	1701
Derby	2020-10-10	320
Leicester	2020-10-10	616
Nottingham	2020-10-10	1701

## 11.14 tidyverse::drop\_na

In other cases, it might be simpler or safer to just **remove** all the rows with missing data

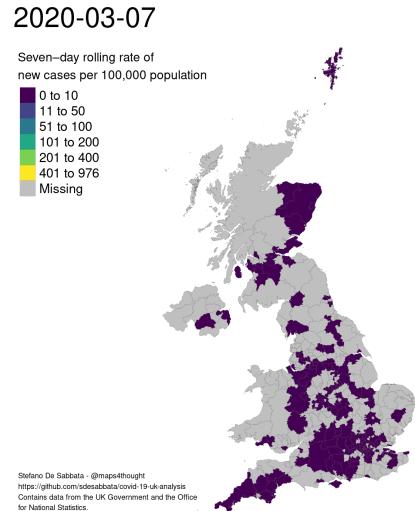
```
city_info_long_noNAs <-
  city_info_long %>%
  # Columns to drop where NA
  tidyverse::drop_na(cases)
```

city	week_ending	cases
Leicester	2020-10-03	473
Nottingham	2020-10-03	1701
Derby	2020-10-10	320
Leicester	2020-10-10	616

## 11.15 tidyverse::complete

Finally, some analysis or visualisation procedures might require a *complete* table

- where missing values are represented as NAs
- for instance, when creating a map (as in this example)
  - you might want to use a specific colour for missing values
  - rather than a missing polygon



## 11.16 tidy::complete

Complete table by turning implicit missing values into explicit missing values

```
city_info_long_noNAs %>%
  # Complete table with all week_ending and city combinations
  # making missing values for remaining columns explicit
  tidyr::complete(week_ending, city)
```

city	week_ending	cases
Derby	2020-10-03	NA
Derby	2020-10-10	320
Leicester	2020-10-03	473
Leicester	2020-10-10	616
Nottingham	2020-10-03	1701
Nottingham	2020-10-10	NA

## 11.17 Summary

Tidy-up your data

- Wide and long data
- Re-shape data
- Handle missing values

Next: Read and write data

- file formats
- read

- write

# Chapter 12

## Read and write data

### 12.1 Summary

Tidy-up your data

- Wide and long data
- Re-shape data
- Handle missing values

Next: Read and write data

- file formats
- read
- write

### 12.2 Text file formats

A series of formats based on plain-text files

For instance

- comma-separated values files .csv
- semi-colon-separated values files .csv
- tab-separated values files .tsv
- other formats using custom delimiters
- fix-width files .fwf

### 12.3 Comma Separated Values

The file `2011_OAC_supgrp_Leicester.csv` contains

- one row for each Output Area (OA) in Leicester

- Lower-Super Output Area (LSOA) containing the OA
- code and name of the supergroup assigned to the OA by the 2011 Output Area Classification
- total population of the OA

Extract showing only the first few rows

```
OA11CD,LSOA11CD,supgrpcode,supgrpname,Total_Population
E00069517,E01013785,6,Suburbanites,313
E00069514,E01013784,2,Cosmopolitans,323
E00169516,E01013713,4,Multicultural Metropolitans,341
E00169048,E01032862,4,Multicultural Metropolitans,345
```

## 12.4 readr

The `readr` (pronounced *read-er*) library is part of `tidyverse`

Provides functions to read and write text files

- `readr::read_csv`: comma-separated files `.csv`
- `readr::read_csv2`: semi-colon-separated files `.csv`
- `readr::read_tsv`: tab-separated files `.tsv`
- `readr::read_fwf`: fix-width files `.fwf`
- `readr::read_delim`: files using a custom delimiter

and their *write* counterpart, such as

- `readr::write_csv`: comma-separated files `.csv`

## 12.5 readr::read\_csv

The `readr::read_csv` function of the `readr` library reads a `csv` file from the path provided as the first argument

```
leicester_2011OAC <-
  readr::read_csv("2011_OAC_supgrp_Leicester.csv")

leicester_2011OAC

## # A tibble: 969 x 5
##   OA11CD  LSOA11CD supgrpcode supgrpname    Total_Population
##   <chr>   <chr>      <dbl> <chr>          <dbl>
## 1 E00069~ E010137~       6 Suburbanites     313
## 2 E00069~ E010137~       2 Cosmopolitans    323
## 3 E00169~ E010137~       4 Multicultural~    341
## # ... with 966 more rows
```

## 12.6 Read options

Read functions provide options about how to interpret a file contents

- For instance, `readr::read_csv`
  - `col_names`:
    - \* TRUE or FALSE whether top row is column names
    - \* or a vector of column names
  - `col_types`:
    - \* a `cols()` specification or a string
  - `skip`: lines to skip before reading data
  - `n_max`: max number of record to read

## 12.7 Column specifications

- `col_logical()` or `l` as logic values
- `col_integer()` or `i` as integer
- `col_double()` or `d` as numeric (double)
- `col_character()` or `c` as character
- `col_factor(levels, ordered)` or `f` as factor
- `col_date(format = "")` or `D` as data type
- `col_time(format = "")` or `t` as time type
- `col_datetime(format = "")` or `T` as datetime
- `col_number()` or `n` as numeric (dropping marks)
- `col_skip()` or `_` or `-` don't import
- `col_guess()` or `?` use best type based on the input

## 12.8 `readr::read_csv`

Using `readr::read_csv` as in the previous example with no further options will generate the following warning

```
leicester_2011OAC <-
  readr::read_csv("2011_OAC_supgrp_Leicester.csv")
```

```
leicester_2011OAC
```

```
Parsed with column specification:
cols(
  OA11CD = col_character(),
  LSOA11CD = col_character(),
  supgrpcode = col_double(),
  supgrpname = col_character(),
  Total_Population = col_double()
)
```

## 12.9 readr::read\_csv

```
leicester_2011OAC <- readr::read_csv(
  "2011_OAC_supgrp_Leicester.csv",
  col_types = cols(
    OA11CD = col_character(),
    LSOA11CD = col_character(),
    supgrpcode = col_character(),
    supgrpname = col_character(),
    Total_Population = col_integer()
  )
)

## # A tibble: 969 x 5
##   OA11CD  LSOA11CD supgrpcode supgrpname   Total_Population
##   <chr>    <chr>     <chr>      <chr>                <int>
## 1 E00069~ E010137~ 6        Suburbanites       313
## 2 E00069~ E010137~ 2        Cosmopolitans      323
## 3 E00169~ E010137~ 4        Multicultura~     341
## # ... with 966 more rows
```

## 12.10 readr::read\_csv

```
leicester_2011OAC <- readr::read_csv(
  "2011_OAC_supgrp_Leicester.csv",
  col_types = "cccci"
)

## # A tibble: 969 x 5
##   OA11CD  LSOA11CD supgrpcode supgrpname   Total_Population
##   <chr>    <chr>     <chr>      <chr>                <int>
## 1 E00069~ E010137~ 6        Suburbanites       313
## 2 E00069~ E010137~ 2        Cosmopolitans      323
## 3 E00169~ E010137~ 4        Multicultura~     341
## 4 E00169~ E010328~ 4        Multicultura~     345
## 5 E00169~ E010328~ 4        Multicultura~     322
## 6 E00069~ E010136~ 4        Multicultura~     334
## 7 E00169~ E010328~ 4        Multicultura~     336
## # ... with 962 more rows
```

## 12.11 readr::write\_csv

The function `write_csv` can be used to save a dataset to csv

Example:

1. **read** the 2011 OAC dataset
2. **select** a few columns
3. **filter** only those OA in the supergroup *Suburbanites* (code 6)
4. **write** the results to a file named *2011\_OAC\_supgrp\_Leicester\_supgrp6.csv*

```
readr::read_csv("2011_OAC_supgrp_Leicester.csv") %>%
  dplyr::select(OA11CD, supgrpcode, Total_Population) %>%
  dplyr::filter(supgrpcode == "6") %>%
  readr::write_csv("2011_OAC_supgrp_Leicester_supgrp6.csv")
```

## 12.12 readr::write\_tsv

```
readr::read_csv("2011_OAC_supgrp_Leicester.csv") %>%
  dplyr::select(OA11CD, supgrpcode, Total_Population) %>%
  dplyr::filter(supgrpcode == "6") %>%
  readr::write_tsv("2011_OAC_supgrp_Leicester_supgrp6.tsv")
```

OA11CD	supgrpcode	Total_Population
E00069517	6	313
E00069468	6	251
E00069528	6	270
E00069538	6	307
E00069174	6	321
E00069170	6	353
E00069171	6	351
E00068713	6	265
E00069005	6	391
E00069014	6	316
E00068989	6	354

## 12.13 Other data imports

Tidyverse also imports other packages for reading data

- Tabular formats
  - **readxl** for Excel (.xls and .xlsx)
  - **haven** for SPSS, Stata, and SAS data.
- Databases
  - **DBI** for relational databases
- NoSQL
  - **jsonlite** for JSON
  - **xml2** for XML
- Web
  - **httr** for web APIs

## 12.14 Summary

Read and write data

- file formats
- read
- write

**N**ext: Practical session

- Read and write data
- Tidy data
- Join operations

# Chapter 13

# Reproducibility

## 13.1 Recap

Prev: Table operations

- 211 Join operations
- 212 Data pivot
- 213 Read and write data
- 214 Practical session

Now: Reproduciblity

- Reproduciblity and software engineering
- Reproduciblity in GIScience
- Guidelines

## 13.2 Reproduciblity

In quantitative research, an analysis or project are considered to be **reproducible** if:

- “*the data and code used to make a finding are available and they are sufficient for an independent researcher to recreate the finding.*” Christopher Gandrud, *Reproducible Research with R and R Studio*

That is becoming more and more important in science:

- as programming and scripting are becoming integral in most disciplines
- as the amount of data increases

### 13.3 Why?

In **scientific research**:

- verifiability of claims through replication
- incremental work, avoid duplication

For your **working practice**:

- better working practices
  - coding
  - project structure
  - versioning
- better teamwork
- higher impact (not just results, but code, data, etc.)

### 13.4 Reproducibility and software engineering

Core aspects of **software engineering** are:

- project design
- software **readability**
- testing
- **versioning**

As programming becomes integral to research, similar necessities arise among scientists and data analysts.

### 13.5 Reproducibility and “big data”

There has been a lot of discussions about “**big data**”...

- volume, velocity, variety, ...

Beyond the hype of the moment, as the **amount** and **complexity** of data increases

- the time required to replicate an analysis using point-and-click software becomes unsustainable
- room for error increases

Workflow management software (e.g., ArcGIS ModelBuilder) is one answer, reproducible data analysis based on script languages like R is another.

### 13.6 Reproducibility in GIScience

Singleton *et al.* have discussed the issue of reproducibility in GIScience, identifying the following best practices:

1. Data should be accessible within the public domain and available to researchers.
2. Software used should have open code and be scrutable.
3. Workflows should be public and link data, software, methods of analysis and presentation with discursive narrative
4. The peer review process and academic publishing should require submission of a workflow model and ideally open archiving of those materials necessary for replication.
5. Where full reproducibility is not possible (commercial software or sensitive data) aim to adopt aspects attainable within circumstances

## 13.7 Document everything

In order to be reproducible, every step of your project should be documented in detail

- data gathering
- data analysis
- results presentation

Well documented R scripts are an excellent way to document your project.

## 13.8 Document well

Create code that can be **easily understood** by someone outside your project, including yourself in six-month time!

- use a style guide (e.g. tidyverse) consistently
- also add a **comment** before any line that could be ambiguous or particularly difficult or important
- add a **comment** before each code block, describing what the code does
- add a **comment** at the beginning of a file, including
  - date
  - contributors
  - other files the current file depends on
  - materials, sources and other references

## 13.9 Workflow

Relationships between files in a project are not simple:

- in which order are file executed?
- when to copy files from one folder to another, and where?

A common solution is using **make files**

- commonly written in *bash* on Linux systems

- they can be written in R, using commands like
  - *source* to execute R scripts
  - *system* to interact with the operative system

## 13.10 granolarr Mark.R

Section of the *granolarr* project make file Make.R that generates the current slides for the lecture session 221

```
cat("\n\n">>>> Rendering 221_L_Reproducibility.Rmd <<<\n\n")
rmarkdown::render(
  paste0(
    Sys.getenv("GRANOLARR_HOME"),
    "/src/lectures/221_L_Reproducibility.Rmd"
  ),
  quiet = TRUE,
  output_dir = paste0(
    Sys.getenv("GRANOLARR_HOME"),
    "/docs/lectures/html"
  )
)
```

## 13.11 Future-proof formats

Complex formats (e.g., .docx, .xlsx, .shp, ArcGIS .mxd)

- can become obsolete
- are not always portable
- usually require proprietary software

Use the simplest format to **future-proof** your analysis. **Text files** are the most versatile

- data: .txt, .csv, .tsv
- analysis: R scripts, python scripts
- write-up: LaTeX, Markdown, HTML

## 13.12 Store and share

Reproducible data analysis is particularly important when working in teams, to share and communicate your work.

- Dropbox
  - good option to work in teams, initially free
  - no versioning, branches
- Git

- free and opensource control system
- great to work in teams and share your work publically
- can be more difficult at first
- GitHub public repositories are free, private ones are not
- GitLab offers free private repositories

## 13.13 This repository

The screenshot shows the GitHub repository page for `sdesabbata/granolarr`. The repository has 199 commits across 1 branch and 1 tag. The commit history is as follows:

- `DockerConfig`: Made using Rscript 2 months ago
- `data`: Revised practical 214 6 days ago
- `docs`: Revised practical 214 6 days ago
- `src`: Revised practical 214 6 days ago
- `gffattributes`: Added gffattributes 12 months ago
- `gitignore`: Updated profile picture 24 days ago
- `Docker_Build.sh`: Docker setup 2 months ago
- `Docker_Make.sh`: Added Docker RStudio start and stop scripts 2 months ago
- `Docker_Make_WinPowerShell.sh`: Added PowerShell version of Docker\_Make 2 months ago
- `Docker_RSStudio_Start.sh`: Added Docker RStudio start and stop scripts 2 months ago
- `Docker_RSStudio_Start_WinPowerS...`: Added Docker RStudio start and stop scripts 2 months ago
- `Docker_RSStudio_Stop.sh`: Added Docker RStudio start and stop scripts 2 months ago
- `Dockerfile`: Made using Rscript 2 months ago
- `LICENSE`: Initial Commit 12 months ago
- `Make.R`: Renamed Lecture 212 as TidyData 9 days ago
- `Make_Clean.R`: Make clean remove lectures and practicals folders in root dir 2 months ago
- `README.md`: Renamed Lecture 212 as TidyData 9 days ago
- `granolarr.Rproj`: Created R project 12 months ago

**About**: A reproducible resource for teaching geographic data science in R  
**Releases**: No releases published  
**Packages**: No packages published  
**Contributors**: Stefano De Sabbata, Robinlovelace Robin  
**Languages**: R 82.4%, Dockerfile 4.0%, Shell 4.3%, Text 7.3%

[github.com/sdesabbata/granolarr](https://github.com/sdesabbata/granolarr)

## 13.14 Summary

Reproduciblity

- Reproduciblity and software engineering
- Reproduciblity in GIScience
- Guidelines

Next: RMarkdown

- Markdown
- RMarkdown



# Chapter 14

## RMarkdown

### 14.1 Recap

Prev: Reproduciblity

- Reproduciblity and software engineering
- Reproduciblity in GIScience
- Guidelines

Now: RMarkdown

- Markdown
- RMarkdown

### 14.2 Markdown

**Markdown** is a simple markup language

- allows to mark-up plain text
- to specify more complex features (such as *italics text*)
- using a very simple syntax

Markdown can be used in conjunction with numerous tools

- to produce HTML pages
- or even more complex formats (such as PDF)

These slides are written in Markdown

### 14.3 Markdown example code

```
### This is a third level heading
```

```
Text can be specified as *italic* or **bold**
```

- and list can be created
    - very simply
1. also numbered lists
    1. [add a link like this] (<http://le.ac.uk>)

Tables	Can	Be
a bit	complicated	at first
but	it gets	easier

## 14.4 Markdown example output

### 14.4.1 This is a third level heading

Text can be specified as *italic* or **bold**

- and list can be created
    - very simply
1. also numbered lists
    1. add a link like this

Tables	Can	Be
a bit	complicated	at first
but	it gets	easier

## 14.5 RMarkdown

The rmarkdown library and its RStudio plug-in

- provide functionalities to *compile* scripts containing
  - **Markdown** text
    - \* rendered to documents (e.g., *.pdf* and *.doc*)
  - chunks of **R** code (other supported, e.g., Python, SQL)
    - \* included in output document
    - \* interpreted
    - \* results included in output document

```
```{r, echo=TRUE}
# Example of R chunck
sqrt(2)
```
```

## 14.6 RMarkdown example

Content of an RMarkdown file: `First_example.Rmd`

This is an **RMarkdown** document. The *code chunk* below:

```
- loads the necessary libraries
- loads the flights from New York City in 2013
- presents a few columns from the first row

```{r, echo=TRUE, message=FALSE, warning=FALSE}
library(tidyverse)
library(nycflights13)

nycflights13::flights %>%
  dplyr::select(year:day, origin, dest, flight) %>%
  dplyr::slice_head(1) %>%
  knitr::kable()
```

```

## 14.7 RMarkdown example

This is an **RMarkdown** document. The *code chunk* below:

- loads the necessary libraries
- loads the flights from New York City in 2013
- presents a few columns from the first row

```
library(tidyverse)
library(nycflights13)

nycflights13::flights %>%
  dplyr::select(year:day, origin, dest, flight) %>%
  dplyr::slice_head(1) %>%
  knitr::kable()
```

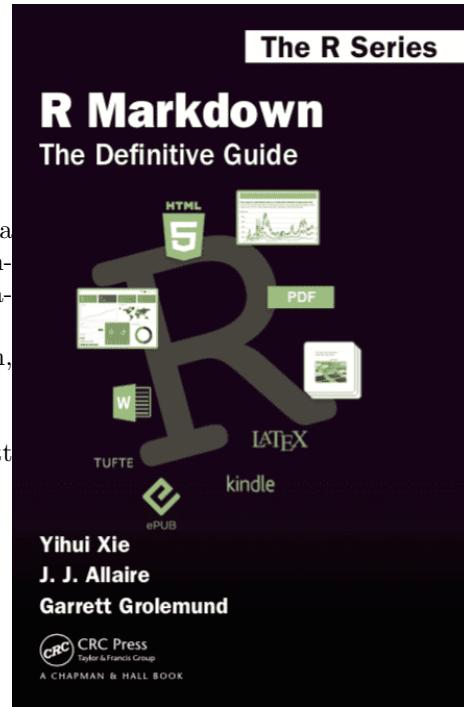
| year | month | day | origin | dest | flight |
|------|-------|-----|--------|------|--------|
| 2013 | 1     | 1   | EWR    | IAH  | 1545   |

## 14.8 The Definitive Guide

Markdown is a rather simple for a markup language, but still fairly complex, especially when used in combination with R.

For an complete guide to RMarkdown, please see:

R Markdown: The Definitive Guide  
by Yihui Xie, J. J. Allaire, Garrett Grolemund.



## 14.9 Summary

RMarkdown

- Markdown
- RMarkdown

**Next:** Git and Docker

- Git operations
- Git and RStudio
- Docker

# Chapter 15

## Git

### 15.1 Recap

RMarkdown

- Markdown
- RMarkdown

Next: Git and Docker

- Git operations
- Git and RStudio
- Docker

### 15.2 What's git?

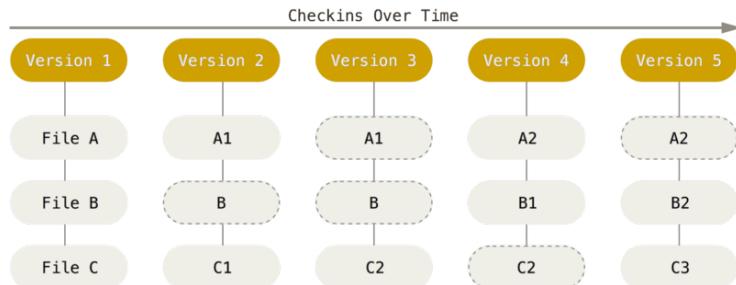
Git is a free and opensource version control system

- commonly used through a server
  - where a master copy of a project is kept
  - can also be used locally
- allows storing versions of a project
  - syncronisation
  - consistency
  - history
  - multiple branches

### 15.3 How git works

A series of snapshots

- each commit is a snapshot of all files
- if no change to a file, link to previous commit
- all history stored locally

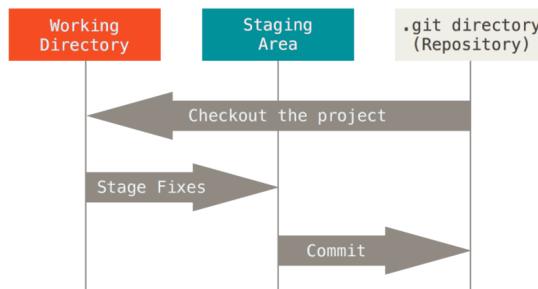


by Scott Chacon and Ben Straub, licensed under CC BY-NC-SA 3.0

## 15.4 Three stages

When working with a git repository

- first checkout the latest version
- select the edits to stage
- commit what has been staged in a permanent snapshot



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## 15.5 Basic git commands

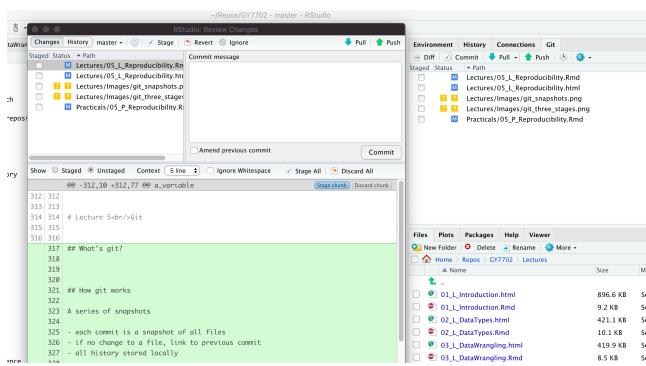
- `git clone`
  - copy a repository from a server
- `git fetch`
  - get the latest version from a branch
- `git pull`
  - incorporate changes from a remote repository
- `git add`
  - stage new files

- `git commit`
  - create a commit
- `git push`
  - upload commits to a remote repository

## 15.6 Git and RStudio

RStudio includes a git plug-in

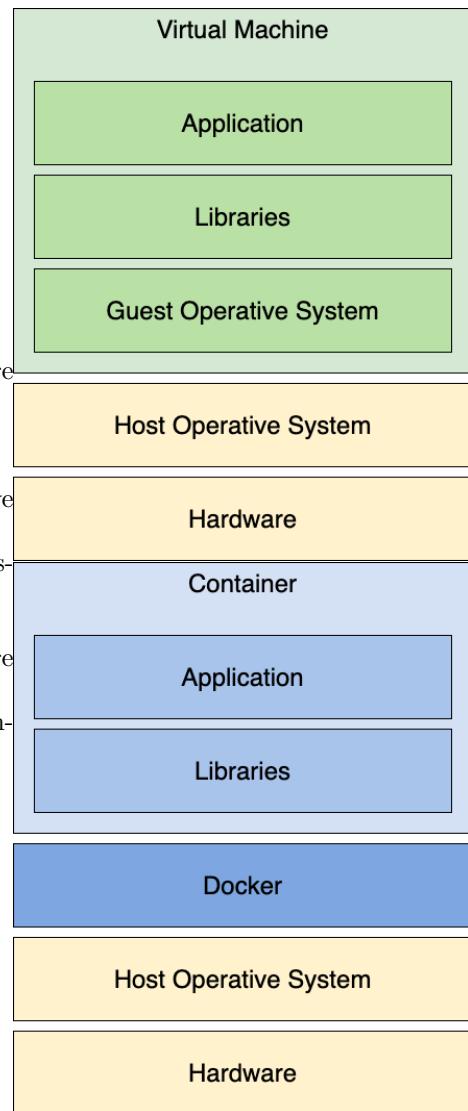
- clone R projects from repositories
- stage and commit changes
- push and pull changes



## 15.7 What's Docker?

Docker allows to encapsulate and share computational environments

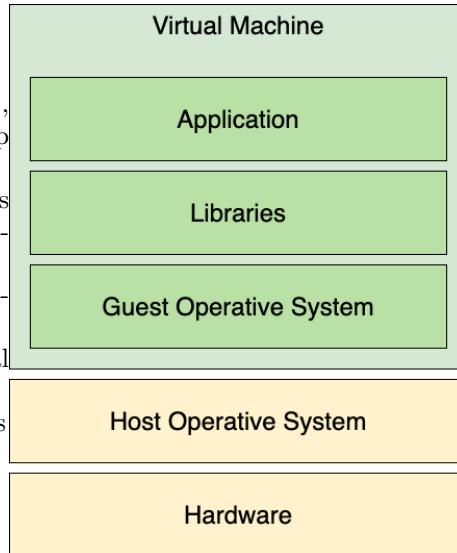
- First released in 2013
- Similar to virtual machines
  - simulates a guest operative system
  - within a host operative system
- Lightweight
  - doesn't simulate an entire system
  - only the “*user space*” is simulated



## 15.8 Virtual machines

Virtual machines software (e.g., VMWare) simulate a computer on top of your operative system

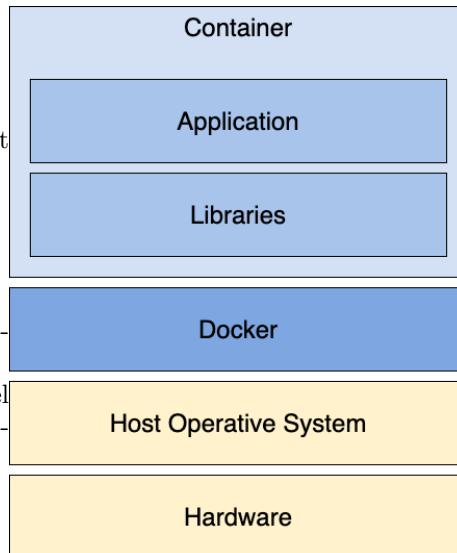
- allows **virtual machine** to access physical resources (e.g., disk, keyboard) of a **host**
- allows to run full operative systems
- e.g., run a full Windows virtual machine on a Mac host
- have been around since the 1970s
- can be *heavy* to run



## 15.9 Docker containers

Docker runs *containers*

- developed for flexible deployment of (web) services
  - compartmentalised
  - lightweight
  - (frequently) transient
- **kernel** is not simulated
  - kernels are the bulk of operative systems
  - containers share host's kernel
  - can also share binaries and libraries



## 15.10 Docker and reproducibility

Why are dockers useful for reproducibility?

One of the key issues of reproducing a study is replicating the computational environment used

- e.g., all the libraries in their correct version

Creating a Docker image (from which a container is instantiated)

- defined using a *Dockerfile*
- requires to list a full system configuration
  - version of programming language, libraries, etc
- once created / defined
  - other researchers or developers can run your script **in the exact same computational environment**

## 15.11 granolarr Dockerfile

```
# Base image https://hub.docker.com/r/rocker/ml
FROM rocker/geospatial:4.0.2

# create an R user
ENV USER rstudio

## Install additional required R libraries
COPY ./DockerConfig/Requirements.R /tmp/Requirements.R
RUN Rscript /tmp/Requirements.R

## Install additional required TeX libraries
RUN tlmgr install amsmath
RUN tlmgr install latex-amsmath-dev
RUN tlmgr install iftex
RUN tlmgr install euenc
RUN tlmgr install fontspec
[... continues]
```

## 15.12 Summary

Git and Docker

- Git operations
- Git and RStudio
- Docker

**Next:** Practical

- Reproducible data analysis
- RMarkdown
- Git

# Chapter 16

## Data visualisation

### 16.1 Recap

Prev: Reproducibility

- 221 Reproducibility
- 222 R and Markdown
- 223 Git
- 224 Practical session

Now: Data visualisation

- Grammar of graphics
- ggplot2

### 16.2 Grammar of graphics

Grammars provide rules for languages

*“The grammar of graphics takes us beyond a limited set of charts (words) to an almost unlimited world of graphical forms (statements)”* (Wilkinson, 2005)

Statistical graphic specifications are expressed in six statements:

1. **Data** manipulation
2. **Variable** transformations (e.g., rank),
3. **Scale** transformations (e.g., log),
4. **Coordinate system** transformations (e.g., polar),
5. **Element**: mark (e.g., points) and visual variables (e.g., color)
6. **Guides** (axes, legends, etc.).

### 16.3 Visual variables

A **visual variable** is an aspect of a **mark** that can be controlled to change its appearance.

Visual variables include:

- Size
- Shape
- Orientation
- Colour (hue)
- Colour value (brightness)
- Texture
- Position (2 dimensions)

### 16.4 ggplot2

The **ggplot2** library offers a series of functions for creating graphics **declaratively**, based on the Grammar of Graphics.

To create a graph in **ggplot2**:

- provide the data
- specify elements
  - which visual variables (**aes**)
  - which marks (e.g., **geom\_point**)
- apply transformations
- guides

### 16.5 Aesthetics

The **aes** element provides a “*mapping*” from the data *columns* (attributes) to the graphic’s *visual variables*, including:

- **x** and **y**
- **fill** (fill colour) and **colour** (border colour)
- **shape**
- **size**

```
data %>%
  ggplot2::ggplot(
    aes(
      x = column_1,
      y = column_2
    )
  )
```

## 16.6 Graphical primitives

Marks (graphical primitives) can be specified through a series of functions, such as `geom_line`, `geom_bar` or `geom_point`

These can be added to the construction of the graph using `+`

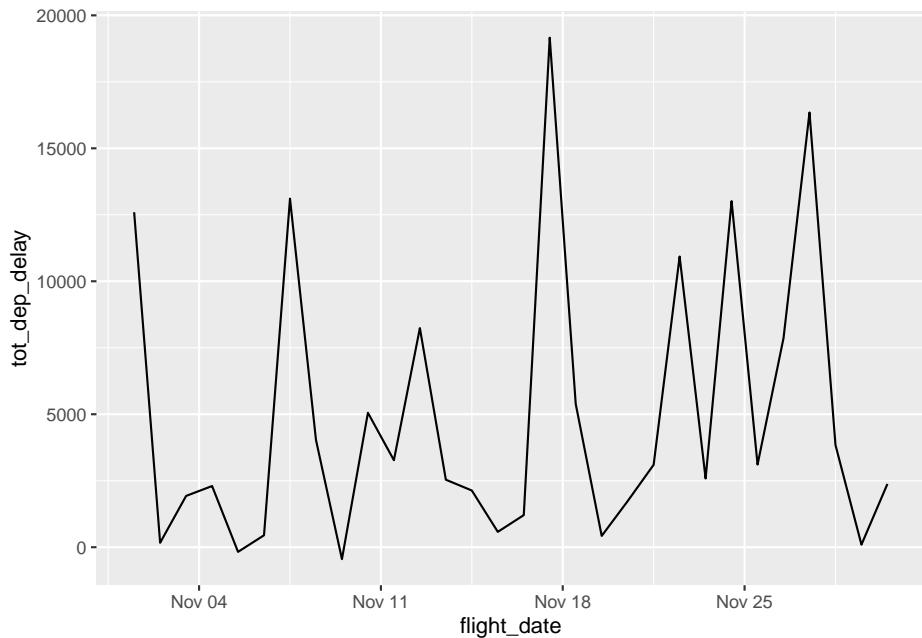
```
ggplot2::ggplot(
  aes(
    x = column_1, y = column_2
  )
) +
  ggplot2::geom_line()
```

## 16.7 ggplot2::geom\_line

- x: a column to “map” to the x-axis, e.g. days (category)
- y: a column to “map” to the y-axis, e.g. delay (continuous)
- `ggplot2::geom_line`: line mark (graphical primitive)

```
nycflights13::flights %>%
  dplyr::filter(!is.na(dep_delay) & month == 11) %>%
  dplyr::mutate(flight_date = ISOdate(year, month, day)) %>%
  dplyr::group_by(flight_date) %>%
  dplyr::summarize(tot_dep_delay = sum(dep_delay)) %>%
  ggplot2::ggplot(aes(
    x = flight_date,
    y = tot_dep_delay
  )) +
  ggplot2::geom_line()
```

## 16.8 ggplot2::geom\_line

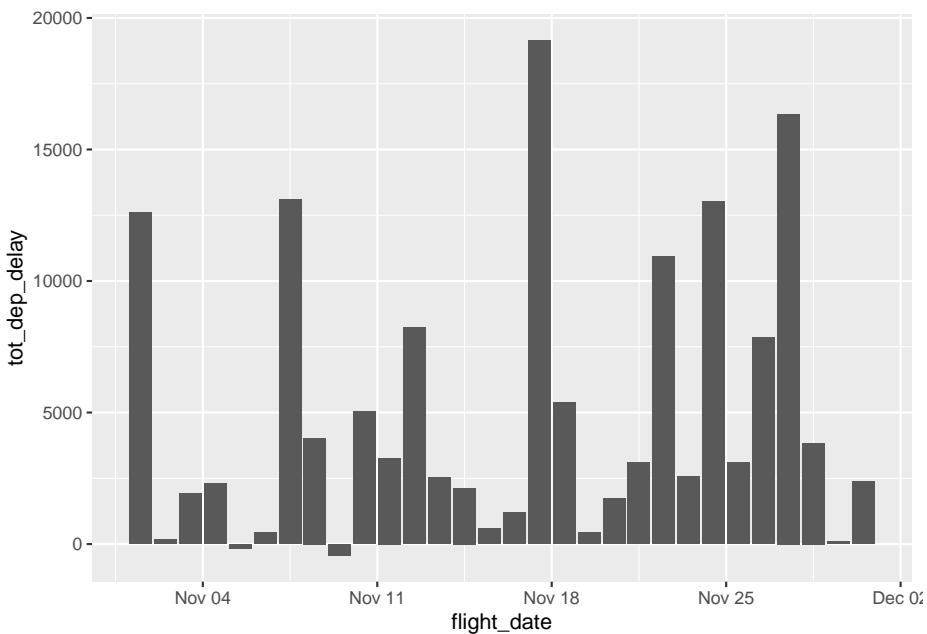


## 16.9 ggplot2::geom\_col

- x: a column to “map” to the x-axis, e.g. days (category)
- y: a column to “map” to the y-axis, e.g. delay (continuous)
- ggplot2::geom\_col: bar mark (graphical primitive)
  - ggplot2::geom\_bar instead illustrates count per category

```
nycflights13::flights %>%
  dplyr::filter(!is.na(dep_delay) & month == 11) %>%
  dplyr::mutate(flight_date = ISOdate(year, month, day)) %>%
  dplyr::group_by(flight_date) %>%
  dplyr::summarize(tot_dep_delay = sum(dep_delay)) %>%
  ggplot2::ggplot(aes(
    x = flight_date,
    y = tot_dep_delay
  )) +
  ggplot2::geom_col()
```

## 16.10 ggplot2::geom\_col



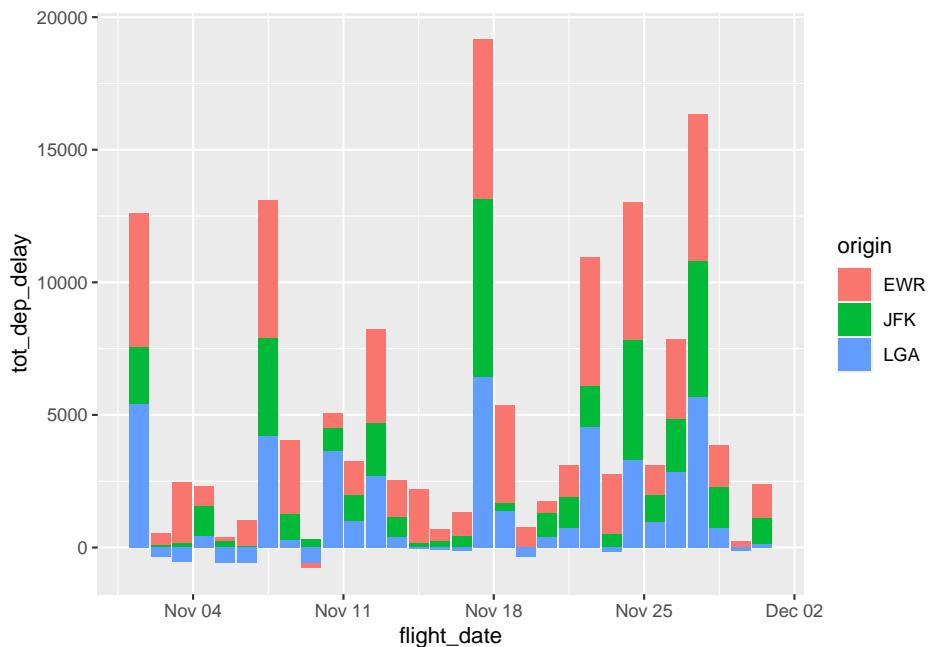
## 16.11 ggplot2::geom\_col

... then, why not add some colour?

- **fill:** a column to “map” to the visual variable *colour* as fill of the mark, e.g. origin (category)
  - *colour* can be used to “map” a column to the visual variable *colour* as border of the mark

```
nycflights13::flights %>%
  dplyr::filter(!is.na(dep_delay) & month == 11) %>%
  dplyr::mutate(flight_date = ISOdate(year, month, day)) %>%
  dplyr::group_by(flight_date, origin) %>%
  dplyr::summarize(tot_dep_delay = sum(dep_delay)) %>%
  ggplot2::ggplot(aes(
    x = flight_date,
    y = tot_dep_delay,
    fill = origin
  )) +
  ggplot2::geom_col()
```

## 16.12 ggplot2::geom\_col

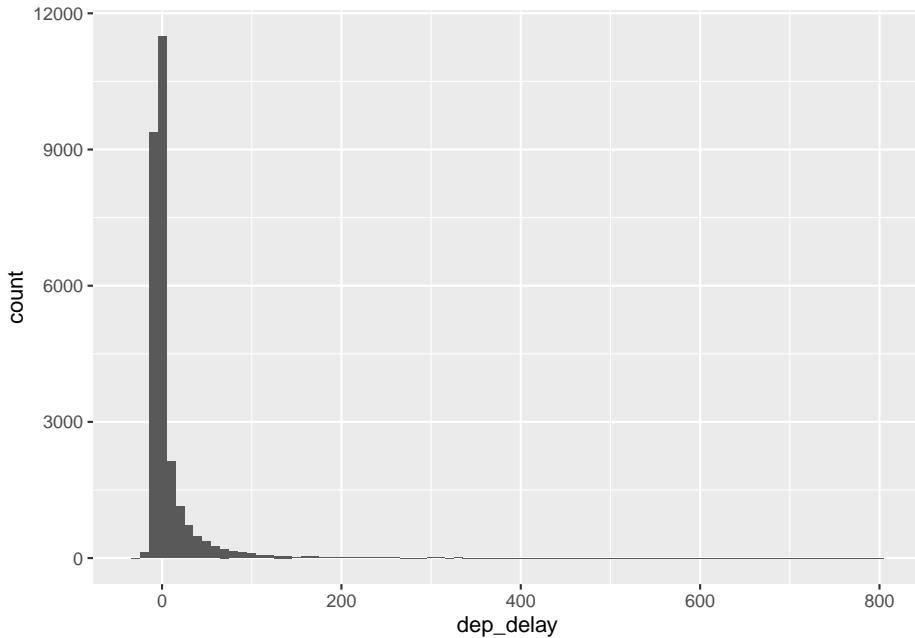


## 16.13 Histograms

- x a column to “map” to the x-axis, e.g. delay (continuous)
- `ggplot2::geom_histogram` to illustrate count over intervals of continuous variable on x-axis
  - `ggplot2::geom_bar` instead illustrates count per category

```
nycflights13::flights %>%
  dplyr::filter(month == 11) %>%
  ggplot2::ggplot(
    aes(
      x = dep_delay
    )
  ) +
  ggplot2::geom_histogram(
    binwidth = 10
  )
```

## 16.14 Histograms



```
...  
nycflights13::flights %>%  
  filter(month == 11) %>%  
  ggplot2::ggplot(  
    aes(  
      x = distance  
    )  
  ) +  
  ggplot2::geom_histogram() +  
  scale_x_log10()
```

## 16.15 Boxplots

- x: a column to “map” to the x-axis, e.g. carrier (category)
- y: a column to “map” to the y-axis, e.g. delay (continuous)
- geom\_boxplot: to illustrate distribution of continuous variable on y-axis per each category on x-axis

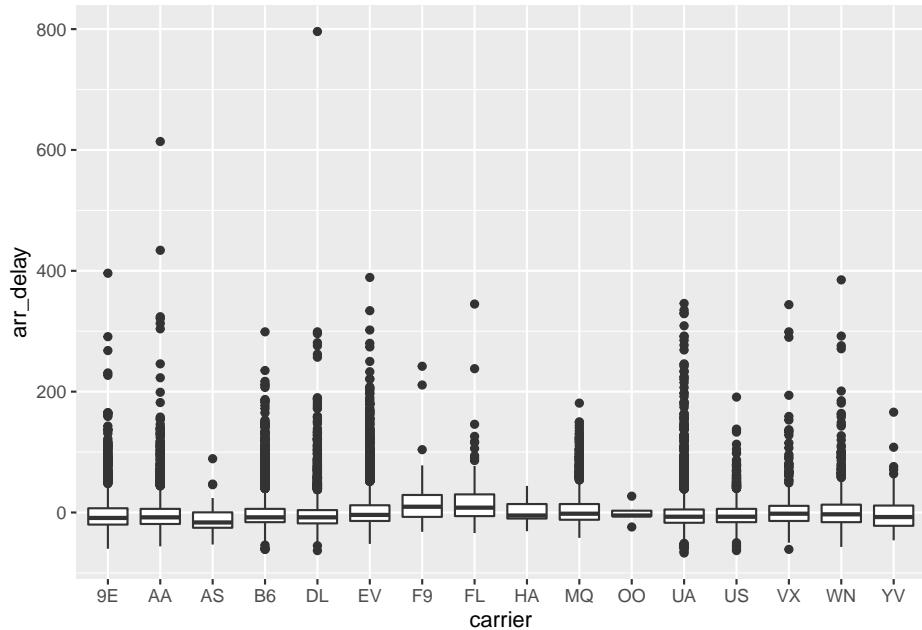
```
nycflights13::flights %>%  
  dplyr::filter(month == 11) %>%  
  ggplot2::ggplot(  
    aes(  
      x = carrier,
```

```

    y = arr_delay
)
) +
ggplot2::geom_boxplot()

```

## 16.16 Boxplots



## 16.17 Jittered points

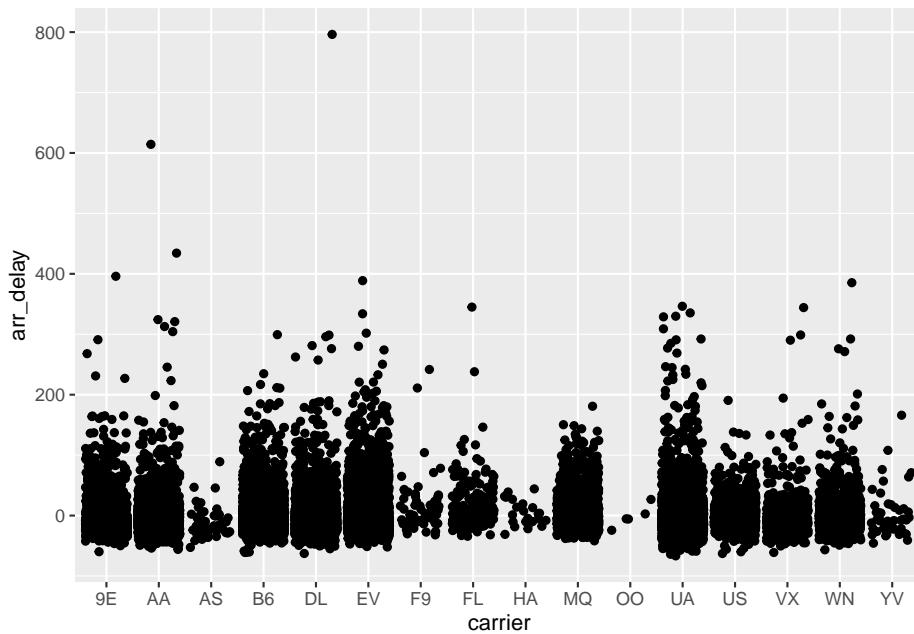
- x categorical variable
- y variable to plot
- geom\_jitter

```

nycflights13::flights %>%
dplyr::filter(month == 11) %>%
ggplot2::ggplot(
  aes(
    x = carrier,
    y = arr_delay
  )
) +
ggplot2::geom_jitter()

```

## 16.18 Jittered points

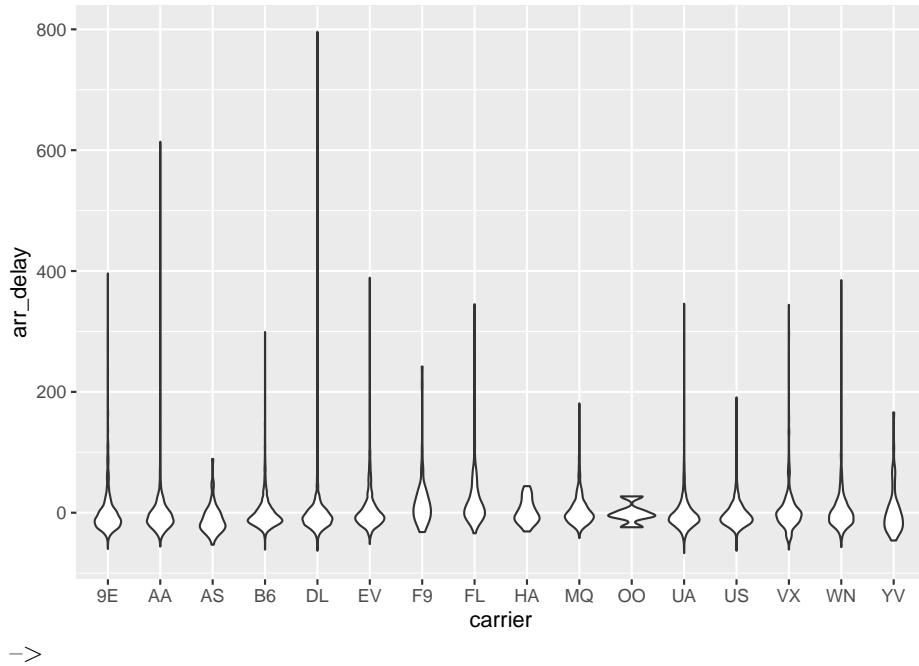


## 16.19 Violin plot

- x categorical variable
- y variable to plot
- geom\_violin

```
nycflights13::flights %>%
  dplyr::filter(month == 11) %>%
  ggplot2::ggplot(
    aes(
      x = carrier,
      y = arr_delay
    )
  ) +
  ggplot2::geom_violin()
```

## 16.20 Violin plot



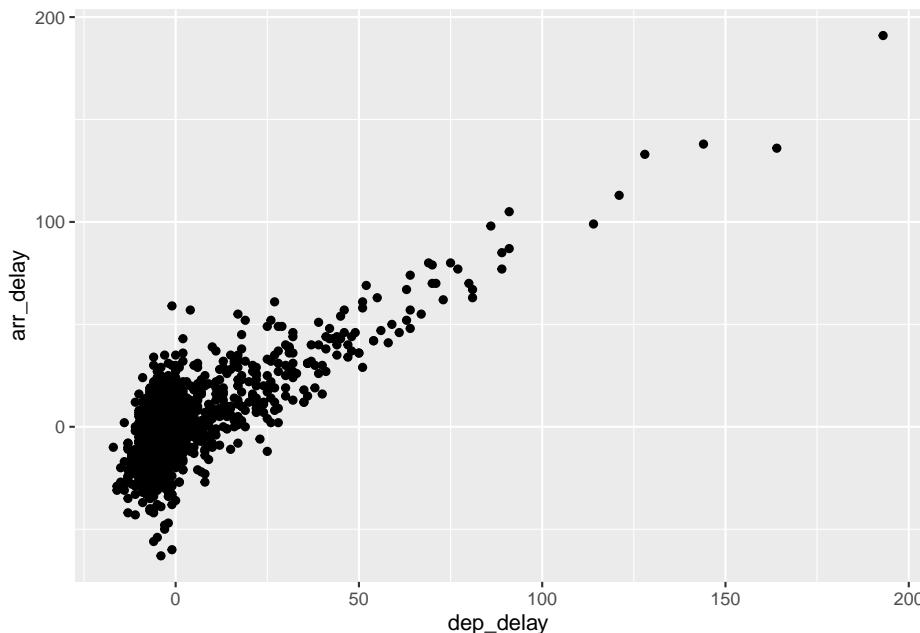
->

## 16.21 Scatterplots

- x and y variables to plot
- `ggplot2::geom_point`

```
nycflights13::flights %>%
  dplyr::filter(
    month == 11,
    carrier == "US",
    !is.na(dep_delay),
    !is.na(arr_delay)
  ) %>%
  ggplot2::ggplot(aes(
    x = dep_delay,
    y = arr_delay
  )) +
  ggplot2::geom_point()
```

## 16.22 Scatterplots

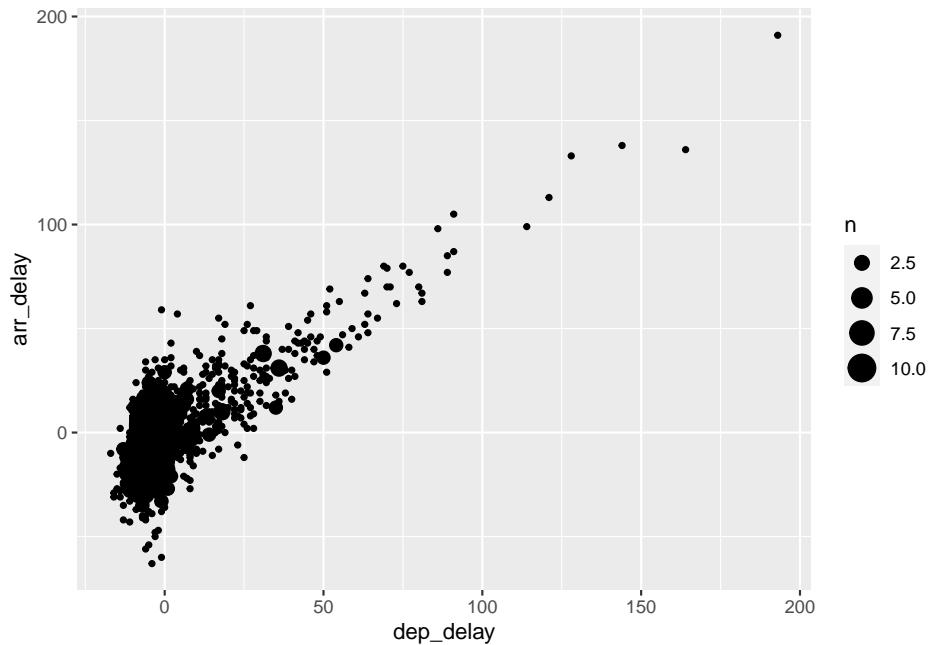


## 16.23 Overlapping points

- x and y variables to plot
- `ggplot2::geom_count` counts overlapping points and maps the count to size

```
nycflights13::flights %>%
  dplyr::filter(
    month == 11, carrier == "US",
    !is.na(dep_delay), !is.na(arr_delay)
  ) %>%
  ggplot2::ggplot(aes(
    x = dep_delay,
    y = arr_delay
  )) +
  ggplot2::geom_count()
```

## 16.24 Overlapping points

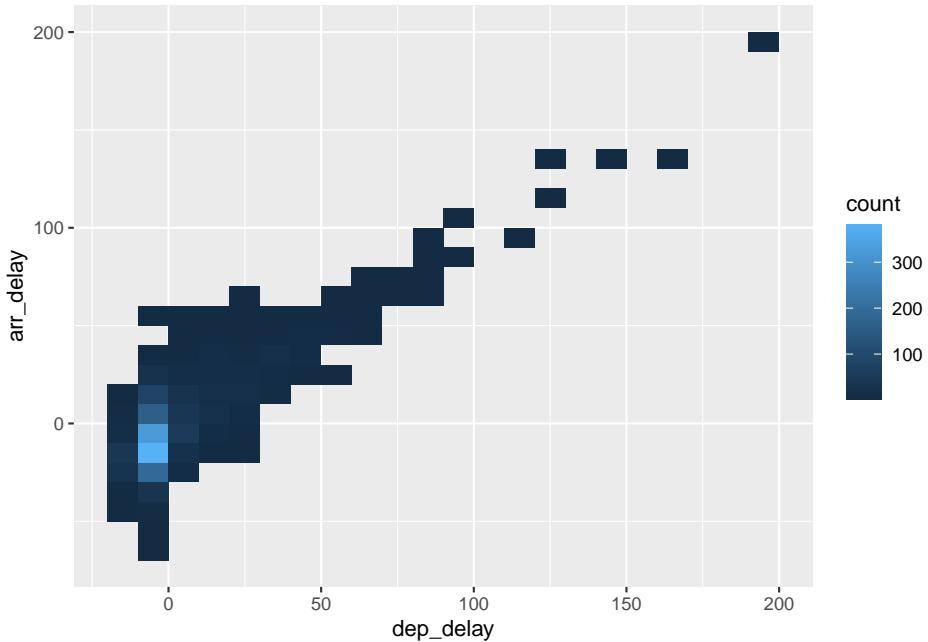


## 16.25 Bin counts

- x and y variables to plot
- `ggplot2::geom_bin2d` with 10 minutes binwidth

```
nycflights13::flights %>%
  dplyr::filter(
    month == 11,
    carrier == "US",
    !is.na(dep_delay),
    !is.na(arr_delay)
  ) %>%
  ggplot2::ggplot(aes(
    x = dep_delay,
    y = arr_delay
  )) +
  ggplot2::geom_bin2d(binwidth = 10)
```

## 16.26 Bin counts

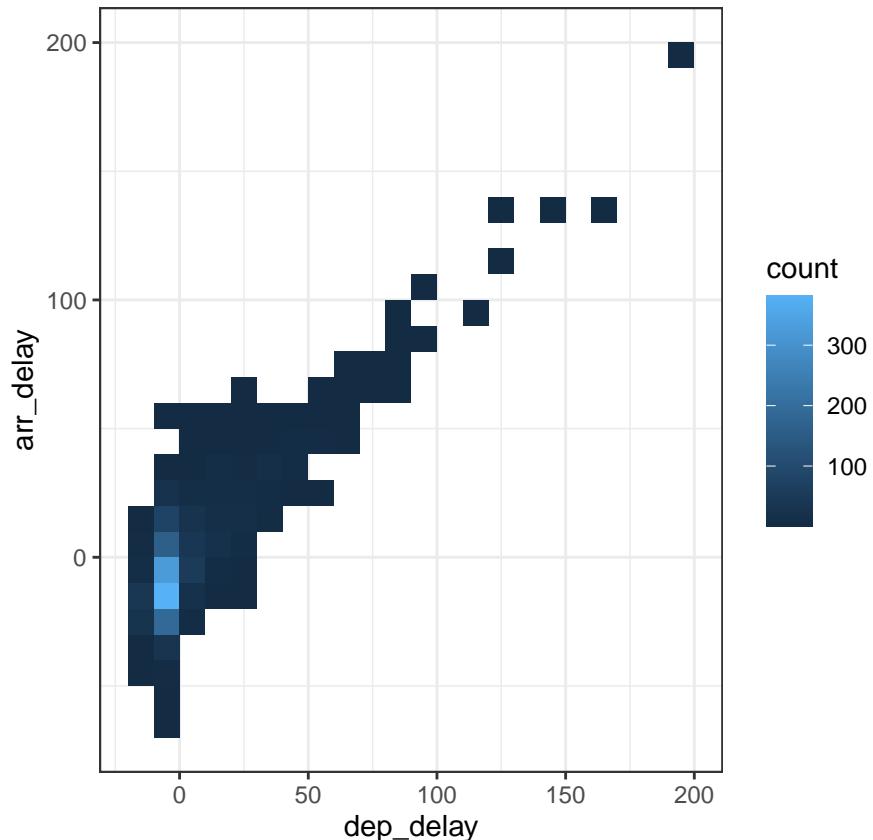


## 16.27 Coordinates transformations

- `ggplot2::coord_fixed` manipulates coordinates property
- `ggplot2::theme_bw` classic dark-on-light theme

```
nycflights13::flights %>%
  dplyr::filter(
    month == 11,
    carrier == "US",
    !is.na(dep_delay),
    !is.na(arr_delay)
  ) %>%
  ggplot2::ggplot(aes(
    x = dep_delay,
    y = arr_delay
  )) +
  ggplot2::geom_bin2d(binwidth = 10) +
  ggplot2::coord_fixed(ratio = 1) +
  theme_bw()
```

## 16.28 Coordinates transformations



## 16.29 Summary

Data visualisation

- Grammar of graphics
- ggplot2

Next: Descriptive statistics

- pastecs::stat.desc
- dplyr::across

# Chapter 17

## Descriptive statistics

### 17.1 Summary

Data visualisation

- Grammar of graphics
- ggplot2

Next: Descriptive statistics

- pastecs::stat.desc
- dplyr::across

### 17.2 Meet the Palmer penguins

Original data collected and released by Dr. Kristen Gorman and the Palmer Station, Antarctica LTER, a member of the Long Term Ecological Research Network.

Horst AM, Hill AP, Gorman KB (2020). palmerpenguins: Palmer Archipelago (Antarctica) penguin data. R package version 0.1.0. doi:10.5281/zenodo.3960218.

```
library(palmerpenguins)
```



Artwork by @allison\_horst

### 17.3 Descriptive statistics

Quantitatively describe or summarize variables

- `stat.desc` from `pastecs` library
  - `base` includes counts
  - `desc` includes descriptive stats
  - `norm` (default is `FALSE`) includes distribution stats

```
library(pastecs)

palmerpenguins::penguins %>%
  dplyr::select(bill_length_mm, bill_depth_mm) %>%
  pastecs::stat.desc() %>%
  knitr::kable(digits = c(2, 2))
```

### 17.4 stat.desc output

|              | bill_length_mm | bill_depth_mm |
|--------------|----------------|---------------|
| nbr.val      | 342.00         | 342.00        |
| nbr.null     | 0.00           | 0.00          |
| nbr.na       | 2.00           | 2.00          |
| min          | 32.10          | 13.10         |
| max          | 59.60          | 21.50         |
| range        | 27.50          | 8.40          |
| sum          | 15021.30       | 5865.70       |
| median       | 44.45          | 17.30         |
| mean         | 43.92          | 17.15         |
| SE.mean      | 0.30           | 0.11          |
| CI.mean.0.95 | 0.58           | 0.21          |
| var          | 29.81          | 3.90          |
| std.dev      | 5.46           | 1.97          |
| coef.var     | 0.12           | 0.12          |

### 17.5 stat.desc: basic

- `nbr.val`: overall number of values in the dataset
- `nbr.null`: number of `NULL` values – `NULL` is often returned by expressions and functions whose values are undefined
- `nbr.na`: number of `NAs` – missing value indicator

|          | bill_length_mm | bill_depth_mm |
|----------|----------------|---------------|
| nbr.val  | 342.0          | 342.0         |
| nbr.null | 0.0            | 0.0           |
| nbr.na   | 2.0            | 2.0           |
| min      | 32.1           | 13.1          |
| max      | 59.6           | 21.5          |
| range    | 27.5           | 8.4           |
| sum      | 15021.3        | 5865.7        |

## 17.6 stat.desc: basic

- **min** (also **min()**): **minimum** value in the dataset
- **max** (also **max()**): **maximum** value in the dataset
- **range**: difference between **min** and **max** (different from **range()**)
- **sum** (also **sum()**): sum of the values in the dataset

|          | bill_length_mm | bill_depth_mm |
|----------|----------------|---------------|
| nbr.val  | 342.0          | 342.0         |
| nbr.null | 0.0            | 0.0           |
| nbr.na   | 2.0            | 2.0           |
| min      | 32.1           | 13.1          |
| max      | 59.6           | 21.5          |
| range    | 27.5           | 8.4           |
| sum      | 15021.3        | 5865.7        |

## 17.7 stat.desc: desc

- **mean** (also **mean()**): **arithmetic mean**, that is **sum** over the number of values not **NA**
- **median** (also **median()**): **median**, that is the value separating the higher half from the lower half the values
- **mode()**function is available: **mode**, the value that appears most often in the values

|              | bill_length_mm | bill_depth_mm |
|--------------|----------------|---------------|
| median       | 44.45          | 17.30         |
| mean         | 43.92          | 17.15         |
| SE.mean      | 0.30           | 0.11          |
| CI.mean.0.95 | 0.58           | 0.21          |
| var          | 29.81          | 3.90          |
| std.dev      | 5.46           | 1.97          |
| coef.var     | 0.12           | 0.12          |

## 17.8 Sample statistics

Assuming that the data in the dataset are a sample of a population

- `SE.mean`: **standard error of the mean** – estimation of the variability of the mean calculated on different samples of the data (see also *central limit theorem*)
- `CI.mean.0.95`: **95% confidence interval of the mean** – indicates that there is a 95% probability that the actual mean is within that distance from the sample mean

## 17.9 Estimating variation

- `var`: **variance** ( $\sigma^2$ ), it quantifies the amount of variation as the average of squared distances from the mean

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n (\mu - x_i)^2$$

- `std.dev`: **standard deviation** ( $\sigma$ ), it quantifies the amount of variation as the square root of the variance

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (\mu - x_i)^2}$$

- `coef.var`: **variation coefficient** it quantifies the amount of variation as the standard deviation divided by the mean

## 17.10 dplyr::across

The `dplyr` verb `across` allows to apply `summarise` verbs on multiple columns. Instead of...

```
palmerpenguins::penguins %>%
  # filter out rows with missing data
  dplyr::filter(!is.na(bill_length_mm)) %>%
  # summarise
  dplyr::summarise(
    avg_bill_len_mm = mean(bill_length_mm),
    avg_bill_dpt_mm = mean(bill_depth_mm),
    avg_flip_len_mm = mean(flipper_length_mm),
    avg_body_mass_g = mean(body_mass_g)
  ) %>%
  knitr::kable(digits = c(2, 2, 2, 2))
```

| avg_bill_len_mm | avg_bill_dpt_mm | avg_flip_len_mm | avg_body_mass_g |
|-----------------|-----------------|-----------------|-----------------|
| 43.92           | 17.15           | 200.92          | 4201.75         |

## 17.11 dplyr::across

The verb `across` can also be used with `mutate`, to apply the same function to a number of columns

```
palmerpenguins::penguins %>%
  # mutate cross columns
  dplyr::mutate(
    dplyr::across(
      c(bill_length_mm, bill_depth_mm, flipper_length_mm),
      # add 1 to all values in the columns above
      function(x){ x / 25.4 }
    )
  ) %>%
  rename(
    bill_length_in = bill_length_mm,
    bill_depth_in = bill_depth_mm,
    flipper_length_in = flipper_length_mm
  )
```

## 17.12 dplyr::across

Old columns:

```
## # A tibble: 344 x 3
##   bill_length_mm bill_depth_mm flipper_length_mm
##       <dbl>        <dbl>          <int>
## 1     39.1        18.7         181
## 2     39.5        17.4         186
## # ... with 342 more rows
```

New columns:

```
## # A tibble: 344 x 3
##   bill_length_in bill_depth_in flipper_length_in
##       <dbl>        <dbl>          <dbl>
## 1     1.54        0.736         7.13
## 2     1.56        0.685         7.32
## # ... with 342 more rows
```

## 17.13 Summary

Descriptive statistics

- `pastecs::stat.desc`
- `dplyr::across`

**Next:** Exploring assumptions

- Normality
- Skewness and kurtosis
- Homogeneity of variance

# Chapter 18

## Exploring assumptions

### 18.1 Recap

Prev: Descriptive statistics

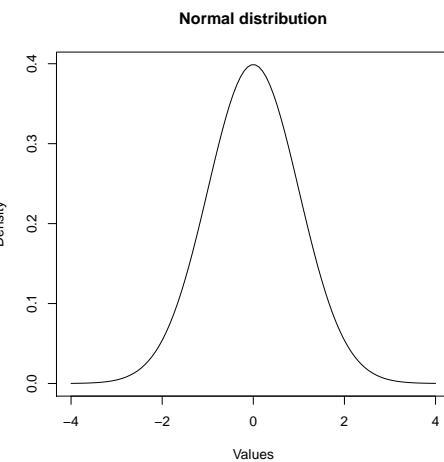
- stat.desc
- dplyr::across

Next: Exploring assumptions

- Normality
- Skewness and kurtosis
- Homogeneity of variance

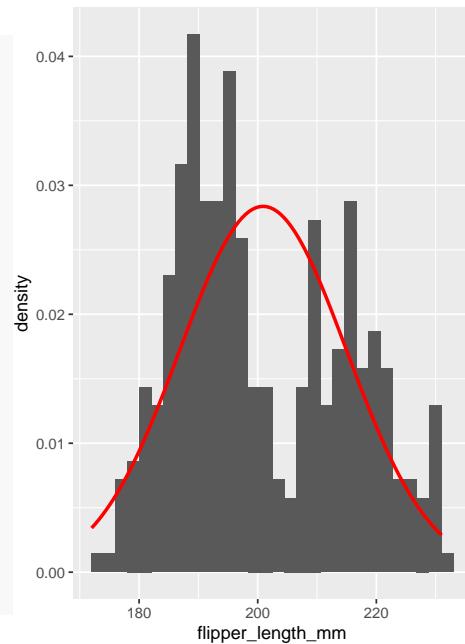
### 18.2 Normal distribution

- characterized by the bell-shaped curve
- majority of values lie around the centre of the distribution
- the further the values are from the centre, the lower their frequency
- about 95% of values within 2 standard deviations from the mean



### 18.3 Density histogram

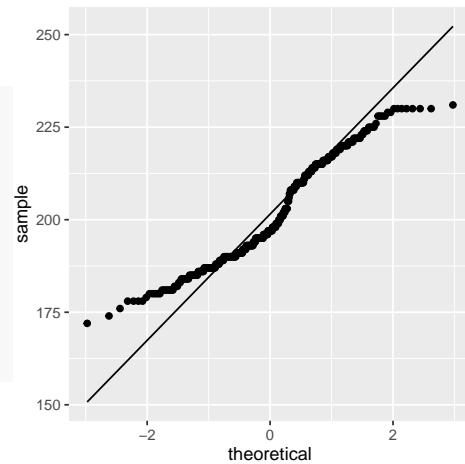
```
palmerpenguins::penguins %>%
  ggplot2::ggplot(
    aes(x = flipper_length_mm)
  ) +
  ggplot2::geom_histogram(
    aes(
      y = ..density..
    )
  ) +
  ggplot2::stat_function(
    fun = dnorm,
    args = list(
      # mean and stddev
      # calculations
      # omitted here
      mean = ...,
      sd = ... ),
    colour = "black", size = 1)
```



### 18.4 Q-Q plot

Values against the cumulative probability of a particular distribution (in this case, *normal* distribution)

```
palmerpenguins::penguins %>%
  ggplot2::ggplot(
    aes(
      sample =
        flipper_length_mm
    )
  ) +
  ggplot2::stat_qq() +
  ggplot2::stat_qq_line()
```



## 18.5 Normality

**Shapiro–Wilk test** compares the distribution of a variable with a normal distribution having same mean and standard deviation

- If significant, the distribution is not normal
- `shapiro.test` function in `stats`
- or `normtest` values in `pastecs::stat.desc`

```
palmerpenguins::penguins %>%
  dplyr::pull(flipper_length_mm) %>%
  stats::shapiro.test()
```

```
## 
## Shapiro-Wilk normality test
## 
## data: .
## W = 0.95155, p-value = 3.54e-09
```

## 18.6 Significance

Most statistical tests are based on the idea of hypothesis testing

- a **null hypothesis** is set
- the data are fit into a statistical model
- the model is assessed with a **test statistic**
- the **significance** is the probability of obtaining that test statistic value by chance

The threshold to accept or reject an hypothesis is arbitrary and based on conventions (e.g.,  $p < .01$  or  $p < .05$ )

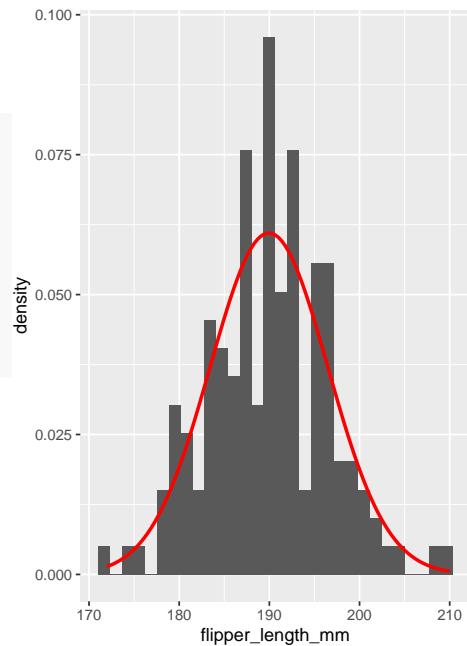
**Example:** The null hypothesis of the Shapiro–Wilk test is that the sample is normally distributed and  $p < .01$  indicates that the probability of that being true is very low. So, the *flipper length* of penguins in the Palmer Station dataset **is not** normally distributed.

## 18.7 Example

The *flipper length* of **Adelie** penguins **is normally distributed**

```
palmerpenguins::penguins %>%
  filter(
    species == "Adelie"
  ) %>%
  dplyr::pull(
    flipper_length_mm
  ) %>%
  stats::shapiro.test()

## 
## Shapiro-Wilk normality test
##
## data: .
## W = 0.99339, p-value = 0.72
```

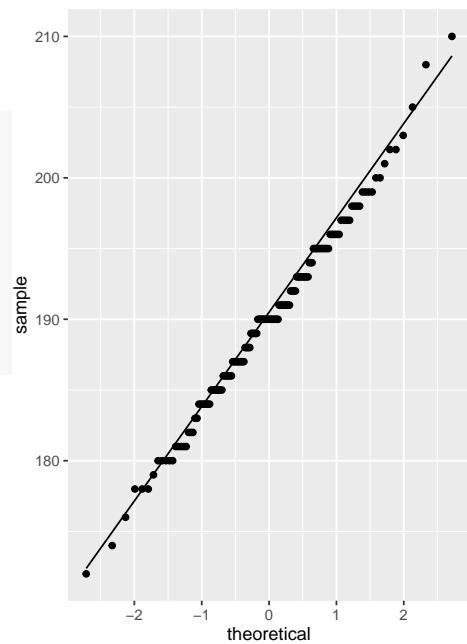


## 18.8 Example

The *flipper length* of Adelie penguins is normally distributed

```
palmerpenguins::penguins %>%
  filter(
    species == "Adelie"
  ) %>%
  dplyr::pull(
    flipper_length_mm
  ) %>%
  stats::shapiro.test()

## 
## Shapiro-Wilk normality test
##
## data: .
## W = 0.99339, p-value = 0.72
```



## 18.9 Skewness and kurtosis

In a normal distribution, *skewness* and *kurtosis* should be **zero**

- **skewness:** **skewness** value indicates
  - positive: the distribution is skewed towards the left
  - negative: the distribution is skewed towards the right
- **kurtosis:** **kurtosis** value indicates
  - positive: heavy-tailed distribution
  - negative: flat distribution
- **skew.2SE** and **kurt.2SE:** skewness and kurtosis divided by 2 standard errors. Therefore
  - if  $> 1$  (or  $< -1$ ) then the stat significant ( $p < .05$ )
  - if  $> 1.29$  (or  $< -1.29$ ) then stat significant ( $p < .01$ )

## 18.10 Example

*Flipper length* is not normally distributed

- skewed left (skewness positive, **skew.2SE**  $> 1.29$ )
- flat distribution (kurtosis negative, **kurt.2SE**  $< -1.29$ )

```
palmerpenguins::penguins %>%
  dplyr::select(bill_length_mm, bill_depth_mm, flipper_length_mm) %>%
  pastecs::stat.desc(basic = FALSE, desc = FALSE, norm = TRUE)
```

|            | bill_length_mm | bill_depth_mm | flipper_length_mm |
|------------|----------------|---------------|-------------------|
| skewness   | 0.0526530      | -0.1422086    | 0.3426554         |
| skew.2SE   | 0.1996290      | -0.5391705    | 1.2991456         |
| kurtosis   | -0.8931397     | -0.9233523    | -0.9991866        |
| kurt.2SE   | -1.6979696     | -1.7554076    | -1.8995781        |
| normtest.W | 0.9748548      | 0.9725838     | 0.9515451         |
| normtest.p | 0.0000112      | 0.0000044     | 0.0000000         |

## 18.11 Example

Values are instead not significant for **Adelie** penguins

- both **skew.2SE** and **kurt.2SE** between  $-1$  and  $1$

```
palmerpenguins::penguins %>%
  filter(species == "Adelie") %>%
  dplyr::select(bill_length_mm, bill_depth_mm, flipper_length_mm) %>%
  pastecs::stat.desc(basic = FALSE, desc = FALSE, norm = TRUE)
```

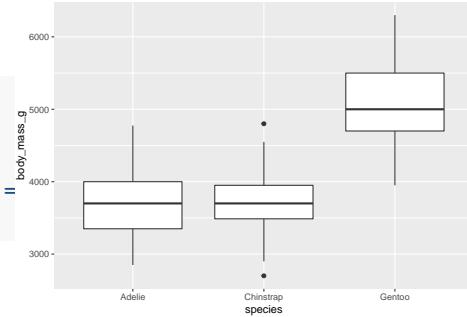
|            | bill_length_mm | bill_depth_mm | flipper_length_mm |
|------------|----------------|---------------|-------------------|
| skewness   | 0.1584764      | 0.3148847     | 0.0856093         |
| skew.2SE   | 0.4014211      | 0.7976035     | 0.2168485         |
| kurtosis   | -0.2285951     | -0.1361153    | 0.2382734         |
| kurt.2SE   | -0.2913388     | -0.1734755    | 0.3036734         |
| normtest.W | 0.9933618      | 0.9846683     | 0.9933916         |
| normtest.p | 0.7166005      | 0.0924897     | 0.7200466         |

## 18.12 Homogeneity of variance

Levene's test for equality of variance in different levels

- If significant, the variance is different in different levels

```
library(car)
palmerpenguins:::penguins %>%
  car::leveneTest(
    body_mass_g ~ species, data =
  )
```



```
## Levene's Test for Homogeneity of Variance (center = median)
##          Df F value   Pr(>F)
## group     2  5.1203 0.006445 **
##            339
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

## 18.13 Summary

Exploring assumptions

- Normality
- Skewness and kurtosis
- Homogeneity of variance

Next: Practical session

- Data visualisation
- Descriptive statistics
- Exploring assumptions

# Chapter 19

## Comparing groups

### 19.1 Recap

Prev: Exploratory data analysis

- 301 Lecture Data visualisation
- 302 Lecture Descriptive statistics
- 303 Lecture Exploring assumptions
- 304 Practical session

Now: Comparing groups

- T-test
- ANOVA
- Chi-square

## 19.2 Libraries

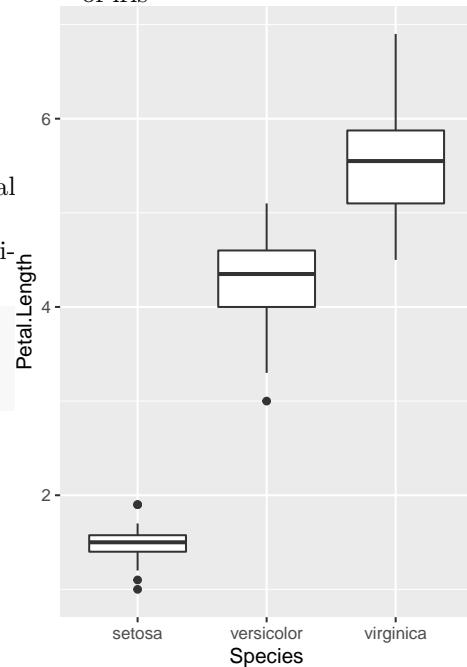
But let's start from a simple example from `datasets`

- 50 flowers from each of 3 species of iris

Today's libraries

- mostly working with the usual `nycflights13`
- exposition pipe `%$%` from the library `magrittr`

```
library(tidyverse)
library(magrittr)
library(nycflights13)
```



## 19.3 Example

```
iris %>% filter(Species == "setosa") %>% pull(Petal.Length) %>% shapiro.test()

##
## Shapiro-Wilk normality test
##
## data: .
## W = 0.95498, p-value = 0.05481
iris %>% filter(Species == "versicolor") %>% pull(Petal.Length) %>% shapiro.test()

##
## Shapiro-Wilk normality test
##
## data: .
## W = 0.966, p-value = 0.1585
iris %>% filter(Species == "virginica") %>% pull(Petal.Length) %>% shapiro.test()

##
## Shapiro-Wilk normality test
##
```

```
## data: .
## W = 0.96219, p-value = 0.1098
```

## 19.4 T-test

Independent T-test tests whether two group means are different

$$\text{outcome}_i = (\text{group mean}) + \text{error}_i$$

- groups defined by a predictor, categorical variable
- outcome is a continuous variable
- assuming
  - normally distributed values in groups
  - homogeneity of variance of values in groups
    - \* if groups have different sizes
  - independence of groups

## 19.5 Example

Values are normally distributed, groups have same size, and they are independent (different flowers, check using `leveneTest`)

```
iris %>%
  filter(Species %in% c("versicolor", "virginica")) %$% # Note %$%
  t.test(Petal.Length ~ Species)

##
## Welch Two Sample t-test
##
## data: Petal.Length by Species
## t = -12.604, df = 95.57, p-value < 2.2e-16
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
## -1.49549 -1.08851
## sample estimates:
## mean in group versicolor mean in group virginica
##                 4.260             5.552
```

The difference is significant  $t(95.57) = -12.6, p < .01$

## 19.6 ANOVA

ANOVA (analysis of variance) tests whether more than two group means are different

$$\text{outcome}_i = (\text{group mean}) + \text{error}_i$$

- groups defined by a predictor, categorical variable

- outcome is a continuous variable
- assuming
  - normally distributed values in groups
    - \* especially if groups have different sizes
  - homogeneity of variance of values in groups
    - \* if groups have different sizes
  - independence of groups

## 19.7 Example

Values are normally distributed, groups have same size, they are independent (different flowers, check using `leveneTest`)

```
iris %$%
  aov(Petal.Length ~ Species) %>%
  summary()

##           Df Sum Sq Mean Sq F value Pr(>F)
## Species      2  437.1   218.55   1180 <2e-16 ***
## Residuals  147   27.2     0.19
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The difference is significant  $t(2, 147) = 1180.16, p < .01$

## 19.8 Summary

Comparing groups

- T-test
- ANOVA
- Chi-square

**Next:** Correlation

- Pearson's r
- Spearman's rho
- Kendall's tau
- Pairs plot

# Chapter 20

## Correlation

### 20.1 Recap

Prev: Comparing groups

- T-test
- ANOVA
- Chi-square

Now: Correlation

- Pearson's r
- Spearman's rho
- Kendall's tau
- Pairs plot

### 20.2 Correlation

Two variables can be related in three different ways

- related
  - positively: entities with high values in one tend to have high values in the other
  - negatively: entities with high values in one tend to have low values in the other
- not related at all

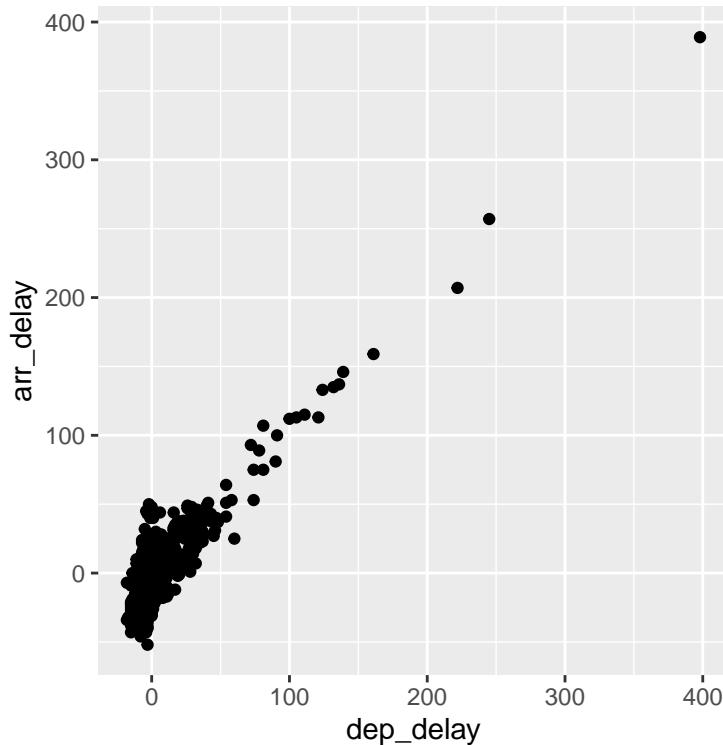
**Correlation** is a standardised measure of covariance

### 20.3 Libraries and data

```
library(tidyverse)
library(magrittr)
library(nycflights13)

flights_nov_20 <- nycflights13::flights %>%
  filter(!is.na(dep_delay), !is.na(arr_delay), month == 11, day == 20)
```

### 20.4 Example



### 20.5 Example

```
flights_nov_20 %>%
  pull(dep_delay) %>% shapiro.test()

##
## Shapiro-Wilk normality test
##
## data: .
## W = 0.39881, p-value < 2.2e-16
```

```
flights_nov_20 %>%
  pull(arr_delay) %>% shapiro.test()
```

```
##  
## Shapiro-Wilk normality test  
##  
## data: .  
## W = 0.67201, p-value < 2.2e-16
```

## 20.6 Pearson's r

If two variables are **normally distributed** use **Pearson's r**

The square of the correlation value indicates the percentage of shared variance

*If they were normally distributed, but they are not*

- $0.882^2 = 0.778$
- departure and arrival delay *would share* 77.8% of variance

```
# note the use of %$%
#instead of %>%
flights_nov_20 %$%
cor.test(dep_delay, arr_delay)
```

```
## Pearson's product-moment correlation
## data: dep_delay and arr_delay
## t = 58.282, df = 972, p-value < 2.2e-16
## alternative hypothesis: true correlation is not equal to 0
## 95 percent confidence interval:
##  0.8669702 0.8950078
## sample estimates:
##      cor
## 0.8817655
```

## 20.7 Spearman's rho

If two variables are **not** normally distributed, use **Spearman's rho**

The square of the correlation value indicates the percentage of shared variance

*If few ties, but there are*

- non-parametric
- based on rank difference
- departure and arrival delay *would share* 28.7% of variance

```
flights_nov_20 %$%
cor.test(
  dep_delay, arr_delay,
  method = "spearman")
```

```
## Warning in cor.test.default(dep_delay, arr_delay, method = "spearman"): Cannot compute exact p-value with ties
## Spearman's rank correlation rho
## data: dep_delay and arr_delay
## S = 71437522, p-value < 2.2e-16
## alternative hypothesis: true rho is not equal to 0
## sample estimates:
##      rho
## 0.5361247
```

## 20.8 Kendall's tau

```

flights_nov_20 %$%
If not normally distributed and there is a large number of ties, use Kendall's tau
  • non-parametric
  • based on rank difference
The square of the correlation value indicates the percentage of shared variance
Departure and arrival delay seem actually to share
  •  $0.396^2 = 0.157$ 
  • 15.7% of variance

```

```

## flights_nov_20 %$%
## cor.test(
##   dep_delay, arr_delay,
##   method = "kendall")
## Kendall's rank correlation tau
## z = 17.859, p-value < 2.2e-16
## alternative hypothesis: true tau is not equal to 0
## sample estimates:
## tau
## 0.3956265

```

## 20.9 Pairs plot

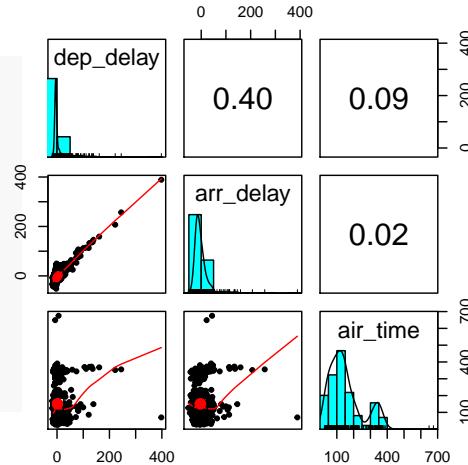
Combines in one visualisation: histograms, scatter plots, and correlation values for a set of variables

```

library(psych)

flights_nov_20 %>%
  select(
    dep_delay,
    arr_delay,
    air_time
  ) %>%
  pairs.panels(
    method = "kendall"
  )

```



## 20.10 Summary

Correlation

- Pearson's r
- Spearman's rho
- Kendall's tau
- Pairs plot

**Next:** Data transformations

- Z-scores
- Logarithmic transformations

# Chapter 21

## Data transformations

### 21.1 Recap

Prev: Correlation

- Pearson's r
- Spearman's rho
- Kendall's tau
- Pairs plot

Now: Data transformations

- Z-scores
- Logarithmic transformations

### 21.2 Libraries and data

```
library(tidyverse)
library(magrittr)
library(nycflights13)

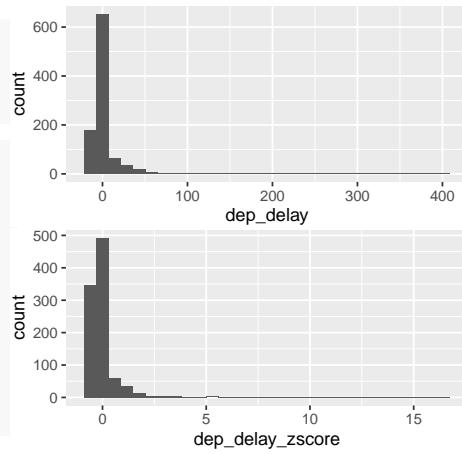
flights_nov_20 <- nycflights13::flights %>%
  filter(!is.na(dep_delay), !is.na(arr_delay), month == 11, day == 20)
```

### 21.3 Z-scores

*Z-scores* transform the values as relative to the distribution mean and standard deviation

```
flights_nov_20 %>%
  ggplot(aes(x = dep_delay)) +
  geom_histogram()

flights_nov_20 %>%
  mutate(
    dep_delay_zscore =
      scale(dep_delay)
  ) %>%
  ggplot(
    aes(x = dep_delay_zscore)
  ) +
  geom_histogram()
```

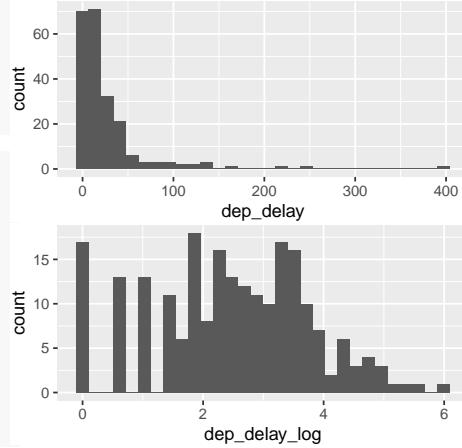


## 21.4 Log transformation

*Logarithmic* transformations (e.g., `log` and `log10`) are useful to “*un-skew*” variables, but only possible on values  $> 0$

```
flights_nov_20 %>%
  filter(dep_delay > 0) %>%
  ggplot(aes(x = dep_delay)) +
  geom_histogram()

flights_nov_20 %>%
  filter(dep_delay > 0) %>%
  mutate(
    dep_delay_log =
      log(dep_delay)
  ) %>%
  ggplot(
    aes(x = dep_delay_log)) +
  geom_histogram()
```

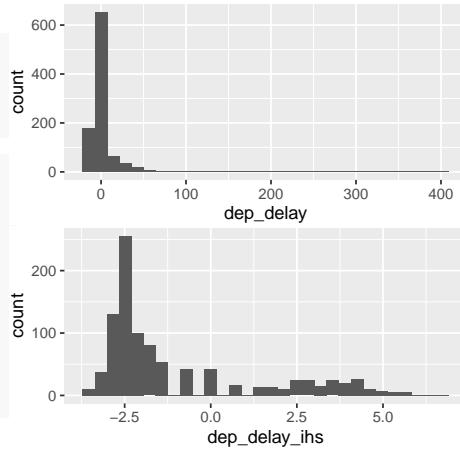


## 21.5 Inverse hyperbolic sine

*Inverse hyperbolic sine* (`asinh`) transformations are useful to “*un-skew*” variables, similar to logarithmic transformations, work on all values

```
flights_nov_20 %>%
  ggplot(aes(x = dep_delay)) +
  geom_histogram()

flights_nov_20 %>%
  mutate(
    dep_delay_ihs =
      asinh(dep_delay)
  ) %>%
  ggplot(
    aes(x = dep_delay_ihs)) +
  geom_histogram()
```



## 21.6 Summary

Data transformations

- Z-scores
- Logarithmic transformations

Next: Practical session

- Comparing means
- Correlation



# Chapter 22

## Simple Regression

### 22.1 Recap

Prev: Comparing data

- 311 Lecture Comparing groups
- 312 Lecture Correlation
- 313 Lecture Data transformations
- 314 Practical session

Now: Simple Regression

- Regression
- Ordinary Least Squares
- Fit

### 22.2 Regression analysis

**Regression analysis** is a supervised machine learning approach

Predict the value of one outcome variable as

$$\text{outcome}_i = (\text{model}) + \text{error}_i$$

- one predictor variable (**simple / univariate** regression)

$$Y_i = (b_0 + b_1 * X_{i1}) + \epsilon_i$$

- more predictor variables (**multiple / multivariate** regression)

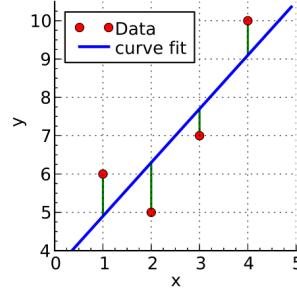
$$Y_i = (b_0 + b_1 * X_{i1} + b_2 * X_{i2} + \dots + b_M * X_{iM}) + \epsilon_i$$

## 22.3 Least squares

**Least squares** is the most commonly used approach to generate a regression model

The model fits a line

- to minimise the squared values of the **residuals** (errors)
- that is squared difference between
  - **observed values**
  - **model**



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$$\text{deviation} = \sum (\text{observed} - \text{model})^2$$

## 22.4 Libraries and data

```
library(tidyverse)
library(magrittr)
library(nycflights13)

flights_nov_20 <- nycflights13::flights %>%
  filter(!is.na(dep_delay), !is.na(arr_delay), month == 11, day == 20)
```

## 22.5 Example

```
arr_delay_i = (b_0 + b_1 * dep_delay_i) + \epsilon_i

delay_model <- flights_nov_20 %$% # Note %$%
  lm(arr_delay ~ dep_delay)

delay_model %>% summary()

## 
## Call:
## lm(formula = arr_delay ~ dep_delay)
## 
## Residuals:
##       Min     1Q   Median     3Q    Max 
## -43.906 -9.022 -1.758  8.678 57.052 
## 
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)    
## (Intercept) -4.96717   0.43748 -11.35   <2e-16 ***
## dep_delay    1.04229   0.01788  58.28   <2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 13.62 on 972 degrees of freedom
## Multiple R-squared:  0.7775, Adjusted R-squared:  0.7773
## F-statistic:  3397 on 1 and 972 DF,  p-value: < 2.2e-16
```

## 22.6 Overall fit

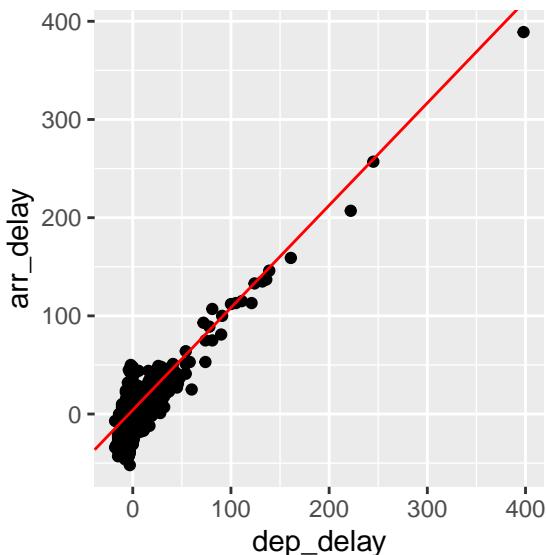
The output indicates

- **p-value:**  $< 2.2\text{e-}16$ :  $p < .001$  the model is significant
  - derived by comparing the calculated **F-statistic** value to F distribution 3396.74 having specified degrees of freedom (1, 972)
  - Report as:  $F(1, 972) = 3396.74$
- **Adjusted R-squared:** **0.7773**: the departure delay can account for 77.73% of the arrival delay
- **Coefficients**
  - Intercept estimate -4.9672 is significant
  - `dep_delay` (slope) estimate 1.0423 is significant

## 22.7 Parameters

$$\text{arr\_delay}_i = (\text{Intercept} + \text{Coefficient}_{\text{dep\_delay}} * \text{dep\_delay}_{i1}) + \epsilon_i$$

```
flights_nov_20 %>%
  ggplot(aes(x = dep_delay, y = arr_delay)) +
  geom_point() + coord_fixed(ratio = 1) +
  geom_abline(intercept = 4.0943, slope = 1.04229, color="red")
```



## 22.8 Summary

Simple Regression

- Regression
- Ordinary Least Squares
- Fit

**N**ext: Assessing regression assumptions

- Normality
- Homoscedasticity
- Independence

# Chapter 23

## Assessing regression assumptions

### 23.1 Recap

Prev: Simple Regression

- Regression
- Ordinary Least Squares
- Fit

Now: Assessing regression assumptions

- Normality
- Homoscedasticity
- Independence

### 23.2 Checking assumptions

- **Linearity**
  - the relationship is actually linear
- **Normality** of residuals
  - standard residuals are normally distributed with mean 0
- **Homoscedasticity** of residuals
  - at each level of the predictor variable(s) the variance of the standard residuals should be the same (*homo-scedasticity*) rather than different (*hetero-scedasticity*)
- **Independence** of residuals
  - adjacent standard residuals are not correlated
- When more than one predictor: **no multicollinearity**

- if two or more predictor variables are used in the model, each pair of variables not correlated

### 23.3 Libraries and data

```
library(tidyverse)
library(magrittr)
library(nycflights13)

flights_nov_20 <- nycflights13::flights %>%
  filter(!is.na(dep_delay), !is.na(arr_delay), month == 11, day == 20)
```

### 23.4 Example

$$arr\_delay_i = (b_0 + b_1 * dep\_delay_{i1}) + \epsilon_i$$

```
delay_model <- flights_nov_20 %$% # Note %$%
  lm(arr_delay ~ dep_delay)

delay_model %>% summary()

##
## Call:
## lm(formula = arr_delay ~ dep_delay)
##
## Residuals:
##     Min      1Q  Median      3Q     Max 
## -43.906   -9.022  -1.758   8.678  57.052 
## 
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)    
## (Intercept) -4.96717   0.43748 -11.35   <2e-16 ***
## dep_delay    1.04229   0.01788  58.28   <2e-16 ***
## ---        
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## 
## Residual standard error: 13.62 on 972 degrees of freedom
## Multiple R-squared:  0.7775, Adjusted R-squared:  0.7773 
## F-statistic: 3397 on 1 and 972 DF,  p-value: < 2.2e-16
```

### 23.5 Normality

Shapiro-Wilk test for normality of standard residuals,

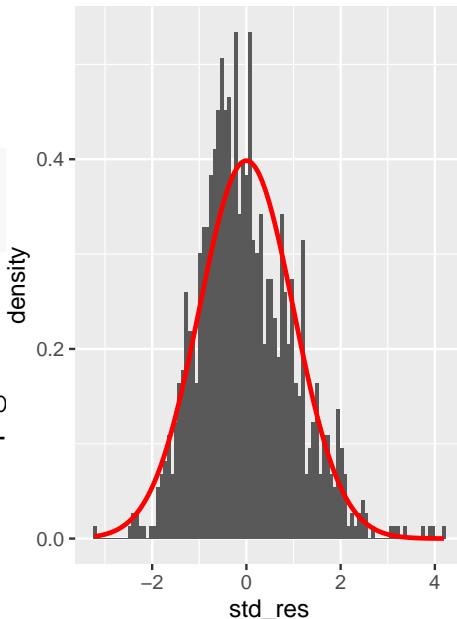
- robust models: should be not significant

```

delay_model %>%
  rstandard() %>%
  shapiro.test()

## 
## Shapiro-Wilk normality test
## 
## data: .
## W = 0.98231, p-value = 1.73e-0
Standard residuals are NOT normally distributed

```



## 23.6 Homoscedasticity

Breusch-Pagan test for homoscedasticity of standard residuals

- robust models: should be not significant

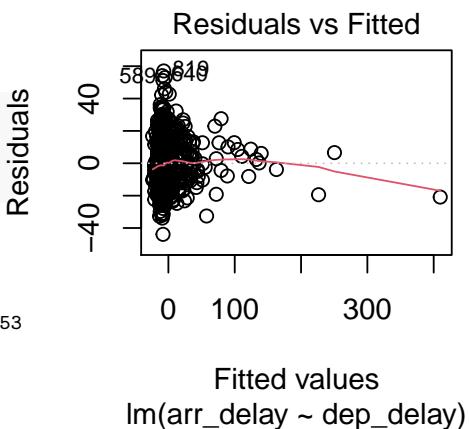
```

library(lmtest)

delay_model %>%
  bptest()

## 
## studentized Breusch-Pagan test
## 
## data: .
## BP = 0.017316, df = 1, p-value = 0.8953
Standard residuals are homoscedastic

```



## 23.7 Independence

Durbin-Watson test for the independence of residuals

- robust models: statistic should be close to 2 (between 1 and 3) and not significant

```
# Also part of the library lmtest
delay_model %>%
  dwtest()

##
## Durbin-Watson test
##
## data: .
## DW = 1.8731, p-value = 0.02358
## alternative hypothesis: true autocorrelation is greater than 0
```

**Standard residuals might not be completely independent**

Note: the result depends on the order of the data.

## 23.8 Summary

Assessing regression assumptions

- Normality
- Homoscedasticity
- Independence

**Next:** Assessing regression assumptions

- Normality
- Homoscedasticity
- Independence

# Chapter 24

## Multiple Regression

### 24.1 Recap

Prev: Assessing regression assumptions

- Normality
- Homoscedasticity
- Independence

Now: Multiple Regression

- Fit
- Multicollinearity
- Comparing models

### 24.2 TO-DO

### 24.3 Summary

Multiple Regression

- Fit
- Multicollinearity
- Comparing models

Next: Practical session

- Simple regression
- Testing assumptions
- Multiple regression



# Chapter 25

# Machine Learning

## 25.1 Recap

Prev: Comparing data

- 321 Lecture Simple regression
- 322 Lecture Assessing regression assumptions
- 323 Lecture Multiple regression
- 324 Practical session

Now: Machine Learning

- What's Machine Learning?
- Types
- Limitations

## 25.2 Definition

*“The field of machine learning is concerned with the question of how to construct computer programs that automatically improve with experience.”*

Mitchell, T. (1997). Machine Learning. McGraw Hill.

## 25.3 Origines

- **Computer Science:**
  - how to manually program computers to solve tasks
- **Statistics:**
  - what conclusions can be inferred from data
- **Machine Learning:**
  - intersection of **computer science** and **statistics**

- how to get computers to **program themselves** from experience plus some initial structure
- effective data capture, store, index, retrieve and merge
- computational tractability

Mitchell, T.M., 2006. The discipline of machine learning (Vol. 9). Pittsburgh, PA: Carnegie Mellon University, School of Computer Science, Machine Learning Department.

## 25.4 Types of machine learning

Machine learning approaches are divided into two main types

- **Supervised**
  - training of a “*predictive*” model from data
  - one attribute of the dataset is used to “predict” another attribute
  - e.g., classification
- **Unsupervised**
  - discovery of *descriptive* patterns in data
  - commonly used in data mining
  - e.g., clustering

## 25.5 Supervised

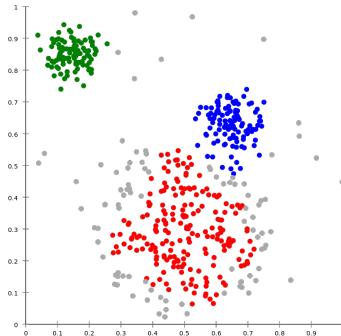
- Training dataset
  - input attribute(s)
  - attribute to predict
- Testing dataset
  - input attribute(s)
  - attribute to predict
- Type of learning model
- Evaluation function
  - evaluates difference between prediction and output in testing data

|   |
|---|
| 0 |
| 1 |
| 2 |
| 3 |
| 4 |
| 5 |
| 6 |
| 7 |
| 8 |
| 9 |

by Josef Steppan via Wikimedia Commons, CC-BY-SA-4.0

## 25.6 Unsupervised

- Dataset
  - input attribute(s) to explore
- Type of model for the learning process
  - most approaches are iterative
  - e.g., hierarchical clustering
- Evaluation function
  - evaluates the quality of the pattern under consideration during one iteration



by Chire via Wikimedia Commons, CC-BY-SA-3.0

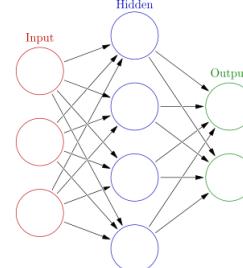
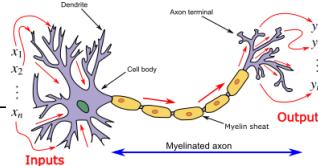
## 25.7 ... more

- **Semi-supervised learning**
  - between unsupervised and supervised learning
  - combines a small amount of labelled data with a larger un-labelled dataset
  - continuity, cluster, and manifold (lower dimensionality) assumption
- **Reinforcement learning**
  - training agents take actions to maximize reward
  - balancing
    - \* exploration (new paths/options)
    - \* exploitation (of current knowledge)

## 25.8 Neural networks

Supervised learning approach simulating simplistic neurons

- Classic model with 3 sets
  - input neurons
  - output neurons
  - hidden layer
    - \* combines input values using **weights**
    - \* **activation function**
- The **training algorithm** is used to define the best weights



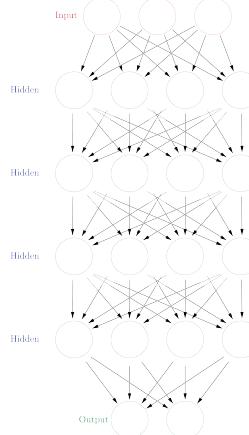
by Egm4313.s12 and Glosser.ca via Wikimedia Commons, CC-BY-SA-3.0

## 25.9 Deep neural networks

Neural networks with **multiple hidden layers**

The fundamental idea is that “*deeper*” neurons allow for the encoding of more complex characteristics

**Example:** De Sabbata, S. and Liu, P. (2019). Deep learning geodemographics with autoencoders and geographic convolution. In proceedings of the 22nd AGILE Conference on Geographic Information Science, Limassol, Cyprus.



derived from work by Glosser.ca via Wikimedia Commons, CC-BY-SA-3.0

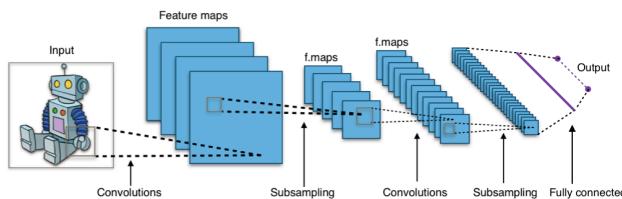
## 25.10 Convolutional neural networks

Deep neural networks with **convolutional hidden layers**

- used very successfully on image object recognition
- convolutional hidden layers “*convolve*” the images

- a process similar to applying smoothing filters

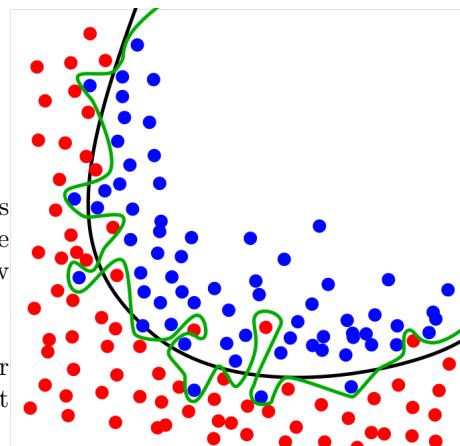
**Example:** Liu, P. and De Sabbata, S. (2019). Learning Digital Geographies through a Graph-Based Semi-supervised Approach. In proceedings of the 15th International Conference on GeoComputation, Queenstown, New Zealand.



by Aphex34 via Wikimedia Commons, CC-BY-SA-4.0

## 25.11 Limits

- Complexity
- Training dataset quality
  - garbage in, garbage out
  - e.g., Facial Recognition Is Accurate, if You're a White Guy by Steve Lohr (New York Times, Feb. 9, 2018)
- Overfitting
  - creating a model perfect for the training data, but not generic enough to be useful



## 25.12 Summary

Machine Learning

- What's Machine Learning?
- Types
- Limitations

**Next:** Centroid-based clustering

- K-means
- Fuzzy c-means
- Geodemographic classification



# Chapter 26

## Deep learning

### 26.1 Recap

Prev: Machine learning

- X
- Y
- Z

Now: Artificial Neural Networks

- X
- Y
- Z

### 26.2 TO-DO

### 26.3 Summary

Artificial Neural Networks

- X
- Y
- Z

Next: Support vector machines

- 
- 
-



# Chapter 27

## Support vector machines

### 27.1 Recap

Prev: Artificial Neural Networks

- X
- Y
- Z

Now: Support vector machines

- X
- Y
- Z

### 27.2 TO-DO

### 27.3 Summary

Support vector machines

- X
- Y
- Z

Next: Practical session

- X
- Y
- Z



## Chapter 28

# Principal Component Analysis

### 28.1 Recap

Prev: Comparing data

- 321 Lecture Introduction to Machine Learning
- 322 Lecture
- 323 Lecture
- 324 Practical session

Now: Principal Component Analysis

- X
- Y
- Z

### 28.2 TO-DO

### 28.3 Summary

Principal Component Analysis

- X
- Y
- Z

Next: Centroid-based clustering

- K-means
- Fuzzy c-means

- Geodemographic classification

# Chapter 29

## Centroid-based clustering

### 29.1 Recap

Prev: Principal Component Analysis

- 
- 
- 

Now: Centroid-based clustering

- K-means
- Fuzzy c-means
- Geodemographic classification

### 29.2 Clustering task

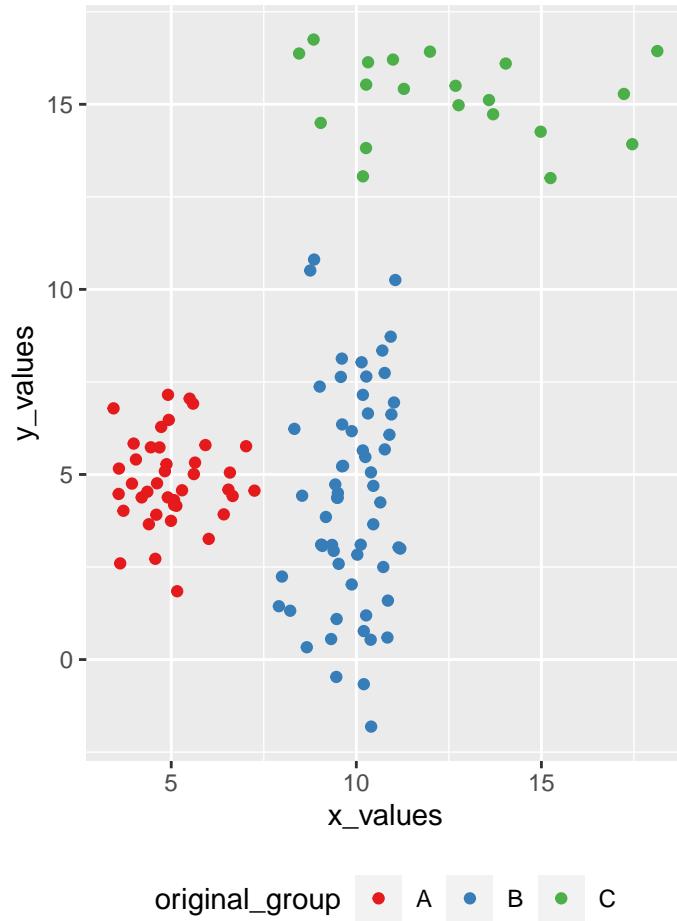
*"Clustering is an unsupervised machine learning task that automatically divides the data into **clusters**, or groups of similar items".* (Lantz, 2019)

Methods:

- Centroid-based
  - k-means
  - fuzzy c-means
- Hierarchical
- Mixed
  - bootstrap aggregating
- Density-based
  - DBSCAN

### 29.3 Example

```
data_to_cluster <- data.frame(
  x_values = c(rnorm(40, 5, 1), rnorm(60, 10, 1), rnorm(20, 12, 3)),
  y_values = c(rnorm(40, 5, 1), rnorm(60, 5, 3), rnorm(20, 15, 1)),
  original_group = c(rep("A", 40), rep("B", 60), rep("C", 20)) )
```



### 29.4 k-means

k-mean clusters  $n$  observations in  $k$  clusters, minimising the within-cluster sum of squares (WCSS)

**Algorithm:**  $k$  observations randomly selected as initial centroids, then repeat

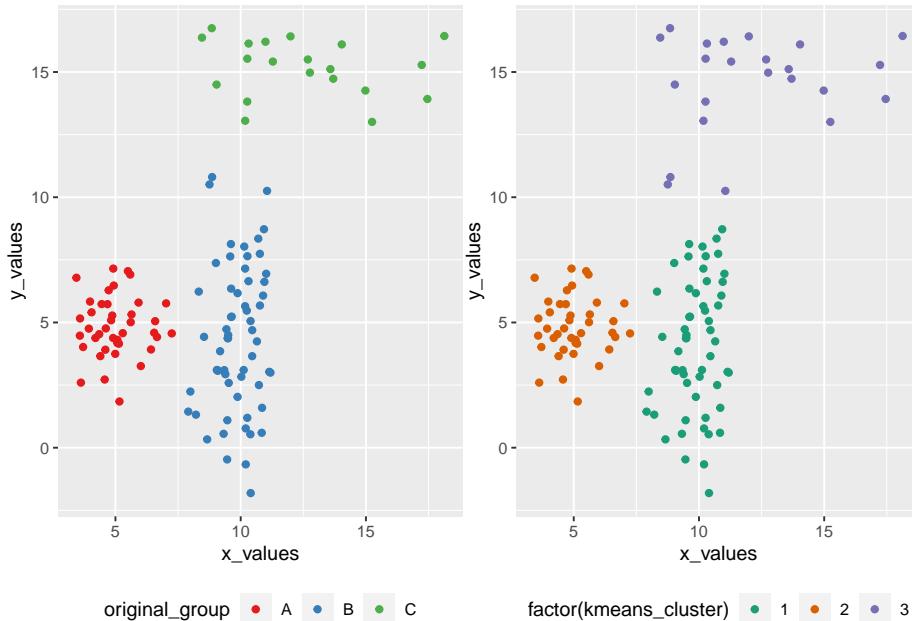
- **assignment step:** observations are assigned to the closest centroids
- **update step:** calculate means for each cluster to use as new the centroid

until centroids don't change anymore, the algorithm has **converged**

```
kmeans_found_clusters <- data_to_cluster %>%
  select(x_values, y_values) %>%
  kmeans(centers=3, iter.max=50)

data_to_cluster <- data_to_cluster %>%
  add_column(kmeans_cluster = kmeans_found_clusters$cluster)
```

## 29.5 K-means result



## 29.6 Fuzzy c-means

Fuzzy c-means is similar to k-means but allows for "fuzzy" membership to clusters

Each observation is assigned with a value per each cluster

- usually from 0 to 1
- indicates how well the observation fits within the cluster
- i.e., based on the distance from the centroid

```
library(e1071)

cmeans_result <- data_to_cluster %>%
  select(x_values, y_values) %>%
```

```
cmeans(centers=3, iter.max=50)

data_to_cluster <- data_to_cluster %>%
  add_column(c_means_assigned_cluster = cmeans_result$cluster)
```

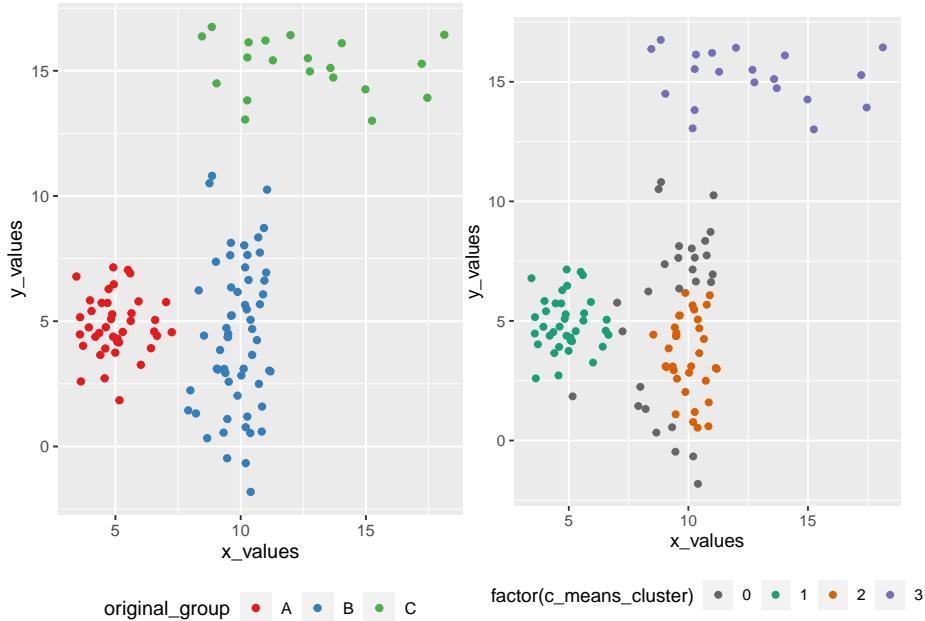
## 29.7 Fuzzy c-means

A “*crisp*” classification can be created by picking the highest membership value.

- that also allows to set a membership threshold (e.g., 0.75)
- leaving some observations without a cluster

```
data_to_cluster <- data_to_cluster %>%
  add_column(
    c_means_membership = apply(cmeans_result$membership, 1, max)
  ) %>%
  mutate(
    c_means_cluster = ifelse(
      c_means_membership > 0.75,
      c_means_assigned_cluster,
      0
    )
  )
```

## 29.8 Fuzzy c-means result



## 29.9 Geodemographic classifications

In GIScience, the clustering is commonly used to create *geodemographic classifications* such as the 2011 Output Area Classification (Gale *et al.*, 2016)

- initial set of 167 prospective variables from the United Kingdom Census 2011
  - 86 were removed,
  - 41 were retained as they are
  - 40 were combined
  - final set of 60 variables.
- k-means clustering approach to create
  - 8 supergroups
  - 26 groups
  - 76 subgroups.

## 29.10 Summary

Centroid-based clustering

- K-means
- Fuzzy c-means
- Geodemographic classification

**Next:** Hierarchical and density-based clustering

- Hierarchical
- Mixed
- Density-based

# Chapter 30

## Hierarchical and density-based clustering

### 30.1 Recap

Prev: Centroid-based clustering

- K-means
- Fuzzy c-means
- Geodemographic classification

Now: Hierarchical and density-based clustering

- Hierarchical
- Mixed
- Density-based

### 30.2 Libraries

```
library(tidyverse)

## -- Attaching packages ----- tidyverse 1.3.0 --
## v ggplot2 3.3.2     v purrr   0.3.4
## v tibble  3.0.3     v dplyr    1.0.0
## v tidyverse 1.1.0    v stringr  1.4.0
## v readr   1.3.1     vforcats 0.5.0

## -- Conflicts ----- tidyverse_conflicts() --
## x dplyr::filter() masks stats::filter()
## x dplyr::lag()   masks stats::lag()
```

```
library(e1071)
library(dbscan)
```

### 30.3 Example

```
data_to_cluster <- data.frame(
  x_values = c(rnorm(40, 5, 1), rnorm(60, 10, 1), rnorm(20, 12, 3)),
  y_values = c(rnorm(40, 5, 1), rnorm(60, 5, 3), rnorm(20, 15, 1)),
  original_group = c(rep("A", 40), rep("B", 60), rep("C", 20)) )
```

### 30.4 Hierarchical clustering

**Algorithm:** each object is initialised as, then repeat

- join the two most similar clusters based on a distance-based metric
- e.g., Ward's (1963) approach is based on variance

until only one single cluster is achieved

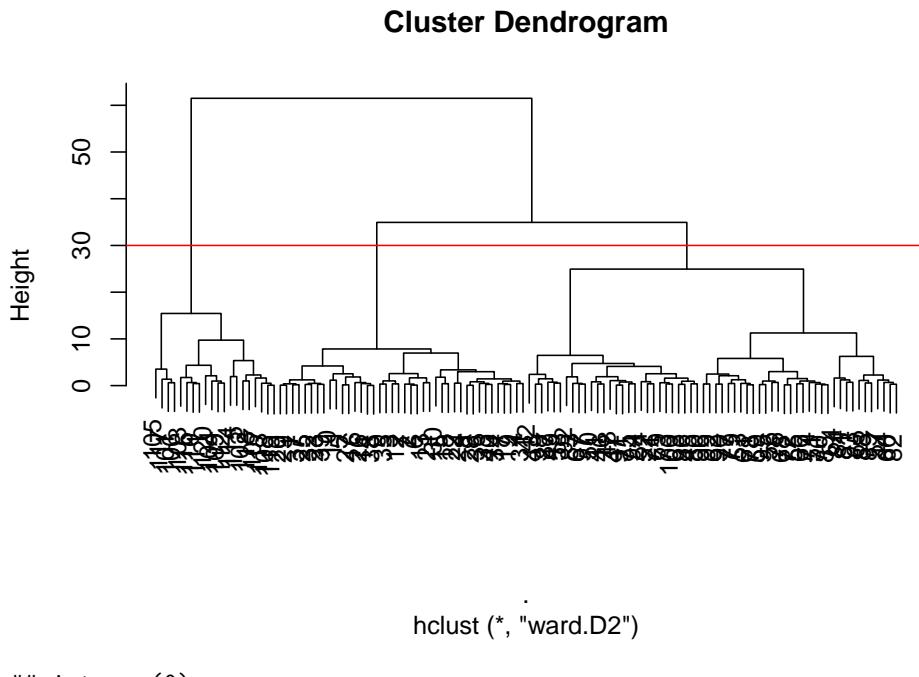
```
hclust_result <- data_to_cluster %>%
  select(x_values, y_values) %>%
  dist(method="euclidean") %>%
  hclust(method="ward.D2")

data_to_cluster <- data_to_cluster %>%
  add_column(hclust_cluster = cutree(hclust_result, k=3))
```

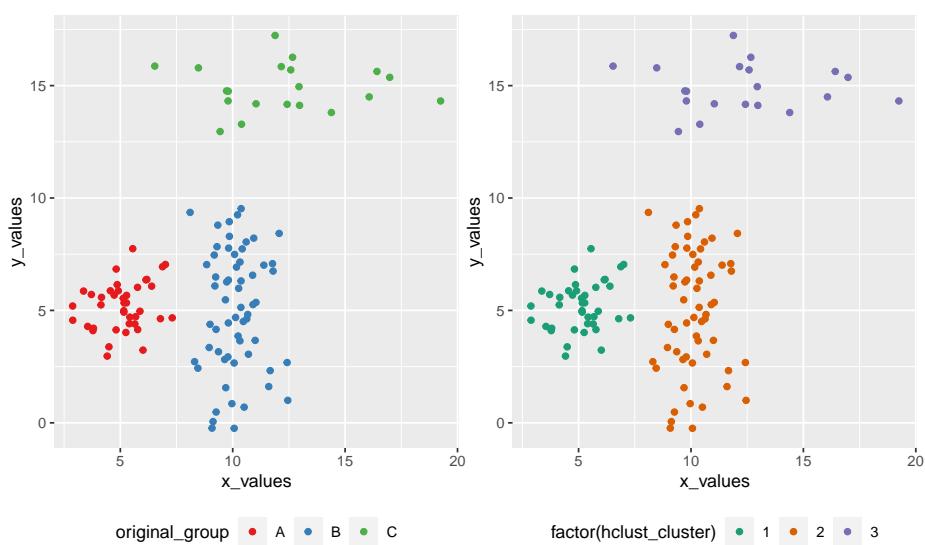
### 30.5 Clustering tree

This approach generates a clustering tree (dendrogram), which can then be “cut” at the desired height

```
plot(hclust_result) + abline(h = 30, col = "red")
```



## 30.6 Hierarchical clustering result



## 30.7 Bagged clustering

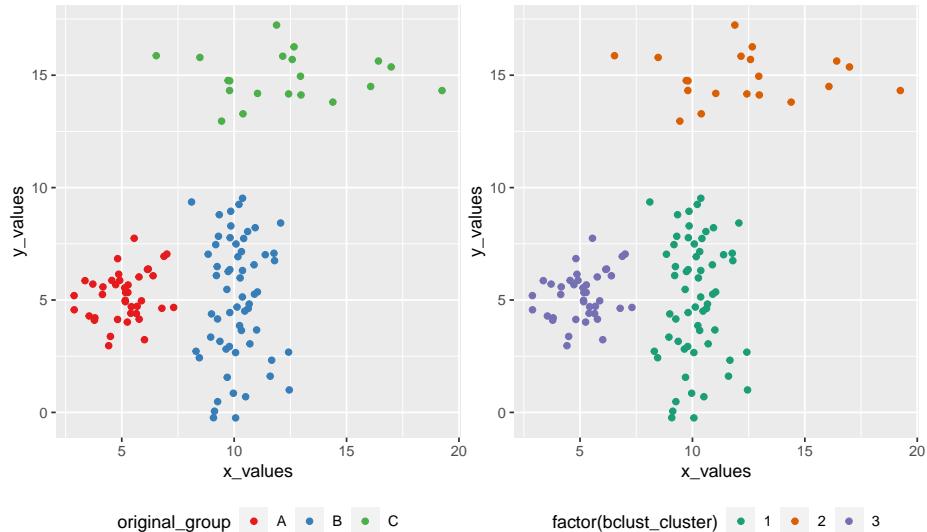
Bootstrap aggregating (*b-agg-ed*) clustering approach (Leisch, 1999)

- first k-means on samples
- then a hierarchical clustering of the centroids generated through the samples

```
bclust_result <- data_to_cluster %>%
  select(x_values, y_values) %>%
  bclust(hclust.method="ward.D2", resample = TRUE)

data_to_cluster <- data_to_cluster %>%
  add_column(bclust_cluster = clusters.bclust(bclust_result, 3))
```

## 30.8 Bagged clustering result



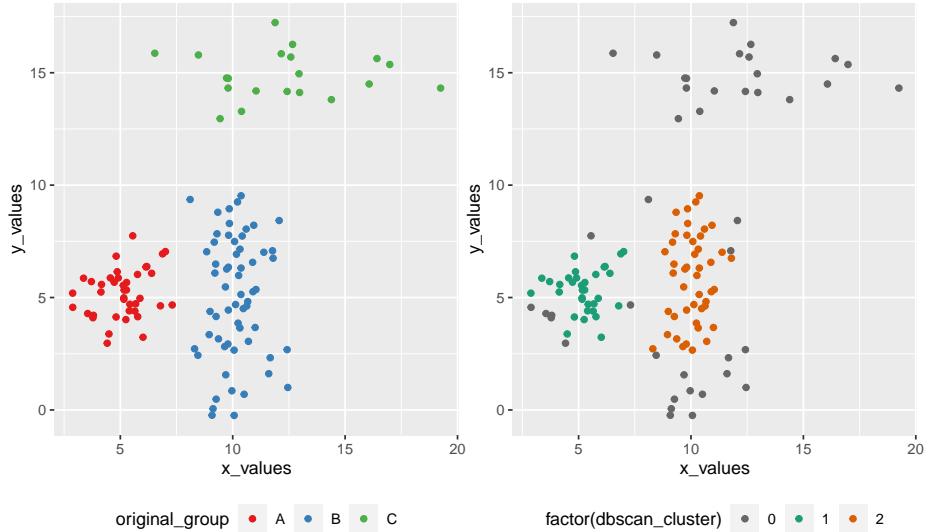
## 30.9 Density based clustering

DBSCAN (“density-based spatial clustering of applications with noise”) starts from an unclustered point and proceeds by aggregating its neighbours to the same cluster, as long as they are within a certain distance. (Ester *et al*, 1996)

```
dbscan_result <- data_to_cluster %>%
  select(x_values, y_values) %>%
  dbscan(eps = 1, minPts = 5)

data_to_cluster <- data_to_cluster %>%
  add_column(dbscan_cluster = dbscan_result$cluster)
```

## 30.10 DBSCAN result



## 30.11 Summary

Hierarchical and density-based clustering

- Hierarchical
- Mixed
- Density-based

**Next:** Practical session

- Geodemographic classification