

Reproducible Science

Margherita Calderan
Replicability School

June 6, 2025

About me 🖐️

- Post-doctoral researcher in **Cognitive Psychology**, University of Padova.
- Research: Computational modeling of **cognitive** and **learning processes**, **Bayesian** hypothesis testing.
- PhD in Psychological Science, completed **March 6, 2025**.
- Passionate about reproducible science after struggling with disorganized datasets in my early research!

Our job is hard 🔥

- Running experiments
- Analyzing data
- Managing trainees
- Writing papers
- Responding to reviewers



Reproducibility helps!



- **Organizes** your workflow.
- **Saves time** by documenting steps.
- **Builds trust** in your findings.
- Enables others to **reproduce** and **extend** your work.

What is reproducible science?

At its core, reproducible science means that someone else, or even you, in the future, can **reproduce** your **results** from your **materials**: your data, your code, your documentation.

It means your workflow is **transparent**.

Keys to reproducible science

- **Data:** organize, document, and share your datasets in ways that are usable by others and understandable by you (even years later).
- **Code:** write analysis scripts that are clean, transparent, and reusable..
- **Literate programming:** combine code and text in the same document, so your reports are dynamic and replicable.
- **Version Control and Sharing:** track changes, collaborate, and make your work openly available using tools like GitHub and OSF.

So... Is reproducible science even harder?

At first, yes - but then...  

- Helps you stay **organized**.
- Makes it **easier to remember** what you did.
- Allows others to **understand, reproduce, and build on** your work.

Learning the tools takes effort but once you do, your workflow becomes smoother, clearer, and more reliable.

Outline

Data

Code

R projects

Literate Programming

Version Control

Data

Data types in research

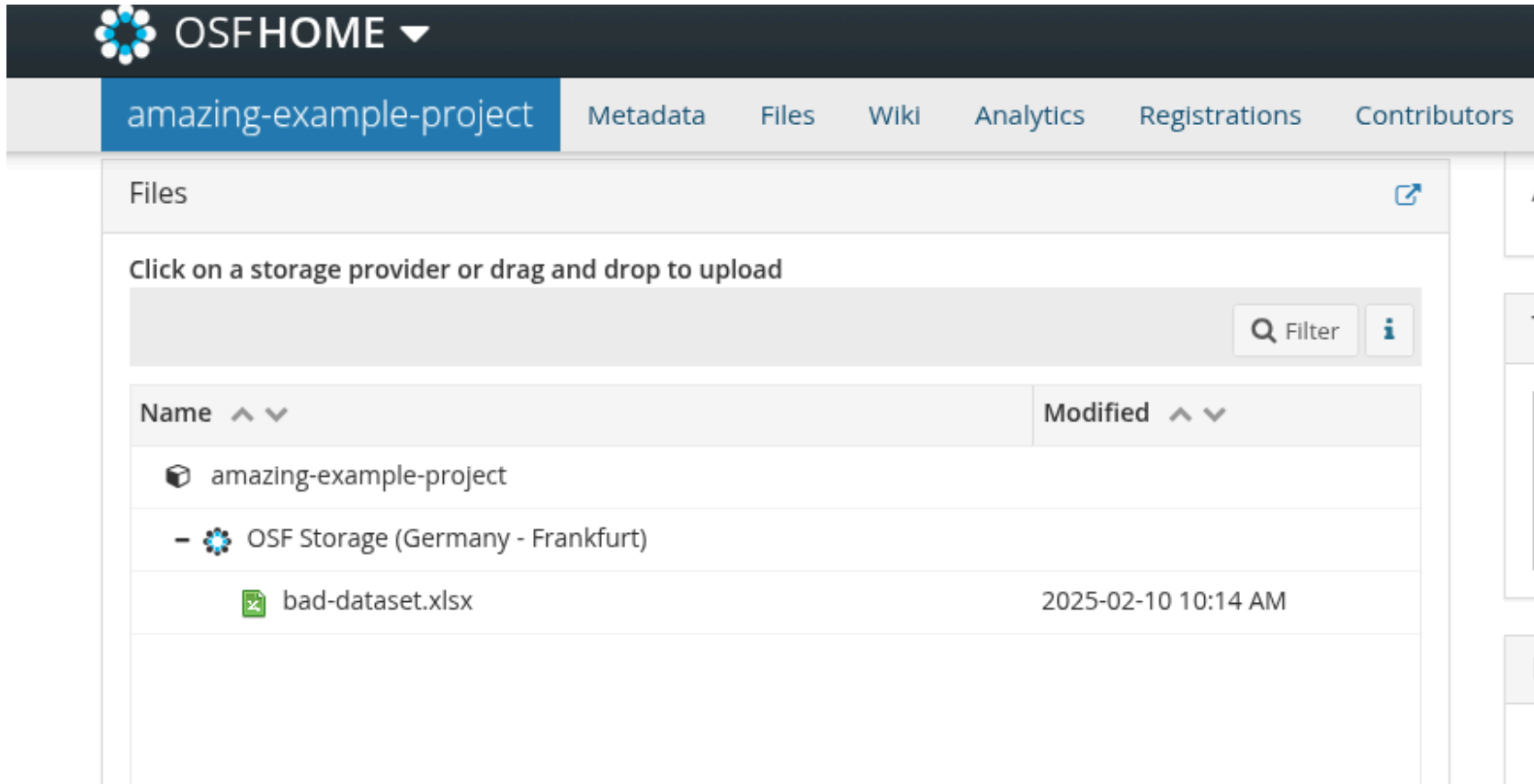


Open Science Framework

- Free platform to **organize**, **document**, and **share** research.
- Supports **preregistration**, **archiving**, and **collaboration**.
- Integrates with GitHub, Dropbox, Google Drive.

Bad data sharing example

Imagine this scenario: you read a paper that seems really relevant to your research. At the end, you're excited to see they've shared their data on OSF. You go to the repository, and there's one file...



The screenshot shows the OSFHOME interface. At the top, there's a dark blue header with the OSFHOME logo and a dropdown arrow. Below this is a navigation bar with tabs: 'amazing-example-project' (selected), 'Metadata', 'Files', 'Wiki', 'Analytics', 'Registrations', and 'Contributors'. The main content area is titled 'Files' and contains a message: 'Click on a storage provider or drag and drop to upload'. Below this is a search bar with a 'Filter' button and an information icon. A table lists the files in the project:

Name ^ v	Modified ^ v
amazing-example-project	
- OSF Storage (Germany - Frankfurt)	
bad-dataset.xlsx	2025-02-10 10:14 AM

Bad data sharing example

You download it, open it, and you see this: . . .

x1	x2	x3	x4	x5	x6	x7
0.3981105	13.912435	a	0	-0.6775811	0.8759740	-0.2051604
-0.1434733	1.093743	c	0	0.7055193	0.2521987	1.8816947
-0.2526000	4.898035	c	0	0.4744651	-0.5628840	0.3245589
-1.2272588	14.717053	b	0	-0.5132792	-1.1368242	-0.1355150
-0.4360417	8.547025	c	1	-0.1736804	-0.7120962	-1.2714320

What do these variables mean? What's x3?

What do 0 and 1 represent? How are missing values coded?

Is x6 a z-score or raw data?

Good data sharing practices

- Use **plain-text formats** (e.g., `.csv`, `.txt`).
- Include a **data dictionary** with variable descriptions.
- Add a **README** with key details.
- Follow **FAIR principles** (Findable, Accessible, Interoperable, Reusable).

Data dictionary

- A **data dictionary** defines each variable in your dataset.
- Boosts **transparency** and **collaboration**.
- Saves time for **collaborators** and **future-you**.

datadictionary

```
1 library(datadictionary)
2 df <- data.frame( id = factor(letters[1:5]),
3                   anx = rnorm(5, 0, 1),
4                   edu = factor(c("PhD", "BSc", "MSc", "PhD", "BSc")))
5 df_labels <- list(
6   anx = "Beck Anxiety Inventory, standardized",
7   edu = "Last degree obtained"
8 )
9 create_dictionary(df, id_var = "id", var_labels = df_labels)
```

	item	label	class	summary	value
1				Rows in dataset	5
2				Columns in dataset	3
3	id	Unique identifier		unique values	5
4				missing	0
5	anx	Beck Anxiety Inventory, standardized	numeric	mean	0
6				median	0
7				min	-1.65
8				max	2.12
9				missing	0
10	edu	Last degree obtained	factor	BSc (1)	2
11				MSc (2)	1
12				PhD (3)	2
13				missing	0

Data dictionary - Good data sharing example

Data-dictionary.txt



- `ID`: Factor indexing participants identification codes (e.g., "S001", "S002", etc.)
- `day`: Integer indexing the day of participation (from 1 to 10)
- `SBP_aft`, `DBP_aft`: Numeric indexing afternoon measurements (mmHg) of systolic and diastolic blood pressure, respectively. Note: these variables have been computed by averaging each pair of consecutive recordings
- `WHLSM1` ... `WHLSM6`: Item scores at the state workaholism measure (1-7) administered in the afternoon
- `SBP_eve`, `DBP_eve`: Numeric indexing evening measurements (mmHg) of systolic and diastolic blood pressure, respectively. Note: these variables have been computed by averaging each pair of consecutive recordings
- `EE1` ... `EE4`: Item scores at the emotional exhaustion measure (1-7) administered in the evening
- `R.det1` ... `R.det3`: Item scores at the psychological detachment measure (1-7) administered in the evening
- `SQ1` ... `SQ4`: Item scores at the sleep disturbances measure (1-7) administered in the morning. Note: higher values indicate worse sleep disturbances; these measures are related to the following day
- `gender`: Factor indexing participants' gender ("F" or "M")
- `age`: Integer indexing participants' age (years)
- `BMI`: Numeric indexing participants' body mass index ($\text{\$/kg/m}^2$)
- `IN.resp`: Factor indexing whether the participant was included in the main sample based on the response rate inclusion criteria (TRUE) or not (FALSE)
- `IN.bp`: Factor indexing whether the participant was included in the sample considered for blood pressure analyses (TRUE) or not (FALSE)

README files

A **README** file is the first thing someone sees when they open your dataset/project folder. It should answer basic questions like:

- What is this dataset?
- How was it collected?
- What are the variables?

README - Good data sharing example

Wearing face masks when no longer mandatory: An exploratory study about a...

README.txt



This repository "data" contains a CSV file that serves as the data source for the network analysis and regression analysis discussed in the accompanying article. Each column within the CSV file corresponds to a node in the network analysis.

Run first the Network_analysis.R script and then the "Generalized linear mixed effect modeling.R script.

README - Good data sharing example

README.md



Tracking the Unconscious: Neural evidence for the retention of unaware information in visual working memory



This repository contains the code to reproduce the analysis, figures and tables of the paper *Tracking the Unconscious: Neural evidence for the retention of unaware information in visual working memory* by Gambarota et al. The repository contains also the code to run the experiment using Psychopy along with raw EEG and behavioral data.

Structure

- The `data` folder contains the raw and cleaned EEG and behavioral data:

<!-- -->

```
data
├── clean
│   ├── behavioral
│   └── eeg
└── raw
    ├── behavioral
    │   ├── csv
    │   └── pkl
    └── eeg
```

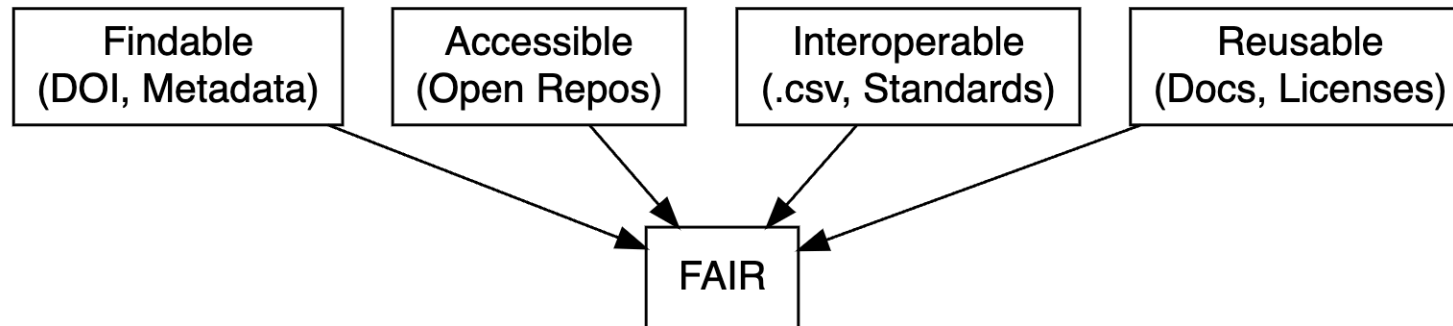
- The `experiment/` folder contains python scripts to run the experiment.

<!-- -->

```
experiment
├── experiment.py
└── triggers.py
```

FAIR data principles

- **Findable:** Use metadata and DOIs to make data easy to locate.
- **Accessible:** Ensure data is retrievable via open repositories.
- **Interoperable:** Use standard formats (e.g., `.csv`, `.txt`) for compatibility.
- **Reusable:** Include clear documentation and open licenses.



Data licensing

A license tells others what they can and can't do with your data. If you don't include one, legally speaking, people might not be allowed to use it, even if you meant to share it openly.

- **Licenses** clarify how others can use your data.
- Common licenses:
 - **CC BY**: Requires attribution.
 - **CC0**: No restrictions.
 - **ODC-BY**: Database-specific attribution.
- Choose based on **discipline norms** and **data sensitivity**.

Code

Scripts

Reproducible: You can rerun them.

Documented: You can see what you did and when.

Shareable: Others can inspect and reproduce your analysis.

R and RStudio

- **R**: Free, open-source, with thousands of packages for analysis.
- **RStudio**: Intuitive interface for coding, plotting, and debugging.
- Vibrant **community** for support and resources.
- Scripting ensures **transparent, reproducible** workflows.

The SPSS Workflow

- Click menu items to run analysis
- “exclude <18”
- Click through everything again
- Forget a step? Round differently?
- Now the results don’t match the manuscript...

Stressful, error-prone, and undocumented.

R Workflow

```
1 # Load data
2 data <- read.csv("data.csv")
3
4 # Filter
5 data <- data[data$age >= 18, ]
6
7 # Analyze
8 summary(lm(score ~ condition, data = data))
9
10 # Make plot
11 ggplot(data, aes(x = condition, y = score)) +
12   geom_boxplot()
```

One line change, rerun, and everything updates.

Writing better code



- **Organize scripts:** Load packages and data upfront.
- **Comment clearly:** Document your logic for clarity.
- **Name descriptively:** Use `snake_case` or `camelCase` for readability.

Organized scripts

Global operations at the beginning of the script:

- loading packages
- loading datasets
- changing general options (`options()`)

```
1 # packages
2 library(tidyverse)
3 library(lme4)
4
5 # options
6
7 options(scipen = 999)
8
9 # loading data
10 dat <- read.csv(...)
```

Comments, comments and comments...

Write the code for your future self and for others, not for yourself right now.

Try to open a (not well documented) old coding project after a couple of years and you will understand :)

Invest time in writing more comprehensible and documented code for you and others.

```
1 # Remove participants with missing anxiety scores
2 dat <- dat %>% filter(!is.na(anxi))
3 #vs.
4 dat <- dat %>% filter(!is.na(anxi)) # <-- What is this doing?
```

Use descriptive names

Another best practice: name your variables clearly.

```
1 # Bad
2 x1 <- c("Psychology", "Medicine", "Biology")
3 # Better
4 uni_dep <- c("Psychology", "Medicine", "Biology")
```

Consistency helps too. Use either snake_case or camelCase, but pick one and stick to it.

Summary

- Scripts beat point-and-click
- Structure matters
- Comment often
- Name things well

Functions to avoid repetition

Functions are the primary building blocks of your program. You write small, reusable, self-contained functions that do one thing well, and then you combine them.

Avoid repeating the same operation multiple times in the script. The rule is, if you are doing the same operation more than two times, write a function.

A function can be re-used, tested and changed just one time affecting the whole project.

Functional Programming, example...

We have a dataset (`mtcars`) and we want to calculate the mean, median, standard deviation, minimum and maximum of each column and store the result in a table.

```
1 head(mtcars, n = 3)
```

	mpg	cyl	disp	hp	drat	wt	qsec	vs	am	gear	carb
Mazda RX4	21.0	6	160	110	3.90	2.620	16.46	0	1	4	4
Mazda RX4 Wag	21.0	6	160	110	3.90	2.875	17.02	0	1	4	4
Datsun 710	22.8	4	108	93	3.85	2.320	18.61	1	1	4	1

```
1 str(mtcars)
```

```
'data.frame':  32 obs. of  11 variables:
 $ mpg : num  21 21 22.8 21.4 18.7 18.1 14.3 24.4 22.8 19.2 ...
 $ cyl : num  6 6 4 6 8 6 8 4 4 6 ...
 $ disp: num  160 160 108 258 360 ...
 $ hp  : num  110 110 93 110 175 105 245 62 95 123 ...
 $ drat: num  3.9 3.9 3.85 3.08 3.15 2.76 3.21 3.69 3.92 3.92 ...
 $ wt  : num  2.62 2.88 2.32 3.21 3.44 ...
 $ qsec: num  16.5 17 18.6 19.4 17 ...
 $ vs  : num  0 0 1 1 0 1 0 1 1 1 ...
 $ am  : num  1 1 1 0 0 0 0 0 0 0 ...
 $ gear: num  4 4 4 3 3 3 3 4 4 4 ...
 $ carb: num  4 4 1 1 2 1 4 2 2 4 ...
```

Functional Programming

The standard (~imperative) option is using a **for** loop, iterating through columns, calculate the values and store into another data structure.

```
1  ncols <- ncol(mtcars)
2  means <- medians <- mins <- maxs <- rep(0, ncols)
3
4  for(i in 1:ncols){
5    means[i] <- mean(mtcars[[i]])
6    medians[i] <- median(mtcars[[i]])
7    mins[i] <- min(mtcars[[i]])
8    maxs[i] <- max(mtcars[[i]])
9  }
10
11 results <- data.frame(means, medians, mins, maxs)
12 results$col <- names(mtcars)
13
14 head(results, n = 3)
```

	means	medians	mins	maxs	col
1	20.09062	19.2	10.4	33.9	mpg
2	6.18750	6.0	4.0	8.0	cyl
3	230.72188	196.3	71.1	472.0	disp

Functional Programming

The main idea is to decompose the problem writing a function and loop over the columns of the dataframe:

```
1  summ <- function(x){  
2    data.frame(means = mean(x),  
3              medians = median(x),  
4              mins = min(x),  
5              maxs = max(x))  
6  }  
7  ncols <- ncol(mtcars)  
8  dfs <- vector(mode = "list", length = ncols)  
9  
10 for(i in 1:ncols){  
11   dfs[[i]] <- summ(mtcars[[i]])  
12 }
```

Functional Programming

```
1 results <- do.call(rbind, dfs)
2 head(results, n = 6)
```

	means	medians	mins	maxs
1	20.090625	19.200	10.400	33.900
2	6.187500	6.000	4.000	8.000
3	230.721875	196.300	71.100	472.000
4	146.687500	123.000	52.000	335.000
5	3.596563	3.695	2.760	4.930
6	3.217250	3.325	1.513	5.424

Functional Programming, `*apply`

- The `*apply` family is one of the best tool in R. The idea is pretty simple: apply a function to each element of a list.
- The powerful side is that in R everything can be considered as a list. A vector is a list of single elements, a dataframe is a list of columns etc.
- Internally, R is still using a `for` loop but the verbose part (preallocation, choosing the iterator, indexing) is encapsulated into the `*apply` function.

```
1 means <- rep(0, ncol(mtcars))
2 for(i in 1:length(means)){
3   means[i] <- mean(mtcars[[i]])
4 }
5
6 # the same with sapply
7 means <- sapply(mtcars, mean)
```

The **apply* Family

Apply **your** function...

```
1 results <- lapply(mtcars, summ)
```

Now results is a list of data frames, one per column.

We can stack them into one big data frame:

```
1 results_df <- do.call(rbind, results)
```

This gives us a clean summary for every variable in just a few lines of code.
No loops, no repetition.

Using `sapply`, `vapply`, and `apply`

- `lapply()` always returns a list.
- `sapply()` tries to simplify the result into a vector or matrix.
- `vapply()` is like `sapply()` but safer (you specify the return type).
- `apply()` is for applying functions over rows or columns of a matrix or data frame.

```
1 sapply(mtcars, mean) == apply(mtcars, MARGIN = 2, mean) # MARGIN = 2, apply to columns
```

```
mpg  cyl  disp    hp  drat    wt  qsec    vs    am  gear  carb
TRUE TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE
```


for loops are bad?

for loops are the core of each operation in R (and in every programming language). For complex operation they are more readable and effective compared to `*apply`. In R we need extra care for writing efficient for loops.

Extremely slow, no preallocation:

```
1 res <- c()
2 for(i in 1:1000){
3   # do something
4   res[i] <- i^2
5 }
```

Very fast:

```
1 res <- rep(0, 1000)
2 for(i in 1:length(res)){
3   # do something
4   res[i] <- i^2
5 }
```

microbenchmark

```
1 library(microbenchmark)
2
3 microbenchmark(
4   grow_in_loop = {
5     res <- c()
6     for (i in 1:10000) {
7       res[i] <- i^2
8     }
9   },
10  preallocated = {
11    res <- rep(0, 10000)
12    for (i in 1:length(res)) {
13      res[i] <- i^2
14    }
15  }, times = 100)
```

Unit: microseconds

expr	min	lq	mean	median	uq	max	neval	cld
grow_in_loop	1150.419	1213.005	1413.5623	1277.130	1320.733	6504.281	100	a
preallocated	655.877	688.964	720.3774	700.731	712.990	2333.925	100	b

Going further: custom function lists

Let's define a list of functions:

```
1 funs <- list(mean = mean, sd = sd, min = min, max = max, median = median)
```

Now we can apply all of these to every column:

```
1 sapply(funs, function(f) apply(mtcars, 2, f))
```

	mean	sd	min	max	median
mpg	20.090625	6.0269481	10.400	33.900	19.200
cyl	6.187500	1.7859216	4.000	8.000	6.000
disp	230.721875	123.9386938	71.100	472.000	196.300
hp	146.687500	68.5628685	52.000	335.000	123.000
drat	3.596563	0.5346787	2.760	4.930	3.695
wt	3.217250	0.9784574	1.513	5.424	3.325
qsec	17.848750	1.7869432	14.500	22.900	17.710
vs	0.437500	0.5040161	0.000	1.000	0.000
am	0.406250	0.4989909	0.000	1.000	0.000
gear	3.687500	0.7378041	3.000	5.000	4.000
carb	2.812500	1.6152000	1.000	8.000	2.000

This gives you a matrix with rows as variables and columns as statistics.

Pure vs. Impure functions

Pure function

Same input, same output, no side effects.

```
1 x = 4
2 add_pure<- function(x) {
3   return(x + 1)
4 }
5 add_pure(2)
```

```
[1] 3
```

```
1 print(x)
```

```
[1] 4
```

Impure function

Modifies external variables.

```
1 add_impure <- function(x) {
2   x <- x + 1
3 }
4 add_impure(x)
5 print(x)
```

```
[1] 5
```

Test your functions - **fuzzr**

When you write your own functions, it's smart to test them. In R, we can use **fuzzr** to do **property-based testing**.

Define your function...

```
1 my_mean <- function(x, na.rm = TRUE) {  
2   if (!is.numeric(x)) stop("`x` must be numeric")  
3   if (length(x) == 0) return(NA)  
4   if (na.rm) x <- x[!is.na(x)]  
5   if (length(x) == 0) return(NA)  
6   sum(x) / length(x)  
7 }
```

Define properties that should always hold true...

```
1 property_mean_correct <- function(x) {  
2   x_no_na <- x[!is.na(x)] #remove NA  
3   if (length(x_no_na) == 0) return(TRUE)  
4   abs(my_mean(x) - mean(x, na.rm = TRUE)) < 1e-16  
5 }
```

This runs the property on different random numeric vectors and checks whether it holds.

```
1 # Property-based testing with 'fuzzr'
2 library(fuzzr)
3 test = fuzz_function(fun = property_mean_correct,
4                       arg_name = "x",
5                       tests = test_dbl())
6 lapply(test, function(res) res$test_result$value)
```

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

```
[[2]]
[1] TRUE
```

```
[[3]]
[1] TRUE
```

```
[[4]]
[1] TRUE
```

```
[[5]]
[1] TRUE
```

```
[[6]]
[1] TRUE
```

```
1 fuzzr::test_dbl()
```

```
$dbl_empty
numeric(0)
```

```
$dbl_single
[1] 1.5
```

```
$dbl_multiple
[1] 1.5 2.5 3.5
```

```
$dbl_with_na
[1] 1.5 2.5 NA
```

```
$dbl_single_na
[1] NA
```

```
$dbl_all_na
[1] NA NA NA
```

Why functional programming?

- We can write less and reusable code that can be shared and used in multiple projects.
- The scripts are more compact, easy to modify and less error prone (imagine that you want to improve the `summ` function, you only need to change it once instead of touching the `for` loop).
- Functions can be easily and consistently documented (see `roxygen` documentation) improving the reproducibility and readability of your code.

Functional programming in the wild

You can write some R scripts only with functions and `source()` them into the global environment.

```
project/  
├─ R/  
│   ├─ utils.R  
│   └─ analysis.R
```

```
1 source("R/utils.R")  
2 results <- lapply(mtcars, summ)  
3 results_df <- do.call(rbind, results)
```

This is reproducible, modular, and maintainable.

More about functional programming in R

- Advanced R by Hadley Wickham, section on Functional Programming (<https://adv-r.hadley.nz/fp.html>)
- Hands-On Programming with R by Garrett Grolemund <https://rstudio-education.github.io/hopr/>
- Hadley Wickham: The Joy of Functional Programming (for Data Science) (<https://www.youtube.com/watch?v=bzUmK0Y07ck>)

Wrapping up

- Avoid repetition by using functions.
- Favor pure functions.
- Test your functions.
- The `*apply` functions are your friends.

Organize your project

R Projects

R Projects are a feature implemented in RStudio to organize a working directory.

- They automatically set the working directory
- They allow the use of ***relative paths*** instead of ***absolute paths***
- They provide quick access to a specific project

The Working Directory Problem

How many times have you opened an R script and seen this at the top?

```
setwd("C:/Users/margherita/Documents/PhD/final_data/mess") #change
```

Instead of hardcoding paths, we want to use projects with **relative paths**.

R Projects

An R Project (.Rproj) is a file that defines a self-contained workspace.

When you open an R Project, your working directory is automatically set to the project root, no need to use `setwd()` ever again.

Open RStudio

File → New Project → New Directory → New Project

Relative Path (to the working directory)

Absolute path: `read.csv("Users/tita/workinMemo/data/clean_data.csv")`

Relative path: `read.csv("data/clean_data.csv")`

A Minimal Project Structure

```
1  my-project/  
2      |  
3      ├── data/  
4          ├── raw/  
5          └── processed/  
6      ├── R/  
7          └── analysis.R  
8      |  
9      ├── outputs/  
10         ├── figures/  
11         └── tables/  
12      |  
13      ├── my-project.Rproj  
14      |  
15      └── README.md
```

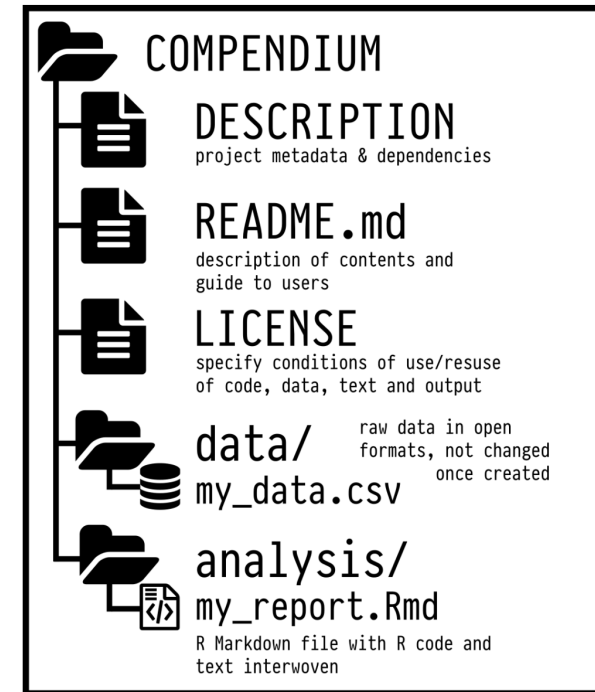

Project organization with `rrtools`

To make this even “easier”, you can use the `rrtools` package to create what’s called a reproducible research compendium.

```
1 install.packages("rrtools")  
2  
3 rrtools::create_compendium("my-awesome-project")
```

Reproducible research compendium

... the goal is to provide a standard and easily recognisable way for organising the digital materials of a project to enable others to inspect, reproduce, and extend the research... (Marwick et al., 2018)



Research compendium **rrtools**

- Organize its files according to the prevailing conventions.
- Maintain a clear separation of data (original data is untouched!), method, and output.
- Specify the computational environment that was used for the original analysis

> [Tutorial](#)

`rrtools::create_compendium()` builds the basic structure for a research compendium.

- Storage for general metadata (e.g., citation details)
- Dependency management via **DESCRIPTION** file
- Function storage and documentation in R/ folder

> Example

renv: locking your R environment

Another challenge for reproducibility is package versions.

You write some code today using `dplyr 1.1.2`.

In six months, `dplyr` gets updated... 🥲

`renv` helps you create reproducible environments for your R projects!

What does **renv** do?

- It records all the packages you use, with versions, in a lockfile
- It installs them in a project-specific library
- It ensures that anyone who runs your code gets exactly the same environment

Project specific library

```
install.packages("renv")
```

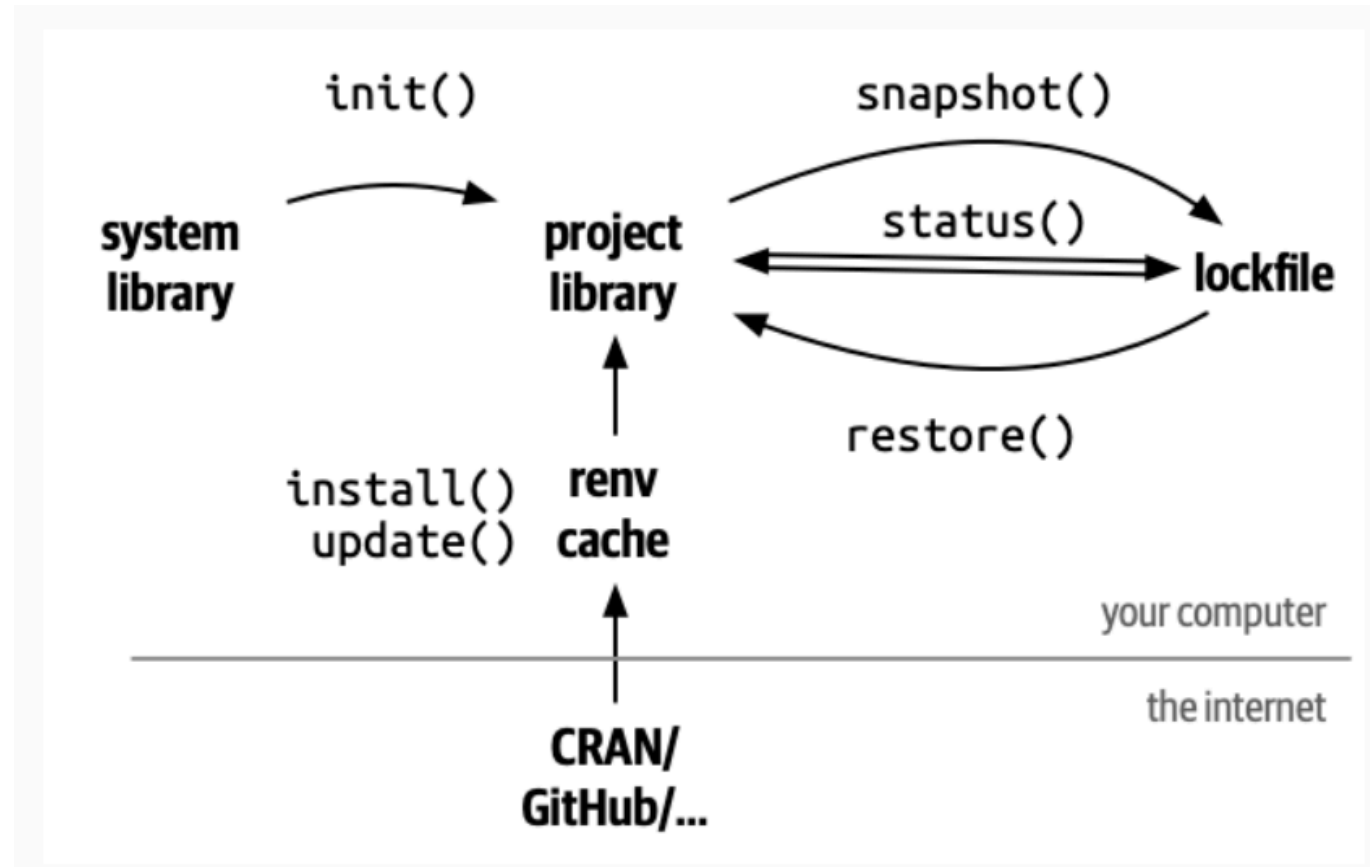
```
renv::init()
```

```
install.packages('bayesplot')
```

These packages will be installed into "~/repro-pre-school/example-renv/renv/library/macos/R-4.4/aarch64-apple-darwin20".

> Example

renv commands



`renv::snapshot()` # update lockfile

`renv::restore()` # re-install from lockfile

Research `rrtools` + `renv`

- `rrtools`: Organizes your project into a **reproducible compendium** with clear folders.
- `renv`: Locks **R package versions** for consistent environments.
- Together, they ensure **structure** and **reproducibility** across teams and time.
- Run `rrtools::create_compendium()` to start, then `renv::init()` to lock dependencies.



Docker

- Packages your project's **software**, **dependencies**, and **system settings** into a *container*.
- Ensures **consistency** across different computers or servers.
- Ideal for **sharing** complex analyses with others.

Documenting your environment

- `sessionInfo()`: Captures your **R version**, **packages**, and **platform** in one command.
- Easy way to **document** and **share** your environment.

```
1 sessionInfo()
```

```
R version 4.4.2 (2024-10-31)
```

```
Platform: aarch64-apple-darwin20
```

```
Running under: macOS Sequoia 15.5
```

```
Matrix products: default
```

```
BLAS: /Library/Frameworks/R.framework/Versions/4.4-arm64/Resources/lib/libRblas.0.dylib
```

```
LAPACK: /Library/Frameworks/R.framework/Versions/4.4-arm64/Resources/lib/libRlapack.dylib; LAPACK  
version 3.12.0
```

```
locale:
```

```
[1] en_US.UTF-8/en_US.UTF-8/en_US.UTF-8/C/en_US.UTF-8/en_US.UTF-8
```

```
time zone: Europe/Rome
```

```
tzcode source: internal
```

```
attached base packages:
```

```
[1] stats      graphics  grDevices  utils      datasets  methods   base
```

Organizing for reproducibility

- Don't hardcode paths, use `R Projects`
- Create a logical folder structure for your project
- Use `rrtools` to scaffold a research compendium
- Use `renv` to lock your package versions

All of this structure isn't just for you, it makes it easier to work with others.

Literate Programming

What's wrong about Microsoft Word?

MS Word is a WYSIWYG (*what you see is what you get editor*) that force users to think about formatting, numbering, etc. Markup languages receive the content (plain text) and the rules and creates the final document.

What's wrong about Microsoft Word?

Beyond the pure writing process, there are other aspects related to research data.

- writing math formulas
- reporting statistics in the text
- producing tables
- producing plots

In MS Word (or similar) we need to produce everything outside and then manually put figures and tables.

Think about the typical MW workflow

- You run your analysis in R
- You copy the results into a Word document
- You tweak the formatting
- You insert a figure generate with R manually
- You change your analysis, but forget to update the results in the text...

Literate Programming

A document where:

- The code is part of the text
- The results are generated *dynamically*
- The figures are rendered *automatically*
- Everything is in *sync*

For example **jupyter notebooks**, **R Markdown** and now **Quarto** are literate programming frameworks to integrate code and text.

Literate Programming, the markup language

Beyond the coding part, the markup language is the core element of a literate programming framework.

The idea of a markup language is separating the result from what you actually write. Some examples are:

- LaTeX
- HTML
- Markdown
- XML
- ...

LaTeX

```
1 % This is a simple sample document. For more complicated documents take a look
  in the exercise tab. Note that everything that comes after a % symbol is treated
  as comment and ignored when the code is compiled.
2
3 \documentclass{article} % \documentclass{} is the first command in any LaTeX
  code. It is used to define what kind of document you are creating such as an
  article or a book, and begins the document preamble
4
5 \usepackage{amsmath} % \usepackage is a command that allows you to add
  functionality to your LaTeX code
6
7 \title{Simple Sample} % Sets article title
8 \author{My Name} % Sets authors name
9 \date{\today} % Sets date for date compiled
10
11 % The preamble ends with the command \begin{document}
12 \begin{document} % All begin commands must be paired with an end command
  somewhere
13     \maketitle % creates title using information in preamble (title, author,
      date)
14
15     \section{Hello World!} % creates a section
16
17     \textbf{Hello World!} Today I am learning \LaTeX. %notice how the command
      will end at the first non-alphabet charecter such as the . after \LaTeX
18     \LaTeX{} is a great program for writing math. I can write in line math such
      as  $a^2+b^2=c^2$  %$ tells LaTeX to compile as math
19     . I can also give equations their own space:
20     \begin{equation} % Creates an equation environment and is compiled as math
21     \gamma^2+\theta^2=\omega^2
22     \end{equation}
23     If I do not leave any blank lines \LaTeX{} will continue this text without
      making it into a new paragraph. Notice how there was no indentation in the
      text after equation (1).
24     Also notice how even though I hit enter after that sentence and here
      \downarrow
25     \LaTeX{} formats the sentence without any break. Also look how it
      doesn't matter how many spaces I put between
      my words.
26
```

Simple Sample

My Name

July 4, 2024

1 Hello World!

Hello World! Today I am learning \LaTeX . \LaTeX is a great program for writing math. I can write in line math such as $a^2 + b^2 = c^2$. I can also give equations their own space:

$$\gamma^2 + \theta^2 = \omega^2 \quad (1)$$

If I do not leave any blank lines \LaTeX will continue this text without making it into a new paragraph. Notice how there was no indentation in the text after equation (1). Also notice how even though I hit enter after that sentence and here \downarrow \LaTeX formats the sentence without any break. Also look how it doesn't matter how many spaces I put between my words.

For a new paragraph I can leave a blank space in my code.

Markdown

Markdown Live Preview Reset Copy ☐ Sync scroll

```
1 # Markdown syntax guide
2
3 ## Headers
4
5 # This is a Heading h1
6 ## This is a Heading h2
7 ##### This is a Heading h6
8
9 ## Emphasis
10
11 *This text will be italic*
12 _This will also be italic_
13
14 **This text will be bold**
15 __This will also be bold__
16
17 _You **can** combine them_
18
19 ## Lists
20
21 ### Unordered
```

Markdown syntax guide

Headers

This is a Heading h1

This is a Heading h2

This is a Heading h6

Emphasis

This text will be italic

This will also be italic

Markdown

Markdown is one of the most popular markup languages for several reasons:

- easy to write and read compared to Latex and HTML
- easy to convert from Markdown to basically every other format using [pandoc](#)
- easy to implement new features

Markdown (source code)

Also the source code can be used to take notes and read.

```
1  ## My Section
2  - Write bold text.
3  - Include a [link](https://quarto.org)
4  - Run code: `r mean(mtcars$mpg)`.
```

Latex and HTML need to be compiled otherwise they are very hard to read.

Quarto

Quarto (<https://quarto.org/>) is the evolution of R Markdown that integrate a programming language with the Markdown markup language. It is very simple but quite powerful.



Basic Markdown

Markdown can be learned in minutes. You can go to the following link <https://quarto.org/docs/authoring/markdown-basics.html> and try to understand the syntax.

[Guide](#) > [Authoring](#) > Markdown Basics

Markdown Basics

Overview

Quarto is based on Pandoc and uses its variation of markdown as its underlying document syntax. Pandoc markdown is an extended and slightly revised version of John Gruber's [Markdown](#) syntax.

Markdown is a plain text format that is designed to be easy to write, and, even more importantly, easy to read:

A Markdown-formatted document should be publishable as-is, as plain text, without looking like it's been marked up with tags or formatting instructions. – [John Gruber](#)

Quarto

You write your documents in **Markdown**, and **Quarto** turns them into:

- HTML reports
- PDF articles
- Word documents
- Slides
- Website
- Academic manuscripts
- ...

Quarto

- If your data changes, your summary table updates.
- If you update your model, your coefficients update.
- If you change a plot's colors, the new version appear, without having to re-export and re-insert anything.

This eliminates a huge source of human error: **manual updates**.

> Example

Outputs

Quarto can generate multiple output formats from the same source file.

With one command, you get three outputs:

- A PDF to send to your colleagues
- A Word document for your co-author who hates PDFs
- An HTML report for your own website

Everything from the same source. No duplication. **Synchronization.**

> [Example](#)

Extra Tools: citations and cross-referencing

- Citations with BibTeX or Zotero
- Cross-references for figures and tables
- Numbered equations with LaTeX syntax
- Footnotes, tables of contents, and more

You can write scientific documents that look and behave just like journal articles, without ever opening Word.

Writing Papers – APA quarto

APA Quarto is a Quarto extension that makes it easy to write documents in APA 7th edition style, with automatic formatting for title pages, headings, citations, references, tables, and figures.

A Quarto Extension for Creating APA 7 Style Documents

lifecycle experimental

This article template creates [APA Style 7th Edition documents](#) in .docx, .html, and .pdf. The .pdf format can be rendered via Latex (i.e., apaquarto-pdf) or via Typst (apaquarto-typst). The Typst output for this extension is still experimental and requires Quarto 1.5 or greater.

Because the .docx format is still widely used—and often required—my main priority was to ensure compatibility for .docx. This is still a work in progress, and I encourage filing a “New Issue” on GitHub if something does not work or if there is a feature missing.

See [instructions and template options for apaquarto here](#).

[Version History](#)

Example Outputs

The apaquarto-docx form looks like this:

Let's see an example...

> Example

Quarto + Zotero


-5.


Example how to cite @Q or DOI


Method

Participants

Measures

 @2006-99014-227200601... Clemons, S 20...
A taxometric comparison of attention deficit hypera...

 @2008-01388-01720070101 Pineda, D 2007
Taxometría de conglomerados del trastorno por dé...

 @2012-08848-00320120501 Haslam, N 2012
Categories i|zversus i|z dimensions in personality a...

Choose your reference:

apaquarto-pdf:
documentmode: man

<!-- The introduction should not have a level-1 h
Introduction. -->

This is my first paragraph. Any section headings in the i
-5.

Example how to cite @ba

Method

Participants

Measures

Citation from Zotero

Citation Id:
wagenmakers2010

Citation:

Title	Bayesian hypothesis testing for psychologists: A tutorial on the Savage-Dickey method
Authors	Wagenmakers, E, Lodewyckx, T, Kuriyal, H, and Grasman, R
Issue Date	2010
Publication	Cognitive Psychology
Volume	60
Page(s)	158-189
Type	article-journal

Add to bibliography:
bibliography.bib

OK Cancel

```
Untitled1* x manuscript.qmd x bibliography.bib x
80  {American Psychological Association}},
81  publisher = {Author},
82  address = {Washington},
83  doi = {10.1037/0000173-000},
84  url = {http://content.apa.org/books/16157-000},
85  urldate = {2024-03-02},
86  isbn = {978-1-4338-3273-4 978-1-4338-3276-5},
87  langid = {english}
88  }
89  @book{americanpsychologicalassociationMasteringAPAStyle2021,
90    title = {Mastering {APA Style} student workbook.},
91    year = {2021},
92    author = {{American Psychological Association}},
93    publisher = {Author},
94    address = {Washington},
95    doi = {10.1037/0000271-000},
96    isbn = {978-1-4338-3854-5},
97    langid = {english}
98  }
99
100 @article{wagenmakers2010,
101   title = {Bayesian hypothesis testing for psychologists: A tutorial on the
102   author = {Wagenmakers, Eric-Jan and Lodewyckx, Tom and Kuriyal, Himanshu a
103   year = {2010},
104   month = {05},
105   date = {2010-05},
106   journal = {Cognitive Psychology},
107   pages = {158--189},
108   volume = {60},
109   number = {3},
110   doi = {10.1016/j.cogpsych.2009.12.001},
111   url = {https://linkinghub.elsevier.com/retrieve/pii/S0010028509000826},
112   langid = {en}
113 }
```


More about Quarto and R Markdown

The topic is extremely vast. You can do everything in Quarto, a website, thesis, your CV, etc.

- Yihui Xie - R Markdown Cookbook <https://bookdown.org/yihui/rmarkdown-cookbook/>
- Yihui Xie - R Markdown: The Definitive Guide <https://bookdown.org/yihui/rmarkdown/>
- Quarto documentation <https://quarto.org/docs/guide/>

Version Control

Why Version Control?

You're working on a project. You save your script as:

- `analysis.R`
- `analysis2.R`
- `analysis_final.R`
- `analysis_final_revised.R`
- `analysis_final_revised_0K_for_real.R`

What Is Git?

Git is a version control system. It works like a time machine for your project.

```
1 git init
```

Then, save changes with commits:

```
1 git add analysis.R  
2 git commit -m "Added initial analysis"
```

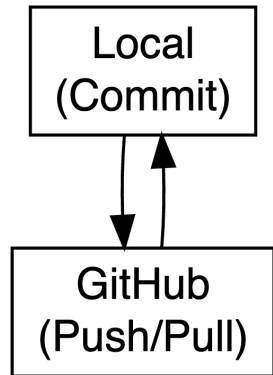
GitHub

Git works **locally**. GitHub is the **online platform** for:

- Backing up your project
- Sharing it publicly or privately
- Collaborating with others
- Tracking issues and progress

<https://github.com>

GitHub in Practice



```
1 # 1. Initialize a Git repository in your current project folder
2 git init
3
4 # 2. Stage a file to be tracked (e.g., your script)
5 git add analysis.R
6
7 # 3. Save a snapshot of your work with a message
8 git commit -m "Initial commit"
9
10 # 4. Rename the default branch to 'main' (recommended)
11 git branch -M main
12
13 # 5. Connect your local project to a GitHub repo (change the URL)
14 git remote add origin https://github.com/yourname/repo.git
15
16 # 6. Upload your commits to GitHub
17 git push -u origin main
```


Commit message 🖋️

- Write meaningful messages:
- ✅ "Fix bug in anxiety scoring function"
- ❌ "stuff"
- Use the imperative mood: "Add README", "Update plots"
- Keep lines to 50–72 characters

Branching & merging

- Try out new features
- Fix bugs safely
- Work on different versions in parallel

```
1 # Create and switch to a new branch called 'new-feature'
2 git checkout -b new-feature
3
4 # (Make your changes in code, then stage and commit them)
5 # Save those changes with a descriptive message
6 git commit -m "Add new plot"
7
8 # Switch back to the main branch
9 git checkout main
10
11 # Merge the changes from 'new-feature' into 'main'
12 git merge new-feature
```

Use branches to keep your `main` branch clean.

Handling conflicts

Sometimes, Git can't automatically merge changes. This happens when two branches modify the same line in a file.

```
1 <<<<<< HEAD
2 plot(data)
3 =====
4 plot(data, col = "blue")
5 >>>>>> new-feature
```

Git will insert conflict markers directly into the file:

The code between <<<<<< HEAD and ===== is from the current branch (e.g., main)

The code between ===== and >>>>>> new-feature is from the other branch you're merging (e.g., new-feature)

Handling conflicts

To resolve the conflict, choose the correct version (or combine them), delete the markers, and save the file.

For example:

```
1 plot(data, col = "blue") # resolved version
```

Then:

```
1 git add file.R
2 git commit -m "Resolve merge conflict in file.R"
```

GitHub + RStudio Integration

- Clone repos with `File → New Project → Version Control`
- Commit and push from the **Git** tab in RStudio
- View commit history in **History** pane

Practice & resources

- Happy Git and GitHub for the useR
- GitHub Education: <https://education.github.com>
- Try GitHub Desktop (GUI client)

Start small. Use Git for one script. Then grow your skills from there.

If Git and GitHub feel too technical, or if your collaborators are less technical, the OSF is a fantastic alternative or complement.

- Upload data, code, and documents
- Create public or private projects
- Add collaborators
- Create preregistrations
- Generate DOIs for citation
- Track changes

| You can also connect OSF to GitHub.

Integrated workflow

1. Develop your analysis using **R** and **Quarto**.
2. Track code and scripts using **Git**.
3. Host your code on **GitHub** (public or private).
4. Upload your data and materials to **OSF**, including a data dictionary.
5. Link your GitHub repository to your OSF project.
6. Use [renv](#) for reproducible R environments.
7. Share the OSF project and cite it in your paper.



Reproducibility

It's about **credibility** and **transparency**.

Reproducible science is **not** about being **perfect**.

It's about showing your work so that others can **follow**, **understand**, and **build upon** it.

Start simple

“... anything you do — providing the raw data, posting any small scripts, detailing the versions of programs you used together with their parameters — will be tremendously welcome to anyone trying to validate or build off your paper...”

C. Titus Brown

**Start simple, don't wait until
you're "ready", and teach what
you learn!**

References

Marwick, B., Boettiger, C., & Mullen, L. (2018). Packaging data analytical work reproducibly using r (and friends). *The American Statistician*, 72(1), 80–88. <https://doi.org/10.1080/00031305.2017.1375986>