

Julia Data Science

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1 *Preface*

There are many programming languages and each and every one of them has its strengths and weaknesses. Some languages are very quick, but verbose. Other languages are very easy to write in, but slow. This is known as the *two-language* problem and Julia aims at circumventing this problem. Even though all three of us come from different fields, we all found the Julia language more effective for our research than languages that we've used before. We discuss some of our arguments in Section 2. However, compared to other languages, Julia is one of the newest languages around. This means that the ecosystem around the language is sometimes difficult to navigate through. It's difficult to figure out where to start and how all the different packages fit together. That is why we decided to create this book! We wanted to make it easier for researchers, and especially our colleagues, to start using this awesome language.

As discussed above, each language has its strengths and weaknesses. In our opinion, data science is definitely a strength of Julia. At the same time, all three of us used data science tools in our day to day life. And, probably, you want to use data science too! That is why this book has a focus on data science.

In the next part of this section, we emphasize the “**data**” part of **data science** and why data skills are, and will remain, in **high demand** in industry as well as in academia. We make an argument for **incorporating software engineering practices into data science** which should reduce friction when updating and sharing code with collaborators. Most data analyses are collaborative endeavors; that is why these software practices will help you.

1.0.1 *Data is Everywhere*

Data is abundant and will be even more so in the near future. A report from late 2012 concluded that, from 2005 to 2020, the amount of data stored digitally will **grow by a factor of 300, from 130 exabytes¹ to a whopping 40,000 exabytes** ([Gantz & Reinsel, 2012](#)). This is equal to 40 trillion gigabytes and, to put it into perspective, more than **5.2 terabytes for every living human currently on this planet!** In 2020, on average, every person created **1.7 MB of data per second** ([Domo, 2018](#)). A recent report predicted that almost **two thirds (65%) of national GDPs will have undergone digitization by 2022** ([Fitzgerald et al., 2020](#)).

¹ 1 exabyte (EB) = 1,000,000 terabyte (TB).

Every profession will be impacted by the increasing availability of data and data's increased importance (Chen et al., 2014; Khan et al., 2014). Data is used to communicate and build knowledge, and to make decisions. This is why data skills are important. If you become comfortable with handling data, you will become a valuable researcher or professional. In other words, you will become **data literate**.

1.1 *What is Data Science?*

Data science is not only machine learning and statistics, and it's not all about prediction. Alas, it is not even a discipline fully contained within STEM (Science, Technology, Engineering, and Mathematics) fields (Meng, 2019). But one thing that we can assert with high confidence is that data science is always about **data**. Our aims of this book are twofold:

- We focus on the backbone of data science: **data**.
- We use the **Julia** programming language to process the data.

We cover why Julia is an extremely effective language for data science in Section 2. For now, let's turn our attention towards data.

1.1.1 *Data Literacy*

According to Wikipedia², the formal definition of **data literacy** is “the ability to read, understand, create, and communicate data as information.”. We also like the informal idea that, being data literate, you won't feel overwhelmed by data, but instead can use it to make the right decisions. Data literacy can be seen as a highly competitive skill to possess. In this book we'll cover two aspects of data literacy:

1. **Data Manipulation** with `DataFrames.jl` (Chapter 4) and `DataFramesMeta.jl` (Chapter 5). In these chapters you will learn how to:
 1. Read CSV and Excel data into Julia.
 2. Process data in Julia, that is, learn how to answer data questions.
 3. Filter and subset data.
 4. Handle missing data.
 5. Join multiple data sources together.
 6. Group and summarize data.
 7. Export data out of Julia to CSV and Excel files.
2. **Data Visualization** with `Makie.jl` (Chapter 6). In this chapter you will learn how to:

² https://en.wikipedia.org/wiki/Data_literacy

1. Plot data with different `Makie.jl` backends.
2. Save visualizations in several formats such as PNG or PDF.
3. Use different plotting functions to make diverse data visualizations.
4. Customize visualizations with attributes.
5. Use and create new plotting themes.
6. Add *LATEX* elements to plots.
7. Manipulate color and palettes.
8. Create complex figure layouts.

1.2 *Software Engineering*

Unlike most books on data science, this book lays more emphasis on properly **structuring code**. The reason for this is that we noticed that many data scientists simply place their code into one large file and run all the statements sequentially. You can think of this like forcing book readers to always read it from beginning to end, without being allowed to revisit earlier sections or jump to interesting sections right away. This works fine for small and simple projects, but, as the project becomes bigger or more complex, more problems will start to arise. For example, in a well-written book, the book is split into distinctly-named chapters and sections which contain several references to other parts in the book. The software equivalent of this is **splitting code into functions**. Each function has a name and some contents. By using functions, you can tell the computer at any point in your code to jump to some other place and continue from there. This allows you to more easily re-use code between projects, update code, share code, collaborate, and see the big picture. Hence, with functions, you can **save time**.

So, while reading this book, you will eventually get used to reading and using functions. Another benefit of having good software engineering skills is that it will allow you to more easily read the source code of the packages that you're using, which could be greatly beneficial when you are debugging your code or wondering how exactly the package that you're using works. Finally, you can rest assured that we did not invent this emphasis on functions ourselves. In industry, it is common practice to encourage developers to use "**functions instead of comments**". This means that, instead of writing a comment for humans and some code for the computer, the developers write a function which is read by both humans and computers.

Also, we've put much effort into sticking to a consistent style guide. Programming style guides provide guidelines for writing code; for example, about where there should be whitespace and what names should be capitalized or not. Sticking to a strict style guide might sound pedantic and it sometimes is.

However, the more consistent the code is, the easier it is to read and understand the code. To read our code, you don't need to know our style guide. You'll figure it out when reading. If you do want to see the details of our style guide, check out Section 8.2.

1.3 Acknowledgements

Many people have contributed directly and indirectly to this book.

Jose Storopoli would like to thank his family, especially his wife for the support and love during the writing and reviewing process. He would also like to thank his colleagues, especially Fernando Serra³, Wonder Alexandre Luz Alves⁴ and André Librantz⁵, for their encouragement.

Rik Huijzer would first like to thank his PhD supervisors at the University of Groningen, Peter de Jonge⁶, Ruud den Hartigh⁷ and Frank Blaauw⁸ for their support. This feedback helps in improving the book and finding motivation to improve the book further. Most importantly, he would like to thank his parents and girlfriend for being hugely supportive during the holiday and all the weekends and evenings that were involved in making this book.

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⁸ <https://frankblaauw.nl/>

Lazaro Alonso would like to thank his wife and daughters for their encouragement to get involved in this project.

2 *Why Julia?*

The world of data science is filled with different open source programming languages.

Industry has, mostly, adopted Python and academia R. **Why bother learning another language?** To answer this question, we will address two common backgrounds:

1. **Did not program before** – see Section [2.1](#).
2. **Did program before** – see Section [2.2](#).

2.1 *For Non-Programmers*

In the first background, we expect the common underlying story to be the following.

Data science has captivated you, making you interested in learning what is it all about and how can you use it to build your career in academia or industry. Then, you try to find resources to learn this new craft and you stumble into a world of intricate acronyms: `pandas`, `dplyr`, `data.table`, `numpy`, `matplotlib`, `ggplot2`, `bokeh`, and the list goes on and on.

Out of the blue you hear a name: “Julia.” What is this? How is it any different from other tools that people tell you to use for data science?

Why should you dedicate your precious time into learning a language that is almost never mentioned in any job listing, lab position, postdoc offer, or academic job description? The answer is that **Julia is a fresh approach** to both programming and data science. Everything that you do in Python or in R, you can do it in Julia with the advantage of being able to write readable¹, fast, and powerful code. Therefore, the Julia language is gaining traction, and for good reasons.

So, if you don’t have any programming background knowledge, we highly encourage you to take up Julia as a first programming language and data science framework.

¹ no C++ or FORTRAN API calls.

2.2 For Programmers

In the second background, the common underlying story changes a little bit. You are someone who knows how to program and probably does this for a living. You are familiar with one or more languages and can easily switch between them. You've heard about this new flashy thing called "data science" and you want to jump on the bandwagon. You begin to learn how to do stuff in `numpy`, how to manipulate `DataFrames` in `pandas` and how to plot things in `matplotlib`. Or maybe you've learned all that in R by using the `tidyverse` and `tibbles`, `data.frames`, `%>%` (pipes) and `geom_*`...

Then, from someone or somewhere you become aware of this new language called "Julia." Why bother? You are already proficient in Python or R and you can do everything that you need. Well, let us contemplate some plausible scenarios.

Have you ever in Python or R:

1. Done something and were unable to achieve the performance that you needed?

Well, in Julia, Python or R minutes can be translated to seconds². We referred Section 2.4 for displaying successful Julia use cases in both academia and industry.

2. Tried to do something different from `numpy/dplyr` conventions and discovered that your code is slow and you'll probably have to learn dark magic³ to make it faster? In Julia you can do your custom different stuff without loss of performance.

3. Had to debug code and somehow you see yourself reading Fortran or C/C++ source code and having no idea what you are trying to accomplish? In Julia you only read Julia code, no need to learn another language to make your original language fast. This is called the "two-language problem" (see Section 2.3.2). It also covers the use case for when "you had an interesting idea and wanted to contribute to an open source package and gave up because almost everything is not in Python or R but in C/C++ or Fortran"⁴.

4. Wanted to use a data structure defined in another package and found that doesn't work and that you'll probably need to build an interface⁵. Julia allows users to easily share and reuse code from different packages. Most of Julia user-defined types and functions work right out of the box⁶ and some users marvelled upon discovering how their packages are being used by other libraries in ways that they could not have imagined. We have some examples in Section 2.3.3.

5. Needed to have a better project management, with dependencies and version control tightly controlled, manageable, and replicable? Julia has an

² and sometimes milliseconds.

³ numba, or even Rcpp or cython?

⁴ have a look at some deep learning libraries in GitHub and you'll be surprised that Python is only 25%-33% of the codebase.

⁵ this is mostly a Python ecosystem problem, and while R doesn't suffer heavily from this, it's not blue skies either.

⁶ or with little effort necessary.

amazing project management solution and a great package manager. Unlike traditional package managers, which install and manage a single global set of packages, Julia's package manager is designed around "environments": independent sets of packages that can be local to an individual project or shared between projects. Each project maintains its own independent set of package versions.

If we got your attention by exposing somewhat familiar or plausible situations, you might be interested to learn more about this newcomer called Julia.

Let's proceed then!

2.3 *What Julia Aims to Accomplish?*

NOTE: In this section we will explain the details of what makes Julia shine as a programming language. If it becomes too technical for you, you can skip and go straight to Section 4 to learn about tabular data with `DataFrames.jl`.

The Julia programming language (Bezanson et al., 2017) is a relatively new language, first released in 2012, and aims to be **both easy and fast**. It "runs like C⁷ but reads like Python" (Perkel, 2019). It was made for scientific computing, capable of handling **large amounts of data and computation** while still being fairly **easy to manipulate, create, and prototype code**.

The creators of Julia explained why they created Julia in a 2012 blogpost⁸. They said:

We are greedy: we want more. We want a language that's open source, with a liberal license. We want the speed of C with the dynamism of Ruby. We want a language that's homoiconic, with true macros like Lisp, but with obvious, familiar mathematical notation like Matlab. We want something as usable for general programming as Python, as easy for statistics as R, as natural for string processing as Perl, as powerful for linear algebra as Matlab, as good at gluing programs together as the shell. Something that is dirt simple to learn, yet keeps the most serious hackers happy. We want it interactive and we want it compiled.

Most users are attracted to Julia because of the **superior speed**. After all, Julia is a member of a prestigious and exclusive club. The **petaflop club**⁹ is comprised of languages who can exceed speeds of **one petaflop¹⁰ per second at peak performance**. Currently only C, C++, Fortran, and Julia belong to the petaflop club¹¹.

But, speed is not all that Julia can deliver. The **ease of use, Unicode support**, and a language that makes **code sharing effortless** are some of Julia's features.

⁷ sometimes even faster than C.

⁸ <https://julialang.org/blog/2012/02/why-we-created-julia/>

⁹ <https://www.hpcwire.com/off-the-wire/julia-joins-petaflop-club/>

¹⁰ a petaflop is one thousand trillion, or one quadrillion, operations per second.

¹¹ <https://www.nextplatform.com/2017/11/2/8/julia-language-delivers-petascale-hpc-performance/>

We'll address all those features in this section, but we want to focus on the Julia code sharing feature for now.

The Julia ecosystem of packages is something unique. It enables not only code sharing but also allows sharing of user-created types. For example, Python's `pandas` uses its own `Datetime` type to handle dates. The same with R `tidyverse`'s `lubridate` package, which also defines its own `datetime` type to handle dates. Julia doesn't need any of this, it has all the date stuff already baked into its standard library. This means that other packages don't have to worry about dates. They just have to extend Julia's `DateTime` type to new functionalities by defining new functions and do not need to define new types. Julia's `Dates` module can do amazing stuff, but we are getting ahead of ourselves now. Let's talk about some other features of Julia.

2.3.1 Julia Versus Other Programming Languages

In Figure 2.1, a highly opinionated representation is shown that divides the main open source and scientific computing languages in a 2x2 diagram with two axes: **Slow-Fast** and **Easy-Hard**. We've omitted closed source languages because there are many benefits to allowing other people to run your code for free as well as being able to inspect the source code in case of issues.

We've put C++ and FORTRAN in the hard and fast quadrant. Being static languages that need compilation, type checking, and other professional care and attention, they are really hard to learn and slow to prototype. The advantage is that they are **really fast** languages.

R and Python go into the easy and slow quadrant. They are dynamic languages that are not compiled and they execute in runtime. Because of this, they are really easy to learn and fast to prototype. Of course, this comes with a disadvantage: they are **really slow** languages.

Julia is the only language in the easy and fast quadrant. We don't know any other serious language that would want to be hard and slow, so this quadrant is left empty.

Julia is fast! Very fast! It was designed for speed from the beginning. In the rest of this section, we go into details about why this is. If you don't have (much) programming experience yet, feel free to skip to the next section and maybe come later to this at a later moment.

Julia accomplishes its speed partially due to multiple dispatch. Basically, the idea is to generate very efficient LLVM¹² code. LLVM code, also known as LLVM instructions, are very low-level, that is, very close to the actual operations that your computer is executing. So, in essence, Julia converts your hand

¹² LLVM stands for Low Level Virtual Machine, you can find more at the LLVM website (<http://llvm.org>).

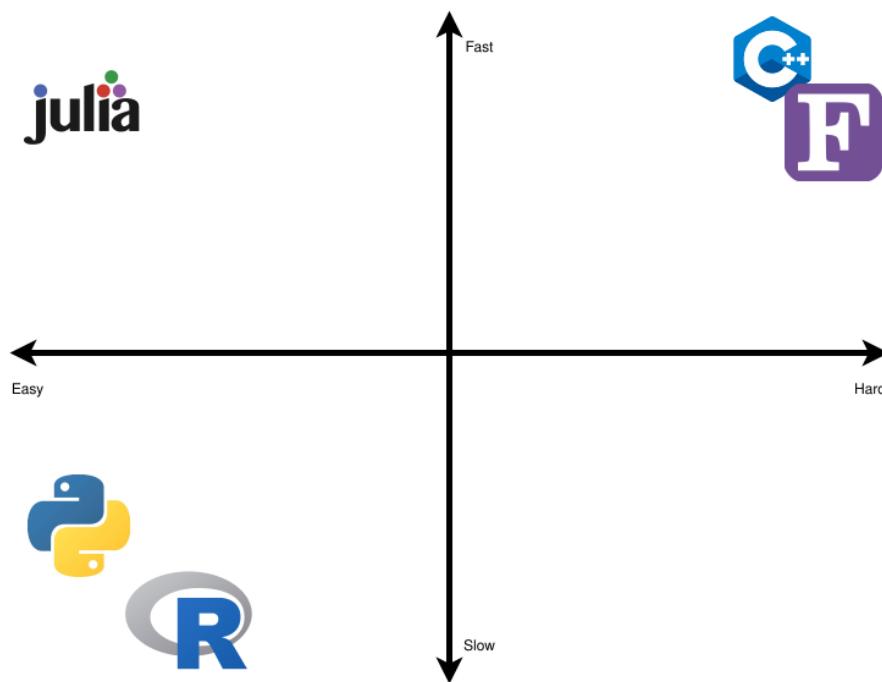


Figure 2.1: Scientific Computing Language Comparisons: logos for FORTRAN, C++, Python, R and Julia.

written and easy to read code to LLVM machine code which is very hard for humans to read, but easy for computers to read. For example, if you define a function taking one argument and pass an integer into the function, then Julia will create a *specialized MethodInstance*. The next time that you pass an integer to the function, Julia will look up the *MethodInstance* that was created earlier and refer execution to that. Now, the **great** trick is that you can also do this inside a function that calls a function. For example, if some data type is passed into function `outer` and `outer` calls function `inner` and the data types passed to `inner` are known inside the specialized `outer` instance, then the generated function `inner` can be hardcoded into function `outer`! This means that Julia doesn't even have to lookup *MethodInstances* any more, and the code can run very efficiently.

Let's show this in practice. We can define the two functions, `inner`:

```
inner(x) = x + 3
```

and `outer`:

```
outer(x) = inner(2 * x)
```

For example, we can now calculate `outer` for, let's say, 3:

```
outer(3)
```

If you step through this calculation of `outer`, you'll see that the program needs to do quite a lot of things:

1. calculate $2 * 3$
2. pass the outcome of $2 * 3$ to `inner`
3. calculate $3 +$ the outcome of the previous step

But, if we ask Julia for the optimized code via `@code_typed`, we see what instructions the computer actually get:

```
@code_llvm debuginfo=:none outer(3)
```

```
define i64 @julia_outer_232(i64 signext %0) #0 {
top:
    %1 = shl i64 %0, 1
    %2 = add i64 %1, 3
    ret i64 %2
}
```

This is low-level LLVM code showing that the program only does the following:

1. shift the input (3) one bit to the left, which has the same effect as multiplying by 2; and
2. add 3.

and that's it! Julia has realized that calling `inner` can be removed, so that's not part of the calculation anymore! Now, imagine that this function is called a thousand or even a million times. These optimizations will reduce the running time significantly.

The trade-off, here, is that there are cases where earlier assumptions about the hardcoded `MethodInstances` are invalidated. Then, the `MethodInstance` has to be recreated which takes time. Also, the trade-off is that it takes time to infer what can be hardcoded and what not. This explains why it can often take very long before Julia does the first thing: in the background, it is optimizing your code.

So, Julia creates optimized LLVM machine code¹³. You can find benchmarks¹⁴

¹³ if you like to learn more about how Julia is designed you should definitely check [Bezanson et al. \(2017\)](#).

¹⁴ <https://julialang.org/benchmarks/>

¹⁵ please note that the Julia results depicted above do not include compile time.

¹⁶ <https://julialang.org/benchmarks/>

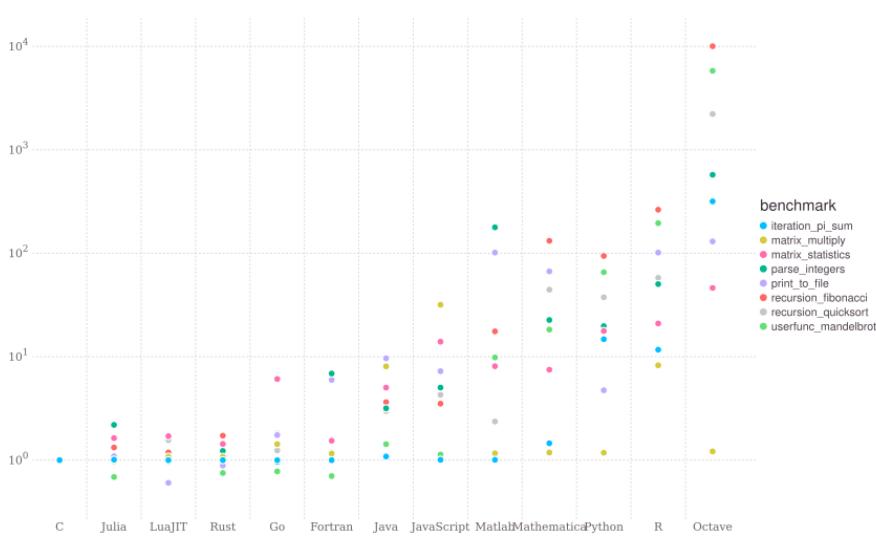


Figure 2.2: Julia versus other programming languages.

for Julia and several other languages here. Figure 2.2 was taken from Julia’s website benchmarks section^{15,16}. As you can see Julia is **indeed** fast.

We really believe in Julia. Otherwise, we wouldn’t be writing this book. We think that Julia is the **future of scientific computing and scientific data analysis**. It enables the user to develop rapid and powerful code with a simple syntax. Usually, researchers develop code by prototyping using a very easy, but slow, language. Once the code is assured to run correctly and fulfill its goal, then begins the process of converting the code to a fast, but hard, language. This is known as the “Two-Language Problem” and we discuss next.

2.3.2 The Two-Language Problem

The “Two-Language Problem” is a very typical situation in scientific computing where a researcher devises an algorithm or a solution to tackle a desired problem or analysis at hand. Then, the solution is prototyped in an easy to code language (like Python or R). If the prototype works, the researcher would code in a fast language that would not be easy to prototype (C++ or FORTRAN). Thus, we have two languages involved in the process of developing a new solution. One which is easy to prototype but is not suited for implementation (mostly due to being slow). And another which is not so easy to code, and consequently not easy to prototype, but suited for implementation because it is fast. Julia avoids such situations by being the **same language that you prototype (ease of use) and implement the solution (speed)**.

Also, Julia lets you use **Unicode characters as variables or parameters**. This

means no more using `sigma` or `sigma_i`, and instead just use σ or σ_i as you would in mathematical notation. When you see code for an algorithm or for a mathematical equation, you see almost the same notation and idioms. We call this feature “**One-To-One Code and Math Relation**” which is a powerful feature.

We think that the “Two-Language problem” and the “One-To-One Code and Math Relation” are best described by one of the creators of Julia, Alan Edelman, in a TEDx Talk¹⁷ ([TEDx Talks, 2020](https://youtu.be/qGW0GT1rCvs)).

¹⁷ <https://youtu.be/qGW0GT1rCvs>

2.3.3 Multiple Dispatch

Multiple dispatch is a powerful feature that allows us to extend existing functions or to define custom and complex behavior for new types. Suppose that you want to define two new `structs` to denote two different animals:

```
abstract type Animal end
struct Fox <: Animal
    weight::Float64
end
struct Chicken <: Animal
    weight::Float64
end
```

Basically, this says “define a fox which is an animal” and “define a chicken which is an animal.” Next, we might have one fox called Fiona and a chicken called Big Bird.

```
fiona = Fox(4.2)
big_bird = Chicken(2.9)
```

Next, we want to know how much they weight together, for which we can write a function:

```
combined_weight(A1::Animal, A2::Animal) = A1.weight + A2.weight
```

```
combined_weight (generic function with 1 method)
```

And we want to know whether they go well together. One way to implement that is to use conditionals:

```
function naive_trouble(A::Animal, B::Animal)
    if A isa Fox && B isa Chicken
        return true
    elseif A isa Chicken && B isa Fox
        return true
    end
```

```

elseif A isa Chicken && B isa Chicken
    return false
end
end

```

```
naive_trouble (generic function with 1 method)
```

Now, let's see whether leaving Fiona and Big Bird together would give trouble:

```
naive_trouble(fiona, big_bird)
```

```
true
```

Okay, so this sounds right. Writing the `naive_trouble` function seems to be easy enough. However, using multiple dispatch to create a new function `trouble` can have their benefits. Let's create our new function as follows:

```

trouble(F::Fox, C::Chicken) = true
trouble(C::Chicken, F::Fox) = true
trouble(C1::Chicken, C2::Chicken) = false

```

```
trouble (generic function with 3 methods)
```

After defining these methods, `trouble` gives the same result as `naive_trouble`. For example:

```
trouble(fiona, big_bird)
```

```
true
```

And leaving Big Bird alone with another chicken called Dora is also fine

```

dora = Chicken(2.2)
trouble(dora, big_bird)

```

```
false
```

So, in this case, the benefit of multiple dispatch is that you can just declare types and Julia will find the correct method for your types. Even more so, for many cases when multiple dispatch is used inside code, the Julia compiler will actually optimize the function calls away. For example, we could write:

```
function trouble(A::Fox, B::Chicken, C::Chicken)
    return trouble(A, B) || trouble(B, C) || trouble(C, A)
end
```

Depending on the context, Julia can optimize this to:

```
function trouble(A::Fox, B::Chicken, C::Chicken)
    return true || false || true
end
```

because the compiler **knows** that `A` is a Fox, `B` is a chicken and so this can be replaced by the contents of the method `trouble(F::Fox, C::Chicken)`. The same holds for `trouble(C1::Chicken, C2::Chicken)`. Next, the compiler can optimize this to:

```
function trouble(A::Fox, B::Chicken, C::Chicken)
    return true
end
```

Another benefit of multiple dispatch is that when someone else now comes by and wants to compare the existing animals to their animal, a Zebra, then that's possible. In their package, they can define a Zebra:

```
struct Zebra <: Animal
    weight::Float64
end
```

and also how the interactions with the existing animals would go:

```
trouble(F::Fox, Z::Zebra) = false
trouble(Z::Zebra, F::Fox) = false
trouble(C::Chicken, Z::Zebra) = false
trouble(Z::Zebra, F::Fox) = false
```

trouble (generic function with 6 methods)

Now, we can see whether Marty (our zebra) is safe with Big Bird:

```
marty = Zebra(412)
trouble(big_bird, marty)
```

false

Even better, we can also calculate **the combined weight of zebra's and other animals without defining any extra function at our side**:

```
combined_weight(big_bird, marty)
```

414.9

So, in summary, the code that was written with only Fox and Chicken in mind works even for types that it **has never seen before!** In practice, this means that Julia makes it often easy to re-use code from other projects.

If you are excited as much as we are by multiple dispatch, here are two more in-depth examples. The first is a fast and elegant implementation of a one-hot vector¹⁸ by [Storopoli \(2021\)](#). The second is an interview with Christopher Rackauckas¹⁹ at Tanmay Bakshi YouTube's Channel²⁰ (see from time 35:07 onwards) ([tanmay bakshi, 2021](#)). Chris mentions that, while using `DifferentialEquations.jl`²¹, a package that he developed and currently maintains, a user filed an issue that his GPU-based quaternion ODE solver didn't work. Chris was quite surprised by this request since he would never have expected that someone would combine GPU computations with quaternions and solving ODEs. He was even more surprised to discover that the user made a small mistake and that it all worked. Most of the merit is due to multiple dispatch and high user code/type sharing.

To conclude, we think that multiple dispatch is best explained by one of the creators of Julia: Stefan Karpinski at JuliaCon 2019²².

¹⁸ https://storopoli.io/Bayesian-Julia/pages/1_why_Julia/#example_one-hot_vector

¹⁹ <https://www.chrisrakaukas.com/>

²⁰ <https://youtu.be/moyPlhwv4Nk?t=2107>

²¹ <https://diffeq.sciml.ai/dev/>

²² <https://youtu.be/kc9HwsxE1OY>

2.4 Julia in the Wild

In Section 2.3, we explained why we think Julia is such a unique programming language. We showed simple examples about the main features of Julia. If you would like to have a deep dive on how Julia is being used, we have some **interesting use cases**:

1. NASA uses Julia in a supercomputer to analyze the "Largest Batch of Earth-Sized Planets Ever Found"²³ and achieve a whopping **1,000x speedup** to catalog 188 million astronomical objects in 15 minutes.
2. The Climate Modeling Alliance (CliMa)²⁴ is using mostly Julia to **model climate in the GPU and CPU**. Launched in 2018 in collaboration with researchers at Caltech, the NASA Jet Propulsion Laboratory, and the Naval Postgraduate School, CliMA is utilizing recent progress in computational science to develop an Earth system model that can predict droughts, heat waves, and rainfall with unprecedented precision and speed.

²³ <https://exoplanets.nasa.gov/news/1669/ven-rocky-trappist-1-planets-may-be-made-of-similar-stuff/>

²⁴ <https://clima.caltech.edu/>

3. US Federal Aviation Administration (FAA) is developing an **Airborne Collision Avoidance System (ACAS-X)** using Julia²⁵. This is a nice example of the “Two-Language Problem” (see Section 2.3). Previous solutions used Matlab to develop the algorithms and C++ for a fast implementation. Now, FAA is using one language to do all this: Julia.
4. **175x speedup** for Pfizer’s pharmacology models using GPUs in Julia²⁶. It was presented as a poster²⁷ in the 11th American Conference of Pharmacometrics (ACoP11) and won a quality award²⁸.
5. The Attitude and Orbit Control Subsystem (AOCS) of the Brazilian satellite Amazonia-1 is **written 100% in Julia**²⁹ by Ronan Arraes Jardim Chagas (<https://ronanarraes.com/>).
6. Brazil’s national development bank (BNDES) ditched a paid solution and opted for open-source Julia modeling and gained a **10x speedup**.³⁰

If this is not enough, there are more case studies in JuliaHub website³¹.

²⁵ <https://youtu.be/19zm1Fn0S9M>

²⁶ <https://juliahub.com/case-studies/pfizer/>

²⁷ https://chrirsrackauckas.com/assets/Posters/ACoP11_Poster_Abstracts_2020.pdf

²⁸ <https://web.archive.org/web/20210121164011/https://www.go-acop.org/abstract-awards>

²⁹ <https://discourse.julialang.org/t/julia-and-the-satellite-amazonia-1/57541>

³⁰ <https://youtu.be/NY0HcGqHj3g>

³¹ <https://juliahub.com/case-studies/>

3 Julia Basics

NOTE: In this chapter we cover the basics of Julia as a programming language. Please note that this is not *strictly necessary* for you to use Julia as a tool for data manipulation and data visualization. Having a basic understanding of Julia will definitely make you more *effective* and *efficient* in using Julia. However, if you prefer to get started straight away, you can jump to Section 4 to learn about tabular data with `DataFrames.jl`.

This is going to be a very brief and *not* an in-depth overview of the Julia language. If you are already familiar and comfortable with other programming languages, we highly encourage you to read Julia’s documentation (<https://docs.julialang.org/>). The docs are an excellent resource for taking a deep dive into Julia. It covers all the basics and corner cases, but it can be cumbersome, especially if you aren’t familiar with software documentation.

We’ll cover the basics of Julia. Imagine that Julia is a fancy feature-loaded car, such as a brand-new Tesla. We’ll just explain to you how to “drive the car, park it, and how to navigate in traffic.” If you want to know what “all the buttons in the steering wheel and dashboard do,” this is not the resource you are looking for.

3.1 Development Environments

Before we can dive into the language syntax, we need to answer how to run code. Going into details about the various options is out of scope for this book. Instead, we will provide you with some pointers to various solutions.

The simplest way is to use the Julia REPL. This means starting the Julia executable (`julia` or `julia.exe`) and running code there. For example, we can start the Julia REPL and execute some code:

```
julia> x = 2
2

julia> x + 1
3
```

This works all very well, but what if we want to save the code that we wrote? To save our code, one can write “.jl” files such as “script.jl” and load these into Julia. Say, that “script.jl” contains:

```
x = 3
y = 4
```

We can load this into Julia:

```
julia> include("script.jl")
julia> y
4
```

Now the problem becomes that we would like Julia to re-read our script every time before executing code. This can be done via `Revise.jl`¹. Because compilation time in Julia is often long, `Revise.jl` is a must-have for Julia development. For more information, see the `Revise.jl` documentation or simply Google a bit if you have specific questions.

¹ <https://github.com/timholy/Revise.jl>

We are aware that `Revise.jl` and the REPL requires some manual actions which aren't super clearly documented. Luckily, there is `Pluto.jl`². `Pluto.jl` automatically manages dependencies, runs code, and **reacts** to changes. For people who are new to programming, `Pluto.jl` is by far the easiest way to get started. The main drawback of the package is that it is less suitable for larger projects.

² <https://github.com/onsp/Pluto.jl>

Other options are to use Visual Studio Code with various Julia extensions or manage your own IDE. If you **don't** know what an IDE is, but do want to manage large projects choose Visual Studio Code. If you **do** know what an IDE is, then you might like building your own IDE with Vim or Emacs and the REPL.

So, to summarize:

- Easiest way to get started -> `Pluto.jl`
- Larger projects -> Visual Studio Code
- Advanced users -> Vim, Emacs and the REPL

3.2 Language Syntax

Julia is a **dynamic-typed language** with a just-in-time compiler. This means that you don't need to compile your program before you run it, like you would do in C++ or FORTRAN. Instead, Julia will take your code, guess types where necessary, and compile parts of code just before running it. Also, you don't need to explicitly specify each type. Julia will guess types for you on the go.

The main differences between Julia and other dynamic languages such as R and Python are the following. First, Julia **allows the user to specify type declarations**. You already saw some types declarations in *Why Julia?* (Section 2): they are those double colons :: that sometimes come after variables. However, if you don't want to specify the type of your variables or functions, Julia will gladly infer (guess) them for you.

Second, Julia allows users to define function behavior across many combinations of argument types via multiple dispatch. We also covered multiple dispatch in Section 2.3. We defined a different type behavior by defining new function signatures for argument types while using the same function name.

3.2.1 Variables

Variables are values that you tell the computer to store with a specific name, so that you can later recover or change its value. Julia has several types of variables but, in data science, we mostly use:

- Integers: `Int64`
- Real Numbers: `Float64`
- Boolean: `Bool`
- Strings: `String`

Integers and real numbers are stored by using 64 bits by default, that's why they have the 64 suffix in the name of the type. If you need more or less precision, there are `Int8` or `Int128` types, for example, where higher means more precision. Most of the time, this won't be an issue so you can just stick to the defaults.

We create new variables by writing the variable name on the left and its value in the right, and in the middle we use the = assignment operator. For example:

```
name = "Julia"
age = 9
```

9

Note that the return output of the last statement (`age`) was printed to the console. Here, we are defining two new variables: `name` and `age`. We can recover their values by typing the names given in the assignment:

```
name
```

Julia

If you want to define new values for an existing variable, you can repeat the steps in the assignment. Note that Julia will now override the previous value with the new one. Suppose, Julia's birthday has passed and now it has turned 10:

```
age = 10
```

10

We can do the same with its `name`. Suppose that Julia has earned some titles due to its blazing speed. We would change the variable `name` to the new value:

```
name = "Julia Rapidus"
```

Julia Rapidus

We can also do operations on variables such as addition or division. Let's see how old Julia is, in months, by multiplying `age` by 12:

```
12 * age
```

120

We can inspect the types of variables by using the `typeof` function:

```
typeof(age)
```

Int64

The next question then becomes: "What else can I do with integers?" There is a nice handy function `methodswith` that spits out every function available, along with its signature, for a certain type. Here, we will restrict the output to the first 5 rows:

```
first(methodswith(Int64), 5)
```

```
[1] AbstractFloat(x::Int64) @ Base float.jl:268
[2] Float16(x::Int64) @ Base float.jl:159
[3] Float32(x::Int64) @ Base float.jl:159
[4] Float64(x::Int64) @ Base float.jl:159
[5] Int64(x::Union{Bool, Int32, Int64, UInt16, UInt32, UInt64, UInt8, Int128,
    ↪Int16, Int8, UInt128}) @ Core boot.jl:784
```

3.2.2 User-defined Types

Having variables around without any sort of hierarchy or relationships is not ideal. In Julia, we can define that kind of structured data with a `struct` (also known as a composite type). Inside each `struct`, you can specify a set of fields. They differ from the primitive types (e.g. integer and floats) that are by default defined already inside the core of Julia language. Since most `structs` are user-defined, they are known as user-defined types.

For example, let's create a `struct` to represent scientific open source programming languages. We'll also define a set of fields along with the corresponding types inside the `struct`:

```
struct Language
    name::String
    title::String
    year_of_birth::Int64
    fast::Bool
end
```

To inspect the field names you can use the `fieldnames` and pass the desired `struct` as an argument:

```
fieldnames(Language)
```

```
(:name, :title, :year_of_birth, :fast)
```

To use `structs`, we must instantiate individual instances (or “objects”), each with its own specific values for the fields defined inside the `struct`. Let's instantiate two instances, one for Julia and one for Python:

```
julia = Language("Julia", "Rapidus", 2012, true)
python = Language("Python", "Letargicus", 1991, false)
```

```
Language("Python", "Letargicus", 1991, false)
```

One thing to note with `structs` is that we can't change their values once they are instantiated. We can solve this with a `mutable struct`. Also, note that mutable objects will, generally, be slower and more error prone. Whenever possible, make everything *immutable*. Let's create a `mutable struct`.

```
mutable struct MutableLanguage
    name::String
    title::String
    year_of_birth::Int64
    fast::Bool
end

julia MutableLanguage("Julia", "Rapidus", 2012, true)
```

```
MutableLanguage("Julia", "Rapidus", 2012, true)
```

Suppose that we want to change `julia MutableLanguage`'s `title`. Now, we can do this since `julia MutableLanguage` is an instantiated `mutable struct`:

```
julia MutableLanguage.title = "Python Obliteratus"

julia MutableLanguage
```

```
MutableLanguage("Julia", "Python Obliteratus", 2012, true)
```

3.2.3 Boolean Operators and Numeric Comparisons

Now that we've covered types, we can move to boolean operators and numeric comparison.

We have three boolean operators in Julia:

- `!:` NOT
- `&&:` AND
- `||:` OR

Here are a few examples with some of them:

```
!true
```

```
false
```

```
(false && true) || (!false)
```

true

```
(6 isa Int64) && (6 isa Real)
```

true

Regarding numeric comparison, Julia has three major types of comparisons:

1. **Equality**: either something is *equal* or *not equal* another
 - `==` “equal”
 - `!=` or `\neq` “not equal”
2. **Less than**: either something is *less than* or *less than or equal to*
 - `<` “less than”
 - `<=` or `\leq` “less than or equal to”
3. **Greater than**: either something is *greater than* or *greater than or equal to*
 - `>` “greater than”
 - `>=` or `\geq` “greater than or equal to”

Here are some examples:

```
1 == 1
```

true

```
1 >= 10
```

false

It even works between different types:

```
1 == 1.0
```

true

We can also mix and match boolean operators with numeric comparisons:

```
(1 != 10) || (3.14 <= 2.71)
```

true

3.2.4 Functions

Now that we already know how to define variables and custom types as `struct ↳s`, let's turn our attention to **functions**. In Julia, a function **maps argument's values to one or more return values**. The basic syntax goes like this:

```
function function_name(arg1, arg2)
    result = stuff with the arg1 and arg2
    return result
end
```

The function declaration begins with the keyword `function` followed by the function name. Then, inside parentheses `()`, we define the arguments separated by a comma `,`. Inside the function, we specify what we want Julia to do with the parameters that we supplied. All variables that we define inside a function are deleted after the function returns. This is nice because it is like an automatic cleanup. After all the operations in the function body are finished, we instruct Julia to return the final result with the `return` statement. Finally, we let Julia know that the function definition is finished with the `end` keyword.

There is also the compact **assignment form**:

```
f_name(arg1, arg2) = stuff with the arg1 and arg2
```

It is the **same function** as before but with a different, more compact, form. As a rule of thumb, when your code can fit easily on one line of up to 92 characters, then the compact form is suitable. Otherwise, just use the longer form with the `function` keyword. Let's dive into some examples.

Creating new Functions

Let's create a new function that adds numbers together:

```
function add_numbers(x, y)
    return x + y
end
```

```
add_numbers (generic function with 1 method)
```

Now, we can use our `add_numbers` function:

```
add_numbers(17, 29)
```

```
46
```

And it works also with floats:

```
add_numbers(3.14, 2.72)
```

```
5.86
```

Also, we can define custom behavior by specifying type declarations. Suppose that we want to have a `round_number` function that behaves differently if its argument is either a `Float64` or `Int64`:

```
function round_number(x::Float64)
    return round(x)
end

function round_number(x::Int64)
    return x
end
```

```
round_number (generic function with 2 methods)
```

We can see that it is a function with multiple methods:

```
methods(round_number)
```

```
round_number(x::Float64)
@ Main none:1
```

```
round_number(x::Int64)
@ Main none:5
```

There is one issue: what happens if we want to round a 32-bit float `Float32`? Or a 8-bit integer `Int8`?

If you want something to function on all float and integer types, you can use an **abstract type** as the type signature, such as `AbstractFloat` or `Integer`:

```
function round_number(x::AbstractFloat)
    return round(x)
end
```

`round_number` (generic function with 3 methods)

Now, it works as expected with any float type:

```
x_32 = Float32(1.1)
round_number(x_32)
```

1.0f0

NOTE: We can inspect types with the `supertypes` and `subtypes` functions.

Let's go back to our `Language` struct that we defined above. This is an example of multiple dispatch. We will extend the `Base.show` function that prints the output of instantiated types and `structs`.

By default, a `struct` has a basic output, which you saw above in the `python` case. We can define a new `Base.show` method to our `Language` type, so that we have some nice printing for our programming languages instances. We want to clearly communicate programming languages' names, titles, and ages in years. The function `Base.show` accepts as arguments a `IO` type named `io` followed by the type you want to define custom behavior:

```
Base.show(io::IO, l::Language) = print(
    io, l.name, ", ",
    2021 - l.year_of_birth, " years old, ",
    "has the following titles: ", l.title
)
```

Now, let's see how `python` will output:

```
python
```

Python, 30 years old, has the following titles: Letargicus

Multiple Return Values

A function can, also, return two or more values. See the new function `add_multiply` ↵ below:

```
function add_multiply(x, y)
    addition = x + y
    multiplication = x * y
    return addition, multiplication
end
```

```
add_multiply (generic function with 1 method)
```

In that case, we can do two things:

1. We can, analogously as the return values, define two variables to hold the function return values, one for each return value:

```
return_1, return_2 = add_multiply(1, 2)
return_2
```

```
2
```

2. Or we can define just one variable to hold the function's return values and access them with either `first` or `last`:

```
all_returns = add_multiply(1, 2)
last(all_returns)
```

```
2
```

Keyword Arguments

Some functions can accept keyword arguments instead of positional arguments. These arguments are just like regular arguments, except that they are defined

after the regular function's arguments and separated by a semicolon ;. For example, let's define a `logarithm` function that by default uses base e (2.718281828459045) as a keyword argument. Note that, here, we are using the abstract type `Real` so that we cover all types derived from `Integer` and `AbstractFloat`, being both themselves subtypes of `Real`:

```
AbstractFloat <: Real && Integer <: Real
```

true

```
function logarithm(x::Real; base::Real=2.7182818284590)
    return log(base, x)
end
```

`logarithm` (generic function with 1 method)

It works without specifying the `base` argument as we supplied a **default argument value** in the function declaration:

```
logarithm(10)
```

2.3025850929940845

And also with the keyword argument `base` different from its default value:

```
logarithm(10; base=2)
```

3.3219280948873626

Anonymous Functions

Often we don't care about the name of the function and want to quickly make one. What we need are **anonymous functions**. They are used a lot in Julia's data science workflow. For example, when using `DataFrames.jl` (Section 4) or `Makie.jl` (Section 6), sometimes we need a temporary function to filter data or format plot labels. That's when we use anonymous functions. They are especially useful when we don't want to create a function, and a simple in-place statement would be enough.

The syntax is simple. We use the `->` operator. On the left of `->` we define the parameter name. And on the right of `->` we define what operations we want to perform on the parameter that we defined on the left of `->`. Here is an example. Suppose that we want to undo the log transformation by using an exponentiation:

```
map(x -> 2.7182818284590^x, logarithm(2))
```

2.0

Here, we are using the `map` function to conveniently map the anonymous function (first argument) to `logarithm(2)` (the second argument). As a result, we get back the same number, because `logarithm` and exponentiation are inverse (at least in the base that we've chosen – 2.7182818284590)

3.2.5 Conditional If-Else-Elseif

In most programming languages, the user is allowed to control the computer's flow of execution. Depending on the situation, we want the computer to do one thing or another. In Julia we can control the flow of execution with `if`, `elseif`, and `else` keywords. These are known as conditional statements.

The `if` keyword prompts Julia to evaluate an expression and, depending on whether it's `true` or `false`, execute certain portions of code. We can compound several `if` conditions with the `elseif` keyword for complex control flow. Finally, we can define an alternative portion to be executed if anything inside the `if` or `elseifs` is evaluated to `true`. This is the purpose of the `else` keyword. Finally, like all the previous keyword operators that we saw, we must tell Julia when the conditional statement is finished with the `end` keyword.

Here's an example with all the `if-elseif-else` keywords:

```
a = 1
b = 2

if a < b
    "a is less than b"
elseif a > b
    "a is greater than b"
else
    "a is equal to b"
end
```

a is less than b

We can even wrap this in a function called `compare`:

```
function compare(a, b)
    if a < b
        "a is less than b"
    elseif a > b
        "a is greater than b"
    else
        "a is equal to b"
    end
end

compare(3.14, 3.14)
```

a is equal to b

3.2.6 For Loop

The classical for loop in Julia follows a similar syntax as the conditional statements. You begin with a keyword, in this case `for`. Then, you specify what Julia should “loop” for, i.e., a sequence. Also, like everything else, you must finish with the `end` keyword.

So, to make Julia print every number from 1 to 10, you can use the following for loop:

```
for i in 1:10
    println(i)
end
```

3.2.7 While Loop

The while loop is a mix of the previous conditional statements and for loops. Here, the loop is executed every time the condition is `true`. The syntax follows the same form as the previous one. We begin with the keyword `while`, followed by a statement that evaluates to `true` or `false`. As usual, you must end with the `end` keyword.

Here's an example:

```
n = 0

while n < 3
    global n += 1
end
```

```
n
```

```
3
```

As you can see, we have to use the `global` keyword. This is because of **variable scope**. Variables defined inside conditional statements, loops, and functions exist only inside them. This is known as the *scope* of the variable. Here, we had to tell Julia that the `n` inside `while` loop is in the global scope with the `global` keyword.

Finally, we also used the `+=` operator which is a nice shorthand for `n = n + 1`.

3.3 Native Data Structures

Julia has several native data structures. They are abstractions of data that represent some form of structured data. We will cover the most used ones. They hold homogeneous or heterogeneous data. Since they are collections, they can be *looped* over with the `for` loops.

We will cover `String`, `Tuple`, `NamedTuple`, `UnitRange`, `Arrays`, `Pair`, `Dict`, `Symbol`.

When you stumble across a data structure in Julia, you can find methods that accept it as an argument with the `methodswith` function. In Julia, the distinction between methods and functions is as follows. Every function can have multiple methods like we have shown earlier. The `methodswith` function is nice to have in your bag of tricks. Let's see what we can do with a `String` for example:

```
first(methodswith(String), 5)
```

```
[1] String(s::String) @ Core boot.jl:360
[2] Symbol(s::String) @ Core boot.jl:513
[3] ==(y::WeakRefStrings.WeakRefString, x::String) @ WeakRefStrings ~/.julia/
    ↪packages/WeakRefStrings/31nkb/src/WeakRefStrings.jl:51
[4] ==(y::InlineString, x::String) @ InlineStrings ~/.julia/packages/
    ↪InlineStrings/rllZ0/src/InlineStrings.jl:347
[5] ==(x::String, y::T) where T<:InlineString @ InlineStrings ~/.julia/packages/
    ↪InlineStrings/rllZ0/src/InlineStrings.jl:341
```

3.3.1 Broadcasting Operators and Functions

Before we dive into data structures, we need to talk about broadcasting (also known as *vectorization*) and the “dot” operator ..

We can broadcast mathematical operations like `*` (multiplication) or `+` (addition) using the dot operator. For example, broadcasted addition would imply a change from `+` to `.+`:

```
[1, 2, 3] .+ 1
```

```
[2, 3, 4]
```

It also works automatically with functions. (Technically, the mathematical operations, or infix operators, are also functions, but that is not so important to know.) Remember our `logarithm` function?

```
logarithm.([1, 2, 3])
```

```
[0.0, 0.6931471805599569, 1.0986122886681282]
```

3.3.2 Functions with a bang !

It is a Julia convention to append a bang `!` to names of functions that modify one or more of their arguments. This convention warns the user that the function is **not pure**, i.e., that it has *side effects*. A function with side effects is useful when you want to update a large data structure or variable container without having all the overhead from creating a new instance.

For example, we can create a function that adds 1 to each element in a vector `V`:

```
function add_one!(V)
    for i in eachindex(V)
        V[i] += 1
    end
    return nothing
end
```

```
my_data = [1, 2, 3]
add_one!(my_data)
my_data
```

```
[2, 3, 4]
```

3.3.3 *String*

Strings are represented delimited by double quotes:

```
typeof("This is a string")
```

String

We can also write a multiline string:

```
text = "
This is a big multiline string.
As you can see.
It is still a String to Julia.
"
```

This is a big multiline string.
As you can see.
It is still a String to Julia.

But it is usually clearer to use triple quotation marks:

```
s = """"
This is a big multiline string with a nested "quotation".
As you can see.
It is still a String to Julia.
"""
```

This is a big multiline string with a nested "quotation".
As you can see.
It is still a String to Julia.

When using triple-backticks, the indentation and newline at the start is ignored by Julia. This improves code readability because you can indent the block in your source code without those spaces ending up in your string.

String Concatenation

A common string operation is **string concatenation**. Suppose that you want to construct a new string that is the concatenation of two or more strings. This is accomplished in Julia either with the `*` operator or the `join` function. This

symbol might sound like a weird choice and it actually is. For now, many Julia codebases are using this symbol, so it will stay in the language. If you're interested, you can read a discussion from 2015 about it at <https://github.com/JuliaLang/julia/issues/11030>.

```
hello = "Hello"
goodbye = "Goodbye"

hello * goodbye
```

HelloGoodbye

As you can see, we are missing a space between `hello` and `goodbye`. We could concatenate an additional " " string with the `*`, but that would be cumbersome for more than two strings. That's where the `join` function comes in handy. We just pass as arguments the strings inside the brackets `[]` and the separator:

```
join([hello, goodbye], " ")
```

Hello Goodbye

String Interpolation

Concatenating strings can be convoluted. We can be much more expressive with **string interpolation**. It works like this: you specify whatever you want to be included in your string with the dollar sign `$`. Here's the example before but now using interpolation:

```
"$hello $goodbye"
```

Hello Goodbye

It even works inside functions. Let's revisit our `test` function from Section 3.2.5:

```
function test_interpolated(a, b)
    if a < b
        "$a is less than $b"
    elseif a > b
        "$a is greater than $b"
    else
```

```

    "$a is equal to $b"
end
end

test_interpolated(3.14, 3.14)

```

3.14 is equal to 3.14

String Manipulations

There are several functions to manipulate strings in Julia. We will demonstrate the most common ones. Also, note that most of these functions accept a Regular Expression (regex)³ as arguments. We won't cover Regular Expressions in this book, but you are encouraged to learn about them, especially if most of your work uses textual data.

³ <https://docs.julialang.org/en/v1/manual/strings/#Regular-Expressions>

First, let us define a string for us to play around with:

```
julia_string = "Julia is an amazing open source programming language"
```

Julia is an amazing open source programming language

1. `contains`, `startswith` and `endswith`: A conditional (returns either `true` or `false`) if the second argument is a:

- **substring** of the first argument

```
contains(julia_string, "Julia")
```

true

- **prefix** of the first argument

```
startswith(julia_string, "Julia")
```

true

- **suffix** of the first argument

```
endswith(julia_string, "Julia")
```

false

2. lowercase, uppercase, titlecase and lowercasefirst:

```
lowercase(julia_string)
```

julia is an amazing open source programming language

```
uppercase(julia_string)
```

JULIA IS AN AMAZING OPEN SOURCE PROGRAMMING LANGUAGE

```
titlecase(julia_string)
```

Julia Is An Amazing Open Source Programming Language

```
lowercasefirst(julia_string)
```

```
julia is an amazing open source programming language
```

3. `replace`: introduces a new syntax, called the `Pair`

```
replace(julia_string, "amazing" => "awesome")
```

```
Julia is an awesome open source programming language
```

4. `split`: breaks up a string by a delimiter:

```
split(julia_string, " ")
```

```
SubString{String}["Julia", "is", "an", "amazing", "open", "source", "  
" ↵programming", "language"]
```

String Conversions

Often, we need to **convert** between types in Julia. To convert a number to a string we can use the `string` function:

```
my_number = 123  
typeof(string(my_number))
```

```
String
```

Sometimes, we want the opposite: convert a string to a number. Julia has a handy function for that: `parse`.

```
typeof(parse(Int64, "123"))
```

```
Int64
```

Sometimes, we want to play safe with these conversions. That's when `tryparse` function steps in. It has the same functionality as `parse` but returns either a value of the requested type, or `nothing`. That makes `tryparse` handy when we want to avoid errors. Of course, you would need to deal with all those `nothing` values afterwards.

```
tryparse(Int64, "A very non-numeric string")
```

nothing

3.3.4 Tuple

Julia has a data structure called **tuple**. They are really *special* in Julia because they are often used in relation to functions. Since functions are an important feature in Julia, every Julia user should know the basics of tuples.

A tuple is a **fixed-length container that can hold multiple different types**. A tuple is an **immutable object**, meaning that it cannot be modified after instantiation. To construct a tuple, use parentheses () to delimit the beginning and end, along with commas , as delimiters between values:

```
my_tuple = (1, 3.14, "Julia")
```

(1, 3.14, "Julia")

Here, we are creating a tuple with three values. Each one of the values is a different type. We can access them via indexing. Like this:

```
my_tuple[2]
```

3.14

We can also loop over tuples with the `for` keyword. And even apply functions to tuples. But we can **never change any value of a tuple** since they are **immutable**.

Remember functions that return multiple values back in Section 3.2.4? Let's inspect what our `add_multiply` function returns:

```
return_multiple = add_multiply(1, 2)
typeof(return_multiple)
```

```
Tuple{Int64, Int64}
```

This is because `return a, b` is the same as `return (a, b)`:

`1, 2`

```
(1, 2)
```

So, now you can see why they are often related.

One more thing about tuples. **When you want to pass more than one variable to an anonymous function, guess what you would need to use? Once again: tuples!**

`map((x, y) -> x^y, 2, 3)`

```
8
```

Or, even more than two arguments:

`map((x, y, z) -> x^y + z, 2, 3, 1)`

```
9
```

3.3.5 Named Tuple

Sometimes, you want to name the values in tuples. That's when **named tuples** comes in. Their functionality is pretty much same as tuples: they are **immutable** and can hold **any type of value**.

The construction of named tuples is slightly different from that of tuples. You have the familiar parentheses () and the comma , value separator. But now you **name the values**:

`my_namedtuple = (i=1, f=3.14, s="Julia")`

```
(i = 1, f = 3.14, s = "Julia")
```

We can access named tuple's values via indexing like regular tuples or, alternatively, **access by their names** with the .:

```
my_namedtuple.s
```

Julia

To finish our discussion of named tuples, there is one important *quick* syntax that you'll see a lot in Julia code. Often Julia users create a named tuple by using the familiar parenthesis () and commas , but without naming the values. To do so you **begin the named tuple construction by specifying first a semicolon ; before the values**. This is especially useful when the values that would compose the named tuple are already defined in variables or when you want to avoid long lines:

```
i = 1
f = 3.14
s = "Julia"

my_quick_namedtuple = (; i, f, s)
```

```
(i = 1, f = 3.14, s = "Julia")
```

3.3.6 Ranges

A **range** in Julia represents an interval between start and stop boundaries. The syntax is start:stop:

```
1:10
```

```
1:10
```

As you can see, our instantiated range is of type `UnitRange{T}` where `T` is the type inside the `UnitRange`:

```
typeof(1:10)
```

```
UnitRange{Int64}
```

And, if we gather all the values, we get:

```
[x for x in 1:10]
```

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

We can also construct ranges for other types:

```
typeof(1.0:10.0)
```

```
StepRangeLen{Float64, Base.TwicePrecision{Float64}, Base.TwicePrecision{Float64
    ↪}, Int64}
```

Sometimes, we want to change the default interval step size behavior. We can do that by adding a step size in the range syntax `start:step:stop`. For example, suppose we want a range of `Float64` from 0 to 1 with steps of size 0.2:

```
0.0:0.2:1.0
```

```
0.0:0.2:1.0
```

If you want to “materialize” a range into a collection, you can use the function `collect`:

```
collect(1:10)
```

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

We have an array of the type specified in the range between the boundaries that we've set. Speaking of arrays, let's talk about them.

3.3.7 Array

In its most basic form, **arrays** hold multiple objects. For example, they can hold multiple numbers in one-dimension:

```
myarray = [1, 2, 3]
```

```
[1, 2, 3]
```

Most of the time you would want **arrays of a single type for performance issues**, but note that they can also hold objects of different types:

```
myarray = ["text", 1, :symbol]
```

```
Any["text", 1, :symbol]
```

They are the “bread and butter” of data scientist, because arrays are what underlies most of **data manipulation** and **data visualization** workflows.

Therefore, **Arrays are an essential data structure**.

Array Types

Let’s start with **array types**. There are several, but we will focus on the two most used in data science:

- `Vector{T}`: **one-dimensional** array. Alias for `Array{T, 1}`.
- `Matrix{T}`: **two-dimensional** array. Alias for `Array{T, 2}`.

Note here that `T` is the type of the underlying array. So, for example, `Vector{Int64}` is a `Vector` in which all elements are `Int64`s, and `Matrix{AbstractFloat}` is a `Matrix` in which all elements are subtypes of `AbstractFloat`.

Most of the time, especially when dealing with tabular data, we are using either one- or two-dimensional arrays. They are both `Array` types for Julia. But, we can use the handy aliases `Vector` and `Matrix` for clear and concise syntax.

Array Construction

How do we **construct** an array? In this section, we start by constructing arrays in a low-level way. This can be necessary to write high performing code in some situations. However, in most situations, this is not necessary, and we can safely use more convenient methods to create arrays. These more convenient methods will be described later in this section.

The low-level constructor for Julia arrays is the **default constructor**. It accepts the element type as the type parameter inside the `{}` brackets and inside the constructor you’ll pass the element type followed by the desired dimensions. It is common to initialize vector and matrices with undefined elements by using the `undef` argument for type. A vector of 10 `Float64` elements can be constructed as:

```
my_vector = Vector{Float64}(undef, 10)
```

```
[0.0, 6.9428053412943e-310, 6.94280534169826e-310, 0.0, 6.9428033245223e-310,
 ←6.9428033245223e-310, 0.0, 6.9428053412943e-310, 6.9428033281428e-310,
 ←0.0]
```

For matrices, since we are dealing with two-dimensional objects, we need to pass two dimension arguments inside the constructor: one for **rows** and another for **columns**. For example, a matrix with 10 rows and 2 columns of `undef` elements can be instantiated as:

```
my_matrix = Matrix{Float64}(undef, 10, 2)
```

```
10×2 Matrix{Float64}:
6.94271e-310 6.94281e-310
0.0 5.0e-324
6.94271e-310 6.94281e-310
0.0 5.0e-324
6.94271e-310 6.94281e-310
0.0 5.0e-324
6.94281e-310 6.94281e-310
5.0e-324 5.0e-324
6.94281e-310 6.94271e-310
5.0e-324 0.0
```

We also have some **syntax aliases** for the most common elements in array construction:

- `zeros` for all elements being initialized to zero. Note that the default type is `Float64` which can be changed if necessary:

```
my_vector_zeros = zeros(10)
```

```
[0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0]
```

```
my_matrix_zeros = zeros(Int64, 10, 2)
```

```
10×2 Matrix{Int64}:
0 0
0 0
0 0
0 0
0 0
```

```
0 0
0 0
0 0
0 0
0 0
```

- `ones` for all elements being initialized to one:

```
my_vector_ones = ones(Int64, 10)
```

```
[1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
```

```
my_matrix_ones = ones(10, 2)
```

```
10x2 Matrix{Float64}:
```

```
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
1.0 1.0
```

For other elements, we can first instantiate an array with `undef` elements and use the `fill!` function to fill all elements of an array with the desired element. Here's an example with `3.14` (π):

```
my_matrix_pi = Matrix{Float64}(undef, 2, 2)
fill!(my_matrix_pi, 3.14)
```

```
2x2 Matrix{Float64}:
3.14 3.14
3.14 3.14
```

We can also create arrays with **array literals**. For example, here's a 2x2 matrix of integers:

```
[[1 2]
 [3 4]]
```

2×2 Matrix{Int64}:

```
1 2
3 4
```

Array literals also accept a type specification before the [] brackets. So, if we want the same 2x2 array as before but now as floats, we can do so:

```
Float64[[1 2]
 [3 4]]
```

2×2 Matrix{Float64}:

```
1.0 2.0
3.0 4.0
```

It also works for vectors:

```
Bool[0, 1, 0, 1]
```

```
Bool[0, 1, 0, 1]
```

You can even **mix and match** array literals with the constructors:

```
[ones(Int, 2, 2) zeros(Int, 2, 2)]
```

2×4 Matrix{Int64}:

```
1 1 0 0
1 1 0 0
```

```
[zeros(Int, 2, 2)
 ones(Int, 2, 2)]
```

4×2 Matrix{Int64}:

```
0 0
0 0
1 1
1 1
```

```
[ones(Int, 2, 2) [1; 2]
 [3 4] 5]
```

3x3 Matrix{Int64}:

```
1 1 1
1 1 2
3 4 5
```

Another powerful way to create an array is to write an **array comprehension**. This way of creating arrays is better in most cases: it avoids loops, indexing, and other error-prone operations. You specify what you want to do inside the [] brackets. For example, say we want to create a vector of squares from 1 to 10:

```
[x^2 for x in 1:10]
```

```
[1, 4, 9, 16, 25, 36, 49, 64, 81, 100]
```

They also support multiple inputs:

```
[x*y for x in 1:10 for y in 1:2]
```

```
[1, 2, 2, 4, 3, 6, 4, 8, 5, 10, 6, 12, 7, 14, 8, 16, 9, 18, 10, 20]
```

And conditionals:

```
[x^2 for x in 1:10 if isodd(x)]
```

```
[1, 9, 25, 49, 81]
```

As with array literals, you can specify your desired type before the [] brackets:

```
Float64[x^2 for x in 1:10 if isodd(x)]
```

```
[1.0, 9.0, 25.0, 49.0, 81.0]
```

Finally, we can also create arrays with **concatenation functions**. Concatenation is a standard term in computer programming and means “to chain together.” For example, we can concatenate strings with “aa” and “bb” to get “aabb”:

```
"aa" * "bb"
```

aabb

And, we can concatenate arrays to create new arrays:

- `cat`: concatenate input arrays along a specific dimension `dims`

```
cat(ones(2), zeros(2), dims=1)
```

[1.0, 1.0, 0.0, 0.0]

```
cat(ones(2), zeros(2), dims=2)
```

2×2 Matrix{Float64}:

1.0	0.0
1.0	0.0

- `vcat`: vertical concatenation, a shorthand for `cat(...; dims=1)`

```
vcat(ones(2), zeros(2))
```

[1.0, 1.0, 0.0, 0.0]

- `hcat`: horizontal concatenation, a shorthand for `cat(...; dims=2)`

```
hcat(ones(2), zeros(2))
```

2×2 Matrix{Float64}:

1.0	0.0
1.0	0.0

Array Inspection

Once we have arrays, the next logical step is to **inspect** them. There are a lot of handy functions that allow the user to have an insight into any array.

It is most useful to know what **type of elements** are inside an array. We can do this with `eltype`:

```
eltype(my_matrix_π)
```

Float64

After knowing its types, one might be interested in **array dimensions**. Julia has several functions to inspect array dimensions:

- **length**: total number of elements

```
length(my_matrix_π)
```

4

- **ndims**: number of dimensions

```
ndims(my_matrix_π)
```

2

- **size**: this one is a little tricky. By default it will return a tuple containing the array's dimensions.

```
size(my_matrix_π)
```

(2, 2)

You can get a specific dimension with a second argument to `size`. Here, the the second axis is columns

```
size(my_matrix_π, 2)
```

2

Array Indexing and Slicing

Sometimes, we want to inspect only certain parts of an array. This is called **indexing** and **slicing**. If you want a particular observation of a vector, or a row or column of a matrix, you'll probably need to **index an array**.

First, we will create an example vector and matrix to play around:

```
my_example_vector = [1, 2, 3, 4, 5]

my_example_matrix = [[1 2 3]
                     [4 5 6]
                     [7 8 9]]
```

Let's start with vectors. Suppose that you want the second element of a vector. You append [] brackets with the desired **index** inside:

```
my_example_vector[2]
```

2

The same syntax follows with matrices. But, since matrices are 2-dimensional arrays, we have to specify *both* rows and columns. Let's retrieve the element from the second row (first dimension) and first column (second dimension):

```
my_example_matrix[2, 1]
```

4

Julia also has conventional keywords for the **first** and **last** elements of an array: `begin` and `end`. For example, the second to last element of a vector can be retrieved as:

```
my_example_vector[end-1]
```

4

This also works for matrices. Let's retrieve the element of the last row and second column:

```
my_example_matrix[end, begin+1]
```

Often, we are not only interested in just one array element, but in a whole **subset of array elements**. We can accomplish this by **slicing** an array. It uses the same index syntax, but with the added colon `:` to denote the boundaries that we are slicing through the array. For example, suppose we want to get the 2nd to 4th element of a vector:

```
my_example_vector[2:4]
```

```
[2, 3, 4]
```

We could do the same with matrices. Particularly with matrices if we want to select **all elements** in a following dimension we can do so with just a colon `:`. For example, to get all the elements in the second row:

```
my_example_matrix[2, :]
```

```
[4, 5, 6]
```

You can interpret this with something like “take the 2nd row and all the columns.”

It also supports `begin` and `end`:

```
my_example_matrix[begin+1:end, end]
```

```
[6, 9]
```

Array Manipulations

There are several ways we could **manipulate** an array. The first would be to manipulate a **singular element of the array**. We just index the array by the desired element and proceed with an assignment `=`:

```
my_example_matrix[2, 2] = 42
```

```
my_example_matrix
```

```
3x3 Matrix{Int64}:
```

```
1 2 3  
4 42 6  
7 8 9
```

Or, you can manipulate a certain **subset of elements of the array**. In this case, we need to slice the array and then assign with `=`:

```
my_example_matrix[3, :] = [17, 16, 15]
my_example_matrix
```

```
3x3 Matrix{Int64}:
 1  2  3
 4  42 6
17 16 15
```

Note that we had to assign a vector because our sliced array is of type `Vector`:

```
typeof(my_example_matrix[3, :])
```

```
Vector{Int64} (alias for Array{Int64, 1})
```

The second way we could manipulate an array is to **alter its shape**. Suppose that you have a 6-element vector and you want to make it a 3x2 matrix. You can do this with `reshape`, by using the array as the first argument and a tuple of dimensions as the second argument:

```
six_vector = [1, 2, 3, 4, 5, 6]
three_two_matrix = reshape(six_vector, (3, 2))
three_two_matrix
```

```
3x2 Matrix{Int64}:
 1  4
 2  5
 3  6
```

You can convert it back to a vector by specifying a tuple with only one dimension as the second argument:

```
reshape(three_two_matrix, (6, ))
```

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

The third way we could manipulate an array is to **apply a function over every array element**. This is where the “dot” operator `.`, also known as *broadcasting*, comes in.

```
logarithm.(my_example_matrix)
```

```
3x3 Matrix{Float64}:
0.0      0.693147  1.09861
1.38629  3.73767   1.79176
2.83321  2.77259   2.70805
```

The dot operator in Julia is extremely versatile. You can even use it to broadcast infix operators:

```
my_example_matrix .+ 100
```

```
3x3 Matrix{Int64}:
101  102  103
104  142  106
117  116  115
```

An alternative to broadcasting a function over a vector is to use `map`:

```
map(logarithm, my_example_matrix)
```

```
3x3 Matrix{Float64}:
0.0      0.693147  1.09861
1.38629  3.73767   1.79176
2.83321  2.77259   2.70805
```

For anonymous functions, `map` is usually more readable. For example,

```
map(x -> 3x, my_example_matrix)
```

```
3x3 Matrix{Int64}:
 3    6    9
12   126   18
51    48   45
```

is quite clear. However, the same broadcast looks as follows:

```
(x -> 3x).(my_example_matrix)
```

```
3x3 Matrix{Int64}:
 3    6    9
12   126   18
51    48   45
```

Next, `map` works with slicing:

```
map(x -> x + 100, my_example_matrix[:, 3])
```

```
[103, 106, 115]
```

Finally, sometimes, and specially when dealing with tabular data, we want to apply a **function over all elements in a specific array dimension**. This can be done with the `mapslices` function. Similar to `map`, the first argument is the function and the second argument is the array. The only change is that we need to specify the `dims` argument to flag what dimension we want to transform the elements.

For example, let's use `mapslices` with the `sum` function on both rows (`dims=1`) and columns (`dims=2`):

```
# rows
mapslices(sum, my_example_matrix; dims=1)
```

```
1x3 Matrix{Int64}:
 22  60  24
```

```
# columns
mapslices(sum, my_example_matrix; dims=2)
```

```
3x1 Matrix{Int64}:
 6
52
48
```

Array Iteration

One common operation is to **iterate over an array with a for loop**. The **regular for loop over an array returns each element**.

The simplest example is with a vector.

```
simple_vector = [1, 2, 3]

empty_vector = Int64[]

for i in simple_vector
    push!(empty_vector, i + 1)
end

empty_vector
```

[2, 3, 4]

Sometimes, you don't want to loop over each element, but actually over each array index. **We can use the `eachindex` function combined with a `for` loop to iterate over each array index.**

Again, let's show an example with a vector:

```
forty_twos = [42, 42, 42]

empty_vector = Int64[]

for i in eachindex(forty_twos)
    push!(empty_vector, i)
end

empty_vector
```

[1, 2, 3]

In this example, the `eachindex(forty_twos)` returns the indices of `forty_twos`, namely [1, 2, 3].

Similarly, we can iterate over matrices. The standard `for` loop goes first over columns then over rows. It will first traverse all elements in column 1, from the first row to the last row, then it will move to column 2 in a similar fashion until it has covered all columns.

For those familiar with other programming languages: Julia, like most scientific programming languages, is “column-major.” Column-major means that the elements in the column are stored next to each other in memory⁴. This also means that iterating over elements in a column is much quicker than over elements in a row.

⁴ or, that the memory address pointers to the elements in the column are stored next to each other.

Ok, let's show this in an example:

```
column_major = [[1 3]
                [2 4]]

row_major = [[1 2]
                [3 4]]
```

If we loop over the vector stored in column-major order, then the output is sorted:

```
indexes = Int64[]

for i in column_major
    push!(indexes, i)
end

indexes
```

[1, 2, 3, 4]

However, the output isn't sorted when looping over the other matrix:

```
indexes = Int64[]

for i in row_major
    push!(indexes, i)
end

indexes
```

[1, 3, 2, 4]

It is often better to use specialized functions for these loops:

- `eachcol`: iterates over an array column first

```
first(eachcol(column_major))
```

[1, 2]

- `eachrow`: iterates over an array row first

```
first(eachrow(column_major))
```

[1, 3]

3.3.8 Pair

Compared to the huge section on arrays, this section on pairs will be brief. **Pair ↪ is a data structure that holds two objects** (which typically belong to each other). We construct a pair in Julia using the following syntax:

```
my_pair = "Julia" => 42
```

```
"Julia" => 42
```

The elements are stored in the fields `first` and `second`.

```
my_pair.first
```

```
Julia
```

```
my_pair.second
```

```
42
```

But, in most cases, it's easier use `first` and `last`⁵:

```
first(my_pair)
```

```
Julia
```

```
last(my_pair)
```

```
42
```

⁵ it is easier because `first` and `last` also work on many other collections, so you need to remember less.

Pairs will be used a lot in data manipulation and data visualization since both `DataFrames.jl` (Section 4) or `Makie.jl` (Section 6) take objects of type `Pair` in their main functions. For example, with `DataFrames.jl` we're going to see that `:a => :b` can be used to rename the column `:a` to `:b`.

3.3.9 Dict

If you understood what a `Pair` is, then `Dict` won't be a problem. For all practical purposes, **Dicts are mappings from keys to values**. By mapping, we mean that if you give a `Dict` some key, then the `Dict` can tell you which value belongs to that key. `keys` and `values` can be of any type, but usually `keys` are strings.

There are two ways to construct `Dicts` in Julia. The first is by passing a vector of tuples as `(key, value)` to the `Dict` constructor:

```
name2number_map = Dict([("one", 1), ("two", 2)])
```

```
Dict{String, Int64} with 2 entries:
"two" => 2
"one" => 1
```

There is a more readable syntax based on the `Pair` type described above. You can also pass `Pairs` of `key => values` to the `Dict` constructor:

```
name2number_map = Dict("one" => 1, "two" => 2)
```

```
Dict{String, Int64} with 2 entries:
"two" => 2
"one" => 1
```

You can retrieve a `Dict`'s `value` by indexing it by the corresponding `key`:

```
name2number_map["one"]
```

```
1
```

To add a new entry, you index the `Dict` by the desired `key` and assign a `value` with the assignment `=` operator:

```
name2number_map["three"] = 3
```

```
3
```

If you want to check if a `Dict` has a certain `key` you can use `keys` and `in`:

```
"two" in keys(name2number_map)
```

```
true
```

To delete a key you can use either the `delete!` function:

```
delete!(name2number_map, "three")
```

```
Dict{String, Int64} with 2 entries:  
  "two" => 2  
  "one" => 1
```

Or, to delete a key while returning its value, you can use `pop!`:

```
popped_value = pop!(name2number_map, "two")
```

```
2
```

Now, our `name2number_map` has only one key:

```
name2number_map
```

```
Dict{String, Int64} with 1 entry:  
  "one" => 1
```

Dicts are also used for data manipulation by `DataFrames.jl` (Section 4) and for data visualization by `Makie.jl` (Section 6). So, it is important to know their basic functionality.

There is another useful way of constructing Dicts. Suppose that you have two vectors and you want to construct a Dict with one of them as keys and the other as values. You can do that with the `zip` function which “glues” together two objects (just like a zipper):

```
A = ["one", "two", "three"]  
B = [1, 2, 3]  
  
name2number_map = Dict(zip(A, B))
```

```
Dict{String, Int64} with 3 entries:  
  "two" => 2  
  "one" => 1  
  "three" => 3
```

For instance, we can now get the number 3 via:

```
name2number_map["three"]
```

3

3.3.10 Symbol

`Symbol` is actually *not* a data structure. It is a type and behaves a lot like a string. Instead of surrounding the text by quotation marks, a symbol starts with a colon (`:`) and can contain underscores:

```
sym = :some_text
```

:some_text

We can easily convert a symbol to string and vice versa:

```
s = string(sym)
```

some_text

```
sym = Symbol(s)
```

:some_text

One simple benefit of symbols is that you have to type one character less, that is, `:some_text` versus `"some text"`. We use `Symbols` a lot in data manipulations with the `DataFrames.jl` package (Section 4) and data visualizations with the `Makie.jl` package (Section 6).

3.3.11 Splat Operator

In Julia we have the “splat” operator `...` which is used in function calls as a **sequence of arguments**. We will occasionally use splatting in some function calls in the **data manipulation** and **data visualization** chapters.

The most intuitive way to learn about splatting is with an example. The `add_elements ↗` function below takes three arguments to be added together:

```
add_elements(a, b, c) = a + b + c
```

```
add_elements (generic function with 1 method)
```

Now, suppose that we have a collection with three elements. The naïve way to this would be to supply the function with all three elements as function arguments like this:

```
my_collection = [1, 2, 3]

add_elements(my_collection[1], my_collection[2], my_collection[3])
```

6

Here is where we use the “splat” operator ... which takes a collection (often an array, vector, tuple, or range) and converts it into a sequence of arguments:

```
add_elements(my_collection...)
```

6

The ... is included after the collection that we want to “splat” into a sequence of arguments. In the example above, the following are the same:

```
add_elements(my_collection...) == add_elements(my_collection[1], my_collection[2]
    ↪, my_collection[3])
```

true

Anytime Julia sees a splatting operator inside a function call, it will be converted on a sequence of arguments for all elements of the collection separated by commas.

It also works for ranges:

```
add_elements(1:3...)
```

6

3.4 Filesystem

In data science, most projects are undertaken in a collaborative effort. We share code, data, tables, figures and so on. Behind everything, there is the **operating system (OS) filesystem**. In a perfect world, the same program would give the **same** output when running on **different** operating systems. Unfortunately, that is not always the case. One instance of this is the difference between Windows paths, such as `C:\Users\john`, and Linux paths, such as `/home/john`. This is why it is important to discuss **filesystem best practices**.

Julia has native filesystem capabilities that **handle the differences between operating systems**. They are located in the `Filesystem`⁶ module from the core Base Julia library.

⁶ <https://docs.julialang.org/en/v1/base/file/>

Whenever you are dealing with files such as CSV, Excel files or other Julia scripts, make sure that your code **works on different OS filesystems**. This is easily accomplished with the `joinpath`, `__FILE__` and `pkgdir` functions.

If you write your code in a package, you can use `pkgdir` to get the root directory of the package. For example, for the Julia Data Science (JDS) package that we use to produce this book, the root directory is:

```
/home/runner/work/JuliaDataScience/JuliaDataScience
```

As you can see, the code to produce this book was running on a Linux computer. If you're using a script, you can get the location of the script file via

```
root = dirname(__FILE__)
```

The nice thing about these two commands is that they are independent of how the user started Julia. In other words, it doesn't matter whether the user started the program with `julia scripts/script.jl` or `julia script.jl`, in both cases the paths are the same.

The next step would be to include the relative path from `root` to our desired file. Since different OS have different ways to construct relative paths with subfolders (some use forward slashes / while others might use backslashes \), we cannot simply concatenate the file's relative path with the `root` string. For that, we have the `joinpath` function, which will join different relative paths and filenames according to your specific OS filesystem implementation.

Suppose that you have a script named `my_script.jl` inside your project's directory. You can have a robust representation of the filepath to `my_script.jl` as:

```
joinpath(root, "my_script.jl")
```

```
/home/runner/work/JuliaDataScience/JuliaDataScience/my_script.jl
```

`joinpath` also handles **subfolders**. Let's now imagine a common situation where you have a folder named `data/` in your project's directory. Inside this folder there is a CSV file named `my_data.csv`. You can have the same robust representation of the filepath to `my_data.csv` as:

```
joinpath(root, "data", "my_data.csv")
```

```
/home/runner/work/JuliaDataScience/JuliaDataScience/data/my_data.csv
```

It's a good habit to pick up, because it's very likely to save problems for you or other people later.

3.5 Julia Standard Library

Julia has a **rich standard library** that is available with *every* Julia installation. Contrary to everything that we have seen so far, e.g. types, data structures and filesystem; you **must load standard library modules into your environment** to use a particular module or function.

This is done via `using` or `import`. In this book, we will load code via `using`:

```
using ModuleName
```

After doing this, you can access all functions and types inside `ModuleName`.

3.5.1 Dates

Knowing how to handle dates and timestamps is important in data science. As we said in *Why Julia?* (Section 2) section, Python's `pandas` uses its own `datetime` type to handle dates. The same is true in the R `tidyverse`'s `lubridate` package, which also defines its own `datetime` type to handle dates. In Julia packages don't need to write their own dates logic, because Julia has a `Dates` module in its standard library called `Dates`.

To begin, let's load the `Dates` module:

```
using Dates
```

Date and DateTime Types

The `Dates` standard library module has **two types for working with dates**:

1. `Date`: representing time in days and
2. `DateTime`: representing time in millisecond precision.

We can construct `Date` and `DateTime` with the default constructor either by specifying an integer to represent year, month, day, hours and so on:

```
Date(1987) # year
```

1987-01-01

```
Date(1987, 9) # year, month
```

1987-09-01

```
Date(1987, 9, 13) # year, month, day
```

1987-09-13

```
DateTime(1987, 9, 13, 21) # year, month, day, hour
```

1987-09-13T21:00:00

```
DateTime(1987, 9, 13, 21, 21) # year, month, day, hour, minute
```

1987-09-13T21:21:00

For the curious, September 13th 1987, 21:21 is the official time of birth of the first author, Jose.

We can also pass `Period` types to the default constructor. **Period types are the human-equivalent representation of time** for the computer. Julia's `Dates` have the following `Period` abstract subtypes:

```
subtypes(Period)
```

DatePeriod

TimePeriod

which divide into the following concrete types, and they are pretty much self-explanatory:

`subtypes(DatePeriod)`

Day

Month

Quarter

Week

Year

`subtypes(TimePeriod)`

Hour

Microsecond

Millisecond

Minute

Nanosecond

Second

So, we could alternatively construct Jose's official time of birth as:

`DateTime(Year(1987), Month(9), Day(13), Hour(21), Minute(21))`

1987-09-13T21:21:00

Parsing Dates

Most of the time, we won't be constructing `Date` or `DateTime` instances from scratch. Actually, we will probably be **parsing strings as Date or DateTime types**.

The `Date` and `DateTime` constructors can be fed a string and a format string. For example, the string "19870913" representing September 13th 1987 can be parsed with:

```
Date("19870913", "yyyymmdd")
```

1987-09-13

Notice that the second argument is a string representation of the format. We have the first four digits representing year `y`, followed by two digits for month `m` and finally two digits for day `d`.

It also works for timestamps with `DateTime`:

```
DateTime("1987-09-13T21:21:00", "yyyy-mm-ddTHH:MM:SS")
```

1987-09-13T21:21:00

You can find more on how to specify different date formats in the Julia `Dates'` documentation⁷. Don't worry if you have to revisit it all the time, we ourselves do that too when working with dates and timestamps.

⁷ <https://docs.julialang.org/en/v1/stdlib/Dates/#DateFormat>

According to Julia `Dates'` documentation⁸, using the `Date(date_string, format_string ↪)` method is fine if it's only called a few times. If there are many similarly formatted date strings to parse, however, it is much more efficient to first create a `DateFormat` type, and then pass it instead of a raw format string. Then, our previous example becomes:

```
format = DateFormat("yyyymmdd")
Date("19870913", format)
```

1987-09-13

Alternatively, without loss of performance, you can use the string literal prefix `dateformat"..."`:

```
Date("19870913", dateformat"yyyymmdd")
```

1987-09-13

Extracting Date Information

It is easy to **extract desired information from Date and DateTime objects**. First, let's create an instance of a very special date:

```
my_birthday = Date("1987-09-13")
```

1987-09-13

We can extract anything we want from my_birthday:

```
year(my_birthday)
```

1987

```
month(my_birthday)
```

9

```
day(my_birthday)
```

13

Julia's Dates module also has **compound functions that return a tuple of values**:

```
yearmonth(my_birthday)
```

(1987, 9)

```
monthday(my_birthday)
```

(9, 13)

```
yearday(my_birthday)
```

(1987, 9, 13)

We can also see the day of the week and other handy stuff:

```
dayofweek(my_birthday)
```

7

```
dayname(my_birthday)
```

Sunday

```
dayofweekofmonth(my_birthday)
```

2

Yep, Jose was born on the second Sunday of September.

NOTE: Here's a handy tip to just recover weekdays from `Dates` instances. Just use a filter on `dayofweek(your_date) <= 5`. For business day you can checkout the `BusinessDays.jl`⁹ package.

⁹ <https://github.com/JuliaFinance/BusinessDays.jl>

Date Operations

We can perform **operations** in `Dates` instances. For example, we can add days to a `Date` or `DateTime` instance. Notice that Julia's `Dates` will automatically perform the adjustments necessary for leap years, and for months with 30 or 31 days (this is known as *calendrical* arithmetic).

```
my_birthday + Day(90)
```

1987-12-12

We can add as many as we like:

```
my_birthday + Day(90) + Month(2) + Year(1)
```

1989-02-11

In case you're ever wondering: "What can I do with dates again? What is available?" then you can use `methodswith` to check it out. We show only the first 20 results here:

```
first(methodswith(Date), 20)
```

```
[1] +(dt::Date, t::Time) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:19
[2] +(dt::Date, y::Year) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:27
[3] +(dt::Date, z::Month) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:54
[4] +(x::Date, y::Quarter) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:73
[5] +(x::Date, y::Week) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/julia
    ↪ /stdlib/v1.9/Dates/src/arithmetic.jl:77
[6] +(x::Date, y::Day) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/julia/
    ↪ stdlib/v1.9/Dates/src/arithmetic.jl:79
[7] +(t::Time, dt::Date) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:20
[8] -(dt::Date, y::Year) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:35
[9] -(dt::Date, z::Month) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:66
[10] -(x::Date, y::Quarter) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:74
[11] -(x::Date, y::Week) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/arithmetic.jl:78
[12] -(x::Date, y::Day) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/julia
    ↪ /stdlib/v1.9/Dates/src/arithmetic.jl:80
[13] (::Colon)(a::T, b::T) where T<:Date @ Dates /opt/hostedtoolcache/julia
    ↪ /1.9.1/x64/share/julia/stdlib/v1.9/Dates/src/ranges.jl:7
[14] convert(::Type{DateTime}, dt::Date) @ Dates /opt/hostedtoolcache/julia
    ↪ /1.9.1/x64/share/julia/stdlib/v1.9/Dates/src/conversions.jl:30
[15] convert(::Type{Day}, dt::Date) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64
    ↪ /share/julia/stdlib/v1.9/Dates/src/conversions.jl:37
[16] floor(dt::Date, p::Year) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share
    ↪ /julia/stdlib/v1.9/Dates/src/rounding.jl:45
[17] floor(dt::Date, p::Month) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/
    ↪ share/julia/stdlib/v1.9/Dates/src/rounding.jl:51
[18] floor(dt::Date, p::Quarter) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/
    ↪ share/julia/stdlib/v1.9/Dates/src/rounding.jl:61
[19] floor(dt::Date, p::Week) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share
    ↪ /julia/stdlib/v1.9/Dates/src/rounding.jl:66
[20] floor(dt::Date, p::Day) @ Dates /opt/hostedtoolcache/julia/1.9.1/x64/share/
    ↪ julia/stdlib/v1.9/Dates/src/rounding.jl:73
```

From this, we can conclude that we can also use the plus + and minus - operator. Let's see how old Jose is, in days:

```
today() - my_birthday
```

13063 days

The **default duration** of `Date` types is a `Day` instance. For the `DateTime`, the default duration is `Millisecond` instance:

```
DateTime(today()) - DateTime(my_birthday)
```

1128643200000 milliseconds

Date Intervals

One nice thing about `Dates` module is that we can also easily construct **date and time intervals**. Julia is clever enough to not have to define the whole interval types and operations that we covered in Section 3.3.6. It just extends the functions and operations defined for range to `Date`'s types. This is known as multiple dispatch and we already covered this in *Why Julia?* (Section 2).

For example, suppose that you want to create a `Day` interval. This is easy done with the colon `:` operator:

```
Date("2021-01-01"):Day(1):Date("2021-01-07")
```

2021-01-01

2021-01-02

2021-01-03

2021-01-04

2021-01-05

2021-01-06

2021-01-07

There is nothing special in using `Day(1)` as the interval, we can **use whatever Period type as interval**. For example, using 3 days as the interval:

```
Date("2021-01-01"):Day(3):Date("2021-01-07")
```

2021-01-01

2021-01-04

2021-01-07

Or even months:

```
Date("2021-01-01"):Month(1):Date("2021-03-01")
```

2021-01-01

2021-02-01

2021-03-01

Note that the **type of this interval is a `StepRange` with the Date and concrete Period type we used as interval inside the colon : operator:**

```
date_interval = Date("2021-01-01"):Month(1):Date("2021-03-01")
typeof(date_interval)
```

`StepRange{Date, Month}`

We can convert this to a **vector** with the `collect` function:

```
collected_date_interval = collect(date_interval)
```

2021-01-01

2021-02-01

2021-03-01

And have all the **array functionalities available**, like, for example, indexing:

```
collected_date_interval[end]
```

2021-03-01

We can also **broadcast date operations** to our vector of `Dates`:

```
collected_date_interval .+ Day(10)
```

2021-01-11

2021-02-11

2021-03-11

Similarly, these examples work for `DateTime` types too.

3.5.2 Random Numbers

Another important module in Julia's standard library is the `Random` module. This module deals with **random number generation**. `Random` is a rich library and, if you're interested, you should consult Julia's `Random` documentation¹⁰. We will cover *only* three functions: `rand`, `randn` and `seed!`.

¹⁰ <https://docs.julialang.org/en/v1/stdlib/Random/>

To begin, we first load the `Random` module. Since we know exactly what we want to load, we can just as well do that explicitly:

```
using Random: seed!
```

We have **two main functions that generate random numbers**:

- `rand`: samples a **random element** of a data structure or type.
- `randn`: samples a random number from a **standard normal distribution** (mean 0 and standard deviation 1).

rand

By default, if you call `rand` without arguments it will return a `Float64` in the interval $[0, 1)$, which means between 0 inclusive to 1 exclusive:

```
rand()
```

```
0.3614851098223981
```

You can modify `rand` arguments in several ways. For example, suppose you want more than 1 random number:

```
rand(3)
```

```
[0.5198511735644762, 0.05828889428445205, 0.7179174655050026]
```

Or, you want a different interval:

```
rand(1.0:10.0)
```

```
1.0
```

You can also specify a different step size inside the interval and a different type. Here we are using numbers without the dot . so Julia will interpret them as Int64 and not as Float64:

```
rand(2:2:20)
```

```
2
```

You can also mix and match arguments:

```
rand(2:2:20, 3)
```

```
[4, 12, 2]
```

It also supports a collection of elements as a tuple:

```
rand((42, "Julia", 3.14))
```

```
Julia
```

And also arrays:

```
rand([1, 2, 3])
```

3

DictS:

```
rand(Dict(:one => 1, :two => 2))
```

:one => 1

For all the `rand` arguments options, you can specify the desired random number dimensions in a tuple. If you do this, the returned type will be an array. For example, here's a 2x2 matrix of `Float64` numbers between 1.0 and 3.0:

```
rand(1.0:3.0, (2, 2))
```

2×2 Matrix{Float64}:

2.0 2.0
2.0 2.0

randn

`randn` follows the same general principle from `rand` but now it only returns numbers generated from the **standard normal distribution**. The standard normal distribution is the normal distribution with mean 0 and standard deviation 1. The default type is `Float64` and it only allows for subtypes of `AbstractFloat` or `Complex`:

```
randn()
```

-1.739362078680267

We can only specify the size:

```
randn((2, 2))
```

2×2 Matrix{Float64}:

1.03226	-1.40816
0.176442	0.175733

seed!

To finish off the `Random` overview, let's talk about **reproducibility**. Often, we want to make something **replicable**. Meaning that, we want the random number generator to generate the **same random sequence of numbers**. We can do so with the `seed!` function:

```
seed!(123)
rand(3)
```

```
[0.521213795535383, 0.5868067574533484, 0.8908786980927811]
```

```
seed!(123)
rand(3)
```

```
[0.521213795535383, 0.5868067574533484, 0.8908786980927811]
```

In some cases, calling `seed!` at the beginning of your script is not good enough. To avoid `rand` or `randn` to depend on a global variable, we can instead define an instance of a `seed!` and pass it as a first argument of **either** `rand` **or** `randn`.

```
my_seed = seed!(123)
```

```
Random.TaskLocalRNG()
```

```
rand(my_seed, 3)
```

```
[0.521213795535383, 0.5868067574533484, 0.8908786980927811]
```

```
rand(my_seed, 3)
```

```
[0.19090669902576285, 0.5256623915420473, 0.3905882754313441]
```

NOTE: Note that these numbers might differ for different Julia versions. To have stable streams across Julia versions use the `StableRNGs.jl` package.

3.5.3 Downloads

We'll also cover the standard library's `Downloads` **module**. It will be really brief because we will only be covering a single function named `download`.

Suppose you want to **download a file from the internet to your local storage**. You can accomplish this with the `download` function. The first and only required argument is the file's url. You can also specify as a second argument the desired output path for the downloaded file (don't forget the filesystem best practices!). If you don't specify a second argument, Julia will, by default, create a temporary file with the `tempfile` function.

Let's load the `Downloads` module:

```
using Downloads
```

For example, let's download our `JuliaDataScience` GitHub repository¹¹ Project. [→toml](#) file. Note that `download` function is not exported by `Downloads` module, so we have to use the `Module.function` syntax. By default, it returns a string that holds the file path for the downloaded file:

```
url = "https://raw.githubusercontent.com/JuliaDataScience/JuliaDataScience/main/
      ↪Project.toml"

my_file = Downloads.download(url) # tempfile() being created
```

```
/tmp/jl_H25sLoXkNY
```

With `readlines`, we can look at the first 4 lines of our downloaded file:

```
readlines(my_file)[1:4]
```

```
4-element Vector{String}:
"name = \"JDS\""
"uuid = \"6c596d62-2771-44f8-8373-3ec4b616ee9d\""
"authors = [\"Jose Storopoli\", \"Rik Huijzer\", \"Lazaro Alonso\"]"
""
```

NOTE: For more complex HTTP interactions such as interacting with web APIs, see the `HTTP.jl` package¹².

¹¹ <https://github.com/JuliaDataScience/JuliaDataScience>

¹² <https://github.com/JuliaWeb/HTTP.jl>

3.5.4 Project Management

One last thing from Julia's standard library for us to cover is the `Pkg module`. As described in Section 2.2, Julia offers a **built-in package manager**, with dependencies and version control tightly controlled, manageable, and replicable.

Unlike traditional package managers, which install and manage a single global set of packages, Julia's package manager is designed around "environments": independent sets of packages that can be local to an individual project or shared between projects. Each project maintains its own independent set of package versions.

`Project.toml` and `Manifest.toml`

¹³ <https://toml.io>

Inside every project environment there is a simple setup involving `.toml`¹³ files in a folder. The folder, in this context, can be perceived as a "project" folder. The project environment is derived on two `.toml` files:

- `Project.toml`: *higher-level* description of the project environment with the top-level package list.
- `Manifest.toml`: *lower-level* description of the project environment with the full dependencies list and their versions. This file is machine-generated, which means that users are not encouraged to edit it.

Creating Project Environments

In order to create a new project environment, you can enter the `Pkg REPL mode` by typing `]` (right-bracket) in the Julia REPL:

```
julia>]
```

Then it becomes the `Pkg REPL mode`:

```
(@v1.8) pkg>
```

Here we can see that the REPL prompts changes from `julia>` to `pkg>`. There's also additional information inside the parentheses regarding which project environment is currently active, `(@v1.8)`. The `v1.8` project environment is the default environment for your currently Julia installation (which in our case is Julia version `1.8.x`).

NOTE: You can see a list of available commands in the `Pkg` REPL mode with the `help command`.

Julia has separate default environments for each minor release, the `xs` in the `1.x` Julia version. Anything that we perform in this default environment will impact any fresh Julia session on that version. Hence, we need to create a new environment by using the `activate` **command**:

```
(@v1.8) pkg> activate .
Activating project at `~/user/folder`

(folder) pkg>
```

This activates a project environment in the directory that your Julia REPL is running. In my case this is located at `~/user/folder`. Now we can start adding packages to our project environment with the `add` **command** in the `Pkg` REPL mode:

```
(folder) pkg> add DataFrames
Updating registry at `~/julia/registries/General.toml`
Resolving package versions...
Updating `~/user/folder/Project.toml`
[a93c6f00] + DataFrames v1.4.3
  Updating `~/user/folder/Manifest.toml`
[34da2185] + Compat v4.4.0
[a8cc5b0e] + Crayons v4.1.1
[9a962f9c] + DataAPI v1.13.0
[a93c6f00] + DataFrames v1.4.3
[864edb3b] + DataStructures v0.18.13
[e2d170a0] + DataValueInterfaces v1.0.0
[59287772] + Formatting v0.4.2
[41ab1584] + InvertedIndices v1.1.0
[82899510] + IteratorInterfaceExtensions v1.0.0
[b964fa9f] + LaTeXStrings v1.3.0
[e1d29d7a] + Missings v1.0.2
[bac558e1] + OrderedCollections v1.4.1
[2dfb63ee] + PooledArrays v1.4.2
[08abe8d2] + PrettyTables v2.2.1
[189a3867] + Reexport v1.2.2
[66db9d55] + SnoopPrecompile v1.0.1
[a2af1166] + SortingAlgorithms v1.1.0
[892a3eda] + StringManipulation v0.3.0
[3783bdb8] + TableTraits v1.0.1
[bd369af6] + Tables v1.10.0
[56f22d72] + Artifacts
[2a0f44e3] + Base64
[ade2ca70] + Dates
[9fa8497b] + Future
```

```
[b77e0a4c] + InteractiveUtils
[8f399da3] + Libdl
[37e2e46d] + LinearAlgebra
[56ddb016] + Logging
[d6f4376e] + Markdown
[de0858da] + Printf
[3fa0cd96] + REPL
[9a3f8284] + Random
[ea8e919c] + SHA v0.7.0
[9e88b42a] + Serialization
[6462fe0b] + Sockets
[2f01184e] + SparseArrays
[10745b16] + Statistics
[8dfed614] + Test
[cf7118a7] + UUIDs
[4ec0a83e] + Unicode
[e66e0078] + CompilerSupportLibraries_jll v0.5.2+0
[4536629a] + OpenBLAS_jll v0.3.20+0
[8e850b90] + libblastrampoline_jll v5.1.1+0
```

From the `add` output, we can see that Julia automatically creates *both* the `Project.toml` and `Manifest.toml` files. In the `Project.toml`, it adds a new package to the project environment package list. Here are the contents of the `Project.toml`:

```
[deps]
DataFrames = "a93c6f00-e57d-5684-b7b6-d8193f3e46c0"
```

This is a `.toml` file where:

- `[deps]`: a TOML table (also known as *hash tables* or *dictionaries*)
- `DataFrames`: a key in the TOML `deps` table; this is the name of the package
- `"a93c6f00-e57d-5684-b7b6-d8193f3e46c0"`: the value for the `DataFrames` key; this is the universally unique identifier (UUID)¹⁴ of the package.

¹⁴ https://en.wikipedia.org/wiki/Universally_unique_identifier

Let's also take a peek into the `Manifest.toml`. Here we will truncate the output since it is a big machine-generated file:

```
# This file is machine-generated - editing it directly is not advised

julia_version = "1.8.3"
manifest_format = "2.0"
project_hash = "376d427149ea94494cc22001edd58d53c9b2bee1"

[[deps.Artifacts]]
uuid = "56f22d72-fd6d-98f1-02f0-08ddc0907c33"

...
```

```
[[deps.DataFrames]]
deps = ["Compat", "DataAPI", "Future", "InvertedIndices", "
    ↪IteratorInterfaceExtensions", "LinearAlgebra", "Markdown", "Missings", "
    ↪PooledArrays", "PrettyTables", "Printf", "REPL", "Random", "Reexport", "
    ↪SnoopPrecompile", "SortingAlgorithms", "Statistics", "TableTraits", "
    ↪Tables", "Unicode"]
git-tree-sha1 = "0f44494fe4271cc966ac4fea524111bef63ba86c"
uuid = "a93c6f00-e57d-5684-b7b6-d8193f3e46c0"
version = "1.4.3"

...
[[deps.libblastrampoline_jll]]
deps = ["Artifacts", "Libdl", "OpenBLAS_jll"]
uuid = "8e850b90-86db-534c-a0d3-1478176c7d93"
version = "5.1.1+0"
```

The three dots above (...) represents truncated output. First, the `Manifest.toml` presents us a comment saying that it is machine-generated and discouraging editing it directly. Then, there are entries for the Julia version (`julia_version`), `Manifest.toml` format version (`manifest_format`), and project environment hash (`project_hash`). Finally, it proceeds with a TOML array of tables which are the double brackets entries ([[...]]). These entries stands for the dependencies of all packages necessary to create the environment described in the `Project.toml`. Therefore all of the `DataFrames.jl`'s dependencies and its dependencies' dependencies (and so on...) are listed here with their name, UUID, and version.

NOTE: Julia's standard library module do not have a `version` key in the `Manifest.toml` because they are already specified by the Julia version (`julia_version`). This is the case for the `Artifacts` entry in the truncated `Manifest.toml` output above, since it is a module in Julia's standard library.

We can keep adding as many packages as we like with the `add` command. To remove a package you can use the `rm` command in the `Pkg` REPL mode:

```
(folder) pkg> rm DataFrames
  Updating `~/user/folder/Project.toml'
[a93c6f00] - DataFrames v1.4.3
  Updating `~/user/folder/Manifest.toml'
[34da2185] - Compat v4.4.0
[a8cc5b0e] - Crayons v4.1.1
[9a962f9c] - DataAPI v1.13.0
[a93c6f00] - DataFrames v1.4.3
[864edb3b] - DataStructures v0.18.13
[e2d170a0] - DataValueInterfaces v1.0.0
[59287772] - Formatting v0.4.2
```

```
[41ab1584] - InvertedIndices v1.1.0
[82899510] - IteratorInterfaceExtensions v1.0.0
[b964fa9f] - LaTeXStrings v1.3.0
[e1d29d7a] - Missings v1.0.2
[bac558e1] - OrderedCollections v1.4.1
[2dfb63ee] - PooledArrays v1.4.2
[08abe8d2] - PrettyTables v2.2.1
[189a3867] - Reexport v1.2.2
[66db9d55] - SnoopPrecompile v1.0.1
[a2af1166] - SortingAlgorithms v1.1.0
[892a3eda] - StringManipulation v0.3.0
[3783bdb8] - TableTraits v1.0.1
[bd369af6] - Tables v1.10.0
[56f22d72] - Artifacts
[2a0f44e3] - Base64
[ade2ca70] - Dates
[9fa8497b] - Future
[b77e0a4c] - InteractiveUtils
[8f399da3] - Libdl
[37e2e46d] - LinearAlgebra
[56ddb016] - Logging
[d6f4376e] - Markdown
[de0858da] - Printf
[3fa0cd96] - REPL
[9a3f8284] - Random
[ea8e919c] - SHA v0.7.0
[9e88b42a] - Serialization
[6462fe0b] - Sockets
[2f01184e] - SparseArrays
[10745b16] - Statistics
[8dfed614] - Test
[cf7118a7] - UUIDs
[4ec0a83e] - Unicode
[e66e0078] - CompilerSupportLibraries_jll v0.5.2+0
[4536629a] - OpenBLAS_jll v0.3.20+0
[8e850b90] - libblas trampoline_jll v5.1.1+0
```

NOTE: Julia's `Pkg` REPL mode supports autocompletion with `<TAB>`. You can, for example, in the above command start typing `rm DataFrame` and it will autocomplete to `rm DataFrame`.

We can see that `rm DataFrame` undoes `add DataFrame` by removing entries in *both* `Project.toml` and `Manifest.toml`.

Sharing Project Environments

Once you have a project environment with *both* the `Project.toml` and `Manifest.toml` files, you can **share** it with any user to have a **perfectly reproducible project environment**.

Now let's cover the other end of the process. Suppose you received a `Project.toml` and a `Manifest.toml` from someone.

How would you proceed to **instantiate a Julia project environment**?

It is a simple process:

1. Put the `Project.toml` and a `Manifest.toml` files into a folder.
2. Open a Julia REPL in that folder and activate it as a project environment with `]activate`.
3. Instantiate the environment with the `]instantiate` command.

That's it! Once the project environment finished downloading and instantiating the dependencies listed in the `Project.toml` and `Manifest.toml` files, you'll have an exact copy of the project environment sent to you.

NOTE: You can also add `[compat]` bounds in the `Project.toml` to specify which package versions your project environment is compatible with. This is an advanced-user functionality which we will not cover. Take a look at the `Pkg.jl` standard library module documentation on compatibility¹⁵. For people new to Julia, we recommend sharing *both* `Project.toml` and `Manifest.toml` for a fully reproducible environment.

¹⁵ <https://pkgdocs.julialang.org/v1/compatibility/>

4 *DataFrames.jl*

Data comes mostly in a tabular format. By tabular, we mean that the data consists of a table containing rows and columns. Entries within any one column are usually of the same data type, whereas entries within a given row typically have different types. The rows, in practice, denote observations while columns denote variables. For example, we can have a table of TV shows containing the country in which each was produced and our personal rating, see Table 4.1.

name	country	rating
Game of Thrones	United States	8.2
The Crown	England	7.3
Friends	United States	7.8
...

Table 4.1: TV shows.

Here, the dots mean that this could be a very long table and we only show a few rows. While analyzing data, often we come up with interesting questions about the data, also known as *data queries*. For large tables, computers would be able to answer these kinds of questions much quicker than you could do it by hand. Some examples of these so-called *queries* for this data could be:

- Which TV show has the highest rating?
- Which TV shows were produced in the United States?
- Which TV shows were produced in the same country?

But, as a researcher, real science often starts with having multiple tables or data sources. For example, if we also have data from someone else's ratings for the TV shows (Table 4.2):

name	rating
Game of Thrones	7
Friends	6.4
...	...

Table 4.2: Ratings.

Now, questions that we could ask ourselves could be:

- What is Game of Thrones' average rating?
- Who gave the highest rating for Friends?
- What TV shows were rated by you but not by the other person?

In the rest of this chapter, we will show you how you can easily answer these questions in Julia. To do so, we first show why we need a Julia package called `DataFrames.jl`. In the next sections, we show how you can use this package and, finally, we show how to write fast data transformations (Section 4.10).

NOTE: `DataFrames.jl` has some guiding principles¹. Notably, we would like to highlight two of them:

1. Stay **consistent with Julia's Base** module functions.
2. **Minimize the number of functions** `DataFrames.jl` provides.

¹ <https://bkamins.github.io/julialang/2021/05/14/nrow.html>

Those two principles are really powerful because if you have a good grasp of Julia's basic functions, such as `filter`, then you can do powerful operations on tabular data.

This is a benefit over Python's `pandas` or R's `dplyr` which differ more from the core languages.

Let's look at a table of grades like the one in Table 4.3:

name	age	grade_2020
Bob	17	5.0
Sally	18	1.0
Alice	20	8.5
Hank	19	4.0

Table 4.3: Grades for 2020.

Here, the column `name` has type `string`, `age` has type `integer`, and `grade` has type `float`.

So far, this book has only handled Julia's basics. These basics are great for many things, but not for tables. To show that we need more, let's try to store the tabular data in arrays:

```
function grades_array()
    name = ["Bob", "Sally", "Alice", "Hank"]
    age = [17, 18, 20, 19]
    grade_2020 = [5.0, 1.0, 8.5, 4.0]
    (; name, age, grade_2020)
end
```

Now, the data is stored in so-called column-major form, which is cumbersome when we want to get data from a row:

```
function second_row()
    name, age, grade_2020 = grades_array()
    i = 2
    row = (name[i], age[i], grade_2020[i])
end
JDS.second_row()
```

("Sally", 18, 1.0)

Or, if you want to have the grade for Alice, you first need to figure out in what row Alice is:

```
function row_alice()
    names = grades_array().name
    i = findfirst(names .== "Alice")
end
row_alice()
```

3

and then we can get the value:

```
function value_alice()
    grades = grades_array().grade_2020
    i = row_alice()
    grades[i]
end
value_alice()
```

8.5

DataFrames.jl can easily solve these kinds of issues. You can start by loading `DataFrames.jl` with using:

```
using DataFrames
```

With `DataFrames.jl`, we can define a `DataFrame` to hold our tabular data:

```
names = ["Sally", "Bob", "Alice", "Hank"]
grades = [1, 5, 8.5, 4]
df = DataFrame(; name=names, grade_2020=grades)
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

which gives us a variable `df` containing our data in table format.

NOTE: This works, but there is one thing that we need to change straight away. In this example, we defined the variables `name`, `grade_2020` and `df` in global scope. This means that these variables can be accessed and edited from anywhere. If we would continue writing the book like this, we would have a few hundred variables at the end of the book even though the data that we put into the variable `name` should only be accessed via `DataFrame!` The variables `name` and `grade_2020` were never meant to be kept for long! Now, imagine that we would change the contents of `grade_2020` a few times in this book. Given only the book as PDF, it would be near impossible to figure out the contents of the variable by the end.

We can solve this very easily by using functions.

Let's do the same thing as before but now in a function:

```
function grades_2020()
    name = ["Sally", "Bob", "Alice", "Hank"]
    grade_2020 = [1, 5, 8.5, 4]
    DataFrame(; name, grade_2020)
end
grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

Table 4.5: Grades 2020.

Note that `name` and `grade_2020` are destroyed after the function returns, that is, they are only available in the function. There are two other benefits of doing this. First, it is now clear to the reader where `name` and `grade_2020` belong to: they belong to the grades of 2020. Second, it is easy to determine what the output of `grades_2020()` would be at any point in the book. For example, we can now assign the data to a variable `df`:

```
df = grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

Change the contents of `df`:

```
df = DataFrame(name = ["Malice"], grade_2020 = [10])
```

name	grade_2020
Malice	10

And still recover the original data back without any problem:

```
df = grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

Of course, this assumes that the function is not re-defined. We promise to not do that in this book, because it is a bad idea exactly for this reason. Instead of “changing” a function, we will make a new one and give it a clear name.

So, back to the `DataFrames` constructor. As you might have seen, the way to create one is simply to pass vectors as arguments into the `DataFrame` constructor. You can come up with any valid Julia vector and it will work **as long as the vectors have the same length**. Duplicates, Unicode symbols and any sort of numbers are fine:

```
DataFrame(σ = ["a", "a", "a"], δ = [π, π/2, π/3])
```

σ	δ
a	3.141592653589793
a	1.5707963267948966
a	1.0471975511965976

Typically, in your code, you would create a function which wraps around one

or more `DataFrames`' functions. For example, we can make a function to get the grades for one or more names:

```
function grades_2020(names :: Vector{Int})
    df = grades_2020()
    df[names, :]
end
JDS.grades_2020([3, 4])
```

name	grade_2020
Alice	8.5
Hank	4.0

This way of using functions to wrap around basic functionality in programming languages and packages is quite common. Basically, you can think of Julia and `DataFrames.jl` as providers of building blocks. They provide very **generic** building blocks which allow you to build things for your **specific** use case like this `grades` example. By using the blocks, you can make a data analysis script, control a robot or whatever you like to build.

So far, the examples were quite cumbersome, because we had to use indexes. In the next sections, we will show how to load and save data, and many powerful building blocks provided by `DataFrames.jl`.

4.1 Load and Save Files

Having only data inside Julia programs and not being able to load or save it would be very limiting. Therefore, we start by mentioning how to store files to and load files from disk. We focus on CSV, see Section 4.1.1, and Excel, see Section 4.1.2, file formats since those are the most common data storage formats for tabular data.

4.1.1 CSV

Comma-separated values (CSV) files are are very effective way to store tables. CSV files have two advantages over other data storage files. First, it does exactly what the name indicates it does, namely storing values by separating them using commas ,. This acronym is also used as the file extension. So, be sure that you save your files using the ".csv" extension such as "myfile.csv." To demonstrate how a CSV file looks, we can add the `CSV.jl`² package using the `Pkg` REPL mode (Section 3.5.4):

```
julia> ]
```

² <http://csv.juliadata.org/latest/>

```
pkg> add CSV
```

and load it via:

```
using CSV
```

We can now use our previous data:

```
grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

and read it from a file after writing it:

```
function write_grades_csv()
    path = "grades.csv"
    CSV.write(path, grades_2020())
end
```

```
path = write_grades_csv()
read(path, String)
```

```
name,grade_2020
Sally,1.0
Bob,5.0
Alice,8.5
Hank,4.0
```

Here, we also see the second benefit of CSV data format: the data can be read by using a simple text editor. This differs from many alternative data formats which require proprietary software, e.g. Excel.

This works wonders, but what if our data **contains commas**, as values? If we were to naively write data with commas, it would make the files very hard to convert back to a table. Luckily, `CSV.jl` handles this for us automatically. Consider the following data with commas ,:

```
function grades_with_commas()
    df = grades_2020()
```

```

df[3, :name] = "Alice,"
df
end
grades_with_commas()

```

name	grade_2020
Sally	1.0
Bob	5.0
Alice,	8.5
Hank	4.0

Table 4.12: Grades with commas.

If we write this, we get:

```

function write_comma_csv()
    path = "grades-commas.csv"
    CSV.write(path, grades_with_commas())
end
path = write_comma_csv()
read(path, String)

```

```

name,grade_2020
Sally,1.0
Bob,5.0
"Alice,",8.5
Hank,4.0

```

So, `CSV.jl` adds quotation marks " around the comma-containing values. Another common way to solve this problem is to write the data to a tab-separated values (TSV) file format. This assumes that the data doesn't contain tabs, which holds in most cases.

Also, note that TSV files can also be read using a simple text editor, and these files use the ".tsv" extension.

```

function write_comma_tsv()
    path = "grades-comma.tsv"
    CSV.write(path, grades_with_commas(); delim='\t')
end
read(write_comma_tsv(), String)

```

```

name      grade_2020
Sally     1.0
Bob      5.0
Alice,   8.5
Hank     4.0

```

Text file formats like CSV and TSV files can also be found that use other delimiters, such as semicolons ";" spaces "," or even something as unusual as "π."

```
function write_space_separated()
    path = "grades-space-separated.csv"
    CSV.write(path, grades_2020(); delim=' ')
end
read(write_space_separated(), String)
```

```
name grade_2020
Sally 1.0
Bob 5.0
Alice 8.5
Hank 4.0
```

By convention, it's still best to give files with special delimiters, such as ";" the ".csv" extension.

Loading CSV files using `CSV.jl` is done in a similar way. You can use `CSV.read` and specify in what kind of format you want the output. We specify a `DataFrame`.

```
path = write_grades_csv()
CSV.read(path, DataFrame)
```

	name	grade_2020
	Sally	1.0
	Bob	5.0
	Alice	8.5
	Hank	4.0

Conveniently, `CSV.jl` will automatically infer column types for us:

```
path = write_grades_csv()
df = CSV.read(path, DataFrame)
```

4×2 DataFrame		
Row	name	grade_2020
	String	Float64
1	Sally	1.0
2	Bob	5.0
3	Alice	8.5
4	Hank	4.0

It works even for far more complex data:

```
my_data = """
    a,b,c,d,e
    Kim,2018-02-03,3,4.0,2018-02-03T10:00
"""
path = "my_data.csv"
write(path, my_data)
df = CSV.read(path, DataFrame)
```

1×5 DataFrame					
Row	a	b	c	d	e
	String3	Date	Int64	Float64	DateTime
1	Kim	2018-02-03	3	4.0	2018-02-03T10:00:00

These CSV basics should cover most use cases. For more information, see the `CSV.jl` documentation³ and especially the `CSV.File` constructor docstring⁴.

³ <https://csv.juliadata.org/stable>

⁴ <https://csv.juliadata.org/stable/#CSV.File>

4.1.2 Excel

There are multiple Julia packages to read Excel files. In this book, we will only look at `XLSX.jl`⁵, because it is the most actively maintained package in the Julia ecosystem that deals with Excel data. As a second benefit, `XLSX.jl` is written in pure Julia, which makes it easy for us to inspect and understand what's going on under the hood.

⁵ <https://github.com/felipenoris/XLSX.jl>

Load `XLSX.jl` via

```
using XLSX:
    eachtablerow,
    readxlsx,
    writetable
```

To write files, we define a little helper function for data and column names:

```
function write_xlsx(name, df::DataFrame)
    path = "$name.xlsx"
    data = collect(eachcol(df))
    cols = names(df)
    writetable(path, data, cols)
end
```

Now, we can easily write the grades to an Excel file:

```
function write_grades_xlsx()
    path = "grades"
```

```

    write_xlsx(path, grades_2020())
    "$path.xlsx"
end

```

When reading it back, we will see that `XLSX.jl` puts the data in a `XLSXFile` type and we can access the desired `sheet` much like a `Dict`:

```

path = write_grades_xlsx()
xf = readxlsx(path)

```

```

XLSXFile("grades.xlsx") containing 1 Worksheet
    sheetname size      range
-----
Sheet1  5x2          A1:B5

```

```

xf = readxlsx(write_grades_xlsx())
sheet = xf["Sheet1"]
eachtablerow(sheet) |> DataFrame

```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

Notice that we cover just the basics of `XLSX.jl` but more powerful usage and customizations are available. For more information and options, see the `XLSX.jl` documentation⁶.

⁶ <https://felipenoris.github.io/XLSX.jl/stable/>

4.2 Index and Summarize

Let's go back to the example `grades_2020()` data defined before:

```
grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

To retrieve a **vector** for `name`, we can access the `DataFrame` with the `..`, as we did

previously with `structs` in Section 3:

```
function names_grades1()
    df = grades_2020()
    df.name
end
JDS.names_grades1()
```

["Sally", "Bob", "Alice", "Hank"]

or we can index a `DataFrame` much like an `Array` with symbols and special characters. The **second index is the column indexing**:

```
function names_grades2()
    df = grades_2020()
    df[!, :name]
end
JDS.names_grades2()
```

["Sally", "Bob", "Alice", "Hank"]

Note that `df.name` is exactly the same as `df[!, :name]`, which you can verify yourself by doing:

```
julia> df = DataFrame(id=[1]);
julia> @edit df.name
```

In both cases, it gives you the column `:name`. There also exists `df[:, :name]` which copies the column `:name`. In most cases, `df[!, :name]` is the best bet since it is more versatile and does an in-place modification.

For any **row**, say the second row, we can use the **first index as row indexing**:

```
df = grades_2020()
df[2, :]
```

name	grade_2020
Bob	5.0

or create a function to give us any row `i` we want:

```
function grade_2020(i::Int)
    df = grades_2020()
```

```
df[i, :]
end
JDS.grade_2020(2)
```

name	grade_2020
Bob	5.0

We can also get only `names` for the first 2 rows using **slicing** (again similar to an `Array`):

```
grades_indexing(df) = df[1:2, :name]
JDS.grades_indexing(grades_2020())
```

```
["Sally", "Bob"]
```

If we assume that all names in the table are unique, we can also write a function to obtain the grade for a person via their `name`. To do so, we convert the table back to one of Julia's basic data structures (see Section 3.3) which is capable of creating mappings, namely `Dicts`:

```
function grade_2020(name::String)
    df = grades_2020()
    dic = Dict(zip(df.name, df.grade_2020))
    dic[name]
end
grade_2020("Bob")
```

```
5.0
```

which works because `zip` loops through `df.name` and `df.grade_2020` at the same time like a “zipper”:

```
df = grades_2020()
collect(zip(df.name, df.grade_2020))
```

```
("Sally", 1.0)
```

```
("Bob", 5.0)
```

```
("Alice", 8.5)
```

("Hank", 4.0)

However, converting a `DataFrame` to a `Dict` is only useful when the elements are unique. Generally that is not the case and that's why we need to learn how to filter a `DataFrame`.

4.3 Filter and Subset

There are two ways to remove rows from a `DataFrame`, one is `filter` (Section 4.3.1) and the other is `subset` (Section 4.3.2). `filter` was added earlier to `DataFrames.jl`, is more powerful and more consistent with syntax from Julia base, so that is why we start discussing `filter` first. `subset` is newer and often more convenient.

4.3.1 Filter

From this point on, we start to get into the more powerful features of `DataFrames`.
jl. To do this, we need to learn some functions, such as `select` and `filter`. But don't worry! It might be a relief to know that the **general design goal of `DataFrames.jl` is to keep the number of functions that a user has to learn to a minimum**⁷.

Like before, we resume from the `grades_2020`:

<code>grades_2020()</code>

⁷ According to Bogumił Kamiński (lead developer and maintainer of `DataFrames.jl` on Discourse (<https://discourse.julialang.org/t/pull-dataframes-columns-to-the-front/60327/5>).

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

We can filter rows by using `filter(source => f::Function, df)`. Note how this function is very similar to the function `filter(f::Function, V::Vector)` from Julia Base module. This is because `DataFrames.jl` uses **multiple dispatch** (see Section 2.3.3) to define a new method of `filter` that accepts a `DataFrame` as argument.

At first sight, defining and working with a function `f` for filtering can be a bit difficult to use in practice. Hold tight, that effort is well-paid, since **it is a very powerful way of filtering data**. As a simple example, we can create a function `equals_alice` that checks whether its input equals "Alice":

```
equals_alice(name::String) = name == "Alice"
JDS.equals_alice("Bob")
```

false

```
equals_alice("Alice")
```

true

Equipped with such a function, we can use it as our function `f` to filter out all the rows for which `name` equals “Alice”:

```
filter(:name => equals_alice, grades_2020())
```

name	grade_2020
Alice	8.5

Note that this doesn’t only work for `DataFrames`, but also for vectors:

```
filter(equals_alice, ["Alice", "Bob", "Dave"])
```

["Alice"]

We can make it a bit less verbose by using an **anonymous function** (see Section 3.2.4):

```
filter(n -> n == "Alice", ["Alice", "Bob", "Dave"])
```

["Alice"]

which we can also use on `grades_2020`:

```
filter(:name => n -> n == "Alice", grades_2020())
```

name	grade_2020
Alice	8.5

To recap, this function call can be read as “for each element in the column `:name`, let’s call the element `n`, check whether `n` equals Alice.” For some people, this is still too verbose. Luckily, Julia has added a *partial function application* of `==`. The details are not important – just know that you can use it just like any other function:

```
filter(:name => ==(Alice), grades_2020())
```

name	grade_2020
Alice	8.5

To get all the rows which are *not* Alice, `==` (equality) can be replaced by `!=` (inequality) in all previous examples:

```
filter(:name => !=(Alice), grades_2020())
```

name	grade_2020
Sally	1.0
Bob	5.0
Hank	4.0

Now, to show **why functions are so powerful**, we can come up with a slightly more complex filter. In this filter, we want to have the people whose names start with A or B **and** have a grade above 6:

```
function complex_filter(name, grade)::Bool
    interesting_name = startswith(name, 'A') || startswith(name, 'B')
    interesting_grade = 6 < grade
    interesting_name && interesting_grade
end
```

```
filter([:name, :grade_2020] => complex_filter, grades_2020())
```

name	grade_2020
Alice	8.5

4.3.2 Subset

The `subset` function was added to make it easier to work with missing values (Section 4.9). In contrast to `filter`, `subset` works on complete columns instead

of rows or single values. If we want to use our earlier defined functions, we should wrap it inside `ByRow`:

```
subset(grades_2020(), :name => ByRow(equals_alice))
```

name	grade_2020
Alice	8.5

Also note that the `DataFrame` is now the first argument `subset(df, args...)`, whereas in `filter` it was the second one `filter(f, df)`. The reason for this is that Julia defines `filter` as `filter(f, V::Vector)` and `DataFrames.jl` chose to maintain consistency with existing Julia functions that were extended to `DataFrames` types by multiple dispatch.

NOTE: Most of native `DataFrames.jl` functions, which `subset` belongs to, have a **consistent function signature that always takes a `DataFrame` as first argument**.

Just like with `filter`, we can also use anonymous functions inside `subset`:

```
subset(grades_2020(), :name => ByRow(name -> name == "Alice"))
```

name	grade_2020
Alice	8.5

Or, the partial function application for `==`:

```
subset(grades_2020(), :name => ByRow==( "Alice"))
```

name	grade_2020
Alice	8.5

Ultimately, let's show the real power of `subset`. First, we create a dataset with some missing values:

```
function salaries()
    names = ["John", "Hank", "Karen", "Zed"]
    salary = [1_900, 2_800, 2_800, missing]
    DataFrame(; names, salary)
end
salaries()
```

names	salary
John	1900
Hank	2800
Karen	2800
Zed	missing

Table 4.27: Salaries.

This data is about a plausible situation where you want to figure out your colleagues' salaries, and haven't figured it out for Zed yet. Even though we don't want to encourage these practices, we suspect it is an interesting example. Suppose we want to know who earns more than 2000. If we use `filter`, without taking the `missing` values into account, it will fail:

```
filter(:salary => >(2_000), salaries())
```

```
TypeError: non-boolean (Missing) used in boolean context
Stacktrace:
[1] (::DataFrames.var"#103#104"{Base.Fix2{typeof(>), Int64}})(x::Missing)
 @ DataFrames ~/.julia/packages/DataFrames/LteEl/src/abstractdataframe/
 ↪abstractdataframe.jl:1204
...
...
```

subset will also fail, but it will fortunately point us towards an easy solution:

```
subset(salaries(), :salary => ByRow(>(2_000)))
```

```
ArgumentError: missing was returned in condition number 1 but only true or false
 ↪ are allowed; pass skipmissing=true to skip missing values
Stacktrace:
[1] _and(x::Missing)
 @ DataFrames ~/.julia/packages/DataFrames/LteEl/src/abstractdataframe/subset
 ↪.jl:11
...
...
```

So, we just need to pass the keyword argument `skipmissing=true`:

```
subset(salaries(), :salary => ByRow(>(2_000)); skipmissing=true)
```

names	salary
Hank	2800
Karen	2800

4.4 Select

Whereas `filter` removes rows, `select` removes columns. However, `select` is much more versatile than just removing columns, as we will discuss in this section. First, let's create a dataset with multiple columns:

```
function responses()
    id = [1, 2]
    q1 = [28, 61]
    q2 = [:us, :fr]
    q3 = ["F", "B"]
    q4 = ["B", "C"]
    q5 = ["A", "E"]
    DataFrame(; id, q1, q2, q3, q4, q5)
end
responses()
```

	id	q1	q2	q3	q4	q5
1	28	us		F	B	A
2	61	fr		B	C	E

Table 4.29: Responses.

Here, the data represents answers for five questions (`q1`, `q2`, ..., `q5`) in a given questionnaire. We will start by “selecting” a few columns from this dataset. As usual, we use **symbols** to specify columns:

```
select(responses(), :id, :q1)
```

	id	q1
1	28	
2	61	

We can also use **strings** if we want:

```
select(responses(), "id", "q1", "q2")
```

	id	q1	q2
1	28	us	
2	61	fr	

Additionally, we can use **Regular Expressions** with Julia's regex string literal⁸. A string literal in Julia is a prefix that you use while constructing a `String`. For `s`

⁸ <https://docs.julialang.org/en/v1/manual/strings/#man-regex-literal>

example, the regex string literal can be created with `r"..."` where ... is the Regular Expression. For example, suppose you only want to select the columns that start with q:

```
select(responses(), r"^\q")
```

	q1	q2	q3	q4	q5
28	us	F	B	A	
61	fr	B	C	E	

NOTE: We won't cover regular expressions in this book, but you are encouraged to learn about them. To build and test regular expressions interactively, we advise to use online tools for them such as <https://regex101.com/>.

To select **everything except one or more columns**, use `Not` with either a single column:

```
select(responses(), Not(:q5))
```

	id	q1	q2	q3	q4
1	28	us	F	B	
2	61	fr	B	C	

Or, with multiple columns:

```
select(responses(), Not([:q4, :q5]))
```

	id	q1	q2	q3
1	28	us	F	
2	61	fr	B	

It's also fine to mix and match columns that we want to preserve with columns that we do `Not` want to select:

```
select(responses(), :q5, Not(:q5))
```

	q5	id	q1	q2	q3	q4
A	1	28	us	F	B	
E	2	61	fr	B	C	

Note how `q5` is now the first column in the `DataFrame` returned by `select`. There is a more clever way to achieve the same using `:.` The colon `:` can be thought of as “all the columns that we didn’t include yet.” For example:

```
select(responses(), :q5, :)
```

	q5	id	q1	q2	q3	q4
A	1	28	us	F	B	
E	2	61	fr	B	C	

Or, to put `q5` at the second position⁹:

```
select(responses(), 1, :q5, :)
```

	id	q5	q1	q2	q3	q4
1	A	28	us	F	B	
2	E	61	fr	B	C	

⁹ thanks to Sudete on Discourse (<https://discourse.julialang.org/t/pull-dataframes-columns-to-the-front/60327/4>) for this suggestion.

NOTE: As you might have observed there are several ways to select a column. These are known as *column selectors*¹⁰.

We can use:

- Symbol: `select(df, :col)`
- String: `select(df, "col")`
- Integer: `select(df, 1)`
- RegEx: `select(df, r"RegEx")`

¹⁰ <https://bkamins.github.io/julialang/2021/02/06/colsel.html>

Even renaming columns is possible via `select` using the `source => target` pair syntax:

```
select(responses(), 1 => "participant", :q1 => "age", :q2 => "nationality")
```

	participant	age	nationality
1	28		us
2	61		fr

Additionally, thanks to the “splat” operator `...` (see Section 3.3.11), we can also write:

```
renames = (1 => "participant", :q1 => "age", :q2 => "nationality")
select(responses(), renames...)
```

participant	age	nationality
1	28	us
2	61	fr

4.5 Types and Categorical Data

As discussed in Section 4.1, `csv.jl` will do its best to guess what kind of types your data have as columns. However, this won't always work perfectly. In this section, we show why suitable types are important and we fix wrong data types. To be more clear about the types, we show the text output for `DataFrames` instead of a pretty-formatted table. In this section, we work with the following dataset:

```
function wrong_types()
    id = 1:4
    date = ["28-01-2018", "03-04-2019", "01-08-2018", "22-11-2020"]
    age = ["adolescent", "adult", "infant", "adult"]
    DataFrame(; id, date, age)
end
wrong_types()
```

4x3 DataFrame		
Row	id	date
	Int64	String
1	1	28-01-2018
2	2	03-04-2019
3	3	01-08-2018
4	4	22-11-2020

Because the date column has the wrong type, sorting won't work correctly:

```
sort(wrong_types(), :date)
```

4x3 DataFrame		
Row	id	date
	Int64	String
1	3	01-08-2018
2	2	03-04-2019
3	4	22-11-2020
4	1	28-01-2018

To fix the sorting, we can use the `Date` module from Julia's standard library as described in Section 3.5.1:

```
function fix_date_column(df::DataFrame)
    strings2dates(dates::Vector) = Date.(dates, dateformat"dd-mm-yyyy")
    dates = strings2dates(df[:, :date])
    df[:, :date] = dates
    df
end
fix_date_column(wrong_types())
```

4x3 DataFrame			
Row	id	date	age
	Int64	Date	String
1	1	2018-01-28	adolescent
2	2	2019-04-03	adult
3	3	2018-08-01	infant
4	4	2020-11-22	adult

Now, sorting will work as intended:

```
df = fix_date_column(wrong_types())
sort(df, :date)
```

4x3 DataFrame			
Row	id	date	age
	Int64	Date	String
1	1	2018-01-28	adolescent
2	3	2018-08-01	infant
3	2	2019-04-03	adult
4	4	2020-11-22	adult

For the age column, we have a similar problem:

```
sort(wrong_types(), :age)
```

4x3 DataFrame			
Row	id	date	age
	Int64	String	String
1	1	28-01-2018	adolescent
2	2	03-04-2019	adult
3	4	22-11-2020	adult
4	3	01-08-2018	infant

This isn't right, because an infant is younger than adults and adolescents. The solution for this issue and any sort of categorical data is to use CategoricalArrays ↵.jl:

4.5.1 *CategoricalArrays.jl*

```
using CategoricalArrays
```

With the `CategoricalArrays.jl` package, we can add levels that represent the ordering of our categorical variable to our data:

```
function fix_age_column(df)
    levels = ["infant", "adolescent", "adult"]
    ages = categorical(df[!, :age]; levels, ordered=true)
    df[!, :age] = ages
    df
end
fix_age_column(wrong_types())
```

4x3 DataFrame			
Row	id	date	age
	Int64	String	Cat...
1	1	28-01-2018	adolescent
2	2	03-04-2019	adult
3	3	01-08-2018	infant
4	4	22-11-2020	adult

NOTE: Also note that we are passing the argument `ordered=true` which tells `CategoricalArrays.jl`'s `categorical` function that our categorical data is “ordered.” Without this any type of sorting or bigger/smaller comparisons would not be possible.

Now, we can sort the data correctly on the age column:

```
df = fix_age_column(wrong_types())
sort(df, :age)
```

4x3 DataFrame			
Row	id	date	age
	Int64	String	Cat...
1	3	01-08-2018	infant
2	1	28-01-2018	adolescent
3	2	03-04-2019	adult
4	4	22-11-2020	adult

Because we have defined convenient functions, we can now define our fixed data by just performing the function calls:

```
function correct_types()
    df = wrong_types()
    df = fix_date_column(df)
    df = fix_age_column(df)
end
correct_types()
```

4x3 DataFrame			
Row	id	date	age
	Int64	Date	Cat...
1	1	2018-01-28	adolescent
2	2	2019-04-03	adult
3	3	2018-08-01	infant
4	4	2020-11-22	adult

Since age in our data is ordinal (`ordered=true`), we can properly compare categories of age:

```
df = correct_types()
a = df[1, :age]
b = df[2, :age]
a < b
```

true

which would give wrong comparisons if the element type were strings:

```
"infant" < "adult"
```

false

4.6 Join

At the start of this chapter, we showed multiple tables and raised questions also related to multiple tables. However, we haven't talked about combining tables yet, which we will do in this section. In `DataFrames.jl`, combining multiple tables is done via *joins*. Joins are extremely powerful, but it might take a while to wrap your head around them. It is not necessary to know the joins below by heart, because the `DataFrames.jl` documentation¹¹, along with this book,

¹¹ <https://DataFrames.juliadata.org/stable/man/joins/>

will list them for you. But, it's essential to know that joins exist. If you ever find yourself looping over rows in a `DataFrame` and comparing it with other data, then you probably need one of the joins below.

In Section 4, we've introduced the grades for 2020 with `grades_2020`:

```
grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

Now, we're going to combine `grades_2020` with grades from 2021:

```
grades_2021()
```

name	grade_2021
Bob 2	9.5
Sally	9.5
Hank	6.0

To do this, we are going to use joins. `DataFrames.jl` lists no less than seven kinds of join. This might seem daunting at first, but hang on because they are all useful and we will showcase them all.

4.6.1 *innerjoin*

This first is `innerjoin`. Suppose that we have two datasets A and B with respectively columns $A_{-1}, A_{-2}, \dots, A_{-n}$ and $B_{-1}, B_{-2}, \dots, B_{-m}$ and one of the columns has the same name, say A_{-1} and B_{-1} are both called `:id`. Then, the inner join on `:id` will go through all the elements in A_{-1} and compare it to the elements in B_{-1} . If the elements are **the same**, then it will add all the information from A_{-2}, \dots, A_{-n} and B_{-2}, \dots, B_{-m} after the `:id` column.

Okay, so no worries if you didn't get this description. The result on the grades datasets looks like this:

```
innerjoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0

Note that only “Sally” and “Hank” are in both datasets. The name *inner* join makes sense since, in mathematics, the *set intersection* is defined by “all elements in A , that are also in B , or all elements in B that are also in A .”

4.6.2 *outerjoin*

Maybe you’re now thinking “aha, if we have an *inner*, then we probably also have an *outer*.” Yes, you’ve guessed right!

The `outerjoin` is much less strict than the `innerjoin` and just takes any row it can find which contains a name in **at least one of the datasets**:

```
outerjoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	missing
Alice	8.5	missing
Bob 2	missing	9.5

So, this method can create `missing` data even though none of the original datasets had missing values.

4.6.3 *crossjoin*

We can get even more `missing` data if we use the `crossjoin`. This gives the **Cartesian product of the rows**, which is basically multiplication of rows, that is, for every row create a combination with any other row:

```
crossjoin(grades_2020(), grades_2021(); on=:id)
```

```
MethodError: no method matching crossjoin(::DataFrame, ::DataFrame; on::Symbol)
```

```
Closest candidates are:
```

```
crossjoin(::DataFrames.AbstractDataFrame, ::DataFrames.AbstractDataFrame;
    ↪ makeunique) got unsupported keyword argument "on"
@ DataFrames ~/julia/packages/DataFrames/LteEl/src/join/composer.jl:1555
```

```

crossjoin(::DataFrames.AbstractDataFrame, ::DataFrames.AbstractDataFrame, !
    ↪Matched::DataFrames.AbstractDataFrame...; makeunique) got unsupported
    ↪keyword argument "on"
@ DataFrames ~/julia/packages/DataFrames/LteEl/src/join/composer.jl:1577
...

```

Oops. Since `crossjoin` doesn't take the elements in the row into account, we don't need to specify the `on` argument for what we want to join:

```
crossjoin(grades_2020(), grades_2021())
```

`ArgumentError: Duplicate variable names: :name. Pass makeunique=true to make`
 `↪them unique using a suffix automatically.`

Stacktrace:

```

[1] add_names(ind::DataFrames.Index, add_ind::DataFrames.Index; makeunique::
    ↪Bool)
    @ DataFrames ~/julia/packages/DataFrames/LteEl/src/other/index.jl:442
[2] add_names
    @ ~/julia/packages/DataFrames/LteEl/src/other/index.jl:427 [inlined]
[3] merge!(x::DataFrames.Index, y::DataFrames.Index; makeunique::Bool)
    @ DataFrames ~/julia/packages/DataFrames/LteEl/src/other/index.jl:132
[4] merge!
    @ ~/julia/packages/DataFrames/LteEl/src/other/index.jl:131 [inlined]
[5] #merge#12
...

```

Oops again. This is a very common error with `DataFrames` and `joins`. The tables for the 2020 and 2021 grades have a duplicate column name, namely `:name`. Like before, the error that `DataFrames.jl` outputs shows a simple suggestion that might fix the issue. We can just pass `makeunique=true` to solve this:

```
crossjoin(grades_2020(), grades_2021(); makeunique=true)
```

name	grade_2020	name_1	grade_2021
Sally	1.0	Bob 2	9.5
Sally	1.0	Sally	9.5
Sally	1.0	Hank	6.0
Bob	5.0	Bob 2	9.5
Bob	5.0	Sally	9.5
Bob	5.0	Hank	6.0
Alice	8.5	Bob 2	9.5
Alice	8.5	Sally	9.5
Alice	8.5	Hank	6.0
Hank	4.0	Bob 2	9.5
Hank	4.0	Sally	9.5
Hank	4.0	Hank	6.0

So, now, we have one row for each grade from everyone in grades 2020 and grades 2021 datasets. For direct queries, such as “who has the highest grade?” the Cartesian product is usually not so useful, but for “statistical” queries, it can be.

4.6.4 *leftjoin* and *rightjoin*

More useful for scientific data projects are the `leftjoin` and `rightjoin`. The left join gives all the elements in the *left* DataFrame:

```
leftjoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	missing
Alice	8.5	missing

Here, grades for “Bob” and “Alice” were `missing` in the grades 2021 table, so that’s why there are also `missing` elements. The right join does sort of the opposite:

```
rightjoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob 2	missing	9.5

Now, grades in 2020 are missing.

Note that `leftjoin(A, B) != rightjoin(B, A)`, because the order of the columns will differ. For example, compare the output below to the previous output:

```
leftjoin(grades_2021(), grades_2020(); on=:name)
```

name	grade_2021	grade_2020
Sally	9.5	1.0
Hank	6.0	4.0
Bob 2	9.5	missing

4.6.5 *semijoin and antijoin*

Lastly, we have the `semijoin` and `antijoin`.

The semi join is even more restrictive than the inner join. It returns **only the elements from the left DataFrame which are in both DataFrames**. This is like a combination of the left join with the inner join.

```
semijoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020
Sally	1.0
Hank	4.0

The opposite of the semi join is the anti join. It returns **only the elements from the left DataFrame which are *not* in the right DataFrame**:

```
antijoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020
Bob	5.0
Alice	8.5

4.7 Variable Transformations

In Section 4.3.1, we saw that `filter` works by taking one or more source columns and filtering it by applying a “filtering” function. To recap, here’s an example of filter using the `source => f::Function` syntax: `filter(:name => name == "Alice", df)`.

In Section 4.4, we saw that `select` can take one or more source columns and put it into one or more target columns `source => target`. Also to recap here’s an example: `select(df, :name => :people_names)`.

In this section, we discuss how to **transform** variables, that is, how to **modify data**. In `DataFrames.jl`, the syntax is `source => transformation => target`.

Like before, we use the `grades_2020` dataset:

```
function grades_2020()
    name = ["Sally", "Bob", "Alice", "Hank"]
    grade_2020 = [1, 5, 8.5, 4]
    DataFrame(; name, grade_2020)
```

```
end
grades_2020()
```

name	grade_2020
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0

Suppose we want to increase all the grades in `grades_2020` by 1. First, we define a function that takes as argument a vector of data and returns all of its elements increased by 1. Then we use the `transform` function from `DataFrames.jl` that, like all native `DataFrames.jl`'s functions, takes a `DataFrame` as first argument followed by the transformation syntax:

```
plus_one(grades) = grades .+ 1
transform(grades_2020(), :grade_2020 => plus_one)
```

name	grade_2020	grade_2020_plus_one
Sally	1.0	2.0
Bob	5.0	6.0
Alice	8.5	9.5
Hank	4.0	5.0

Here, the `plus_one` function receives the whole `:grade_2020` column. That is the reason why we've added the broadcasting "dot" `.` before the plus `+` operator. For a recap on broadcasting please see Section 3.3.1.

Like we said above, the `DataFrames.jl` minilanguage is always `source => transformation ↪ => target`. So, if we want to keep the naming of the `target` column in the output, we can do:

```
transform(grades_2020(), :grade_2020 => plus_one => :grade_2020)
```

name	grade_2020
Sally	2.0
Bob	6.0
Alice	9.5
Hank	5.0

We can also use the keyword argument `renamecols=false`:

```
transform(grades_2020(), :grade_2020 => plus_one; renamecols=false)
```

name	grade_2020
Sally	2.0
Bob	6.0
Alice	9.5
Hank	5.0

The same transformation can also be written with `select` as follows:

```
select(grades_2020(), :, :grade_2020 => plus_one => :grade_2020)
```

name	grade_2020
Sally	2.0
Bob	6.0
Alice	9.5
Hank	5.0

where the `:` means “select all the columns” as described in Section 4.4. Alternatively, you can also use Julia’s broadcasting and modify the column `grade_2020` by accessing it with `df.grade_2020`:

```
df = grades_2020()
df.grade_2020 = plus_one.(df.grade_2020)
df
```

name	grade_2020
Sally	2.0
Bob	6.0
Alice	9.5
Hank	5.0

But, although the last example is easier since it builds on more native Julia operations, **we strongly advise to use the functions provided by `DataFrames.jl` in most cases because they are more capable and easier to work with.**

4.7.1 Multiple Transformations

To show how to transform two columns at the same time, we use the left joined data from Section 4.6:

```
leftjoined = leftjoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	missing
Alice	8.5	missing

With this, we can add a column saying whether someone was approved by the criterion that one of their grades was above 5.5:

```
pass(A, B) = [5.5 < a || 5.5 < b for (a, b) in zip(A, B)]
transform(leftjoined, [:grade_2020, :grade_2021] => pass; renamemcols=false)
```

name	grade_2020	grade_2021	grade_2020_grade_2021
Sally	1.0	9.5	true
Hank	4.0	6.0	true
Bob	5.0	missing	missing
Alice	8.5	missing	true

We can clean up the outcome and put the logic in a function to get a list of all the approved students:

```
function only_pass()
    leftjoined = leftjoin(grades_2020(), grades_2021(); on=:name)
    pass(A, B) = [5.5 < a || 5.5 < b for (a, b) in zip(A, B)]
    leftjoined = transform(leftjoined, [:grade_2020, :grade_2021] => pass => :
        ↪pass)
    passed = subset(leftjoined, :pass; skipmissing=true)
    return passed.name
end
only_pass()
```

```
["Sally", "Hank", "Alice"]
```

4.8 Groupby and Combine

In the R programming language, Wickham (2011) has popularized the so-called split-apply-combine strategy for data transformations. In essence, this strategy **splits** a dataset into distinct groups, **applies** one or more functions to each group, and then **combines** the result. `DataFrames.jl` fully supports split-apply-combine. We will use the student grades example like before. Suppose that we want to know each student's mean grade:

```
function all_grades()
```

```

df1 = grades_2020()
df1 = select(df1, :name, :grade_2020 => :grade)
df2 = grades_2021()
df2 = select(df2, :name, :grade_2021 => :grade)
rename_bob2(data_col) = replace.(data_col, "Bob 2" => "Bob")
df2 = transform(df2, :name => rename_bob2 => :name)
return vcat(df1, df2)
end
all_grades()

```

	name	grade
	Sally	1.0
	Bob	5.0
	Alice	8.5
	Hank	4.0
	Bob	9.5
	Sally	9.5
	Hank	6.0

The strategy is to **split** the dataset into distinct students, **apply** the mean function to each student, and **combine** the result.

The split is called `groupby` and we give as second argument the column ID that we want to split the dataset into:

```
groupby(all_grades(), :name)
```

GroupedDataFrame with 4 groups based on key: name

Group 1 (2 rows): name = "Sally"

Row	name	grade
1	Sally	1.0
2	Sally	9.5

Group 2 (2 rows): name = "Bob"

Row	name	grade
1	Bob	5.0
2	Bob	9.5

Group 3 (1 row): name = "Alice"

Row	name	grade
1	Alice	8.5

Group 4 (2 rows): name = "Hank"

Row	name	grade
1	Hank	4.0

1	Hank	4.0
2	Hank	6.0

We apply the `mean` function from Julia's standard library `Statistics` module:

```
using Statistics
```

To apply this function, use the `combine` function:

```
gdf = groupby(all_grades(), :name)
combine(gdf, :grade => mean)
```

name	grade_mean
Sally	5.25
Bob	7.25
Alice	8.5
Hank	5.0

Imagine having to do this without the `groupby` and `combine` functions. We would need to loop over our data to split it up into groups, then loop over each split to apply a function, **and** finally loop over each group to gather the final result. Therefore, the split-apply-combine technique is a great one to know.

4.8.1 Multiple Source Columns

But what if we want to apply a function to multiple columns of our dataset?

```
group = [:A, :A, :B, :B]
X = 1:4
Y = 5:8
df = DataFrame(; group, X, Y)
```

group	X	Y
A	1	5
A	2	6
B	3	7
B	4	8

This is accomplished in a similar manner:

```
gdf = groupby(df, :group)
combine(gdf, [:X, :Y] .-> mean; renamecols=false)
```

group	X	Y
A	1.5	5.5
B	3.5	7.5

Note that we've used the dot `.` operator before the right arrow `=>` to indicate that the `mean` has to be applied to multiple source columns `[:X, :Y]`.

To use composable functions, a simple way is to create a function that does the intended composable transformations. For instance, for a series of values, let's first take the `mean` followed by `round` to a whole number (also known as an integer `Int`):

```
gdf = groupby(df, :group)
rounded_mean(data_col) = round(Int, mean(data_col))
combine(gdf, [:X, :Y] .=> rounded_mean; renamecols=false)
```

group	X	Y
A	2	6
B	4	8

4.9 Missing Data

Let's dive into how to **handle missing values** in `DataFrames.jl`. We'll cover **three** main approaches for dealing with missing data:

1. **filtering missing** values with `ismissing` and `dropmissing`
2. **filling or replacing missing** values with `coalesce`
3. **skipping over missing** values with `skipmissing`

First, we need a `DataFrame` filled with missing values to showcase these approaches:

```
df_missing = DataFrame();
name=[missing, "Sally", "Alice", "Hank"],
age=[17, missing, 20, 19],
grade_2020=[5.0, 1.0, missing, 4.0],
)
```

name	age	grade_2020
missing	17	5.0
Sally	missing	1.0
Alice	20	missing
Hank	19	4.0

This is the same `DataFrame` from Section 4 but with some `missing` values added.

4.9.1 Missing type

Some languages have several types to represent missing values. One such example is R which uses `NA`, `NA_integer_`, `NA_real_`, `NA_character_`, and `NA_complex_`. Julia, on the contrary, has **only one**: `Missing`.

```
typeof(missing)
```

Missing

As you can see `missing` is an instance of the type `Missing`.

NOTE: In the Julia Style Guide¹², there's a guidance to use camel case for types and modules (see Section 8.2).

¹² <https://docs.julialang.org/en/v1/manual/style-guide/>

The first thing we need to cover for `missing` values is that they **propagate through several operations**. For example, addition, subtraction, multiplication, and division:

```
missing + 1
```

missing

```
missing - 1
```

missing

```
missing * 1
```

missing

```
missing / 1
```

missing

They also propagate **through equality and comparison operators**:

```
missing == 1
```

missing

missing == missing

missing

missing > 1

missing

missing > missing

missing

That's why we need to be very cautious when comparing and testing equalities in the presence of `missing` values. **For equality testing use the `ismissing` function instead.**

4.9.2 Filtering Missing Values

Most of the time we want to **remove missing values from our data**.

Removing `missings` can be done in two ways:

1. `dropmissing` **function** applied to a whole `DataFrame` or a subset of its columns.
2. `ismissing` **function** applied to a filtering procedure (see Section 4.3).

The `dropmissing` function takes as first positional argument a `DataFrame`, and as an optional second argument either a single column or a vector of columns by which you'll want to remove the missing data from.

By default, if you do not specify column(s), as the second positional argument, it will remove any observation (row) having `missing` values:

```
dropmissing(df_missing)
```

name	age	grade_2020
Hank	19	4.0

Since 3 out of 4 rows had at least one `missing` value, we get back a `DataFrame` with a single row as a result.

However, if we specify column(s) as the second positional argument to `dropmissing` ↵, the resulting `DataFrame` will only drop rows that have `missing` values in the specified column(s).

Here's a single column with a `Symbol`:

```
dropmissing(df_missing, :name)
```

name	age	grade_2020
Sally	missing	1.0
Alice	20	missing
Hank	19	4.0

And now multiple columns with a vector of `Symbols`:

```
dropmissing(df_missing, [:name, :age])
```

name	age	grade_2020
Alice	20	missing
Hank	19	4.0

NOTE: You can use any of the *column selectors* described in Section 4.4 for the second positional argument of `dropmissing`.

The `ismissing` function tests if the underlying value is of the `Missing` type returning either `true` or `false`.

You can use negation `!` to use it both ways:

- `ismissing` to just keep the `missing` values.
- `!ismissing` to keep anything but the `missing` values

```
filter(:name => ismissing, df_missing)
```

name	age	grade_2020
missing	17	5.0

```
filter(:name => !ismissing, df_missing)
```

name	age	grade_2020
Sally	missing	1.0
Alice	20	missing
Hank	19	4.0

4.9.3 Filling or Replacing Missing Values

A common data wrangling pattern is to **replace or fill missing values**.

Like R (and SQL), Julia has the `coalesce` function. We often use it in a broadcasted way over an array to fill all `missing` values with a specific value.

Here's an example of a vector containing two `missing` values:

```
coalesce.([missing, "some value", missing], "zero")
```

```
["zero", "some value", "zero"]
```

You can see that `coalesce` replaces `missing` values with "zero".

We can definitely use it in a transform procedure (Section 4.7):

```
transform(df_missing, :name => ByRow(x -> coalesce(x, "John Doe")); renamecols=→false)
```

name	age	grade_2020
John Doe	17	5.0
Sally	missing	1.0
Alice	20	missing
Hank	19	4.0

4.9.4 Skipping over Missing Values

As we saw on Section 4.8, we can use `combine` to apply summarizing functions to data. However, as explained, **missing values propagate through most operations in Julia**. Suppose you want to calculate the mean of `:grade_2020` column in our `df_missing`:

```
combine(df_missing, :grade_2020 => mean)
```

grade_2020_mean
missing

You can skip missing values in any array or summarizing function by passing the `skipmissing` function:

```
combine(df_missing, :grade_2020 => mean ∘ skipmissing )
```

grade_2020_mean_skipmissing
3.333333333333335

NOTE: We are using the function composition operator `∘` (which you can type with `\circ<TAB>`) to compose two functions into one. It is just like the mathematical operator:

$\text{\$}\$f \circ g(x) = f(g(x))\$\$$

Hence, `(mean ∘ skipmissing)(x)` becomes `mean(skipmissing(x))`.

4.10 Performance

So far, we haven't thought about making our `DataFrames.jl` code **fast**. Like everything in Julia, `DataFrames.jl` can be really fast. In this section, we will give some performance tips and tricks.

4.10.1 In-place operations

Like we explained in Section 3.3.2, functions that end with a bang `!` are a common pattern to denote functions that modify one or more of their arguments. In the context of high performance Julia code, this *means* that **functions** with `!` will just change in-place the objects that we have supplied as arguments.

Almost all the `DataFrames.jl` functions that we've seen have a "`!` twin". For example, `filter` has an *in-place* `filter!`, `select` has `select!`, `subset` has `subset!`, `dropmissing` has `dropmissing!`, and so on. Notice that these functions **do not** return a `newDataFrame`, but instead they **update** the `DataFrame` that they act upon. Additionally, `DataFrames.jl` (version 1.3 onwards) supports in-place `leftjoin` with the function `leftjoin!`. This function updates the left `DataFrame` with the joined columns from the right `DataFrame`. There is a caveat that for each row of left table there must match *at most* one row in right table.

If you want the highest speed and performance in your code, you should definitely use the `!` functions instead of regular `DataFrames.jl` functions.

Let's go back to the example of the `select` function in the beginning of Section 4.4. Here is the responses DataFrame:

```
responses()
```

id	q1	q2	q3	q4	q5
1	28	us	F	B	A
2	61	fr	B	C	E

Now, let's perform the selection with the `select` function, like we did before:

```
select(responses(), :id, :q1)
```

id	q1
1	28
2	61

And here is the *in-place* function:

```
select!(responses(), :id, :q1)
```

id	q1
1	28
2	61

The `@allocated` macro tells us how much memory was allocated. In other words, **how much new information the computer had to store in its memory while running the code**. Let's see how they will perform:

```
df = responses()
@allocated select(df, :id, :q1)
```

6944

```
df = responses()
@allocated select!(df, :id, :q1)
```

6720

As we can see, `select!` allocates less than `select`. So, it should be faster, while consuming less memory.

4.10.2 Copying vs Not Copying Columns

There are **two ways to access a DataFrame column**. They differ in how they are accessed: one creates a “view” to the column without copying and the other creates a whole new column by copying the original column.

The first way uses the regular dot . operator followed by the column name, like in `df.col`. This kind of access **does not copy** the column `col`. Instead `df.col` creates a “view” which is a link to the original column without performing any allocation. Additionally, the syntax `df.col` is the same as `df[!, :col]` with the bang ! as the row selector.

The second way to access a DataFrame column is the `df[:, :col]` with the colon : as the row selector. This kind of access **does copy** the column `col`, so beware that it may produce unwanted allocations.

As before, let’s try out these two ways to access a column in the responses DataFrame:

```
df = responses()
@allocated col = df[:, :id]
```

338690

```
df = responses()
@allocated col = df[!, :id]
```

0

When we access a column without copying it we are making zero allocations and our code should be faster. So, if you don’t need a copy, always access your DataFrames columns with `df.col` or `df[!, :col]` instead of `df[:, :col]`.

4.10.3 CSV.read versus CSV.File

If you take a look at the help output for `CSV.read`, you will see that there is a convenience function identical to the function called `CSV.File` with the same keyword arguments. Both `CSV.read` and `CSV.File` will read the contents of a CSV file, but they differ in the default behavior. `CSV.read`, **by default, will not make copies** of the incoming data. Instead, `CSV.read` will pass all the data to the second argument (known as the “sink”).

So, something like this:

```
df = CSV.read("file.csv", DataFrame)
```

will pass all the incoming data from `file.csv` to the `DataFrame` sink, thus returning a `DataFrame` type that we store in the `df` variable.

For the case of `CSV.File`, the default behavior is the opposite: it will make copies of every column contained in the CSV file. Also, the syntax is slightly different. We need to wrap anything that `CSV.File` returns in a `DataFrame` constructor function:

```
df = DataFrame(CSV.File("file.csv"))
```

Or, with the pipe `|>` operator:

```
df = CSV.File("file.csv") |> DataFrame
```

Like we said, `CSV.File` will make copies of each column in the underlying CSV file. Ultimately, if you want the most performance, you would definitely use `CSV` → `.read` instead of `CSV.File`. That's why we only covered `CSV.read` in Section 4.1.1.

4.10.4 CSV.jl Multiple Files

Now let's turn our attention to the `CSV.jl`. Specifically, the case when we have multiple CSV files to read into a single `DataFrame`. Since version 0.9 of `CSV.jl` we can provide a vector of strings representing filenames. Before, we needed to perform some sort of multiple file reading and then concatenate vertically the results into a single `DataFrame`. To exemplify, the code below reads from multiple CSV files and then concatenates them vertically using `vcat` into a single `DataFrame` with the `reduce` function:

```
files = filter(endswith(".csv"), readdir())
df = reduce(vcat, CSV.read(file, DataFrame) for file in files)
```

One additional trait is that `reduce` will not parallelize because it needs to keep the order of `vcat` which follows the same ordering of the `files` vector.

With this functionality in `CSV.jl` we simply pass the `files` vector into the `CSV.read` function:

```
files = filter(endswith(".csv"), readdir())
df = CSV.read(files, DataFrame)
```

`CSV.jl` will designate a file for each thread available in the computer while it lazily concatenates each thread-parsed output into a `DataFrame`. So we have the **additional benefit of multithreading** that we don't have with the `reduce` option.

4.10.5 *CategoricalArrays.jl compression*

If you are handling data with a lot of categorical values, i.e. a lot of columns with textual data that represent somehow different qualitative data, you would probably benefit by using `CategoricalArrays.jl` compression.

By default, `CategoricalArrays.jl` **will use an unsigned integer of size 32 bits `UInt32` to represent the underlying categories**:

```
typeof(categorical(["A", "B", "C"]))
```

```
CategoricalVector{String, UInt32, String, CategoricalValue{String, UInt32},  
    ↪Union{}}
```

This means that `CategoricalArrays.jl` can represent up to 2^{32} different categories in a given vector or column, which is a huge value (close to 4.3 billion). You probably would never need to have this sort of capacity in dealing with regular data¹³. That's why `categorical` has a `compress` argument that accepts either `true` or `false` to determine whether or not the underlying categorical data is compressed. If you pass `compress=true`, `CategoricalArrays.jl` **will try to compress the underlying categorical data to the smallest possible representation in `UInt`**. For example, the previous categorical vector would be represented as an unsigned integer of size 8 bits `UInt8` (mostly because this is the smallest unsigned integer available in Julia):

```
typeof(categorical(["A", "B", "C"]); compress=true))
```

```
CategoricalVector{String, UInt8, String, CategoricalValue{String, UInt8}, Union  
    ↪{}}
```

What does this all mean? Suppose you have a big vector. For example, a vector with one million entries, but only 4 underlying categories: A, B, C, or D. If you do not compress the resulting categorical vector, you will have one million entries stored as `UInt32`. On the other hand, if you do compress it, you will have one million entries stored instead as `UInt8`. By using `Base.summarysize` function we can get the underlying size, in bytes, of a given object. So let's quantify how much more memory we would need to have if we did not compress our one million categorical vector:

¹³ also notice that regular data (up to 10 000 rows) is not big data (more than 100 000 rows). So, if you are dealing primarily with big data please exercise caution in capping your categorical values.

```
using Random
```

```
one_mi_vec = rand(["A", "B", "C", "D"], 1_000_000)  
Base.summarysize(categorical(one_mi_vec))
```

```
4000612
```

4 million bytes, which is approximately 3.8 MB. Don't get us wrong, this is a good improvement over the raw string size:

```
Base.summarysize(one_mi_vec)
```

```
8000076
```

We reduced 50% of the raw data size by using the default `CategoricalArrays.jl` underlying representation as `UInt32`.

Now let's see how we would fare with compression:

```
Base.summarysize(categorical(one_mi_vec; compress=true))
```

```
1000564
```

We reduced the size to 25% (one quarter) of the original uncompressed vector size without losing information. Our compressed categorical vector now has 1 million bytes which is approximately 1.0 MB.

So whenever possible, in the interest of performance, consider using `compress=true` in your categorical data.

5 *DataFramesMeta.jl*

In this chapter we'll cover `DataFramesMeta.jl`¹, a package that uses **convenient data wrangling syntax translating to `DataFrames.jl` commands**. The syntax is similar to the `dplyr`² package from R's tidyverse. Compared to using pure `DataFrames.jl`, `DataFramesMeta.jl` commands are typically more convenient to write and more similar to `dplyr` which makes `DataFramesMeta.jl` particularly suitable for people familiar with the R programming language.

A major advantage of `DataFramesMeta.jl` is that, contrary to `dplyr`, there are fewer commands that you need to learn. Specifically we'll cover **6 commands**:

- `@select`: column selection
- `@transform`: column transformation
- `@subset`: row selection
- `@orderby`: row sorting
- `@combine`: data summaries
- `@chain`: piping operations

5.1 Macros

You might have noticed that all `DataFramesMeta.jl` commands start with an “at” `@` symbol. These commands have a special category in the Julia language: they are called **macros**.

NOTE: Macros are a way to perform metaprogramming³ in Julia. We won't cover macro's basics here. However, if you want to find out more, please check the Julia documentation section on metaprogramming⁴ and Julius Krumbiegel's blog post on Julia macros⁵.

`DataFramesMeta.jl` macros behave **similar** to `DataFrames.jl` functions:

- they both take a `DataFrame` as a first positional argument
- they have in-place *mutating* functions (as discussed in Section 4.10.1: the bang `!` functions)

¹ <https://juliadata.github.io/DataFramesMeta.jl/stable/>

² <https://dplyr.tidyverse.org>

³ <https://en.wikipedia.org/wiki/Metaprogramming>

⁴ <https://docs.julialang.org/en/v1/manual/metaprogramming/>

⁵ <https://jkrumbiegel.com/pages/2021-06-07-macros-for-beginners/>

Nevertheless, there are some **differences** between using `DataFrames.jl` functions versus `DataFramesMeta.jl` macros.

First, using parentheses in the macro commands are *optional*, and it can be replaced by *spaces* instead. For example:

```
@select(df, :col)
```

is the same as:

```
@select df :col
```

We will be using the space syntax in this chapter.

Second, macros parse *static* commands by default. If you want *dynamic* parsing you'll need to add \$ to your syntax. This happens because macros treat the input as a static string. For example:

```
@select df :col
```

will always work because our intended selected column command with the argument `:col` won't change in *runtime* (the time that Julia is executing code). It will always mean the same operation no matter the context.

Now suppose that you want to use one of the column selectors presented in Section 4.4. Here, the expression inside the `@select` macro needs to be parsed *dynamically*. In other words, it is *not* static and the operation will change with context. For example:

```
@select df Not(:col)
```

Here the columns that we want to select will depend on the actual columns inside `df`. This means that Julia cannot treat the command as something that won't change depending on the context. Hence, it needs to be parsed dynamically. In `DataFramesMeta.jl`, this is solved by wrapping parts of the command that needs to be parsed dynamically with `$()`. The above command needs to be changed to:

```
@select df $(Not(:col))
```

This tells `DataFramesMeta.jl` to treat the `Not(:col)` part of the macro as dynamic. It will parse this expression and replace it by all of the columns except `:col`.

Third, most of `DataFramesMeta.jl` macros have **two different versions**: a *non-vectorized*, and a *vectorized* form. The non-vectorized form is the default form

and treats arguments as whole columns, i.e., they operate on arrays whereas the vectorized form has an `r` prefix (as in `rows`) and vectorizes all operators and functions calls. This is the same behavior as adding the dot operator `.` into the desired operation. Similar to the `ByRow` function from `DataFrames.jl` that we saw in Section 4.3.2.

These 3 operations are equivalent:

```
# DataFrame.jl
transform(df, :col => ByRow(exp))
```

```
# DataFrameMeta.jl non-vectorized (default)
@transform df exp.(:col)
```

```
# DataFrameMeta.jl vectorized with r prefix
@rtransform df exp(:col)
```

NOTE: For most of the `DataFrameMeta.jl` macros we have four variants:

- `@macro`: non-vectorized
- `@rmacro`: vectorized
- `@macro!`: non-vectorized in-place
- `@rmacro!`: vectorized in-place

5.2 Column Selection

Let's revisit our example `all_grades()` data defined in Chapter 4:

```
df = all_grades()
```

name	grade
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0
Bob	9.5
Sally	9.5
Hank	6.0

The `DataFrameMeta.jl` `@select` macro is similar to the `select` `DataFrames.jl` function. It performs **column selection**:

```
@select df :name
```

name
Sally
Bob
Alice
Hank
Bob
Sally
Hank

We can add as many columns as we want to `@select`:

```
@select df :name :grade
```

name	grade
Sally	1.0
Bob	5.0
Alice	8.5
Hank	4.0
Bob	9.5
Sally	9.5
Hank	6.0

To use the column selectors (Section 4.4), you need to wrap them inside `$()`:

```
@select df $(Not(:grade))
```

name
Sally
Bob
Alice
Hank
Bob
Sally
Hank

The `DataFramesMeta.jl` syntax, for some users, is easier and more intuitive than the `DataFrames.jl`'s minilanguage `source => transformation => target`. The minilanguage is replaced by `target = transformation(source)`.

Suppose that you want to represent the grades as a number between 0 and 100:

```
@select df :grade_100 = :grade .* 10
```

grade_100
10.0
50.0
85.0
40.0
95.0
95.0
60.0

Of course, the `.*` can be omitted by using the vectorized form of the macro,
`@rselect`:

```
@rselect df :grade_100 = :grade * 10
```

grade_100
10.0
50.0
85.0
40.0
95.0
95.0
60.0

5.3 Column Transformation

Whereas the `@select` macro variants performs column selection, the `@transform ↪` macro variants do *not* perform any column selection. It can either *overwrite* existent columns or *create* new columns that will be added to the right of our DataFrame.

For example, the previous operation on `:grade` can be invoked as a transformation with:

```
@rtransform df :grade_100 = :grade * 10
```

name	grade	grade_100
Sally	1.0	10.0
Bob	5.0	50.0
Alice	8.5	85.0
Hank	4.0	40.0
Bob	9.5	95.0
Sally	9.5	95.0
Hank	6.0	60.0

As you can see, `@transform` does not perform column selection, and the `:grade_100` column is created as a new column and added to the right of our DataFrame.

`DataFramesMeta.jl` macros also support `begin ... end` statements. For example, suppose that you are creating two columns in a `@transform` macro:

```
@rtransform df :grade_100 = :grade * 10 :grade_5 = :grade / 2
```

name	grade	grade_100	grade_5
Sally	1.0	10.0	0.5
Bob	5.0	50.0	2.5
Alice	8.5	85.0	4.25
Hank	4.0	40.0	2.0
Bob	9.5	95.0	4.75
Sally	9.5	95.0	4.75
Hank	6.0	60.0	3.0

It can be cumbersome and difficult to read the performed transformations. To facilitate that, we can use `begin ... end` statements and put one transformation per line:

```
@rtransform df begin
    :grade_100 = :grade * 10
    :grade_5 = :grade / 2
end
```

name	grade	grade_100	grade_5
Sally	1.0	10.0	0.5
Bob	5.0	50.0	2.5
Alice	8.5	85.0	4.25
Hank	4.0	40.0	2.0
Bob	9.5	95.0	4.75
Sally	9.5	95.0	4.75
Hank	6.0	60.0	3.0

We can also use other columns in our transformations, which makes `DataFramesMeta.jl` more appealing than `DataFrames.jl` due to the easier syntax.

First, let's revisit the `leftjoined` DataFrame from Chapter 4:

```
leftjoined = leftjoin(grades_2020(), grades_2021(); on=:name)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	missing

name	grade_2020	grade_2021
Alice	8.5	missing

Additionally, we'll replace the missing values with 5 (Section 4.9, also note the ! in in-place variant `@rtransform!`):

```
@rtransform! leftjoined :grade_2021 = coalesce(:grade_2021, 5)
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	5
Alice	8.5	5

This is how you calculate the mean of grades in both years using `DataFramesMeta`
`→.jl`:

```
@rtransform leftjoined :mean_grades = (:grade_2020 + :grade_2021) / 2
```

name	grade_2020	grade_2021	mean_grades
Sally	1.0	9.5	5.25
Hank	4.0	6.0	5.0
Bob	5.0	5	5.0
Alice	8.5	5	6.75

This is how you would perform it in `DataFrames.jl`:

```
transform(leftjoined, [:grade_2020, :grade_2021] => ByRow((x, y) -> (x + y) / 2)
         => :mean_grades)
```

name	grade_2020	grade_2021	mean_grades
Sally	1.0	9.5	5.25
Hank	4.0	6.0	5.0
Bob	5.0	5	5.0
Alice	8.5	5	6.75

As you can see, the case for easier syntax is not hard to argue for `DataFramesMeta`
`→.jl`.

5.4 Row Selection

We already covered two macros that operate on *columns*, `@select` and `@transform`.

Now let's cover the only macro we need to **operate on rows**: `@subset`. It follows the same principles we've seen so far with `DataFramesMeta.jl`, *except* that the **operation must return a boolean variable** for row selection.

Let's filter grades above 7:

```
@rsubset df :grade > 7
```

name	grade
Alice	8.5
Bob	9.5
Sally	9.5

As you can see, `@subset` has also a vectorized variant `@rsubset`. Sometimes we want to mix and match vectorized and non-vectorized function calls. For instance, suppose that we want to filter out the grades above the mean grade:

```
@subset df :grade .> mean(:grade)
```

name	grade
Alice	8.5
Bob	9.5
Sally	9.5

For this, we need a `@subset` macro with the `>` operator vectorized, since we want a element-wise comparison, but the `mean` function needs to operate on the whole column of values.

`@subset` also supports multiple operations inside a `begin ... end` statement:

```
@rsubset df begin
    :grade > 7
    startswith(:name, "A")
end
```

name	grade
Alice	8.5

5.5 Row Sorting

DataFramesMeta.jl has a macro for sorting rows: `@orderby`. `@orderby` does not have an in-place or vectorized variant.

Let's sort our `leftjoined` by grade in 2021:

```
@orderby leftjoined :grade_2021
```

name	grade_2020	grade_2021
Bob	5.0	5
Alice	8.5	5
Hank	4.0	6.0
Sally	1.0	9.5

By default, `@orderby` will sort in ascending order. But you can change this to decreasing order with the minus sign - in front of the column:

```
@orderby leftjoined -:grade_2021
```

name	grade_2020	grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	5
Alice	8.5	5

Like all the other `DataFramesMeta.jl` macros, `@orderby` also supports multiple operations inside a `begin ... end` statement:

```
@orderby leftjoined begin
    :grade_2021
    :name
end
```

name	grade_2020	grade_2021
Alice	8.5	5
Bob	5.0	5
Hank	4.0	6.0
Sally	1.0	9.5

Here, we are sorting first by grade in 2020 then by name. Both in ascending order.

5.6 Data Summaries

Similar to the `combine` `DataFrames.jl` function (Section 4.8), `DataFramesMeta.jl` has a `@combine` **macro**.

```
@combine leftjoined :mean_grade_2020 = mean(:grade_2020)
```

mean_grade_2020
4.625

`@combine` also supports multiple operations inside a `begin ... end` statement:

```
@combine leftjoined begin
    :mean_grade_2020 = mean(:grade_2020)
    :mean_grade_2021 = mean(:grade_2021)
end
```

mean_grade_2020	mean_grade_2021
4.625	6.375

Most of the time we would use `@combine` in a grouped dataframe by pairing it with `groupby`:

```
gdf = groupby(leftjoined, :name)
@combine gdf begin
    :mean_grade_2020 = mean(:grade_2020)
    :mean_grade_2021 = mean(:grade_2021)
end
```

name	mean_grade_2020	mean_grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	5.0
Alice	8.5	5.0

5.7 Piping Operations

R users are familiar with the pipe operator `%>%` which allows **chaining** operations together. That means that the output of an operation will be used as input in the next operation and so on.

This can be accomplished with the `@chain` macro. To use it, we start with `@chain` followed by the `DataFrame` and a `begin` statement. Every operation inside the `begin ... end` statement will be used as input for the next operation, therefore chaining operations together.

Here is a simple example with a `groupby` followed by a `@combine`:

```
@chain leftjoined begin
    groupby(:name)
    @combine :mean_grade_2020 = mean(:grade_2020)
end
```

name	mean_grade_2020
Sally	1.0
Hank	4.0
Bob	5.0
Alice	8.5

NOTE: `@chain` will replace the first positional argument while chaining operations. This is not a problem in `DataFrames.jl` and `DataFramesMeta.jl`, since the `DataFrame` is always the first positional argument.

We can also nest as many as `begin ... end` statements we desired inside the operations:

```
@chain leftjoined begin
    groupby(:name)
    @combine begin
        :mean_grade_2020 = mean(:grade_2020)
        :mean_grade_2021 = mean(:grade_2021)
    end
end
```

name	mean_grade_2020	mean_grade_2021
Sally	1.0	9.5
Hank	4.0	6.0
Bob	5.0	5.0
Alice	8.5	5.0

To conclude, let's show a `@chain` example with all of the `DataFramesMeta.jl` macros we covered so far:

```
@chain leftjoined begin
    @rtransform begin
        :grade_2020 = :grade_2020 * 10
    end
end
```

```
:grade_2021 = :grade_2021 * 10
end
groupby(:name)
@combine begin
    :mean_grade_2020 = mean(:grade_2020)
    :mean_grade_2021 = mean(:grade_2021)
end
@rtransform :mean_grades = (:mean_grade_2020 + :mean_grade_2021) / 2
@rsubset :mean_grades > 50
@orderby -:mean_grades
end
```

name	mean_grade_2020	mean_grade_2021	mean_grades
Alice	85.0	50.0	67.5
Sally	10.0	95.0	52.5

6 *Data Visualization with Makie.jl*

From the Japanese word Maki-e, which is a technique to sprinkle lacquer with gold and silver powder. Data is the gold and silver of our age, so let's spread it out beautifully on the screen!

Simon Danisch, Creator of Makie.jl

Makie.jl¹ is a high-performance, extendable, and multi-platform plotting ecosystem for the Julia programming language. In our opinion, it is the prettiest and most powerful plotting package.

¹ <https://docs.makie.org/stable/>

NOTE: There are other plotting packages in the Julia ecosystem. One of the most popular ones is Plots.jl². However, we believe that the future of the Julia plotting tooling is in the Makie.jl ecosystem, due to the native Julia codebase and official support from JuliaHub³. Therefore, this is where we'll focus all of our data visualization efforts.

² <https://docs.juliaplots.org/stable/>

³ <https://juliahub.com>

Makie.jl deals with arrays (Section 3.3.7), such as vectors and matrices. This makes Makie.jl capable of dealing with any tabular data and especially `DataFrames` as we covered in Section 4. Moreover, it uses special point types, i.e. `Point2f` and `Point3f` which come in handy when defining vectors of points in 2d or 3d space.

Like many plotting packages, the code is split into multiple packages. Makie.jl is the front end package that defines all plotting functions required to create plot objects. These objects store all the information about the plots, but still need to be converted into an image. To convert these plot objects into an image, you need one of the Makie backends. By default, Makie.jl is reexported by every backend, so you only need to install and load the backend that you want to use.

There are four main backends which concretely implement all abstract rendering capabilities defined in Makie. These are

- CairoMakie.jl for non-interactive 2D publication-quality vector graphics,
- GLMakie.jl for interactive 2D and 3D plotting in standalone GLFW.jl windows (also GPU-powered), and
- WGLMakie.jl, a WebGL-based interactive 2D and 3D plotting that runs within browsers.

⁴ <https://radeon-pro.gitlab.io/RadeonProRenderDocs/en/index.html>

- RPRMakie.jl, an experimental ray tracing backend using AMDs RadeonProRender⁴. At the time of writing this book this only works on Windows and Linux.

See Makie's documentation for more⁵.

⁵ <https://docs.makie.org/stable/documentation/backends/index.html>

In this book we will only show examples for CairoMakie.jl and GLMakie.jl.

You can activate any backend by using the appropriate package and calling its corresponding `activate!` function. For example:

```
using GLMakie
GLMakie.activate!()
```

Now, we will start with some basic plots and later one some more advanced publication-quality plots. But, before going into plotting it is important to know how to save our plots. The easiest option to save a figure `fig` is to type `save ↪("filename.png", fig)`. Other formats are also available for CairoMakie.jl, such as `svg` and `pdf`. The resolution of the output image can easily be adjusted by passing extra arguments. For example, for vector formats you specify `pt_per_unit ↪`:

```
save("filename.pdf", fig; pt_per_unit=2)
```

or

```
save("filename.pdf", fig; pt_per_unit=0.5)
```

For `png`'s you specify `px_per_unit`. See Exporting a Figure with physical dimensions⁶ for details.

⁶ https://docs.makie.org/stable/documentation/figure_size/

Another important issue is to actually visualize your output plot. Note that for CairoMakie.jl the Julia REPL is not able to show plots, so you will need an IDE (Integrated Development Environment) such as VSCode, Jupyter or Pluto that supports `png` or `svg` as output. On the other hand, GLMakie.jl can open interactive windows, or alternatively display bitmaps inline if `Makie.inline!(true)` is called.

6.1 CairoMakie.jl

Let's start with our first plot: some scatter points with a line across them. Remember, first we call the backend and activate it, namely

```
using CairoMakie
CairoMakie.activate!()
```

And then the plotting function, in this case `scatterlines(x,y)` for points `x=1:10` and `y=1:10`:

```
fig = scatterlines(1:10, 1:10)
```

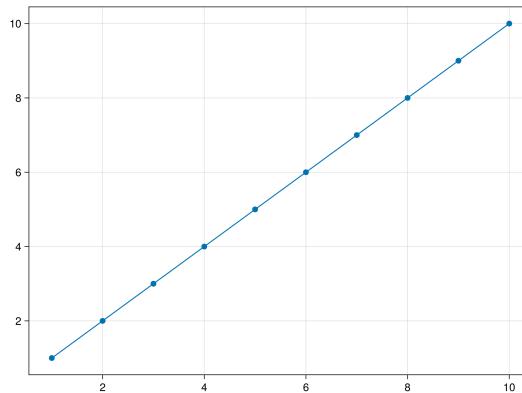


Figure 6.1: First plot.

Note that the previous plot is the default output, which we probably need to tweak by using axis names and labels.

Every plotting function like `scatterlines` creates and returns a new

- Figure
- Axis
- plot object

in a collection called `FigureAxisPlot`. These are known as the `non-mutating` methods. On the other hand, the `mutating` methods (e.g. `scatterlines!`, note the `!`) just return a plot object which can be appended into a given `axis` or the `current_axis ↗()`.

The next question that one might have is: how do I change the color or the marker type? This can be done via `attributes`, which we explain in the next section.

6.2 Attributes

A custom plot can be created by using `attributes`. The attributes can be set through keyword arguments. A list of `attributes` for a plot object, `pltobj`, can be viewed via `pltobj.attributes` as in:

```
fig, ax, pltobj = scatterlines(1:10)
pltobj.attributes
```

```
Attributes with 15 entries:
color => RGBA{Float32}(0.0,0.447059,0.698039,1.0)
colormap => viridis
colorrange => Automatic()
cycle => [:color]
inspectable => true
linestyle => nothing
linewidth => 1.5
marker => circle
markercolor => Automatic()
markercolormap => viridis
markercolorrange => Automatic()
markersize => 12
model => Float32[1.0 0.0 0.0 0.0; 0.0 1.0 0.0 0.0; 0.0 0.0 1.0 0.0; 0.0 0.0
    ↪0.0 1.0]
strokecolor => black
strokewidth => 0
```

Asking for help in the REPL as `?ablines` or `help(ablines)` for any given plotting function will show you their corresponding attributes plus a short description on how to use that specific function. For example, for `ablines`:

```
help(ablines)
```

```
ablines(intercepts, slopes; attrs...)
```

Creates a line defined by $f(x) = \text{slope} * x + \text{intercept}$ crossing a whole Scene with 2D projection at its current limits. You can pass one or multiple intercepts or slopes.

All style attributes are the same as for `LineSegments`.

`ablines` has the following function signatures:

```
(Vector, Vector)
(Vector, Vector, Vector)
(Matrix)
```

Available attributes for `Combined{Makie.ablines}` are:

```
cycle
xautolimits
yautolimits
```

Not only the plot objects have attributes, in the next Section we will see that also the `Axis` and `Figure` objects do.

6.3 Create Plot Figure

The basic container object in Makie is `Figure`, a canvas where we can add objects like `Axis`, `Colorbar`, `Legend`, etc.

For `Figure`, we have have attributes like `backgroundcolor`, `resolution`, `font` and `fontsize` ↵ as well as the `figure_padding` which changes the amount of space around the figure content, see the colored area in Figure 6.3. It can take one number for all sides, or a tuple of four numbers for left, right, bottom and top. Let's dive into these components.

6.3.1 Figure

```
function figure_canvas()
    fig = Figure(
        figure_padding=(5,5,10,10),
        backgroundcolor=:snow2,
        resolution=(600,400),
    )
end
JDS.figure_canvas()
```

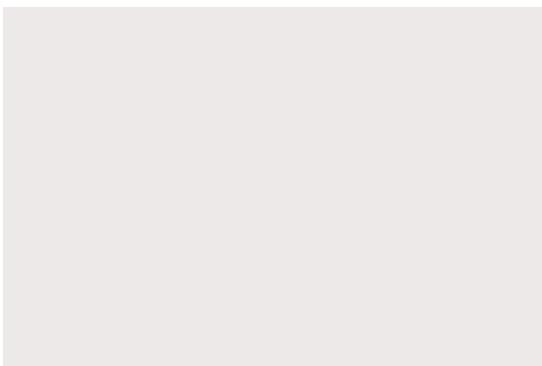


Figure 6.2: Figure canvas.

6.3.2 Figure + Axis

`Axis` has a lot more, some of them are `backgroundcolor`, `xgridcolor` and `title`. For a full list just type `help(Axis)`.

```
function figure_axis()
    fig = Figure(
        figure_padding=(5,5,10,10),
        backgroundcolor=:snow2,
        resolution=(600,400),
    )
```

```

ax = Axis(fig[1,1];
    xlabel="x",
    ylabel="y",
    title="Title",
)
fig
end
JDS.figure_axis()

```



Figure 6.3: Figure and Axis.

You can hide decorations and axis' spines with:

- `hidedecorations!(ax; kwargs...)`
- `hidexdecorations!(ax; kwargs...)`
- `hideydecorations!(ax; kwargs...)`
- `hidespines!(ax; kwargs...)`

Remember, we can always ask for help to see what kind of arguments we can use, e.g.,

```
help(hidespines!)
```

```
hidespines!(la::Axis, spines::Symbol... = (:l, :r, :b, :t)...)
```

Hide all specified axis spines. Hides all spines by default, otherwise choose with the symbols `:l`, `:r`, `:b` and `:t`.

`hidespines!` has the following function signatures:

```
(Vector, Vector)
(Vector, Vector, Vector)
(Matrix)
```

Available attributes for `Combined{Makie.hidespines!}` are:

Alternatively, for decorations

```
help(hidedecorations!)
```

`hidedecorations!(la::Axis)`

Hide decorations of both x and y-axis: label, ticklabels, ticks and grid.

`hidedecorations!` has the following function signatures:

```
(Vector, Vector)
(Vector, Vector, Vector)
(Matrix)
```

Available attributes for `Combined{Makie.hidedecorations!}` are:

For elements that **you don't want to hide**, pass `false`, e.g., `hidedecorations!(ax ↵; ticks=false, grid=false)`.

Setting limits at once or independently for each axis is done by calling

- `limits!(ax; l, r, b, t)`, where `l` is left, `r` right, `b` bottom, and `t` top.

You can also do `ylims!(low, high)` or `xlims!(low, high)`, and even open ones by doing `ylims!(low=0)` or `xlims!(high=1)`.

6.3.3 Figure + Axis + plot

Now, we add a plotting function into our new Axis:

```
function figure_axis_plot()
    fig = Figure(
        figure_padding=(5,5,10,10),
        backgroundcolor=:snow2,
        resolution=(600,400),
    )
    ax = Axis(fig[1,1];
        xlabel="x",
        ylabel="y",
        title="Title",
    )
    lines!(ax, 0.5:0.2:3pi, x -> cos(x)/x;
        color=:black,
        linewidth=2,
        linestyle=:dash,
    )
    fig
end
JDS.figure_axis_plot()
```

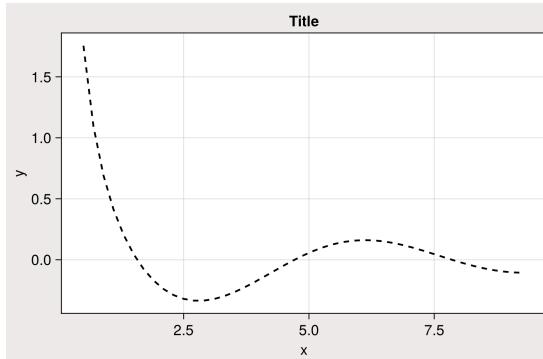


Figure 6.4: Figure, Axis and plot.

This example already includes many of the attributes that are typically used. Additionally, it would be beneficial to include a “legend” for reference, especially if the example has more than one function. This will make it easier to understand.

6.3.4 Figure + Axis + plot + axislegend

So, let's append another mutation `plot` object and add the corresponding legends by calling `axislegend`. This will collect all the `labels` you might have passed to your plotting functions and by default will be located in the right top position. For a different one, the `position=:ct` argument is called, where `:ct` means let's put our label in the `center` and at the `top`, see Figure Figure 6.5:

```
function figure_axis_plot_leg()
    fig = Figure();
    figure_padding=(5,5,10,10),
    backgroundcolor=:snow2,
    resolution=(600,400),
)
ax = Axis(fig[1,1];
    xlabel="x",
    ylabel="y",
    title="Title",
    xgridstyle=:dash,
    ygridstyle=:dash,
)
lines!(ax, 0.5:0.2:3pi, x -> cos(x)/x;
    linewidth=2,
    linestyle=:solid,
    label = "cos(x)/x",
)
scatterlines!(ax, 0.5:0.2:3pi, x -> -cos(x)/x;
    color=:black,
    linewidth=2,
    linestyle=:dash,
```

```

        label = "-cos(x)/x",
    )
axislegend("legend"; position=:rt)
fig
end
JDS.figure_axis_plot_leg()

```

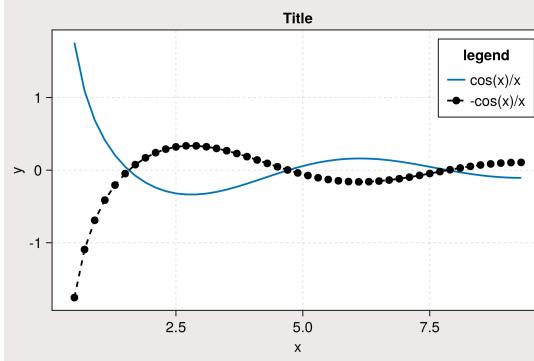


Figure 6.5: Figure, Axis, plot and legend.

Other positions are also available by combining *left(l)*, *center(c)*, *right(r)* and *bottom(b)*, *center(c)*, *top(t)*. For instance, for left top, use *:lt*.

However, having to write this much code just for two lines is cumbersome. So, if you plan on doing a lot of plots with the same general aesthetics, then setting a theme will be better. We can do this with `set_theme!()` as follows:

```

set_theme!();
resolution=(600,400),
backgroundcolor=(:mistyrose, 0.1),
fontsize=16,
Axis=();
    xlabel="x",
    ylabel="y",
    title="Title",
    xgridstyle=:dash,
    ygridstyle=:dash,
),
Legend=();
    bgcolor=(:grey, 0.1),
    framecolor=:orangered,
),
)

```

nothing

Plotting the previous figure should take the new default settings defined by `set_theme!(kwargs)`:

```

function fig_theme()
    fig = Figure()
    ax = Axis(fig[1,1])
    lines!(ax, 0.5:0.2:3pi, x -> cos(x)/x;
        linewidth=2,
        linestyle=:dash,
        label = "cos(x)/x",
    )
    scatterlines!(ax, 0.5:0.2:3pi, x -> -cos(x)/x;
        color=:black,
        linewidth=2,
        linestyle=:dash,
        label = "-cos(x)/x",
    )
    axislegend("legend"; position=:rt)
    fig
    set_theme!()
end
JDS.fig_theme()

```

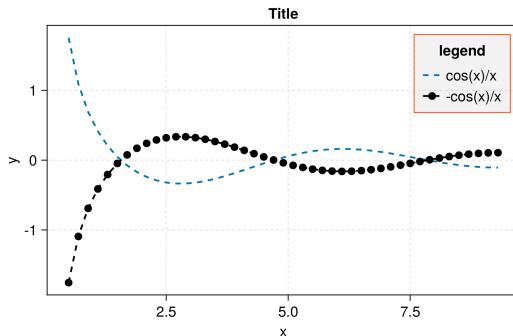


Figure 6.6: Set theme!() example.

Note that the last line is `set_theme!()`, will reset the default's settings of Makie. For more on `themes` please go to Section 6.5.

6.3.5 Figure + Axis + plot + Legend + Colorbar

Before moving on into the next section, it's worthwhile to see an example where an `array` of attributes is passed at once to a plotting function. For this example, we will use the `scatter` plotting function to do a bubble plot.

The data for this could be an `array` with 100 rows and 3 columns, which we generated at random from a normal distribution. Here, the first column could be the positions in the `x` axis, the second one the positions in `y` and the third one an intrinsic associated value for each point. The latter could be represented in

a plot by a different color or with a different marker size. In a bubble plot we can do both.

```
using Random; seed!
seed!(28)
xyz = randn(100, 3)
xyz[1:4, :]
```

```
4x3 Matrix{Float64}:
 0.550992  1.27614  -0.659886
 -1.06587  -0.0287242  0.175126
 -0.721591  -1.84423  0.121052
 0.801169  0.862781  -0.221599
```

Next, the corresponding plot can be seen in Figure 6.7:

```
function fig_bubbles(xyz)
    fig = Figure(resolution=(600,400))
    ax = Axis(fig[1,1]; aspect = DataAspect())
    pltobj = scatter!(xyz[:, 1], xyz[:, 2],
                      color=xyz[:, 3],
                      label="Bubbles",
                      colormap=:plasma,
                      markersize=15 * abs.(xyz[:, 3]),
                      )
    limits!(-3, 3, -3, 3)
    Legend(fig[1, 2], ax, valign=:top)
    Colorbar(fig[1, 2], pltobj, height=Relative(3/4))
    fig
end
JDS.fig_bubbles(xyz)
```

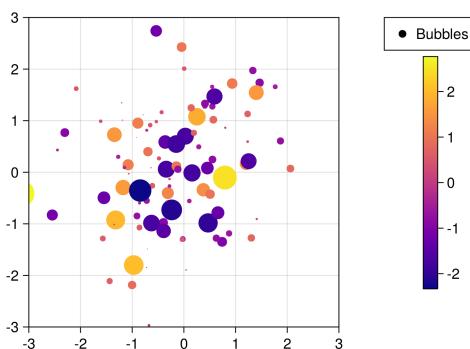


Figure 6.7: Bubble plot.

where we have decomposed the tuple `FigureAxisPlot` into `fig`, `ax`, `pltobj`, in order to be able to add a `Legend` and `Colorbar` outside of the plotted object. We will discuss layout options in more detail in Section 6.8.

We have done some basic but still interesting examples to show how to use `Makie.jl` and by now you might be wondering: what else can we do?

6.4 Cheat Sheets

What are all the possible plotting functions available in `Makie.jl`? To answer this question, a *CHEAT SHEET* is shown in Figure 6.8. These work especially well with the `CairoMakie.jl` backend:

For completeness, in Figure 6.9, we show the corresponding functions *CHEAT SHEET* for `GLMakie.jl`, which supports mostly 3D plots. Those will be explained in detail in Section 6.9.

Now, that we have an idea of all the things we can do, let's go back and continue with the basics. It's time to learn how to change the general appearance of our plots.

6.5 Themes

There are several ways to affect the general appearance of your plots. Either, you could use a predefined theme⁷ or your own custom theme. For example, use the predefined dark theme via `with_theme(your_plot_function, theme_dark())`. Or, build your own with `Theme(kwargs)` or even update the one that is active with `update_theme!(kwargs)`.

⁷ https://docs.makie.org/stable/documentation/theming/predefined_themes/

You can also do `set_theme!(theme; kwargs...)` to change the current default theme to `theme` and override or add attributes given by `kwargs`. If you do this and want to reset all previous settings just do `set_theme!()` with no arguments. See the following examples, where we had prepared a `demo_figure` with different characteristics, such that most attributes for each theme can be appreciated.

Our `demo_figure` plotting function looks like follows:

```
function demo_figure()
    # contourf
    x=y= range(-2.3, 2.3, length=100)
    z=-2x .* exp.(-x .^ 2 .- (y') .^ 2)
    # density
    m00pairs=[[4,2],[2,0.5],[-1,2],[0.25,1],[-4, 2],[8, 1.5]]
    # lines
    xs=range(0, 4π, 100)
    ys=[sin.(xs),cos.(xs),-sin.(xs),-cos.(xs),0.5cos.(xs),-0.5cos.(xs)]
    labs=["sin(x)","cos(x)","-sin(x)","-cos(x)","cos(x)/2","-cos(x)/2"]
    # figure
    fig = Figure(figsize=(10,15,5,35),
```

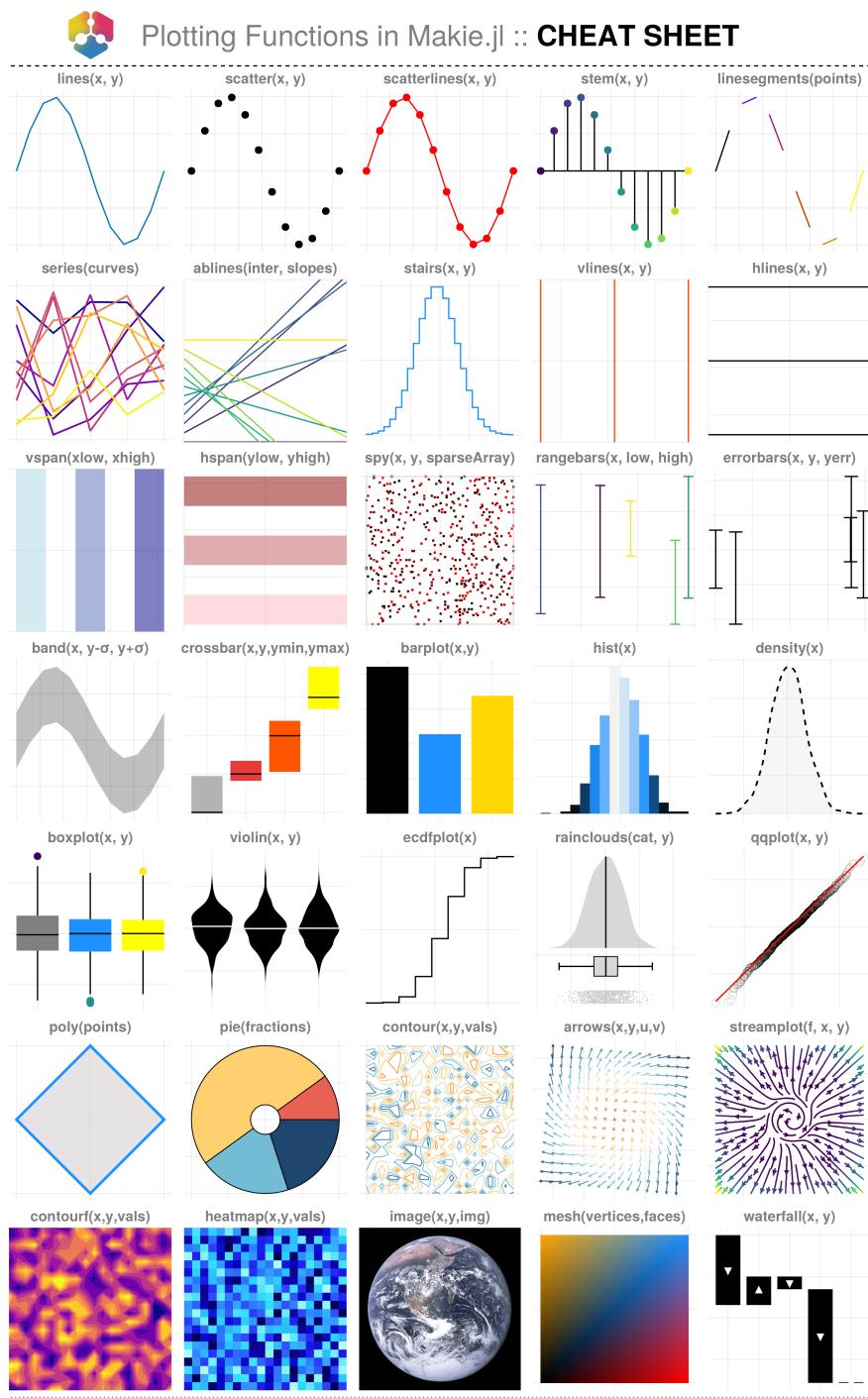


Figure 6.8: Plotting functions: CHEAT SHEET. Output given by CairoMakie.

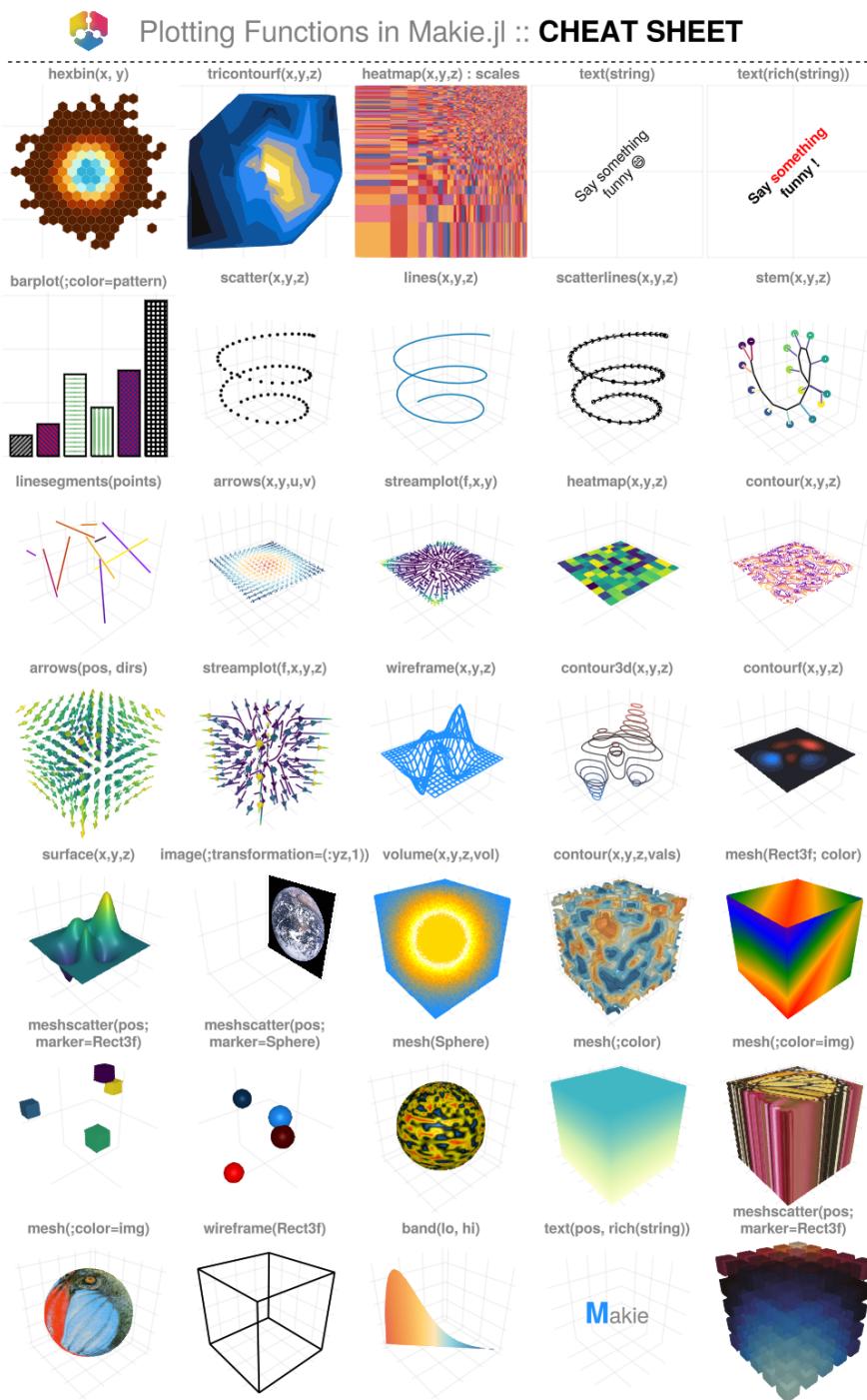


Figure 6.9: Plotting functions: CHEAT SHEET. Output given by GLMakie.

```

resolution = (900,600), fontsize = 20)
ax1 = Axis(fig[1,1]; xlabel="x", ylabel="y")
ax2 = Axis(fig[1,2]; xlabel="x", ylabel="pdf")
ax3 = Axis(fig[2,1:2]; xlabel="x", ylabel="y")
obj = contourf!(ax1, x,y,z; levels=30)
Colorbar(fig[1,1], Top()), obj;
    vertical=false,
    tellheight=false,
    tellwidth=false,
    valign=:top
)
for μσ in μσpairs
    density!(ax2, rand(Distributions.Normal(μσ...),1000);
        label=$(μσ[1]),$(μσ[2]))
end
Legend(fig[1,2], Top()); ax2;
    orientation=:horizontal,
    nbanks=2,
    bgcolor =:transparent,
    tellheight=false,
    valign=:center,
)
limits!(ax2, -10,15,0,1)
[lines!(ax3, xs, y, label = "$(labs[i])") for (i,y) in enumerate(ys)]
limits!(ax3, 0,4π,-1,1)
Legend(fig[2,1:2], Top()); ax3, orientation=:horizontal)
fig
end

```

Where we had use several keyword arguments for `Axis`, `Legend` and `Colorbar`, please play with them and see how they work.

Currently, there are five themes:

- `theme_dark()`
- `theme_black()`
- `theme_ggplot2()`
- `theme_minimal()`
- `theme_light()`

Another alternative is defining a custom `Theme` by doing `with_theme(your_plot, ↪your_theme())`. For instance, the following theme could be a simple version for a publication quality template:

```

publication_theme() = Theme(
    fontsize=16,
    font="CMU Serif",
    Axis=

```

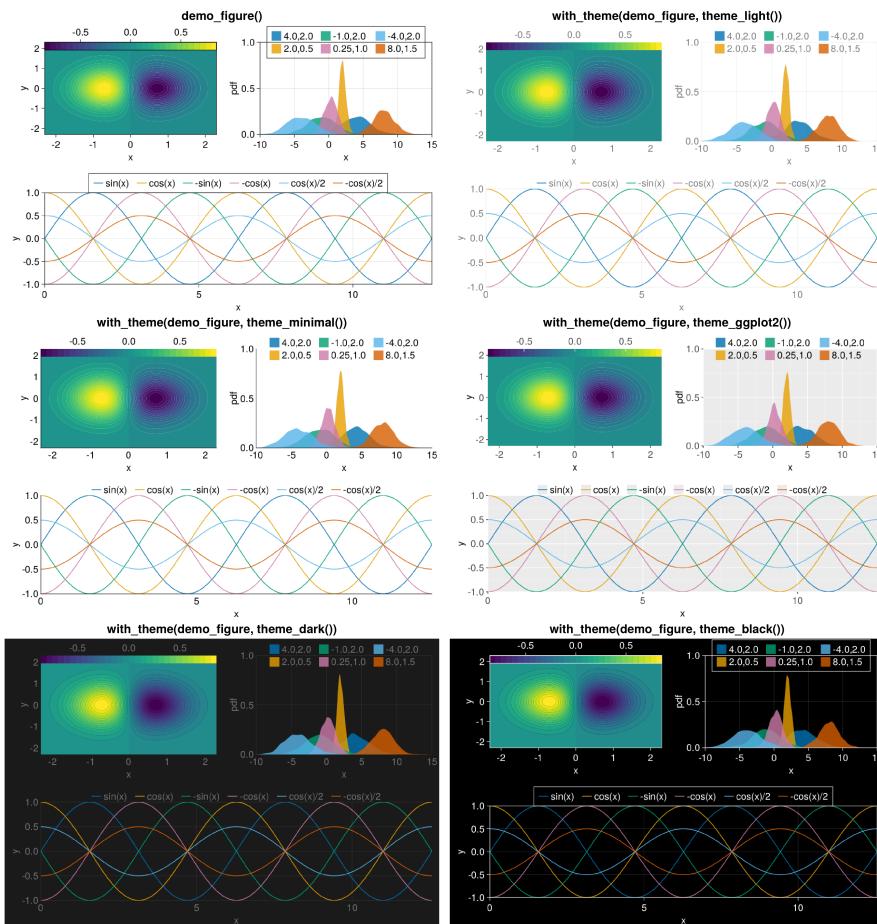


Figure 6.10: Predefined themes.

```

        xlabelsize=20, xlabelpadding=-5,
        xgridstyle=:dash, ygridstyle=:dash,
        tickalign=1, ticklabelalign=1,
        ticksize=10, xticks=10,
        xlabel="x", ylabel="y"
    ),
    Legend=(framecolor=(:black, 0.5), bgcolor=(:white, 0.5)),
    Colorbar=(ticksize=16, tickalign=1, spinewidth=0.5),
)

```

Which, for simplicity we use it to plot `scatterlines` and a heatmap.

```

function plot_with_legend_and_colorbar()
    fig, ax, _ = scatterlines(1:10; label="line")
    hm = heatmap!(ax, range(6, 9, 15), range(2, 5, 15), randn(15, 15);
                  colormap=:Spectral_11)
    axislegend("legend"; position=:lt)
    Colorbar(fig[1, 2], hm, label="values")
    colsizer!(fig.layout, 1, Aspect(1, 1.0))
    ax.title = "my custom theme"
    fig
end

```

Then, using the previously defined `Theme` the output is shown in Figure (Figure 6.11).

```
with_theme(plot_with_legend_and_colorbar, publication_theme())
```

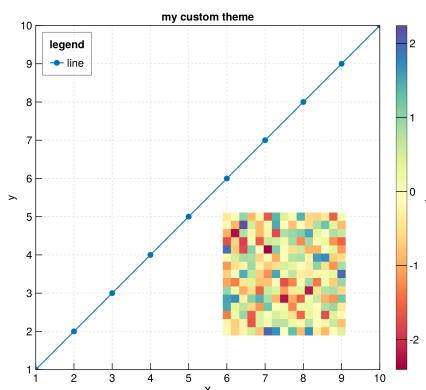


Figure 6.11: Themed plot with Legend and Colorbar.

Here we have use `with_theme` which is more convenient for the direct application of a theme than the `do` syntax. You should use the latter if you want to include extra arguments to the theme that is going to be applied.

Now, if something needs to be changed after `set_theme!(your_theme)`, we can do

it with `update_theme!(resolution=(500, 400), fontsize=18)`, for example. Another approach will be to pass additional arguments to the `with_theme` function:

```
fig = (resolution=(600, 400), figure_padding=1, backgroundcolor=:grey90)
ax = (; aspect=DataAspect(), xlabel=L"x", ylabel=L"y")
cbar = (; height=Relative(4 / 5))
with_theme(publication_theme(); fig..., Axis=ax, Colorbar=cbar) do
    plot_with_legend_and_colorbar()
end
```

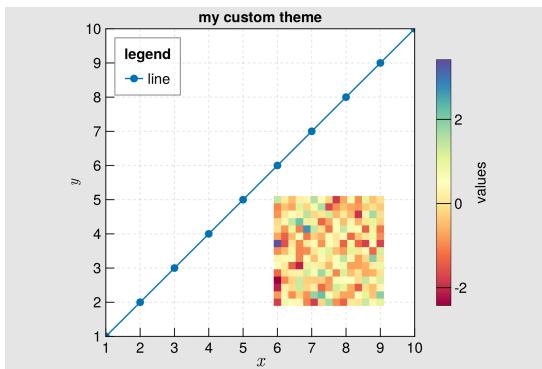


Figure 6.12: Theme with extra args.

Where the x and y labels have a Latex format due to `L"..."`. Most basic Latex strings are already supported by Makie, however to fully exploit this integration is recommended to also load the package `LaTeXStrings` as stated in the next section.

6.6 Using `LaTeXStrings.jl`

`LaTeX` support in `Makie.jl` is also available via `LaTeXStrings.jl`:

```
using LaTeXStrings
```

Simple use cases are shown below (Figure 6.13). A basic example includes `LaTeX` strings for x-y labels and legends:

```
function LaTeX_Strings()
    x = 0:0.05:4π
    lines(x, x -> sin(3x) / (cos(x) + 2) / x;
        label=L"\frac{\sin(3x)}{x(\cos(x)+2)}",
        figure=(; resolution=(600, 400)), axis=(; xlabel=L"x")
    )
    lines!(x, x -> cos(x) / x; label=L"\cos(x)/x")
    lines!(x, x -> exp(-x); label=L"e^{-x}")
    limits!(-0.5, 13, -0.6, 1.05)
    axislegend(L"f(x)"
```

```

    current_figure()
end

with_theme(LaTeX_Strings, publication_theme())

```

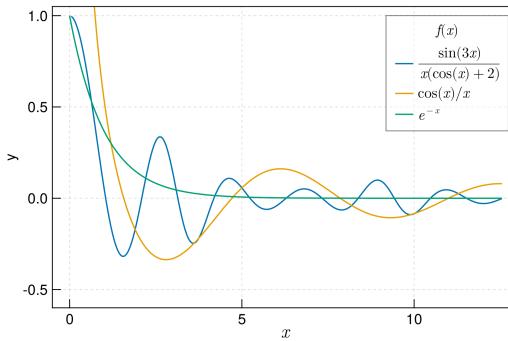


Figure 6.13: Plot with LaTeX strings.

A more involved example will be one with an equation as `text` and increasing legend numbering for curves in a plot:

```

function multiple_lines()
    x = collect(0:10)
    fig = Figure(resolution=(600, 400), font="CMU Serif")
    ax = Axis(fig[1, 1], xlabel=L"x", ylabel=L"f(x,a)")
    for i = 0:10
        lines!(ax, x, i .* x; label=latexstring("$(i) x"))
    end
    axislegend(L"f(x)"; position=:lt, nbanks=2, labelsize=14)
    text!(L"f(x,a) = ax", position=(4, 80))
    fig
end
JDS.multiple_lines()

```

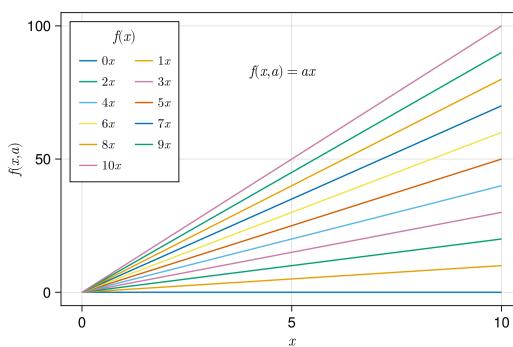


Figure 6.14: Multiple lines.

Where `latexstring` from `LaTeXStrings.jl` has been used to parse the string. An alternative to this simple case is `L"%%i x"`, which is used in the next example.

But, before that, there is another problem, some lines have repeated colors and that's no good. Adding some markers and line styles usually helps. So, let's do that using Cycles⁸ for these types. Setting `covary=true` allows to cycle all elements together:

⁸ <https://docs.makie.org/stable/documentation/theming/#cycles>

```
function multiple_scatters_and_lines()
    x = collect(0:10)
    cycle = Cycle([:color, :linestyle, :marker], covary=true)
    set_theme!(Lines=(cycle=cycle,), Scatter=(cycle=cycle,))
    fig = Figure(resolution=(600, 400), font="CMU Serif")
    ax = Axis(fig[1, 1], xlabel=L"x", ylabel=L"f(x,a)")
    for i in x
        lines!(ax, x, i .* x; label=L"%$i x")
        scatter!(ax, x, i .* x; markersize=13, strokewidth=0.25,
                 label=L"%$i x")
    end
    axislegend(L"f(x)"; merge=true, position=:lt, nbanks=2, labelszie=14)
    text!(L"f(x,a) = ax", position=(4, 80))
    set_theme!() # reset to default theme
    fig
end
JDS.multiple_scatters_and_lines()
```

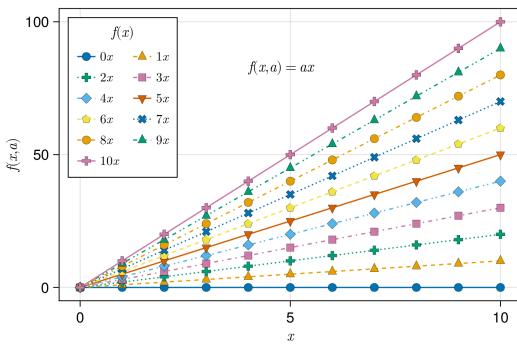


Figure 6.15: Multiple Scatters and Lines.

And voilà. A publication quality plot is here. What more can we ask for? Well, what about different default colors or palettes. In our next section, we will see how to use again Cycles⁹ and learn a little bit more about them, plus some additional keywords in order to achieve this.

⁹ <https://docs.makie.org/stable/documentation/theming/#cycles>

6.7 Colors and Colormaps

Choosing an appropriate set of colors or colorbar for your plot is an essential part when presenting results. Using Colors.jl¹⁰ is supported in Makie.jl so that you can use named colors¹¹ or pass RGB or RGBA values. Additionally, colormaps from ColorSchemes.jl¹² and PerceptualColourMaps.jl¹³ can also be

¹⁰ <https://github.com/JuliaGraphics/Colors.jl>

¹¹ <https://juliographics.github.io/Colors.jl/latest/namedcolors/>

¹² <https://github.com/JuliaGraphics/ColorSchemes.jl>

¹³ [https://github.com/peterekovesi/PerceptualColourMaps.jl](https://github.com/peterkovesi/PerceptualColourMaps.jl)

used. It is worth knowing that you can reverse a colormap by doing `Reverse ↪(:colormap_name)` and obtain a transparent color or colormap with `color=(:red ↪,0.5)` and `colormap=(:viridis, 0.5)`.

Different use cases will be shown next. Then we will define a custom theme with new colors and a colorbar palette.

6.7.1 Colors

By default `Makie.jl` has a predefined set of colors in order to cycle through them automatically, as shown in the previous figures, where no specific color was set. Overwriting these defaults is done by calling the keyword `color` in the plotting function and specifying a new color via a `Symbol` or `String`. See this in the following example:

```
function set_colors_and_cycle()
    # Epicycloid lines
    x(r, k, θ) = r * (k .+ 1.0) .* cos.(θ) .- r * cos.((k .+ 1.0) .* θ)
    y(r, k, θ) = r * (k .+ 1.0) .* sin.(θ) .- r * sin.((k .+ 1.0) .* θ)
    θ = range(0, 6.2π, 1000)

    axis = (; xlabel=L"x(\theta)", ylabel=L"y(\theta)",
              title="Epicycloid", aspect=DataAspect())
    figure = (; resolution=(600, 400), font="CMU Serif")

    fig, ax, _ = lines(x(1, 1, θ), y(1, 1, θ); color="firebrick1", # string
                        label=L"1.0", axis=axis, figure=figure)
    lines!(ax, x(4, 2, θ), y(4, 2, θ); color=:royalblue1, #symbol
          label=L"2.0")
    for k = 2.5:0.5:5.5
        lines!(ax, x(2k, k, θ), y(2k, k, θ); label=latexstring("$(k)")) #cycle
    end
    Legend(fig[1, 2], ax, latexstring("k, r = 2k"), merge=true)
    colsizer!(fig.layout, 1, Aspect(1, 1.0))
    fig
end
JDS.set_colors_and_cycle()
```

Where, in the first two lines we have used the keyword `color` to specify our color. The rest is using the default cycle set of colors. Later, we will learn how to do a custom cycle.

6.7.2 Colormap, Reverse

Regarding colormaps, we are already familiar with the keyword `colormap` for heatmaps and scatters. Here, we show that a colormap can also be specified via

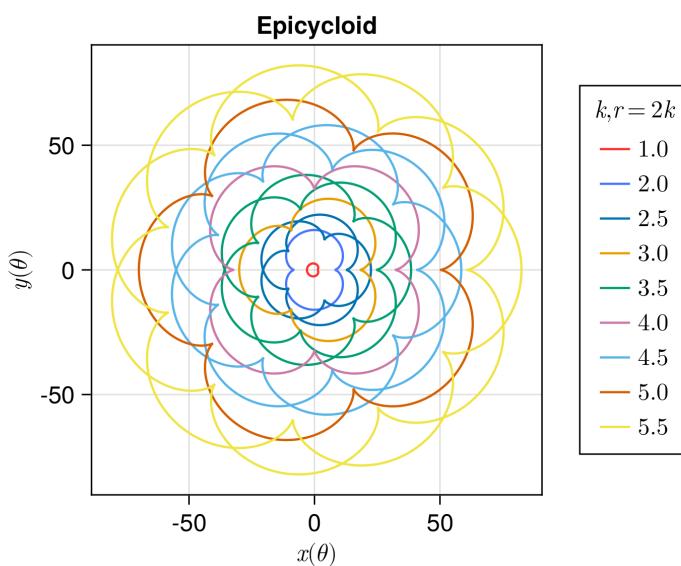


Figure 6.16: Set colors and cycle.

a `Symbol` or a `String`, similar to colors. Or, even a vector of `RGB` colors. Let's do our first example by calling `colormaps` as a `Symbol`, `String` and `cgrad` for categorical values. See `?cgrad` for more information.

```
figure = (; resolution=(600, 400), font="CMU Serif")
axis = (; xlabel=L"x", ylabel=L"y", aspect=DataAspect())
fig, ax, pltobj = heatmap(rand(20, 20); colorrange=(0, 1),
    colormap=Reverse(:viridis), axis=axis, figure=figure)
Colorbar(fig[1, 2], pltobj, label = "Reverse sequential colormap")
colsizer!(fig.layout, 1, Aspect(1, 1.0))
fig
```

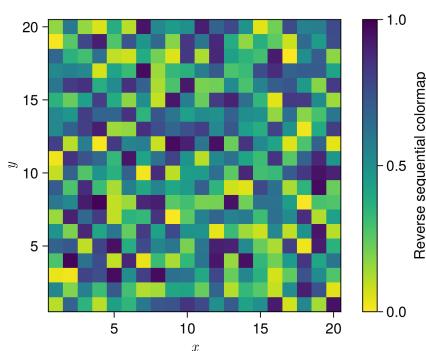


Figure 6.17: Reverse sequential colormap and colorrange.

6.7.3 Colormap, highclip, lowclip

When setting a `colorange` usually the values outside this range are colored with the first and last color from the colormap. However, sometimes it is better to specify the color you want at both ends. We do that with `highclip` and `lowclip`:

```
using ColorSchemes
```

```
figure = (; resolution=(600, 400), font="CMU Serif")
axis = (; xlabel=L"x", ylabel=L"y", aspect=DataAspect())
fig, ax, pltobj = heatmap(randn(20, 20); colorange=(-2, 2),
    colormap="diverging_rainbow_bgymr_45_85_c67_n256",
    highclip=:black, lowclip=:white, axis=axis, figure=figure)
Colorbar(fig[1, 2], pltobj, label = "Diverging colormap")
colsizes!(fig.layout, 1, Aspect(1, 1.0))
fig
```

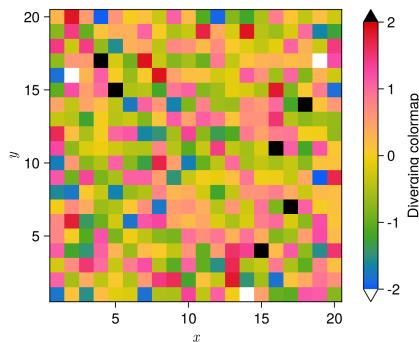


Figure 6.18: Diverging Colormap with low and high clip.

But we mentioned that also RGB vectors are valid options.

6.7.4 Colormap, categorical

For our next example you could pass the custom colormap `perse` or use `cgrad` to force a categorical Colorbar.

```
using Colors, ColorSchemes
```

```
figure = (; resolution=(600, 400), font="CMU Serif")
axis = (; xlabel=L"x", ylabel=L"y", aspect=DataAspect())
#cmap = ColorScheme(range(colorant"red", colorant"green", length=3))
# this is another way to obtain a colormap, not used here, but try it.
mycmap = ColorScheme([RGB{Float64}(i, 1.5i, 2i) for i in [0.0, 0.25, 0.35, 0.5
    ↪]])
fig, ax, pltobj = heatmap(rand(-1:1, 20, 20);
```

```

colormap=cgrad(mycmap, 3, categorical=true, rev=true), # cgrad and Symbol,
    ↪mycmap
axis=axis, figure=figure)
cbar = Colorbar(fig[1, 2], pltobj, label="Categories")
cbar.ticks = ([-0.66, 0, 0.66], ["negative", "neutral", "positive"])
colszie!(fig.layout, 1, Aspect(1, 1.0))
fig

```

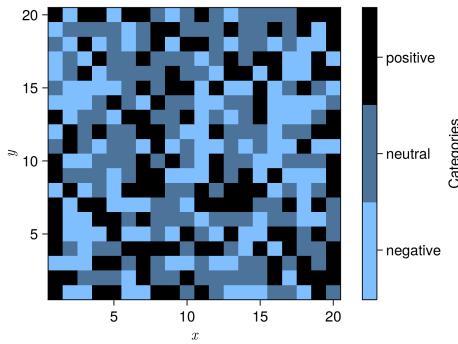


Figure 6.19: Categorical Colormap.

Lastly, the ticks in the colorbar for the categorial case are not centered by default in each color. This is fixed by passing custom ticks, as in `cbar.ticks = (positions, ticks)`.

The last case is when passing multiple colors to `colormap`. You will get an interpolated colormap between those colors. Also, hexadecimal coded colors are accepted. So, on top of our heatmap let's put one semi-transparent point using this.

```

figure = (; resolution=(600, 400), font="CMU Serif")
axis = (; xlabel=L"x", ylabel=L"y", aspect=DataAspect())
fig, ax, pltobj = heatmap(rand(20, 20); colorrange=(0, 1),
    colormap=["red", "black"], axis=axis, figure=figure)
scatter!(ax, [11], [11]; color=(#COCOCO, 0.5), markersize=150)
Colorbar(fig[1, 2], pltobj, label="2 colors")
colszie!(fig.layout, 1, Aspect(1, 1.0))
fig

```

6.7.5 Custom cycle

Here, we could define a global `Theme` with a new cycle for colors, however that is **not the recommend way** to do it. It's better to define a new theme and use as shown before. Let's define a new one with a `cycle` for `:color`, `:linestyle`, `:marker` and a new `colormap` default. And add these new attributes to our previous `publication_theme`.

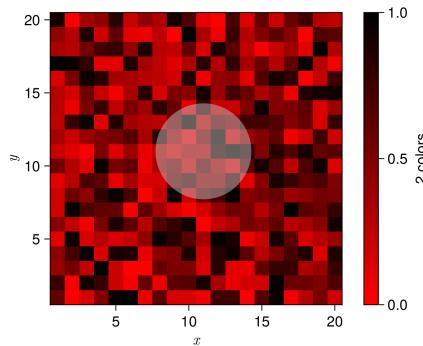


Figure 6.20: Colormap from two colors.

```
function new_cycle_theme()
    # https://nanx.me/ggsci/reference/pal_locuszoom.html
    my_colors = ["#D43F3AFF", "#EEA236FF", "#5CB85CFF", "#46B8DAFF",
                 "#357EBDFF", "#9632B8FF", "#B8B8B8FF"]
    cycle = Cycle([:color, :linestyle, :marker], covary=true) # altogether
    my_markers = [:circle, :rect, :utriangle, :dtriangle, :diamond,
                  :pentagon, :cross, :xcross]
    my_linestyle = [:solid, :dash, :dot, :dashdot, :dashdotdot]
    Theme(
        fontsize=16, font="CMU Serif",
        colormap=:linear_bmy_10_95_c78_n256,
        palette=(color=my_colors, marker=my_markers, linestyle=my_linestyle),
        Lines=(cycle=cycle,),
        Scatter=(cycle=cycle,),
        Axis=(xlabelsize=20, xlabelpadding=-5,
              xgridstyle=:dash, ygridstyle=:dash,
              xtickalign=1, ytickalign=1,
              yticksize=10, xticksize=10,
              xlabel="x", ylabel="y"),
        Legend=(framecolor=(:black, 0.5), bgcolor=(:white, 0.5)),
        Colorbar=(tickszie=16, tickalign=1, spinewidth=0.5),
    )
end
```

And apply it to a plotting function like the following:

```
function scatters_and_lines()
    x = collect(0:10)
    xh = range(4, 6, 25)
    yh = range(70, 95, 25)
    h = randn(25, 25)
    fig = Figure(resolution=(600, 400), font="CMU Serif")
    ax = Axis(fig[1, 1]; xlabel=L"x", ylabel=L"f(x,a)")
    for i in x
        lines!(ax, x, i .* x; label=latexstring("$(i) x"))
        scatter!(ax, x, i .* x; markersize=13, strokewidth=0.25,
```

```

    label=latexstring("$(i) \ x$"))
end

hm = heatmap!(xh, yh, h)
axislegend(L"f(x)"; merge=true, position=:lt, nbanks=2, labelsize=14)
Colorbar(fig[1, 2], hm, label="new default colormap")
limits!(ax, -0.5, 10.5, -5, 105)
colgap!(fig.layout, 5)
fig
end

```

```
with_theme(scatters_and_lines, new_cycle_theme())
```

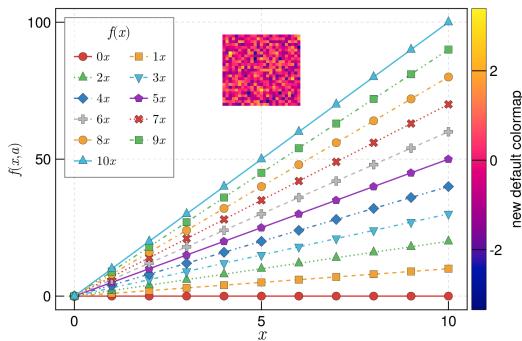


Figure 6.21: Custom theme with new cycle and colormap.

At this point you should be able to have **complete control** over your colors, line styles, markers and colormaps for your plots. Next, we will dive into how to manage and control **layouts**.

6.8 Layouts

A complete *canvas/layout* is defined by `Figure`, which can be filled with content after creation. We will start with a simple arrangement of one `Axis`, one `Legend` and one `Colorbar`. For this task we can think of the canvas as an arrangement of rows and columns in indexing a `Figure` much like a regular `Array/Matrix`. The `Axis` content will be in *row 1, column 1*, e.g. `fig[1, 1]`, the `Colorbar` in *row 1, column 2*, namely `fig[1, 2]`. And the `Legend` in *row 2* and across *column 1 and 2*, namely `fig[2, 1:2]`.

```

function first_layout()
    seed!(123)
    x, y, z = randn(6), randn(6), randn(6)
    fig = Figure(resolution=(600, 400), backgroundcolor=:snow2)
    ax = Axis(fig[1, 1], backgroundcolor=:white)
    pltobj = scatter!(ax, x, y; color=z, label="scatters")
    lines!(ax, x, 1.1y; label="line")

```

```

Legend(fig[2, 1:2], ax, "labels", orientation=:horizontal)
Colorbar(fig[1, 2], pltobj, label="colorbar")
fig
end
JDS.first_layout()

```

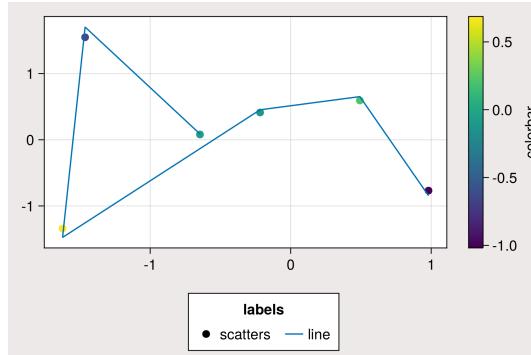


Figure 6.22: First Layout.

This does look good already, but it could be better. We could fix spacing problems using the following keywords and methods:

- `figure_padding=(left, right, bottom, top)`
- `padding=(left, right, bottom, top)`

Taking into account the actual size for a `Legend` or `Colorbar` is done by

- `tellheight=true` or `false`
- `tellwidth=true` or `false`

Setting these to true will take into account the actual size (height or width) for a Legend or Colorbar. Consequently, things will be resized accordingly.

The space between columns and rows is specified as

- `colgap!(fig.layout, col, separation)`
- `rowgap!(fig.layout, row, separation)`

Column gap (colgap!), if col is given then the gap will be applied to that specific column. Row gap (rowgap!), if row is given then the gap will be applied to that specific row.

Also, we will see how to put content into the **protrusions**, i.e. the space reserved for `title`: `x` and `y`; either ticks or label. We do this by plotting into `fig[i, j, protrusion]` where `protrusion` can be `Left()`, `Right()`, `Bottom()` and `Top()`, or for each corner `TopLeft()`, `TopRight()`, `BottomRight()`, `BottomLeft()`. See below how these options are being used:

```

function first_layout_fixed()
    seed!(123)
    x, y, z = randn(6), randn(6), randn(6)
    fig = Figure(figsize_padding=(0, 3, 5, 2), resolution=(600, 400),
                backgroundcolor=:snow2, font="CMU Serif")
    ax = Axis(fig[1, 1], xlabel=L"x", ylabel=L"y",
              title="Layout example", backgroundcolor=:white)
    pltobj = scatter!(ax, x, y; color=z, label="scatters")
    lines!(ax, x, 1.1y; label="line")
    Legend(fig[2, 1:2], ax, "Labels", orientation=:horizontal,
           tellheight=true, titleposition=:left)
    Colorbar(fig[1, 2], pltobj, label="colorbar")
    # additional aesthetics
    Box(fig[1, 1, Right()], color(:snow4, 0.35))
    Label(fig[1, 1, Right()], "protrusion", fontsize=18,
          rotation=pi / 2, padding=(3, 3, 3, 3))
    Label(fig[1, 1, TopLeft()], "(a)", fontsize=18, padding=(0, 3, 8, 0))
    colgap!(fig.layout, 5)
    rowgap!(fig.layout, 5)
    fig
end
JDS.first_layout_fixed()

```

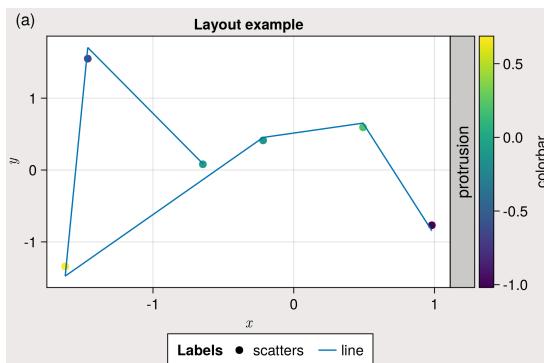


Figure 6.23: First Layout Fixed.

Here, having the label (a) in the `TopLeft()` is probably not necessary, this will only make sense for more than one plot. Also, note the use of `padding`, which allows more fine control over his position.

For our next example let's keep using the previous tools and some more to create a richer and complex figure.

Having the same limits across different plots can be done via your `Axis` with:

- `linkaxes!`, `linkyaxes!` and `linkxaxes!`

This could be useful when shared axis are desired. Another way of getting shared axis will be by setting `limits!`.

Now, the example:

```
function complex_layout_double_axis()
    seed!(123)
    x = range(0, 1, 10)
    y = range(0, 1, 10)
    z = rand(10, 10)
    fig = Figure(resolution=(700, 400),
        font="CMU Serif",
        backgroundcolor=:snow2
    )
    ax1 = Axis(fig, xlabel=L"x", ylabel=L"y")
    ax2 = Axis(fig, xlabel=L"x")
    heatmap!(ax1, x, y, z; colorange=(0, 1))
    series!(ax2, abs.(z[1:4, :]));
    labels=["lab $i" for i = 1:4], color=:Set1_4)
    hm = scatter!(10x, y; color=z[1, :], label="dots", colorange=(0, 1))
    hideydecorations!(ax2, ticks=false, grid=false)
    linkyaxes!(ax1, ax2)
    #layout
    fig[1, 1] = ax1
    fig[1, 2] = ax2
    Label(fig[1, 1], TopLeft()), "(a)", fontsize=18, padding=(0, 6, 8, 0))
    Label(fig[1, 2], TopLeft()), "(b)", fontsize=18, padding=(0, 6, 8, 0))
    Colorbar(fig[2, 1:2], hm, label="colorbar",
        vertical=false, flipaxis=false
    )
    Legend(fig[1, 3], ax2, "Legend")
    colgap!(fig.layout, 5)
    rowgap!(fig.layout, 5)
    fig
end
JDS.complex_layout_double_axis()
```

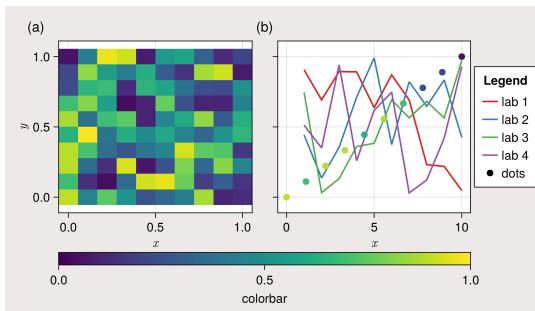


Figure 6.24: Complex layout double axis.

So, now our `Colorbar` is horizontal and the bar ticks are in the lower part. This is done by setting `vertical=false` and `flipaxis=false`. Additionally, note that we can call many `Axis` into `fig`, or even `Colorbar`'s and `Legend`'s, and then afterwards build the layout.

Another common layout is a grid of squares for heatmaps:

```
function squares_layout()
    seed!(123)
    letters = reshape(collect('a':'d'), (2, 2))
    fig = Figure(resolution=(600, 400), fontsize=14, font="CMU Serif",
        backgroundcolor=:snow2)
    axs = [Axis(fig[i, j], aspect=AspectData()) for i = 1:2, j = 1:2]
    hms = [heatmap!(axs[i, j], randn(10, 10), colormap=(-2, 2))
        for i = 1:2, j = 1:2]
    Colorbar(fig[1:2, 3], hms[1], label="colorbar")
    [Label(fig[i, j, TopLeft()], "($letters[i, j])", fontsize=16,
        padding=(-2, 0, -20, 0)) for i = 1:2, j = 1:2]
    colgap!(fig.layout, 5)
    rowgap!(fig.layout, 5)
    fig
end
JDS.squares_layout()
```

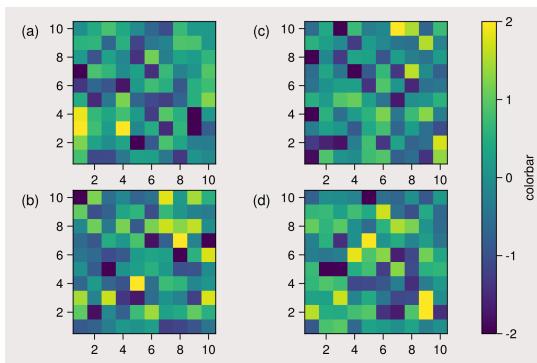


Figure 6.25: Squares layout.

where all labels are in the **protrusions** and each `Axis` has an `AspectData()` ratio. The `Colorbar` is located in the third column and expands from row 1 up to row 2.

The next case uses the so called `Mixed()` **alignmode**, which is especially useful when dealing with large empty spaces between `Axis` due to long ticks. Also, the `Dates` module from Julia's standard library will be needed for this example.

```
using Dates
```

```
function mixed_mode_layout()
    seed!(123)
    longlabels = ["$(today() - Day(1))", "$(today())", "$(today() + Day(1))"]
    fig = Figure(resolution=(600, 400), fontsize=12,
        backgroundcolor=:snow2, font="CMU Serif")
    ax1 = Axis(fig[1, 1], xlabel="x", alignmode=Mixed(bottom=0),
    ax2 = Axis(fig[1, 2], xticklabelrotation=π/2, alignmode=Mixed(bottom=0),
```

```

    xticks=[[1, 5, 10], longlabels))
ax3 = Axis(fig[2, 1:2])
ax4 = Axis(fig[3, 1:2])
axs = [ax1, ax2, ax3, ax4]
[lines!(ax, 1:10, rand(10)) for ax in axs]
hidexdecorations!(ax3; ticks=false, grid=false)
Box(fig[2:3, 1:2, Right()], color=:snow4, 0.35)
Label(fig[2:3, 1:2, Right()], "protrusion", rotation=π/2, fontsize=14,
      padding=(3, 3, 3, 3))
Label(fig[1, 1:2, Top()], "Mixed alignmode", fontsize=16,
      padding=(0, 0, 15, 0))
colsizes!(fig.layout, 1, Auto(2))
rowsizes!(fig.layout, 2, Auto(0.5))
rowsizes!(fig.layout, 3, Auto(0.5))
rowgap!(fig.layout, 1, 15)
rowgap!(fig.layout, 2, 0)
colgap!(fig.layout, 5)
fig
end
JDS.mixed_mode_layout()

```

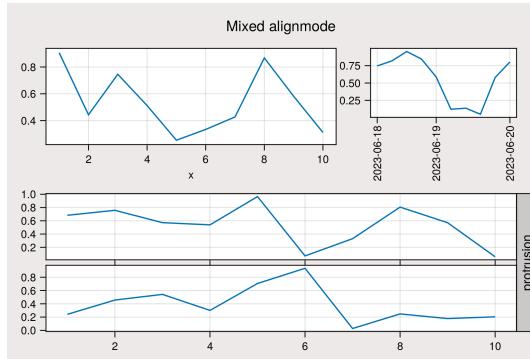


Figure 6.26: Mixed mode layout.

Here, the argument `alignmode=Mixed(bottom=0)` is shifting the bounding box to the bottom, so that this will align with the panel on the left filling the space.

Also, see how `colsizes!` and `rowsizes!` are being used for different columns and rows. You could also put a number instead of `Auto()` but then everything will be fixed. And, additionally, one could also give a `height` or `width` when defining the `Axis`, as in `Axis(fig, height=50)` which will be fixed as well.

6.8.1 Nested Axis (subplots)

It is also possible to define a set of `Axis` (*subplots*) explicitly, and use it to build a main figure with several rows and columns. For instance, the following is a “complicated” arrangement of `Axis`:

```
function nested_sub_plot!(f)
    backgroundcolor = rand(resample_cmap(:Pastel1_6, 6, alpha=0.25))
    ax1 = Axis(f[1, 1]; backgroundcolor)
    ax2 = Axis(f[1, 2]; backgroundcolor)
    ax3 = Axis(f[2, 1:2]; backgroundcolor)
    ax4 = Axis(f[1:2, 3]; backgroundcolor)
    return (ax1, ax2, ax3, ax4)
end
```

which, when used to build a more complex figure by doing several calls, we obtain:

```
function main_figure()
    fig = Figure()
    Axis(fig[1, 1])
    nested_sub_plot!(fig[1, 2])
    nested_sub_plot!(fig[1, 3])
    nested_sub_plot!(fig[2, 1:3])
    fig
end

JDS.main_figure()
```

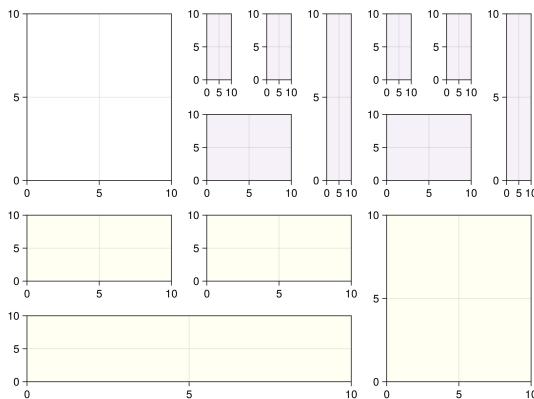


Figure 6.27: Main figure.

Note that different subplot functions can be called here. Also, each `Axis` here is an independent part of `Figure`. So that, if you need to do some `rowgap!`'s or `colsizes!`'s operations, you will need to do it in each one of them independently or to all of them together.

For grouped `Axis` (`subplots`) we can use `GridLayout()` which, then, could be used to compose a more complicated `Figure`.

6.8.2 Nested GridLayout

By using `GridLayout()` we can group subplots, allowing more freedom to build complex figures. Here, using our previous `nested_sub_plot!` we define three sub-groups and one normal `Axis`:

```
function nested_Grid_Layouts()
    fig = Figure(backgroundcolor=RGBf(0.96, 0.96, 0.96))
    ga = fig[1, 1] = GridLayout()
    gb = fig[1, 2] = GridLayout()
    gc = fig[1, 3] = GridLayout()
    gd = fig[2, 1:3] = GridLayout()
    gA = Axis(ga[1, 1])
    nested_sub_plot!(gb)
    axsc = nested_sub_plot!(gc)
    nested_sub_plot!(gd)
    hidedecorations!.(axsc, grid=false, ticks=false)
    colgap!(gc, 5)
    rowgap!(gc, 5)
    rowsize!(fig.layout, 2, Auto(0.5))
    colsizes!(fig.layout, 1, Auto(0.5))
    fig
end
JDS.nested_Grid_Layouts()
```

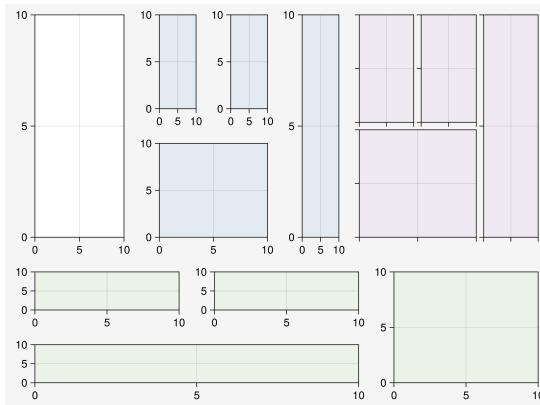


Figure 6.28: Nested Grid Layouts.

Now, using `rowgap!` or `colsizes!` over each group is possible and `rowsize!, colsizes! ↪!` can also be applied to the set of `GridLayout()`s.

6.8.3 Inset plots

Currently, doing inset plots is a little bit tricky. Here, we show two possible ways of doing it by initially defining auxiliary functions. The first one is by doing a `BBox`, which lives in the whole `Figure` space:

```
function add_box_inset(fig; bgcolor=:snow2,
    left=100, right=250, bottom=200, top=300)
    inset_box = Axis(fig, bbox=BBox(left, right, bottom, top),
        xticklabelsize=12, yticklabelsize=12, backgroundcolor=bgcolor)
    translate!(inset_box.scene, 0, 0, 10) # bring content upfront
    return inset_box
end
```

Then, the `inset` is easily done, as in:

```
function figure_box_inset()
    fig = Figure(resolution=(600, 400))
    ax = Axis(fig[1, 1], backgroundcolor=:white)
    inset_ax1 = add_box_inset(fig; bgcolor=:snow2,
        left=100, right=250, bottom=200, top=300)
    inset_ax2 = add_box_inset(fig; bgcolor=(:white, 0.85),
        left=500, right=580, bottom=100, top=200)
    lines!(ax, 1:10)
    lines!(inset_ax1, 1:10)
    scatter!(inset_ax2, 1:10, color=:black)
    fig
end
JDS.figure_box_inset()
```

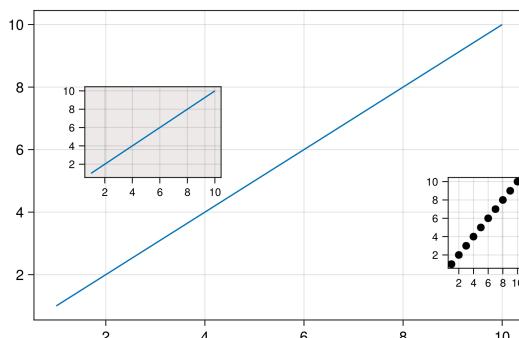


Figure 6.29: Figure box inset.

where the Box dimensions are bound by the Figure's resolution. Note, that an inset can be also outside the Axis. The other approach, is by defining a new Axis into a position `fig[i, j]` specifying his `width`, `height`, `halign` and `valign`. We do that in the following function:

```
function add_axis_inset(pos=fig[1, 1]; bgcolor=:snow2,
    halign, valign, width=Relative(0.5), height=Relative(0.35),
    alignmode=Mixed(left=5, right=5))
    inset_box = Axis(pos; width, height, halign, valign, alignmode,
        xticklabelsize=12, yticklabelsize=12, backgroundcolor=bgcolor)
    # bring content upfront
```

```

    translate!(inset_box.scene, 0, 0, 10)
    return inset_box
end

```

See that in the following example the `Axis` with gray background will be rescaled if the total figure size changes. The `insets` are bound by the `Axis` positioning.

```

function figure_axis_inset()
    fig = Figure(resolution=(600, 400))
    ax = Axis(fig[1, 1], backgroundcolor=:white)
    inset_ax1 = add_axis_inset(fig[1, 1]; bgcolor=:snow2,
        halign=:left, valign=:center,
        width=Relative(0.3), height=Relative(0.35),
        alignmode=Mixed(left=5, right=5, bottom=15))
    inset_ax2 = add_axis_inset(fig[1, 1]; bgcolor=(:white, 0.85),
        halign=:right, valign=:center,
        width=Relative(0.25), height=Relative(0.3))
    lines!(ax, 1:10)
    lines!(inset_ax1, 1:10)
    scatter!(inset_ax2, 1:10, color=:black)
    fig
end
JDS.figure_axis_inset()

```

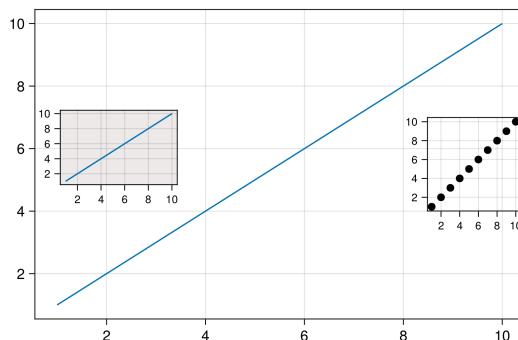


Figure 6.30: Figure axis inset.

And this should cover most used cases for layouting with Makie. Now, let's do some nice 3D examples with `GLMakie.jl`.

6.9 *GLMakie.jl*

`CairoMakie.jl` fulfills all our needs for static 2D images. But sometimes we want interactivity, especially when we are dealing with 3D images. Visualizing data in 3D is also a common practice to gain insight from your data. This is where ¹⁴ <http://www.opengl.org> `GLMakie.jl` comes into play, since it uses OpenGL¹⁴ as a backend that adds in-

teractivity and responsiveness to plots. Like before, a simple plot includes, of course, lines and points. So, we will start with those and since we already know how layouts work, we will put that into practice.

6.9.1 *Scatters and Lines*

For scatter plots we have two options, the first one is `scatter(x, y, z)` and the second one is `meshscatter(x, y, z)`. In the former, markers don't scale in the axis directions and in the latter they do because they are actual geometries in 3D space. See the next example:

```
using GLMakie
GLMakie.activate!()
```

```
function scatters_in_3D()
    seed!(123)
    n = 10
    x, y, z = randn(n), randn(n), randn(n)
    aspect=(1, 1, 1)
    perspectiveness=0.5
    # the figure
    fig = Figure(; resolution=(1200, 400))
    ax1 = Axis3(fig[1, 1]; aspect, perspectiveness)
    ax2 = Axis3(fig[1, 2]; aspect, perspectiveness)
    ax3 = Axis3(fig[1, 3]; aspect=:data, perspectiveness)
    scatter!(ax1, x, y, z; markersize=15)
    meshscatter!(ax2, x, y, z; markersize=0.25)
    hm = meshscatter!(ax3, x, y, z; markersize=0.25,
        marker=Rect3f(Vec3f(0), Vec3f(1)), color=1:n,
        colormap=:plasma, transparency=false)
    Colorbar(fig[1, 4], hm, label="values", height=Relative(0.5))
    colgap!(fig.layout, 5)
    fig
end
JDS.scatters_in_3D()
```

Note also, that a different geometry can be passed as markers, i.e., a square/rectangle, and we can assign a `colormap` for them as well. In the middle panel one could get perfect spheres by doing `aspect = :data` as in the right panel.

And doing `lines` or `scatterlines` is also straightforward:

```
function lines_in_3D()
    seed!(123)
    n = 10
    x, y, z = randn(n), randn(n), randn(n)
    aspect=(1, 1, 1)
```

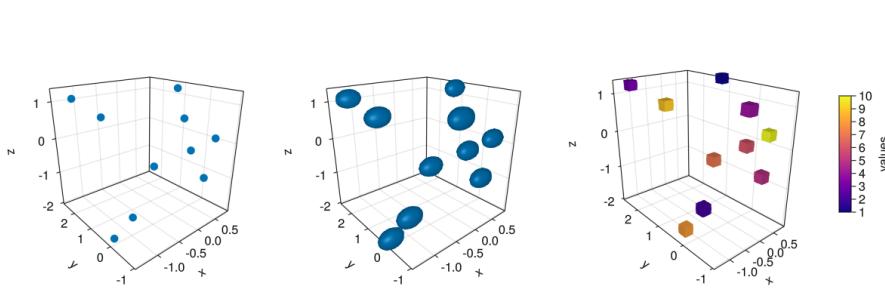


Figure 6.31: Scatters in 3D.

```

perspectiveness=0.5
# the figure
fig = Figure(; resolution=(1200, 500))
ax1 = Axis3(fig[1, 1]; aspect, perspectiveness)
ax2 = Axis3(fig[1, 2]; aspect, perspectiveness)
ax3 = Axis3(fig[1, 3]; aspect=:data, perspectiveness)
lines!(ax1, x, y, z; color=1:n, linewidth=3)
scatterlines!(ax2, x, y, z; markersize=15)
hm = meshscatter!(ax3, x, y, z; markersize=0.2, color=1:n)
lines!(ax3, x, y, z; color=1:n)
Colorbar(fig[2, 1], hm; label="values", height=15, vertical=false,
    flipaxis=false, ticksize=15, tickalign=1, width=Relative(3.55/4))
fig
end
JDS.lines_in_3D()

```

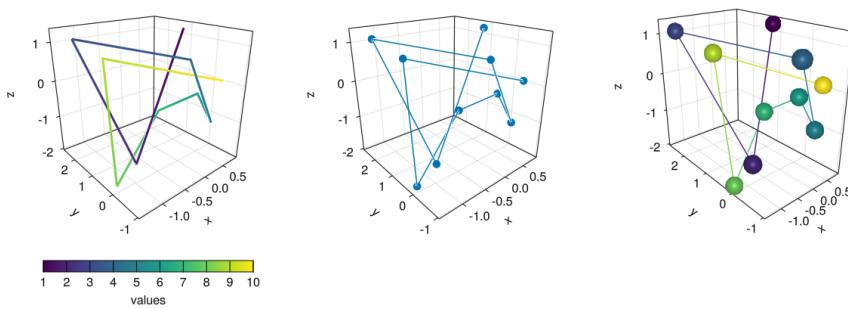


Figure 6.32: Lines in 3D.

Plotting a surface is also easy to do as well as a `wireframe` and `contour` lines in 3D.

6.9.2 Surfaces, wireframe, contour, contourf and contour3d

To show these cases we'll use the following `peaks` function:

```
function peaks(; n=49)
    x = range(-3, 3, n)
    y = range(-3, 3, n)
    a = 3 * (1 .- x') .^ 2 .* exp.(-(x' .^ 2) .- (y .+ 1) .^ 2)
    b = 10 * (x' / 5 .- x' .^ 3 .- y .^ 5) .* exp.(-x' .^ 2 .- y .^ 2)
    c = 1 / 3 * exp.(-(x' .+ 1) .^ 2 .- y .^ 2)
    return (x, y, a .- b .- c)
end
```

The output for the different plotting functions is

```
function plot_peaks_function()
    x, y, z = peaks()
    x2, y2, z2 = peaks(; n=15)
    fig = Figure(resolution=(1200, 400))
    axs = [Axis3(fig[1, i]; aspect=(1, 1, 1)) for i = 1:3]
    hm = surface!(axs[1], x, y, z)
    wireframe!(axs[2], x2, y2, z2)
    contour3d!(axs[3], x, y, z; levels=20)
    Colorbar(fig[1, 4], hm, height=Relative(0.5))
    fig
end
JDS.plot_peaks_function()
```

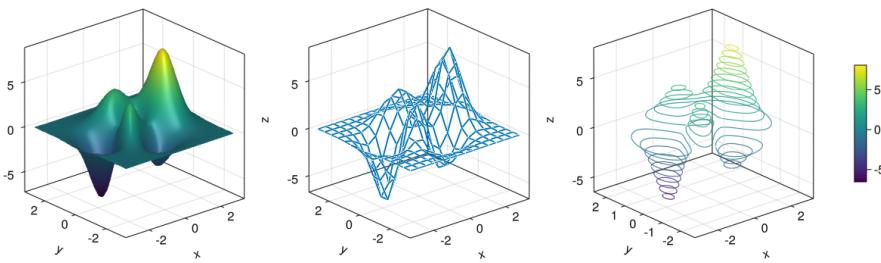


Figure 6.33: Plot peaks function.

But, it can also be plotted with a `heatmap(x, y, z)`, `contour(x, y, z)` or `contourf(x ↳, y, z)`:

```
function heatmap_contour_and_contourf()
    x, y, z = peaks()
    fig = Figure(resolution=(1200, 400))
    axs = [Axis(fig[1, i]; aspect=DataAspect()) for i = 1:3]
    hm = heatmap!(axs[1], x, y, z)
    contour!(axs[2], x, y, z; levels=20)
    contourf!(axs[3], x, y, z)
    Colorbar(fig[1, 4], hm, height=Relative(0.5))
    fig
```

```
end
JDS.heatmap_contour_and_contourf()
```

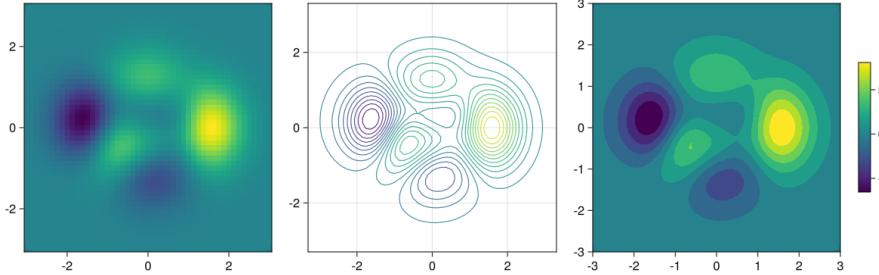


Figure 6.34: Heatmap, contour and contourf.

Additionally, by changing `Axis` to an `Axis3`, these plots will be automatically be in the x-y plane at `z=0`:

```
function heatmap_contour_and_contourf_in_a_3d_plane()
    x, y, z = peaks()
    fig = Figure(resolution=(1200, 400))
    axs = [Axis3(fig[1, i]) for i = 1:3]
    hm = heatmap!(axs[1], x, y, z)
    contour!(axs[2], x, y, z; levels=20)
    contourf!(axs[3], x, y, z)
    Colorbar(fig[1, 4], hm, height=Relative(0.5))
    fig
end
JDS.heatmap_contour_and_contourf_in_a_3d_plane()
```

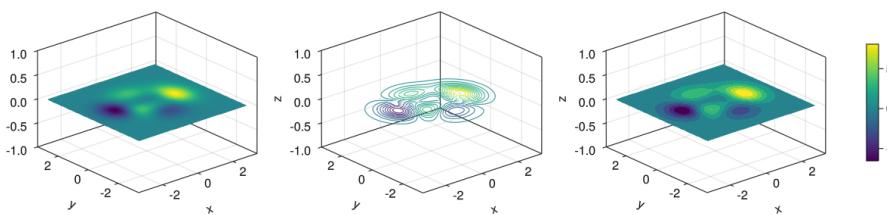


Figure 6.35: Heatmap, contour and contourf in a 3d plane.

Something else that is easy to do is to mix all these plotting functions into just one plot, namely:

```
using TestImages
```

```

function mixing_surface_contour3d_contour_and_contourf()
    img = testimage("coffee.png")
    x, y, z = peaks()
    cmap = :Spectral_11
    fig = Figure(resolution=(1200, 800), fontsize=26)
    ax1 = Axis3(fig[1, 1]; aspect=(1, 1, 1),
                elevation=π/6, perspectiveness=0.5,
                xzpanelcolor=(:black, 0.75), yzpanelcolor=:black,
                zgridcolor=:grey70, ygridcolor=:grey70, xgridcolor=:grey70)
    ax2 = Axis3(fig[1, 3]; aspect=(1, 1, 1),
                elevation=π/6, perspectiveness=0.5)
    hm = surface!(ax1, x, y, z; colormap=(cmap, 0.95), shading=true)
    contour3d!(ax1, x, y, z .+ 0.02; colormap=cmap, levels=20, linewidth=2)
    # get final limits
    xmin, ymin, zmin = minimum(ax1.finallimits[])
    xmax, ymax, zmax = maximum(ax1.finallimits[])
    contour!(ax1, x, y, z; colormap=cmap, levels=20,
              transformation=(:xy, zmax))
    contourf!(ax1, x, y, z; colormap=cmap,
              transformation=(:xy, zmin))
    Colorbar(fig[1, 2], hm, width=15, ticksize=15, tickalign=1,
             height=Relative(0.35))
    # transformations into planes
    heatmap!(ax2, x, y, z; colormap=:viridis,
              transformation=(:yz, 3.5))
    contourf!(ax2, x, y, z; colormap=:CMRmap,
              transformation=(:xy, -3.5))
    contourf!(ax2, x, y, z; colormap=:bone_1,
              transformation=(:xz, 3.5))
    image!(ax2, -3 .. 3, -3 .. 2, rotr90(img);
           transformation=(:xy, 3.8))
    xlims!(ax2, -3.8, 3.8)
    ylims!(ax2, -3.8, 3.8)
    zlims!(ax2, -3.8, 3.8)
    fig
end
JDS.mixing_surface_contour3d_contour_and_contourf()

```

Not bad, right? From there is clear that any `heatmap`'s, `contour`'s, `contourf`'s or `image` can be plotted into any plane via a `transformation` and that the planes can be coloured, i.e. `xzpanelcolor=:black`.

6.9.3 Arrows and Streamplots

`arrows` and `streamplot` are plots that might be useful when we want to know the directions that a given variable will follow. See a demonstration below¹⁵:

¹⁵ we are using the `LinearAlgebra` module from Julia's standard library.

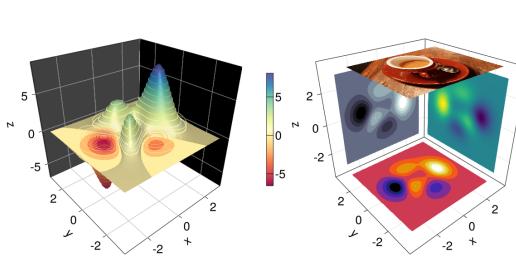


Figure 6.36: Mixing surface, `contour3d`, `contour` and `contourf`.

```
using LinearAlgebra
```

```
function arrows_and_streamplot_in_3d()
    ps = [Point3f(x, y, z) for x=-3:1:3 for y=-3:1:3 for z=-3:1:3]
    ns = map(p -> 0.1 * rand() * Vec3f(p[2], p[3], p[1]), ps)
    lengths = norm.(ns)
    flowField(x, y, z) = Point(-y + x * (-1 + x^2 + y^2)^2,
        x + y * (-1 + x^2 + y^2)^2, z + x * (y - z^2))
    fig = Figure(resolution=(1200, 800), fontsize=26)
    axs = [Axis3(fig[i, i]; aspect=(1,1,1), perspectiveness=0.5) for i=1:2]
    arrows!(axs[1], ps, ns, color=lengths, arrowsize=Vec3f(0.2, 0.2, 0.3),
        linewidth=0.1)
    streamplot!(axs[2], flowField, -4 .. 4, -4 .. 4, -4 .. 4,
        colormap=:plasma, gridsize=(7, 7), arrow_size=0.25, linewidth=1)
    fig
end
JDS.arrows_and_streamplot_in_3d()
```

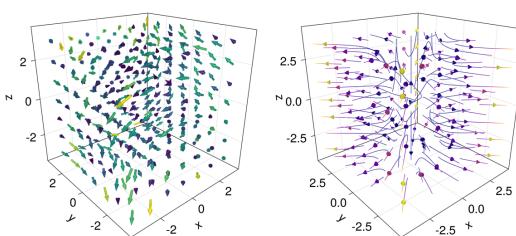


Figure 6.37: Arrows and streamplot in 3d.

Other interesting examples are a `mesh(obj)`, a `volume(x, y, z, vals)`, and a `contour ↪(x, y, z, vals)`.

6.9.4 Meshes and Volumes

Drawing meshes comes in handy when you want to plot geometries, like a Sphere or a Rectangle, i.e. FRect3D. Another approach to visualize points in 3D space is by calling the functions `volume` and `contour`, which implements ray tracing¹⁶ to simulate a wide variety of optical effects. See the next examples:

¹⁶ [https://en.wikipedia.org/wiki/Ray_tracing_\(graphics\)](https://en.wikipedia.org/wiki/Ray_tracing_(graphics))

```
using GeometryBasics
```

```
function mesh_volume_contour()
    # mesh objects
    rectMesh = Rect3f(Vec3f(-0.5), Vec3f(1))
    recmesh = GeometryBasics.mesh(rectMesh)
    sphere = Sphere(Point3f(0), 1)
    # https://juliageometry.github.io/GeometryBasics.jl/stable/primitives/
    spheremesh = GeometryBasics.mesh(Tesselation(sphere, 64))
    # uses 64 for tesselation, a smoother sphere
    colors = [rand() for v in recmesh.position]
    # cloud points for volume
    x = y = z = 1:10
    vals = randn(10, 10, 10)
    fig = Figure(resolution=(1200, 400))
    axs = [Axis3(fig[1, i]; aspect=(1,1,1), perspectiveness=0.5) for i=1:3]
    mesh!(axs[1], recmesh; color=colors, colormap=:rainbow, shading=false)
    mesh!(axs[1], spheremesh; color=(:white, 0.25), transparency=true)
    volume!(axs[2], x, y, z, vals; colormap=Reverse(:plasma))
    contour!(axs[3], x, y, z, vals; colormap=Reverse(:plasma))
    fig
end
JDS.mesh_volume_contour()
```

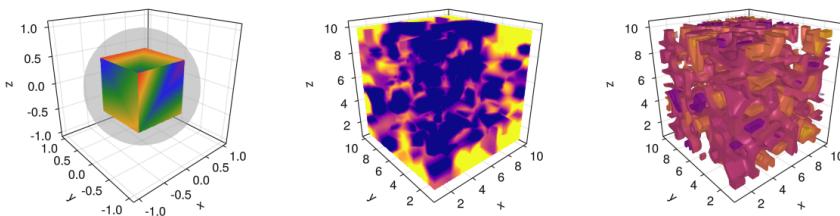


Figure 6.38: Mesh volume contour.

Note that here we are plotting two meshes into the same axis, one transparent sphere and a cube. So far, we have covered most of the 3D use-cases.

Taking as reference the previous example one can do the following custom plot with spheres and rectangles:

```
using GeometryBasics, Colors
```

For the spheres let's do a rectangular grid. Also, we will use a different color for each one of them. Additionally, we can mix spheres and a rectangular plane. Next, we define all the necessary data.

```
seed!(123)
spheresGrid = [Point3f(i,j,k) for i in 1:2:10 for j in 1:2:10
    for k in 1:2:10]
colorSphere = [RGBA(i * 0.1, j * 0.1, k * 0.1, 0.75) for i in 1:2:10
    for j in 1:2:10 for k in 1:2:10]
spheresPlane = [Point3f(i,j,k) for i in 1:2.5:23 for j in 1:2.5:10
    for k in 1:2.5:4]
cmap = get(colorschemes[:plasma], range(0, 1, 50))
colorsPlane = cmap[rand(1:50, 50)]
rectMesh = Rect3f(Vec3f(-1, -1, 2.1), Vec3f(16, 11, 0.5))
recmesh = GeometryBasics.mesh(rectMesh)
colors = [RGBA(rand(4)... for v in recmesh.position]
```

Then, the plot is simply done with:

```
function grid_spheres_and_rectangle_as_plate()
    perspectiveness=0.5
    aspect = :data
    # now the figure
    fig = with_theme(theme_dark()) do
        fig = Figure(resolution=(1200, 800))
        ax1 = Axis3(fig[1, 1]; aspect, perspectiveness, azimuth=0.72)
        ax2 = Axis3(fig[1, 2]; aspect, perspectiveness)
        meshscatter!(ax1, spheresGrid; color=colorSphere, markersize=1,
            shading=false)
        meshscatter!(ax2, spheresPlane; color=colorsPlane, markersize=0.75,
            lightposition=Vec3f(10, 5, 2),
            ambient=Vec3f(0.95, 0.95, 0.95),
            backlight=1.0f0)
        mesh!(recmesh; color=colors, colormap=:rainbow, shading=false)
        limits!(ax1, 0, 10, 0, 10, 0, 10)
        fig
    end
    fig
end
JDS.grid_spheres_and_rectangle_as_plate()
```

Here, the rectangle is semi-transparent due to the alpha channel added to the RGB color. The rectangle function is quite versatile, for instance 3D boxes are easy to implement which in turn could be used for plotting a 3D histogram.

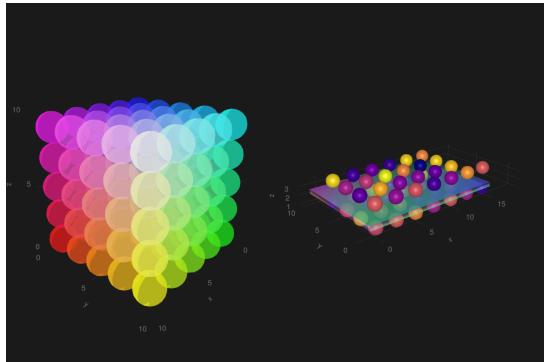


Figure 6.39: Grid spheres and rectangle as plate.

See our next example, where we are using again the `peaks` function and some additional definitions:

```
x, y, z = peaks(; n=15)
δx = (x[2] - x[1]) / 2
δy = (y[2] - y[1]) / 2
cbarPal = :Spectral_11
ztmp = (z .- minimum(z)) ./ (maximum(z .- minimum(z)))
cmap = get(colorschemes[cbarPal], ztmp)
cmap2 = reshape(cmap, size(z))
ztmp2 = abs.(z) ./ maximum(abs.(z)) .+ 0.15
```

here $\delta x, \delta y$ are used to specify the box sizes. `cmap2` will be the color for each box and `ztmp2` will be used as a transparency parameter. See the output in the next figure.

```
function histogram_or_bars_in_3d()
    fig = Figure(resolution=(1200, 800), fontsize=26)
    ax1 = Axis3(fig[1, 1]; aspect=(1,1,1), elevation=π/6,
                perspectiveness=0.5)
    ax2 = Axis3(fig[1, 2]; aspect=(1,1,1), perspectiveness=0.5)
    rectMesh = Rect3f(Vec3f(-0.5, -0.5, 0), Vec3f(1, 1, 1))
    meshscatter!(ax1, x, y, 0 * z; marker=rectMesh, color=z[:],
                markersize=Vec3f.(2δx, 2δy, z[:]), colormap=:Spectral_11,
                shading=false)
    limits!(ax1, -3.5, 3.5, -3.5, 3.5, -7.45, 7.45)
    meshscatter!(ax2, x, y, 0 * z; marker=rectMesh, color=z[:],
                markersize=Vec3f.(2δx, 2δy, z[:]), colormap=(:Spectral_11, 0.25),
                shading=false, transparency=true)
    for (idx, i) in enumerate(x), (idy, j) in enumerate(y)
        rectMesh=Rect3f(Vec3f(i-δx, j-δy, 0), Vec3f(2δx, 2δy, z[idx,idy]))
        recmesh=GeometryBasics.mesh(rectMesh)
        lines!(ax2, recmesh; color=(cmap2[idx, idy], ztmp2[idx, idy]))
    end
    fig
end
```

```
JDS.histogram_or_bars_in_3d()
```

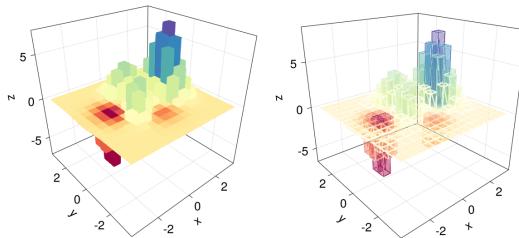


Figure 6.40: Histogram or bars in 3d.

Note, that you can also call `lines` or `wireframe` over a mesh object.

6.9.5 Filled Line and Band

For our last example we will show how to do a filled curve in 3D with `band` and some `linesegments`:

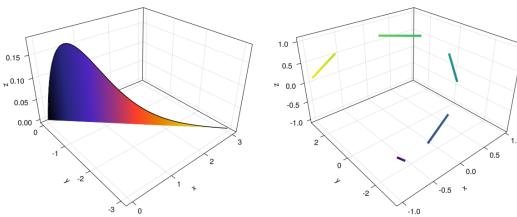
```
function filled_line_and_linesegments_in_3D()
    xs = range(-3, 3, 10)
    lower = [Point3f(i, -i, 0) for i in range(0, 3, 100)]
    upper = [Point3f(i, -i, sin(i) * exp(-(i + i)))
        for i in range(0, 3, length=100)]
    fig = Figure(resolution=(1200, 800))
    axs = [Axis3(fig[1], i; elevation=π/6, perspectiveness=0.5) for i=1:2]
    band!(axs[1], lower, upper; color=repeat(norm.(upper), outer=2),
        colormap=:CMRmap)
    lines!(axs[1], upper, color=:black)
    linesegments!(axs[2], cos.(xs), xs, sin.(xs); linewidth=5,
        color=1:length(xs))
    fig
end
JDS.filled_line_and_linesegments_in_3D()
```

Finally, our journey doing 3D plots has come to an end. You can combine everything we exposed here to create amazing 3D images!

6.10 A Makie recipe for a DataFrame

Unlike other libraries that already support a wide set of input formats via recipes, i.e. `Plots.jl`, in `Makie.jl` most of the time we need to pass the raw data to functions. However, we can also define our own recipe in `Makie.jl`. A recipe is

Figure 6.41: Filled line and linesegments in 3D.



your own custom plotting type command. This extension is done just in `Makie`. ↗`jL`, which means that making a new set of plotting rules for your own types is light, namely, you don't need the complete plotting machinery available to define them. This is specially useful if you want to include your own plotting commands in one of your own packages. However, in order for them to work you will still need to use one of the backends, i.e., `GLMakie` or `CairoMakie`.

As an example we will code a small **full recipe** for a `DataFrame`. Please refer to the documentation¹⁷ for more details.

¹⁷ <https://docs.makie.org/stable/documentation/recipes/>

A `Makie` `recipe` consist of two parts, a plot type name defined via `@recipe` and a custom `plot!(::Makie.plot)` which creates the actual plot via plotting functions already defined.

```
@recipe(DfPlot, df) do scene
    Attributes(
        x = :A,
        y = :B,
        c = :C,
        color = :red,
        colormap = :plasma,
        markersize = 20,
        marker = :rect,
        colorrange = (0,1),
        label = "",
    )
end
```

Note that the macro `@recipe` will automatically create two new functions for us, `dfplot` and `dfplot!`, all lowercase from our type `DfPlot`. The first one will create a complete new figure whereas the second one will plot into the current axis or an axis of your choosing. This allows us to plot `DataFrames` which contains columns named, `x`, `y`, `z`. Now, let's take care of our plot definition. We will do a simple scatter plot:

```
import Makie

function Makie.plot!(p::DfPlot{<:Tuple{<:DataFrame}})
    df = p[:df][]
    x = getproperty(df, p[:x][])
    y = getproperty(df, p[:y][])
    c = getproperty(df, p[:c][])
    scatter!(p, x, y; color = c, markersize = p[:markersize][],
              colormap = p[:colormap][], marker = p[:marker][],
              colorrange = (minimum(x), maximum(c)), label = p[:label][])
    return p
end
```

Note the extras [] at the end of each variable. Those are due to the fact that *recipes* in Makie are dynamic, meaning that our plots will update if our variables change. See observables¹⁸ to know more. Now, we apply our new plotting function to the following DataFrame:

¹⁸ <https://docs.makie.org/stable/documentation/nodes/>

```
df_recipe = DataFrame(A=randn(10), B=randn(10), C=rand(10))
```

```
fig, ax, obj = dfplot(df_recipe; label = "test")
axislegend()
Colorbar(fig[1,2], obj)
fig
```

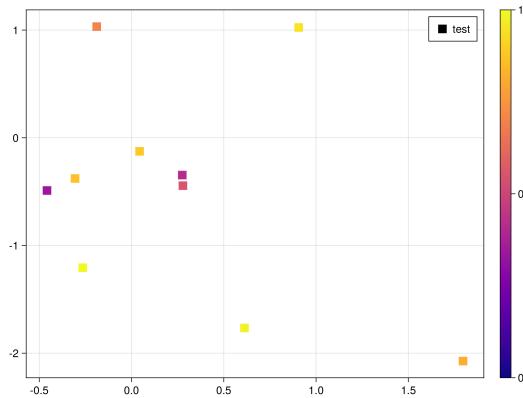


Figure 6.42:
DataFrames recipe.

The named attributes in the recipe allows us to pass custom names to our new plotting function. Namely:

```
df_names = DataFrame(a1=rand(100), a2=rand(100), a3=rand(100))
```

and:

```
dfplot(df_names; x = :a1, y = :a2, c = :a3, marker = 'o',
       axis = (; aspect=1, xlabel = "a1", ylabel = "a2"),
       figure = (; backgroundcolor = :grey90))
```

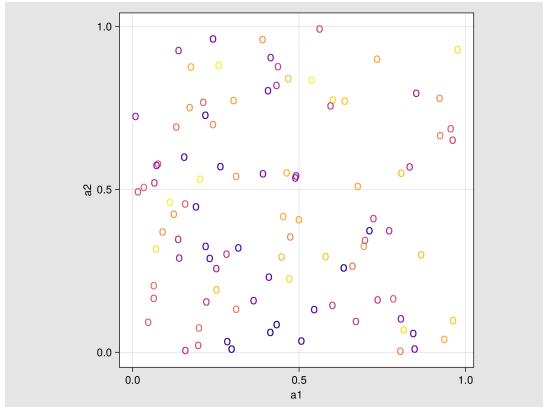


Figure 6.43:
DataFrames recipe
with arguments.

Note, that now we are calling by name each column as well as the marker type, allowing us to use this definition for different DataFrames. Additionally, all our previous options, i.e., `axis` or `figure` also work!

7 Data Visualization with `AlgebraOfGraphics.jl`

`AlgebraOfGraphics.jl` is a higher-level plotting package that uses `Makie.jl` under the hood. It is geared towards data visualization workflows with support for `DataFrames`. `AlgebraOfGraphics.jl` abstracts away some common patterns in data visualization using an interface similar to R's `ggplot2` package.

`AlgebraOfGraphics.jl` follows a layered approach to construct visualizations in a structured manner. There are four main types of layers:

- **data layer**
- **mapping layer**
- **visual transformation layer**
- **statistical transformation layer**

NOTE: `AlgebraOfGraphics.jl` has some guiding principles described in their philosophy section¹.

¹ <https://aog.makie.org/stable/philosophy/>

`AlgebraOfGraphics.jl` allows you to construct all of these types of layers with functions that return a `Layer` object, in which all of the information necessary will be encoded. You can then perform **two operations on layers**:

- **multiplication with `*`:** this fuses two or more layers into a *single* layer
- **addition with `+`:** this superimposes two or more layers into a vector of `Layers`

Finally, as the name suggests, `AlgebraOfGraphics.jl` is an algebra for `Layer` objects. And, as such, it defines two algebraic properties. Let `a`, `b` and `c` be `Layer` objects, then the following two properties hold:

- **associative property:** $(a * b) * c = a * (b * c)$
- **distributive property:** $a * (b + c) = (a * b) + (a * c)$

To get started with `AlgebraOfGraphics.jl`, you'll need to load it along with a desired `Makie.jl` backend (Chapter 6):

```
using AlgebraOfGraphics
using CairoMakie
```

7.1 Layers

We'll cover the **data layer** first, which can be created with the `data` function:

```
data_layer = data(grades_2020())
```

AlgebraOfGraphics.Layer(identity, 4x2 DataFrameColumns)		
Row	name	grade_2020
	String	Float64
1	Sally	1.0
2	Bob	5.0
3	Alice	8.5
4	Hank	4.0, Any[], {})

As you can see, `data` takes any `DataFrame` and returns a `Layer` type. You can see that we do not have any mapping, visual, or statistical transformations information yet. That will need to be specified in different layer type with different functions.

NOTE: data layers can use any `Tables.jl`² data format, including `DataFrames` and `NamedTuples`.

² <https://github.com/JuliaData/Tables.jl/blob/main/INTRODUCING.md>

Let's see how to encode data information in a **mapping layer** with the `mapping` function. This function has the following signature:

```
mapping(
    x, y, z;
    color,
    size,
    ...
)
```

The positional arguments `x`, `y`, and `z` correspond to the X-, Y- and Z-axis mappings and the keyword arguments `color`, `size`, and so on, correspond to the aesthetics mappings. The purpose of `mapping` is to encode in a `Layer` information about which columns of the underlying data `AlgebraOfGraphics.jl` will map onto the axis and other visualization aesthetics, e.g. color and size. Let's use `mapping` to encode information regarding X- and Y-axis:

```
mapping_layer = mapping(:name, :grade_2020)
```

`AlgebraOfGraphics.Layer(identity, nothing, Any[:name, :grade_2020], {})`

We pass the columns as `Symbols` in a similar manner as we did for `DataFrames`. ↵`jl` (Chapter 4) and `DataFramesMeta.jl` (Chapter 5). In the output, we see that we have successfully encoded both `:name` and `:grade_2020` columns as the X- and Y-axis, respectively.

Finally, we can use a **visual transformation layer** to encode which type of plot we want to make. This is done with the `visual` function which takes a `Makie.jl` **plotting type** as a single positional argument. All of the mappings specified in the mapping layer will be passed to the plotting type.

```
visual_layer = visual(BarPlot)
```

```
AlgebraOfGraphics.Layer(AlgebraOfGraphics.Visual(Combined{Makie.barplot}, {}),  
    ↪nothing, Any[], {})
```

The `visual_layer` is a visual transformation layer that encodes information about which type of visual transformation you want to use in your visualization plus keyword arguments that might apply to the selected plotting type.

NOTE: We are using the plotting *type* (`BarPlot`) instead of the plotting *function* (`barplot`). This is due how `AlgebraOfGraphics.jl` works. You can see all of the available mappings for all of the plotting types by inspecting their functions either using Julia's help REPL, e.g. `?barplot`, or `Makie.jl`'s documentation on plotting functions³.

³ https://docs.makie.org/stable/examples/plotting_functions/

7.1.1 Drawing Layers

Once we have all of the necessary layers we can fuse them together with * ↵ and apply the `draw` function to get a plot. The `draw` function will use all of the information from the layer it is being supplied and will send it as **plotting instructions to the activated `Makie.jl` backend**:

```
draw(data_layer * mapping_layer * visual_layer)
```

`AlgebraOfGraphics.jl` will automatically pass the underlying columns of the mapping layer from the data layer's `DataFrame` as the X- and Y-labels.

Note that you can just perform the * operations inside `draw` if you don't want to create intermediate variables:

```
plt = data(grades_2020()) * mapping(:name, :grade_2020) * visual(BarPlot)  
draw=plt)
```

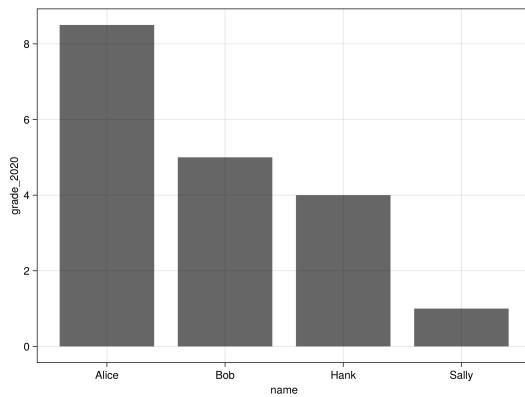


Figure 7.1: AlgebraOf-Graphics bar plot.

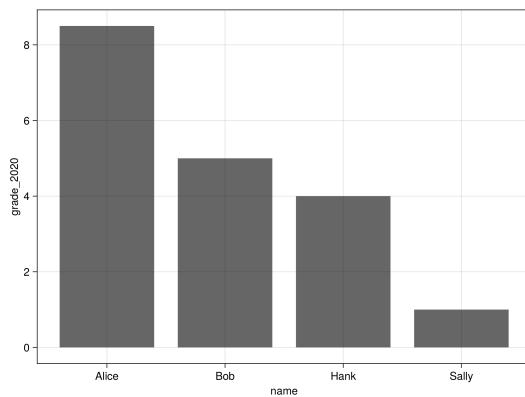


Figure 7.2: AlgebraOf-Graphics bar plot.

7.1.2 Mapping Layer Keyword Arguments

Let's try to use other mappings such as the keyword arguments `color` and `dodge` ↵ in our bar plot, since they are supported by the `BarPlot` plotting type. First, let's revisit our example `all_grades()` data defined in Chapter 4 and add a `:year` column:

```
df = @transform all_grades() :year = ["2020", "2020", "2020", "2020", "2021", "2
    ↪021", "2021"]
```

name	grade	year
Sally	1.0	2020
Bob	5.0	2020
Alice	8.5	2020
Hank	4.0	2020
Bob	9.5	2021
Sally	9.5	2021
Hank	6.0	2021

Now we can pass the `:year` column to be mapped as both a `color` and `dodge` aesthetic inside `mapping`:

```
plt = data(df) *
  mapping(
    :name,
    :grade;
    color=:year,
    dodge=:year) *
  visual(BarPlot)
draw=plt)
```

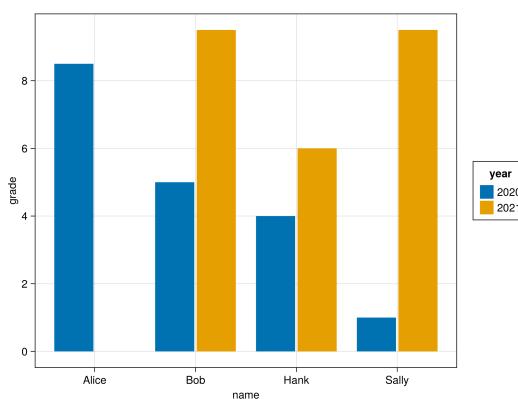


Figure 7.3: AlgebraOfGraphics bar plot with colors as year.

`AlgebraOfGraphics.jl` creates for us a legend with the underlying information from the `color` mapping column inside the data layer's `DataFrame`.

7.1.3 Transformations Inside Mapping Layers

We can also perform **transformations** inside the `mapping` function. It supports the `DataFrames.jl`'s minilanguage `source => transformation => target`. Where `source` is the original column name and `target` is a String representing the new desired label. If we simply use `source => target`, the underlying transformation will be the `identity` function, i.e., no transformation is performed and the data is passed as it is. Here's an example:

```
plt = data(df) *
    mapping(
        :name => "Name",
        :grade => "Grade";
        color=:year => "Year",
        dodge=:year) *
    visual(BarPlot)
draw=plt)
```

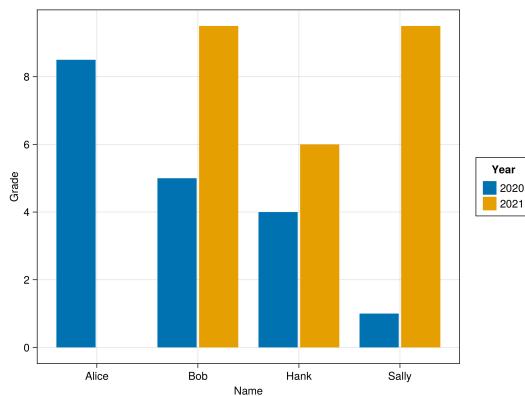


Figure 7.4: AlgebraOfGraphics bar plot with colors as year and custom labels.

Let's make use of the transformation in `source => transformation => target` to transform our grades scale from 0-10 to 0-100 and also our names to uppercase:

```
plt = data(df) *
    mapping(
        :name => uppercase => "Name",
        :grade => (x -> x*10) => "Grade";
        color=:year => "Year",
        dodge=:year) *
    visual(BarPlot)
draw=plt)
```

As you can see, we can pass both regular or anonymous functions.

NOTE: By default `AlgebraOfGraphics.jl` transformations inside `mapping` are vectorized (broadcasted) by default. Hence, we don't need to use the dot operator

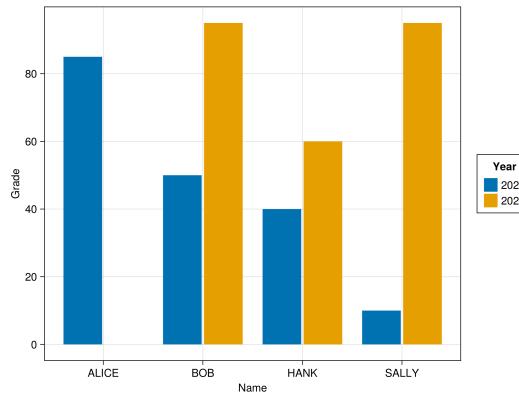


Figure 7.5: AlgebraOfGraphics bar plot with colors as year, custom labels and transformations.

..

7.2 Layouts

`AlgebraOfGraphics.jl` supports layouts with plots in multiple rows and columns, also known as *faceting*. These are specified using the keywords arguments `layout`, `row` and `col` inside `mapping`. If you use `layout`, `AlgebraOfGraphics.jl` will try to use the best combinations of rows and columns to layout the visualization:

```
plt = data(df) *
    mapping(
        :name,
        :grade;
        layout=:year) *
    visual(BarPlot)
draw=plt)
```

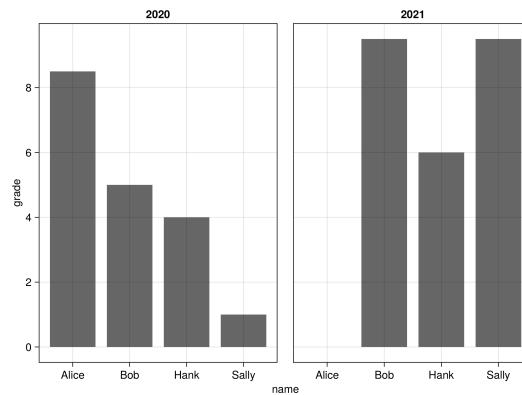


Figure 7.6: AlgebraOfGraphics bar plot with automatic layout.

However, you can override that by using either `row` or `col` for multiple rows or multiple columns layouts, respectively. Here's an example with `row`:

```
plt = data(df) *
    mapping(:name, :grade; row=:year) *
    visual(BarPlot)
draw=plt)
```

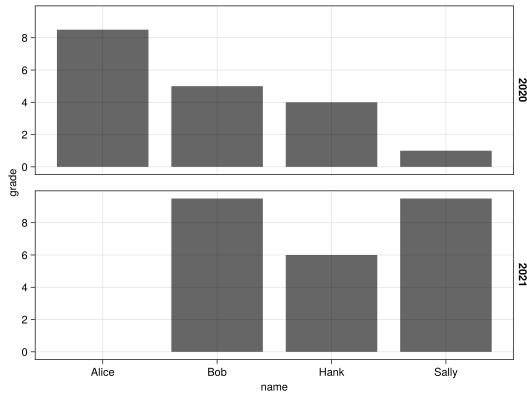


Figure 7.7: AlgebraOfGraphics bar plot with row layout.

And, finally, an example with `col`:

```
plt = data(df) *
    mapping(
        :name,
        :grade;
        col=:year) *
    visual(BarPlot)
draw=plt)
```

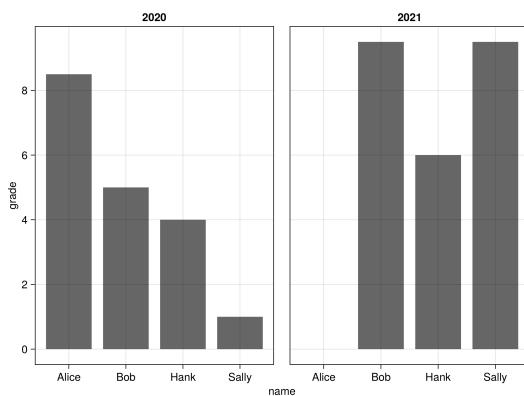


Figure 7.8: AlgebraOfGraphics bar plot with column layout.

NOTE: You use *both* `row` and `col` one for each categorical variable.

7.3 Statistical Visualizations

`AlgebraOfGraphics.jl` can perform **statistical transformations** as layers with five functions:

- `expectation`: calculates the mean (*expectation*) of the underlying Y-axis column
- `frequency`: computes the frequency (*raw count*) of the underlying X-axis column
- `density`: computes the density (*distribution*) of the underlying X-axis column
- `linear`: computes a linear trend relationship between the underlying X- and Y-axis columns
- `smooth`: computes a smooth relationship between the underlying X- and Y-axis columns

Let's first cover `expectation`:

```
plt = data(df) *
    mapping(:name, :grade) *
    expectation()
draw(plt)
```

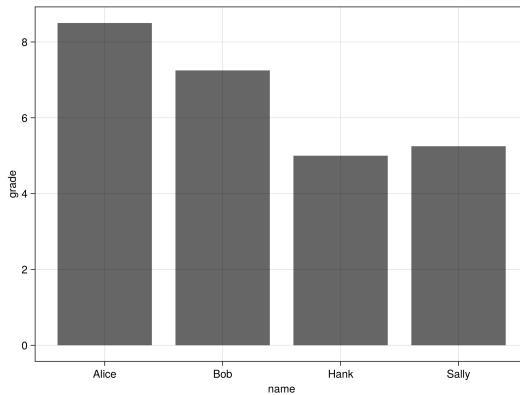


Figure 7.9: `AlgebraOfGraphics` bar plot with `expectation`.

Here, `expectation` adds a statistical transformation layer that tells `AlgebraOfGraphics` ↵.jl to compute the mean of the Y-axis values for every unique X-axis values. In our case, it computed the mean of grades for every student. Note that we could safely remove the visual transformation layer (`visual(BarPlot)`) since it is the default visual transformation for `expectation`.

Next, we'll show an example with `frequency`:

```
plt = data(df) *
    mapping(:name) *
```

```
frequency()
draw(plt)
```

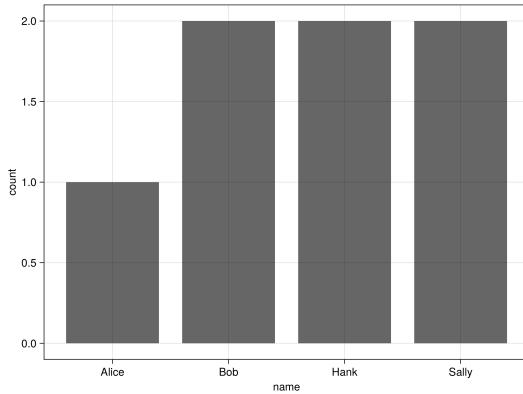


Figure 7.10: AlgebraOfGraphics bar plot with frequency.

Here we are passing just a single positional argument to `mapping` since this is the underlying column that `frequency` will use to calculate the raw count. Note that, as previously, we could also safely remove the visual transformation layer (`visual(BarPlot)`) since it is the default visual transformation for `frequency`.

Now, an example with `density`:

```
plt = data(df) *
    mapping(:grade) *
    density()
draw(plt)
```

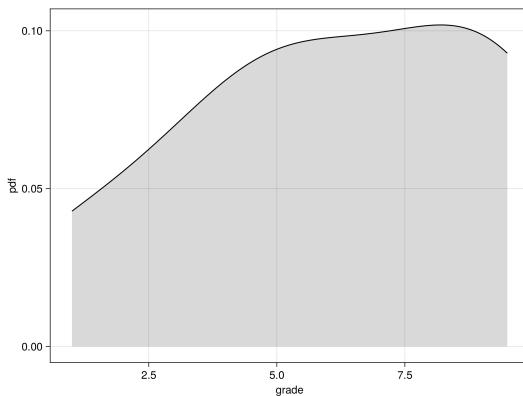


Figure 7.11: AlgebraOfGraphics bar plot with density estimation.

Analogous to the previous examples, `density` does not need a visual transformation layer. Additionally, we only need to pass a single continuous variable as the only positional argument inside `mapping`. `density` will compute the distribution density of this variable which we can fuse all the layers together and visualize the plot with `draw`.

For the last two statistical transformations, `linear` and `smooth`, they cannot be used with the `*` operator. This is because `*` fuses two or more layers into a *single* layer. `AlgebraOfGraphics.jl` cannot represent these transformations with a *single* layer. Hence, we need to **superimpose layers with the `+` operator**. First, let's generate some data:

```
x = rand(1:5, 100)
y = x + rand(100) .* 2
synthetic_df = DataFrame(; x, y)
first(synthetic_df, 5)
```

x	y
1.0	1.96607080855035
5.0	6.993454790161161
5.0	5.709911916334441
3.0	4.544011304772464
4.0	5.382914898287261

Let's begin with `linear`:

```
plt = data(synthetic_df) *
    mapping(:x, :y) *
    (visual(Scatter) + linear())
draw=plt)
```

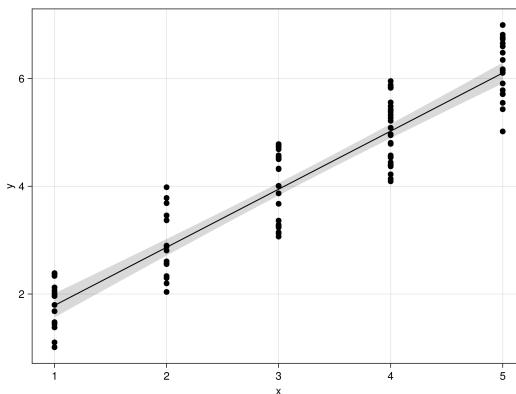


Figure 7.12: AlgebraOfGraphics scatter plot with linear trend estimation.

We are using the **distribute property** (Section 7) for more efficient code inside our `mapping`, $a * (b + c) = (a * b) + (a * c)$, where:

- a: the `data` and `mapping` layers fused into a single layer
- b: the `visual` transformation layer
- c: the statistical `linear` transformation layer

`linear` adds a linear trend between the X- and Y-axis mappings with a 95% confidence interval shaded region.

Finally, the same example as before but now replacing `linear` with `smooth`:

```
plt = data(synthetic_df) *
    mapping(:x, :y) *
    (visual(Scatter) + smooth())
draw(plt)
```

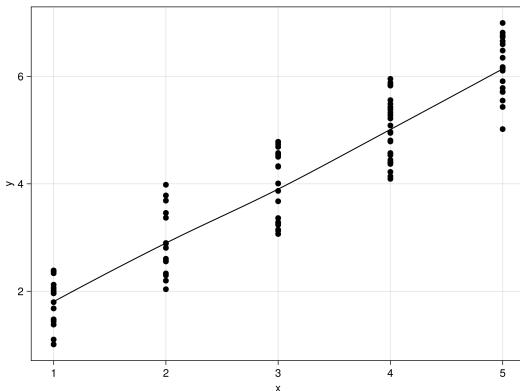


Figure 7.13: AlgebraOfGraphics scatter plot with smooth trend estimation.

`smooth` adds a smooth trend between the X- and Y-axis mappings.

7.4 Plot Customizations

Apart from mappings inside a `mapping` layer, you can **customize** AlgebraOfGraphics **→ visualizations inside the `visual` transformation layers**.

For example the `linear` statistical transformation plot from Section 7.3 can be customized both with the marker objects in the scatter plot but also with the line object in the linear trend plot. We can customize anything that the `Makie.jl`'s plotting types support inside `visual`:

```
blue = visual(Scatter; color=:steelblue, marker=:cross)
red = linear() * visual(; color=:red, linestyle=:dot, linewidth=5)
plt = data(synthetic_df) * mapping(:x, :y) * (blue + red)
draw(plt)
```

As you can see we are adding the following keyword arguments to `visual(Scatter)` transformation layer:

- `color`: a `Symbol` for a light blue color, `:steelblue`

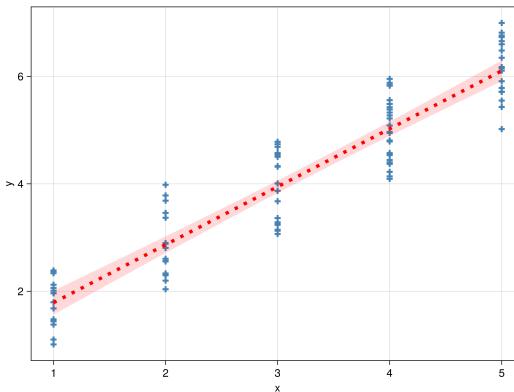


Figure 7.14: AlgebraOfGraphics customized scatter plot with linear trend estimation.

- `marker`: a `Symbol` for a vertical cross marker type, `:cross`

Inside the `linear` statistical transformation we are adding a new layer to be fused into it with the `*` operation, that does not have a positional argument for plotting type since `linear` already provides a default plotting type, and has the following keyword arguments:

- `color`: a `Symbol` for the red color, `:red`
- `linestyle`: a `Symbol` for a dotted line style, `:dot`
- `linewidth`: a number representing the width of our line

You can use as many customizations as you want in your plot.

7.5 Makie.jl and AlgebraOfGraphics.jl

Since `AlgebraOfGraphics.jl` uses `Makie.jl` as a backend, most of **advanced customizations** such as layouts are only possible by interacting directly with `Makie`. `Makie.jl` layouts uses `Figure`, `Axis` and other types (see Section 6.8).

You can instantiate a `Figure` and use the *mutating* `draw!` function to draw a layer into an existing `Figure` or `Axis`. It is preferable to pass a `GridPosition`, e.g. `fig[1, 1]`, instead of an `Axis` because `draw!` can pass `Axis` attributes, such as axis labels and axis tick labels, to the underlying visualization. If you pass an `Axis` to `draw!` these attributes need to be specified again as keyword arguments inside `Axis`:

```
fig = Figure()

# preferable
draw!(fig[1, 1], plt)
```

```
# avoid
ax = Axis(fig[1, 1])
draw!(ax, plt)
```

As an example, let's create an advanced layout by combining `Makie.jl` with `AlgebraOfGraphics.jl`. We'll use visualizations that had been already covered in this chapter:

```
# Figure
fig = Figure()

# First Axis
plt_barplot = data(df) *
    mapping(
        :name,
        :grade;
        color=:year,
        dodge=:year) *
    visual(BarPlot)
subfig1 = draw!(fig[1, 1], plt_barplot)

# Second Axis
plt_custom = data(synthetic_df) *
    mapping(:x, :y) *
    (
        visual(Scatter; color=:steelblue, marker=:cross)
        +
        linear() * visual(; color=:red, linestyle=:dot, linewidth=5)
    )
subfig2 = draw!(fig[2, 1:2], plt_custom)

# Third Axis
plt_expectation = data(df) *
    mapping(:name, :grade) *
    expectation()
subfig3 = draw!(fig[1, 2], plt_expectation)

# Insert the legend
legend!(
    fig[end+1, 1:2],
    subfig1,
    orientation=:horizontal,
    tellheight=true
)

# Recover the Figure
fig
```

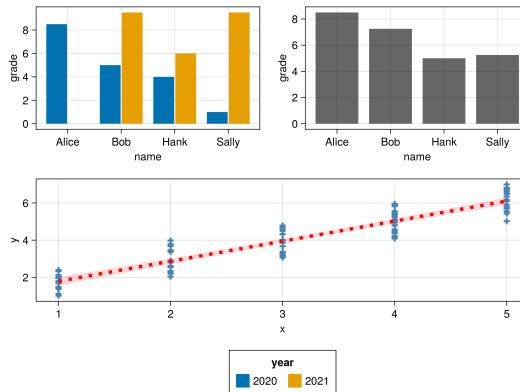


Figure 7.15: AlgebraOfGraphics custom layout with Makie.

Here, we are instantiating a `Figure` called `fig`. Then, we proceed by creating three `Layers` that have the prefix `plt_`. Each one of these are followed by a `draw!` with the desired `fig`'s `GridPosition` as the first position argument followed by the `Layer` as the second argument. Furthermore, we use `AlgebraOfGraphics.jl`'s `legend!` to add the legend to the visualization. They way `legend!` works is by passing first the desired `fig`'s `GridPosition` for the placement of the legend, and the desired legend labels. For the legend's label, we use the output of the `draw ↪!` function that was called in the `Layers` and that has legend labels already, in our case the `plt_barplot`. All of the `Legend/axislegend` keyword arguments (Section 6.2) can be used in `legend!`. Finally, as the last step, we call the `Figure`, `fig`, to recover it after it was mutated by all of the mutating “bang” functions, e.g. `draw!` and `legend!`, in order to render our visualization.

NOTE: Don't forget to check `AlgebraOfGraphics.jl` documentation⁴ for additional examples.

⁴ <https://aog.makie.org>

8 Appendix

8.1 Packages Versions

This book is built with Julia 1.9.1 and the following packages:

```
AlgebraOfGraphics 0.6.16
Books 2.0.5
CSV 0.10.11
CairoMakie 0.10.6
CategoricalArrays 0.10.8
ColorSchemes 3.21.0
Colors 0.12.10
DataFrames 1.5.0
DataFramesMeta 0.14.0
Distributions 0.25.95
Downloads 1.6.0
FileIO 1.16.1
GLMakie 0.8.6
GeometryBasics 0.4.7
ImageMagick 1.2.2
LaTeXStrings 1.3.0
Makie 0.19.6
Pkg 1.9.0
QuartzImageIO 0.7.4
Reexport 1.2.2
Statistics 1.9.0
StatsBase 0.34.0
TestImages 1.7.1
XLSX 0.9.0
```

Build: 2023-06-19 5:45 UTC

8.2 Notation

In this book, we try to keep notation as consistent as possible. This makes reading and writing code easier. We can define the notation into three parts.

8.2.1 Julia Style Guide

Firstly, we attempt to stick to the conventions from the Julia Style Guide¹. Most style-guide/

¹ <https://docs.julialang.org/en/v1/manual/style-guide/>

importantly, we write functions not scripts (see also Section 1.2). Furthermore, we use naming conventions consistent with Julia `base/`, meaning:

- Use camelcase for modules: `module JuliaDataScience, struct MyPoint`. (Note that camel case is so called because the capitalization of words, as in “iPad” or “CamelCase,” makes the word look like a camel).
- Write function names in lowercase letters and separate the words by underscores. It is also allowed to omit the separator when naming functions. For example, these function names are all in line with the conventions: `my_function ↗, myfunction` and `string2int`.

Also, we avoid brackets in conditionals, that is, we write `if a == b` instead of `if (a == b)` and use 4 spaces per indentation level.

8.2.2 BlueStyle

The Blue Style Guide² adds multiple conventions on top of the default Julia Style Guide. Some of these rules might sound pedantic, but we found that they make the code more readable.

² <https://github.com/invencia/BlueStyle>

From the style guide, we attempt to adhere specifically to:

- At most 92 characters per line in code (in Markdown files, longer lines are allowed).
- When loading code via `using`, load at most one module per line.
- No trailing whitespace. Trailing whitespace makes inspecting changes in code more difficult since they do not change the behavior of the code but do show up as changes.
- Avoid extraneous spaces inside brackets. So, write `string(1, 2)` instead of `string(1 , 2)`.
- Global variables should be avoided.
- Try to limit function names to one or two words.
- Use the semicolon to clarify whether an argument is a keyword argument or not. For example, `func(x; y=3)` instead of `func(x, y=3)`.
- Avoid using multiple spaces to align things. So, write

```
a = 1
lorem = 2
```

instead of

```
a      = 1
lorem = 2
```

- Whenever appropriate, surround binary operators with a space, for example, `1 == 2` or `y = x + 1`.
- Indent triple-quotes and triple-backticks:

```
s = """
    my long text:
    [...]
    the end.
"""
```

- Do not omit zeros in floats (even though Julia allows it). Hence, write `1.0` instead of `1.` and write `0.1` instead of `.1`.
- Use `in` in for loops and not `=` or `∈` (even though Julia allows it).

8.2.3 Our additions

- In text, we reference the function call `M.foo(3, 4)` as `M.foo` and not `M.foo(...)` or `M.foo()`.
- When talking about packages, like the `DataFrames` package, we explicitly write `DataFrames.jl` each time. This makes it easier to recognize that we are talking about a package.
- For filenames, we stick to “`file.txt`” and not `file.txt` or `file.txt`, because it is consistent with the code.
- For column names in tables, like the column `x`, we stick to `column :x`, because it is consistent with the code.
- Do not use Unicode symbols in inline code. This is simply a bug in the PDF generation that we have to workaround for now.
- The line before each code block ends with a colon (`:`) to indicate that the line belongs to the code block.

Loading of symbols

Prefer to load symbols explicitly, that is, prefer using `A: foo` over using `A` when not using the REPL (see also, [JuMP Style Guide, 2021](#)). In this context, a symbol means an identifier to an object. For example, even if it doesn’t look like it normally, internally `DataFrame`, `π` and `CSV` are all symbols. We notice this when we use an introspective method from Julia such as `isdefined`:

```
isdefined(Main, :π)
```

```
true
```

Next to being explicit when using `using`, also prefer `using A: foo` over `import A: foo` because the latter makes it easy to accidentally extend `foo`. Note that this isn't just advice for Julia: implicit loading of symbols via `from <module> import *` is also discouraged in Python ([van Rossum et al., 2001](#)).

The reason why being explicit is important is related to semantic versioning. With semantic versioning (<http://semver.org>), the version number is related to whether a package is so-called *breaking* or not. For example, a non-breaking update for package `A` is when the package goes from version `0.2.2` to `0.2.3`. With such a non-breaking version update, you don't need to worry that your package will break, that is, throw an error or change behavior. If package `A` goes from `0.2` to `1.0`, then that's a breaking update and you can expect that you need some changes in your package to make `A` work again. **However**, exporting extra symbols is considered a non-breaking change. So, with implicit loading of symbols, **non-breaking changes can break your package**. That's why it's good practice to explicitly load symbols.

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