Julia Data Science

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# 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](#sec:why_julia). 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.

### 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 exabytes**[[1]](#footnote-20) **to a whopping 40,000 exabytes** ([Gantz & Reinsel, 2012](#ref-gantz2012digital)). 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](#ref-domo2018data)). A recent report predicted that almost **two thirds (65%) of national GDPs will have undergone digitization by 2022** ([Fitzgerald et al., 2020](#ref-fitzgerald2020idc)).

Every profession will be impacted by the increasing availability of data and data’s increased importance ([Chen et al., 2014](#ref-chen2014big); [Khan et al., 2014](#ref-khan2014big)). 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**.

## 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](#ref-Meng2019Data)). 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](#sec:why_julia). For now, let’s turn our attention towards data.

### Data Literacy

According to [Wikipedia](https://en.wikipedia.org/wiki/Data_literacy), 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 (Section [4](#sec:dataframes)). In this chapter 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 (Section [5](#sec:DataVisualizationMakie)). In these chapter you will learn how to:
   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.

## 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 [6.2](#sec:notation).

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# 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](#sec:non-programmers).
2. **Did program before** – see Section [2.2](#sec:programmers).

## 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 readable[[2]](#footnote-34), 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.

## 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 seconds**[[3]](#footnote-36). We reserved Section [2.4](#sec:julia_wild) 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 magic[[4]](#footnote-37) 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](#sec:two_language)). 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”[[5]](#footnote-38).
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 interface[[6]](#footnote-39). **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 box[[7]](#footnote-40) 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](#sec:multiple_dispatch).
5. Needed to have a better project management, with dependencies and version control tightly controlled, manageable, and replicable? **Julia has an 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!

## 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](#sec:dataframes) to learn about tabular data with DataFrames.jl.

The Julia programming language ([Bezanson et al., 2017](#ref-bezanson2017julia)) is a relatively new language, first released in 2012, and aims to be **both easy and fast**. It “runs like C[[8]](#footnote-42) but reads like Python” ([Perkel, 2019](#ref-perkelJuliaComeSyntax2019)). 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 blogpost](https://julialang.org/blog/2012/02/why-we-created-julia/). 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**](https://www.hpcwire.com/off-the-wire/julia-joins-petaflop-club/) is comprised of languages who can exceed speeds of **one petaflop**[[9]](#footnote-45) **per second at peak performance**. Currently only C, C++, Fortran, and Julia belong to the [petaflop club](https://www.nextplatform.com/2017/11/28/julia-language-delivers-petascale-hpc-performance/).

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. 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.

### Julia Versus Other Programming Languages

In Figure [1](#fig:language_comparison), 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.



Figure 1: Scientific Computing Language Comparisons: logos for FORTRAN, C++, Python, R and Julia.

**Julia is fast! Very fast!** It was designed for speed from the beginning. It accomplishes this by multiple dispatch. Basically, the idea is to generate very efficient LLVM[[10]](#footnote-49) 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 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 f and f calls function g and the data types passed to g are known and always the same, then the generated function g can be hardcoded into function f! This means that Julia doesn’t even have to lookup MethodInstances any more, and the code can run very efficiently. 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.

The compiler in turns does what it does best: it optimizes machine code[[11]](#footnote-51). You can find [benchmarks](https://julialang.org/benchmarks/) for Julia and several other languages here. Figure [2](#fig:benchmarks) was taken from [Julia’s website benchmarks section[[12]](#footnote-53)](https://julialang.org/benchmarks/). As you can see Julia is **indeed** fast.

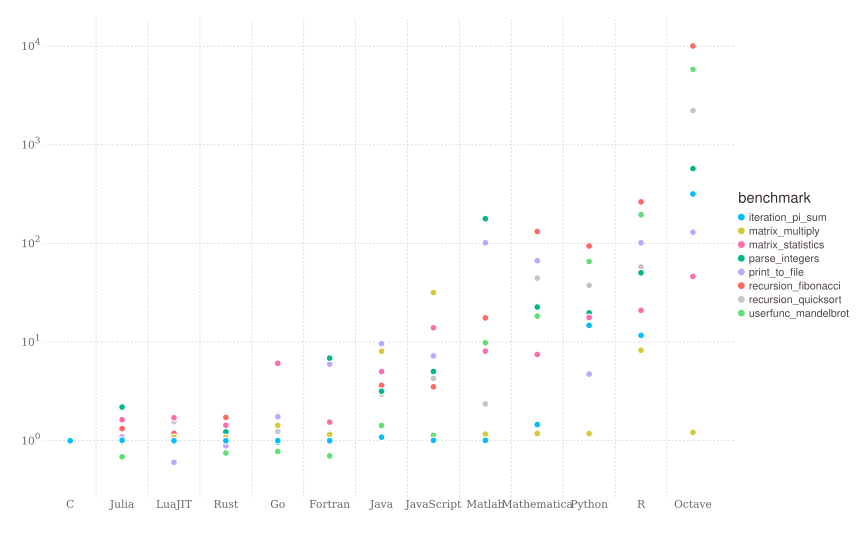


Figure 2: Julia versus other programming languages.

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.

### 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 or 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 Talk](https://youtu.be/qGW0GT1rCvs) ([TEDx Talks, 2020](#ref-tedxtalksProgrammingLanguageHeal2020)).

### 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  
 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 practise, 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 vector](https://storopoli.io/Bayesian-Julia/pages/1_why_Julia/#example_one-hot_vector) by [Storopoli](#ref-storopoli2021bayesianjulia) ([2021](#ref-storopoli2021bayesianjulia)). The second is an interview with [Christopher Rackauckas](https://www.chrisrackauckas.com/) at [Tanmay Bakshi YouTube’s Channel](https://youtu.be/moyPIhvw4Nk?t=2107) (see from time 35:07 onwards) ([tanmay bakshi, 2021](#Xa4604ed72cae164b55eb91abf06c44157967782)). Chris mentions that, while using [DifferentialEquations.jl](https://diffeq.sciml.ai/dev/), 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 2019](https://youtu.be/kc9HwsxE1OY).

## Julia in the Wild

In Section [2.3](#sec:julia_accomplish), 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”](https://exoplanets.nasa.gov/news/1669/seven-rocky-trappist-1-planets-may-be-made-of-similar-stuff/) and achieve a whopping **1,000x speedup** to catalog 188 million astronomical objects in 15 minutes.
2. [The Climate Modeling Alliance (CliMa)](https://clima.caltech.edu/) 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.
3. [US Federal Aviation Administration (FAA) is developing an **Airborne Collision Avoidance System (ACAS-X)** using Julia](https://youtu.be/19zm1Fn0S9M). This is a nice example of the “Two-Language Problem” (see Section [2.3](#sec:julia_accomplish)). 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 Julia](https://juliacomputing.com/case-studies/pfizer/). It was presented as a [poster](https://chrisrackauckas.com/assets/Posters/ACoP11_Poster_Abstracts_2020.pdf) in the 11th American Conference of Pharmacometrics (ACoP11) and [won a quality award](https://web.archive.org/web/20210121164011/https://www.go-acop.org/abstract-awards).
5. [The Attitude and Orbit Control Subsystem (AOCS) of the Brazilian satellite Amazonia-1 is **written 100% in Julia**](https://discourse.julialang.org/t/julia-and-the-satellite-amazonia-1/57541) 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**.](https://youtu.be/NY0HcGqHj3g)

If this is not enough, there are more case studies in [Julia Computing website](https://juliacomputing.com/case-studies/).

# 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](#sec:dataframes) 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.

## 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 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](https://github.com/timholy/Revise.jl). 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.

We are aware that Revise.jl and the REPL requires some manual actions which aren’t super clearly documented. Luckily, there is [Pluto.jl](https://github.com/fonsp/Pluto.jl). 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.

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

## 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](#sec:why_julia)): 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](#sec:julia_accomplish). We defined a different type behavior by defining new function signatures for argument types while using the same function name.

### 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. Supposed, 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, I will restrict the output to the first 5 rows:

first(methodswith(Int64), 5)

[1] ncycle(iter, n::Int64) in IterTools at /home/runner/.julia/packages/IterTools/0dYLc/src/IterTools.jl:807  
[2] partition(xs, n::Int64) in IterTools at /home/runner/.julia/packages/IterTools/0dYLc/src/IterTools.jl:304  
[3] partition(xs::I, n::Int64, step::Int64) where I in IterTools at /home/runner/.julia/packages/IterTools/0dYLc/src/IterTools.jl:306  
[4] takestrict(xs, n::Int64) in IterTools at /home/runner/.julia/packages/IterTools/0dYLc/src/IterTools.jl:139  
[5] clear!(sym::Symbol, pid::Int64; mod) in Distributed at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Distributed/src/clusterserialize.jl:249

### 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\_mutable = MutableLanguage("Julia", "Rapidus", 2012, true)

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

Suppose that we want to change julia\_mutable’s title. Now, we can do this since julia\_mutable is an instantiated mutable struct:

julia\_mutable.title = "Python Obliteratus"  
  
julia\_mutable

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

### 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 ≠ “not equal”
2. **Less than**: either something is *less than* or *less than or equal to*
   * < “less than”
   * <= or ≤ “less than or equal to”
3. **Greater than**: either something is *greater than* or *greater than or equal to*
   * > “greater than”
   * >= or ≥ “greater than or equal to”

Here are some examples:

1 == 1

true

1 >= 10

false

It evens 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

### Functions

Now that we already know how to define variables and custom types as structs, 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)

# 2 methods for generic function "round\_number":  
[1] round\_number(x::Float64) in Main at none:1  
[2] round\_number(x::Int64) in Main at 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)

1.0

***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

1. 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 (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](#sec:dataframes)) or Makie.jl (Section [5](#sec:DataVisualizationMakie)), 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)

### 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

### 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

### 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.

## 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] colormap(cname::String) in Colors at /home/runner/.julia/packages/Colors/yDxFN/src/colormaps.jl:283  
[2] colormap(cname::String, N::Int64; mid, logscale, kvs...) in Colors at /home/runner/.julia/packages/Colors/yDxFN/src/colormaps.jl:283  
[3] getaddrinfo(host::String, T::Type{var"#s814"} where var"#s814"<:Sockets.IPAddr) in Sockets at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Sockets/src/addrinfo.jl:130  
[4] getalladdrinfo(host::String) in Sockets at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Sockets/src/addrinfo.jl:66  
[5] join\_multicast\_group(sock::Sockets.UDPSocket, group\_addr::String) in Sockets at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Sockets/src/Sockets.jl:761

### 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]

#### 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 1:length(V)  
 V[i] += 1  
 end  
 return nothing  
end

my\_data = [1, 2, 3]  
  
add\_one!(my\_data)  
  
my\_data

[2, 3, 4]

### 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](#sec:conditionals):

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)](https://docs.julialang.org/en/v1/manual/strings/#Regular-Expressions) as arguments. We won’t cover RegEx in this book, but you are encouraged to learn about them, especially if most of your work uses textual data.

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

julia\_string = "Julia is an amazing opensource programming language"

Julia is an amazing opensource programming language

1. occursin, startswith and endswith: A conditional (returns either true or false) if the first argument is a:
   * **substring** of the second argument
   * occursin("Julia", julia\_string)
   * true
   * **prefix** of the second argument
   * startswith("Julia", julia\_string)
   * false
   * **suffix** of the second argument
   * endswith("Julia", julia\_string)
   * false
2. lowercase, uppercase, titlecase and lowercasefirst:

* lowercase(julia\_string)
* julia is an amazing opensource programming language
* uppercase(julia\_string)
* JULIA IS AN AMAZING OPENSOURCE PROGRAMMING LANGUAGE
* titlecase(julia\_string)
* Julia Is An Amazing Opensource Programming Language
* lowercasefirst(julia\_string)
* julia is an amazing opensource programming language

1. replace: introduces a new syntax, called the Pair

* replace(julia\_string, "amazing" => "awesome")
* Julia is an awesome opensource programming language

1. split: breaks up a string by a delimiter:

* split(julia\_string, " ")
* SubString{String}["Julia", "is", "an", "amazing", "opensource", "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

### 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 a 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 [3.2.4.2](#sec:function_multiple)? 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

### 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 a 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")

### 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}}

Sometimes, we want to change the default interval stepsize behavior. We can do that by adding a stepsize 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.

### Array

In its most basic form, **array**s 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 Int64s, 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 undef Float64 elements can be constructed as:

my\_vector = Vector{Float64}(undef, 10)

[6.9116703257708e-310, 0.0, 6.911670331049e-310, 6.9116705478126e-310, 0.0, 6.911670331049e-310, 6.91167054778333e-310, 0.0, 6.911670331049e-310, 6.9116704477876e-310]

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}:  
 6.91167e-310 0.0  
 0.0 6.91167e-310  
 6.91167e-310 6.91167e-310  
 6.91167e-310 0.0  
 0.0 6.91167e-310  
 6.91167e-310 6.91167e-310  
 6.91167e-310 0.0  
 0.0 6.91167e-310  
 6.91167e-310 6.91167e-310  
 6.91167e-310 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)
* 10×2 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 ():

my\_matrix\_π = Matrix{Float64}(undef, 2, 2)  
fill!(my\_matrix\_π, 3.14)

2×2 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]

3×3 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, I 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]

8

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

3×3 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

3×3 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]  
tree\_two\_matrix = reshape(six\_vector, (3, 2))  
tree\_two\_matrix

3×2 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(tree\_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)

3×3 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

3×3 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)

3×3 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)

3×3 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)

3×3 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 mapslice with the sum function on both rows (dims=1) and columns (dims=2):

# rows  
mapslices(sum, my\_example\_matrix; dims=1)

1×3 Matrix{Int64}:  
 22 60 24

# columns  
mapslices(sum, my\_example\_matrix; dims=2)

3×1 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 memory[[13]](#footnote-111). This also means that iterating over elements in a column is much quicker than over elements in a row.

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]

### 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[[14]](#footnote-114):

first(my\_pair)

Julia

last(my\_pair)

42

Pairs will be used a lot in data manipulation and data visualization since both DataFrames.jl (Section [4](#sec:dataframes)) or Makie.jl (Section [5](#sec:DataVisualizationMakie)) 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.

### 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 Dicts 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](#sec:dataframes)) and for data visualization by Makie.jl (Section [5](#sec:DataVisualizationMakie)). 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

### 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](#sec:dataframes)) and data visualizations with the Makie.jl package (Section [5](#sec:DataVisualizationMakie)).

### 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

## 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:\\user\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](https://docs.julialang.org/en/v1/base/file/) module from the core Base Julia library.

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:

/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 other 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.

## 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.

### Dates

Knowing how to handle dates and timestamps is important in data science. As we said in *Why Julia?* (Section [2](#sec:why_julia)) 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’ documentation](https://docs.julialang.org/en/v1/stdlib/Dates/#Dates.DateFormat). Don’t worry if you have to revisit it all the time, we ourselves do that too when working with dates and timestamps.

According to [Julia Dates’ documentation](https://docs.julialang.org/en/v1/stdlib/Dates/#Constructors), 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)

yearmonthday(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](https://github.com/JuliaFinance/BusinessDays.jl) package.

#### 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] firstdayofmonth(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:84  
[2] firstdayofquarter(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:157  
[3] firstdayofweek(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:52  
[4] firstdayofyear(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:119  
[5] lastdayofmonth(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:100  
[6] lastdayofquarter(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:180  
[7] lastdayofweek(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:68  
[8] lastdayofyear(dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/adjusters.jl:135  
[9] optimize\_ticks(x\_min::Date, x\_max::Date; extend\_ticks, k\_min, k\_max, scale, granularity\_weight, simplicity\_weight, coverage\_weight, niceness\_weight, strict\_span, span\_buffer) in PlotUtils at /home/runner/.julia/packages/PlotUtils/VgXdq/src/ticks.jl:309  
[10] convert(::Type{Day}, dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/conversions.jl:37  
[11] convert(::Type{DateTime}, dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/conversions.jl:30  
[12] +(dt::Date, t::Time) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:19  
[13] +(dt::Date, y::Year) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:27  
[14] +(dt::Date, z::Month) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:54  
[15] +(x::Date, y::Quarter) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:73  
[16] +(x::Date, y::Week) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:77  
[17] +(x::Date, y::Day) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:79  
[18] +(t::Time, dt::Date) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:20  
[19] -(dt::Date, y::Year) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:35  
[20] -(dt::Date, z::Month) in Dates at /opt/hostedtoolcache/julia/1.6.4/x64/share/julia/stdlib/v1.6/Dates/src/arithmetic.jl:66

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

12497 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)

1079740800000 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 [3.3.5](#sec:ranges). 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](#sec:why_julia)).

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.

### 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 documentation](https://docs.julialang.org/en/v1/stdlib/Random/). We will cover *only* three functions: rand, randn and seed!.

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

using Random: rand, randn, seed!

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

* rand: samples a **random element** of a data structure or type.
* randn: generates a random number that follows a **standard normal distribution** (mean 0 and standard deviation 1) of a specific type.

***NOTE:*** Note that those two functions are already in the Julia Base module. So, you don’t need to import Random if you’re planning to use them.

#### rand

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

rand()

0.8227968271692039

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

rand(3)

[0.7486626091321988, 0.3923192001663973, 0.12082595173835564]

Or, you want a different interval:

rand(1.0:10.0)

4.0

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:

rand(2:2:20)

4

You can also mix and match arguments:

rand(2:2:20, 3)

[4, 10, 20]

It also supports a collection of elements as a tuple:

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

3.14

And also arrays:

rand([1, 2, 3])

2

Dicts:

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

:one => 1

To finish off 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}:  
 3.0 3.0  
 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()

-1.3964056267108158

We can only specify the size:

randn((2, 2))

2×2 Matrix{Float64}:  
 0.639059 -1.25681  
 -0.495648 1.60695

#### 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)

[0.7684476751965699, 0.940515000715187, 0.6739586945680673]

seed!(123)  
rand(3)

[0.7684476751965699, 0.940515000715187, 0.6739586945680673]

In order to avoid tedious and inefficient repetition of seed! all over the place, 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)

MersenneTwister(123)

rand(my\_seed, 3)

[0.3954531123351086, 0.3132439558075186, 0.6625548164736534]

rand(my\_seed, 3)

[0.3954531123351086, 0.3132439558075186, 0.6625548164736534]

***NOTE:*** If you want your code to be reproducible you can just call seed! in the beginning of your script. This will take care of reproducibility in sequential Random operations. No need to use it all rand and randn usage.

### Downloads

One last thing from Julia’s standard library for us to cover is the **Download 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 download method:

using Download: download

For example, let’s download our [JuliaDataScience GitHub repository](https://github.com/JuliaDataScience/JuliaDataScience) 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\_tHZCQb

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\"]"  
 "version = \"0.1.0\""

***NOTE:*** For more complex HTTP interactions such as interacting with web APIs, see the [HTTP.jl package](https://github.com/JuliaWeb/HTTP.jl) package.

# DataFrames.jl

Data comes mostly in a tabular format. By tabular, we mean that the data consists of a table containing rows and columns. Columns are usually of the same data type, whereas rows 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 [1](#tbl:TV_shows).

Table 1: TV shows.

|  |  |  |
| --- | --- | --- |
| name | country | rating |
| Game of Thrones | United States | 8.2 |
| The Crown | England | 7.3 |
| Friends | United States | 7.8 |
| … | … | … |

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 [2](#tbl:ratings)):

Table 2: Ratings.

|  |  |
| --- | --- |
| name | rating |
| Game of Thrones | 7 |
| Friends | 6.4 |
| … | … |

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 [4.9](#sec:df_performance)).

Let’s look at a table of grades like the one in Table [3](#tbl:grades_for_2020):

Table 3: Grades for 2020.

|  |  |  |
| --- | --- | --- |
| name | age | grade\_2020 |
| Bob | 17 | 5.0 |
| Sally | 18 | 1.0 |
| Alice | 20 | 8.5 |
| Hank | 19 | 4.0 |

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, lets 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  
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 where 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()

Table 4: Grades 2020.

|  |  |
| --- | --- |
| name | grade\_2020 |
| Sally | 1.0 |
| Bob | 5.0 |
| Alice | 8.5 |
| Hank | 4.0 |

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  
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.

## 加载和保存文件

仅在 Julia 程序中使用数据非常有局限性，通常还需要能够加载或保存数据。 因此，本节主要讨论如何存储文件到硬盘和从硬盘读取文件。 我们重点关注 CSV 和 Excel 这两类最常见的数据文件格式，分别参见 Section [4.1.1](#sec:csv) 和 Section [4.1.2](#sec:excel)。

### CSV

**C**omma-**s**eparated-**v**alues (CSV) 文件是非常有效的表格存储方式。 CSV 文件相比其他数据存储文件有两点优势。首先，正如名称所指示的那样，它使用逗号,来分隔存储值。此首字母缩写词也被用作文件扩展名。因此，请确保使用“.csv”扩展名（例如“myfile.csv”）保存文件。为了演示 CSV 文件的结构，安装 [CSV.jl](http://csv.juliadata.org/latest/) 包：

julia> ]  
  
pkg> add CSV

并且通过以下方式导入：

using CSV

现在可使用之前的数据：

grades\_2020()

|  |  |
| --- | --- |
| name | grade\_2020 |
| Sally | 1.0 |
| Bob | 5.0 |
| Alice | 8.5 |
| Hank | 4.0 |

并在写入后从文件中读取：

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

上文还能看到 CSV 数据格式的第二个好处：可以使用简单的文本编辑器读取数据。 这与许多需要专有软件的其他数据格式不同，例如 Excel。

这很有效，但是如果我们的数据 **包含逗号 ,** 作为值怎么办？ 如果我们天真地用逗号写入数据，那么文件将很难转换回表格。 幸运的是，CSV.jl 会自动处理此问题。 考虑以下带逗号,的数据：

function grades\_with\_commas()  
 df = grades\_2020()  
 df[3, :name] = "Alice,"  
 df  
end  
grades\_with\_commas()

Table 5: Grades with commas.

|  |  |
| --- | --- |
| name | grade\_2020 |
| Sally | 1.0 |
| Bob | 5.0 |
| Alice, | 8.5 |
| Hank | 4.0 |

如果写入文件，将得到：

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

因此，CSV.jl 在包含逗号的值周围添加引号 "。 解决此问题的另一种常见方法是将数据写入 **t**ab-**s**eparated **v**alues (TSV) 文件格式。 该格式假设数据不包含制表符，这一点在大多数情况下是成立的。

另请注意，也可以使用简单的文本编辑器读取 TSV 文件，这些文件使用“.tsv”扩展名。

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

像 CSV 和 TSV 这样的文本文件格式还可以使用其他分割符，例如分号“;”，空格“ ”，甚至是像“π”这样不寻常的字符。

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

按照惯例，最好还是为文件指定特殊的分隔符，例如“;”，“.csv”扩展名。

使用 CSV.jl 加载 CSV 文件的方式与此类似。 您可以使用 CSV.read 并指定您想要的输出格式。 这里指定为DataFrame。

path = write\_grades\_csv()  
CSV.read(path, DataFrame)

|  |  |
| --- | --- |
| name | grade\_2020 |
| Sally | 1.0 |
| Bob | 5.0 |
| Alice | 8.5 |
| Hank | 4.0 |

方便地，CSV.jl将自动推断列类型：

path = write\_grades\_csv()  
df = CSV.read(path, DataFrame)

4×2 DataFrame  
 Row │ name grade\_2020  
 │ String7 Float64  
─────┼─────────────────────  
 1 │ Sally 1.0  
 2 │ Bob 5.0  
 3 │ Alice 8.5  
 4 │ Hank 4.0

它甚至适用于更复杂的数据：

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

这些CSV基础应该涵盖大多数用例。 关于更多信息，请参阅[CSV.jl 文档](https://csv.juliadata.org/stable)尤其是[CSV.File 构建 docstring](https://csv.juliadata.org/stable/#CSV.File)。

### Excel

多个 Julia 包可以读取 Excel 文件。 本节将只讨论 [XLSX.jl](https://github.com/felipenoris/XLSX.jl)，因为它是 Julia 生态系统中处理 Excel 数据的最积极维护的包。 另外一个优点是，XLSX.jl 是用纯 Julia 编写的，这使得可以轻松地检查和理解指令背后发生的事情。

加载 XLSX.jl 的方式是

using XLSX:  
 eachtablerow,  
 readxlsx,  
 writetable

为了写入文件，我们为数据和列名定义一个辅助函数：

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

现在，可以轻松地将成绩写入 Excel 文件：

function write\_grades\_xlsx()  
 path = "grades"  
 write\_xlsx(path, grades\_2020())  
 "$path.xlsx"  
end

当成绩被读取回来时，我们将看到 XLSX.jl 将数据放在 XLSXFile 类型中，并且可以像访问 Dict 一样访问所需的 sheet：

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 |

请注意，本节只介绍了XLSX.jl的基础知识，但它还提供了更强大的用法和自定义功能。 有关更多信息和选项，请参阅[XLSX.jl 文档](https://felipenoris.github.io/XLSX.jl/stable/).

## 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](#sec:julia_basics):

function names\_grades1()  
 df = grades\_2020()  
 df.name  
end  
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  
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  
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]  
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](#sec:data_structures)) 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.

## Filter and Subset

There are two ways to remove rows from a DataFrame, one is filter (Section [4.3.1](#sec:filter)) and the other is subset (Section [4.3.2](#sec:subset)). 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.

### 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**[[15]](#footnote-155).

Like before, we resume from the grades\_2020:

grades\_2020()

|  |  |
| --- | --- |
| 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](#sec:multiple_dispatch)) 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"  
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 [3.2.4.4](#sec:function_anonymous)):

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 anonymous 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 |

### Subset

The subset function was added to make it easier to work with missing values (Section [4.5](#sec:missing_data)). 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()

Table 6: Salaries.

|  |  |
| --- | --- |
| names | salary |
| John | 1900 |
| Hank | 2800 |
| Karen | 2800 |
| Zed | missing |

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"#89#90"{Base.Fix2{typeof(>), Int64}})(x::Missing)  
 @ DataFrames ~/.julia/packages/DataFrames/vuMM8/src/abstractdataframe/abstractdataframe.jl:1043  
 ...

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/vuMM8/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 |

## 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()

Table 7: Responses.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| id | q1 | q2 | q3 | q4 | q5 |
| 1 | 28 | us | F | B | A |
| 2 | 61 | fr | B | C | E |

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 |

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(:id))

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| q5 | q1 | q2 | q3 | q4 |
| A | 28 | us | F | B |
| E | 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 position[[16]](#footnote-162):

select(responses(), 1, :q5, :)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| id | q5 | q1 | q2 | q3 | q4 |
| 1 | A | 28 | us | F | B |
| 2 | E | 61 | fr | B | C |

***NOTE:*** As you might have observed there are several ways to select a column. These are known as [*column selectors*](https://bkamins.github.io/julialang/2021/02/06/colsel.html).

We can use:

* Symbol: select(df, :col)
* String: select(df, "col")
* Integer: select(df, 1)

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 [3.3.10](#sec:splat)), we can also write:

renames = (1 => "participant", :q1 => "age", :q2 => "nationality")  
select(responses(), renames...)

|  |  |  |
| --- | --- | --- |
| participant | age | nationality |
| 1 | 28 | us |
| 2 | 61 | fr |

## Types and Missing Data

As discussed in Section [4.1](#sec:load_save), 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()

4×3 DataFrame  
 Row │ id date age  
 │ Int64 String String  
─────┼───────────────────────────────  
 1 │ 1 28-01-2018 adolescent  
 2 │ 2 03-04-2019 adult  
 3 │ 3 01-08-2018 infant  
 4 │ 4 22-11-2020 adult

Because the date column has the wrong type, sorting won’t work correctly:

sort(wrong\_types(), :date)

4×3 DataFrame  
 Row │ id date age  
 │ Int64 String String  
─────┼───────────────────────────────  
 1 │ 3 01-08-2018 infant  
 2 │ 2 03-04-2019 adult  
 3 │ 4 22-11-2020 adult  
 4 │ 1 28-01-2018 adolescent

To fix the sorting, we can use the Date module from Julia’s standard library as described in Section [3.5.1](#sec:dates):

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())

4×3 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)

4×3 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)

4×3 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:

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())

4×3 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 comparissons would not be possible.

Now, we can sort the data correctly on the age column:

df = fix\_age\_column(wrong\_types())  
sort(df, :age)

4×3 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()

4×3 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

## 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 documentation](https://DataFrames.juliadata.org/stable/man/joins/), along with this book, 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](#sec:dataframes), 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.

### innerjoin

This first is **innerjoin**. Suppose that we have two datasets A and B with respectively columns A\_1, A\_2, ..., A\_n and B\_1, B\_2, ..., 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, ..., A\_n and B\_2, ..., 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 , that are also in , or all elements in that are also in .”

### 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.

### 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=:id)  
Closest candidates are:  
 crossjoin(::DataFrames.AbstractDataFrame, ::DataFrames.AbstractDataFrame; makeunique) at /home/runner/.julia/packages/DataFrames/vuMM8/src/join/composer.jl:1332 got unsupported keyword argument "on"  
 crossjoin(::DataFrames.AbstractDataFrame, ::DataFrames.AbstractDataFrame, !Matched::DataFrames.AbstractDataFrame...; makeunique) at /home/runner/.julia/packages/DataFrames/vuMM8/src/join/composer.jl:1343 got unsupported keyword argument "on"  
 ...

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/vuMM8/src/other/index.jl:323  
 [2] merge!(x::DataFrames.Index, y::DataFrames.Index; makeunique::Bool)  
 ...

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.

### 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 |

### 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 |

## Variable Transformations

In Section [4.3.1](#sec:filter), 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 -> name == "Alice", df).

In Section [4.4](#sec:select), 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](#sec:broadcasting).

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](#sec:select). 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.**

### Multiple Transformations

To show how to transform two columns at the same time, we use the left joined data from Section [4.6](#sec:join):

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 all of their grades were 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; renamecols=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"]

## Groupby 和 Combine

在 R 编程语言中，[Wickham](#ref-wickham2011split) ([2011](#ref-wickham2011split)) 推广了用于数据转换的 split-apply-combine 模式。 在该模式中，我们先将数据 **split** 成不同组，然后对每一组 **apply** 一个或多个函数，最后 **combine** 每组的结果。 DataFrames.jl 完全支持 split-apply-combine 模式。 本节使用之前的学生成绩数据作为示例。 假设想获得每个学生的平均成绩：

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 |

按照该模式，先将数据集按照学生名称 **split** 为不同组，其次对每组数据 **apply** 均值函数，最后 **combine** 每组的结果。

在 split 步骤中使用的函数为 groupby，并将函数的第二个参数列 ID 指定为数据集分割的条件。

groupby(all\_grades(), :name)

GroupedDataFrame with 4 groups based on key: name  
Group 1 (2 rows): name = "Sally"  
 Row │ name grade  
 │ String Float64  
─────┼─────────────────  
 1 │ Sally 1.0  
 2 │ Sally 9.5  
Group 2 (2 rows): name = "Bob"  
 Row │ name grade  
 │ String Float64  
─────┼─────────────────  
 1 │ Bob 5.0  
 2 │ Bob 9.5  
Group 3 (1 row): name = "Alice"  
 Row │ name grade  
 │ String Float64  
─────┼─────────────────  
 1 │ Alice 8.5  
Group 4 (2 rows): name = "Hank"  
 Row │ name grade  
 │ String Float64  
─────┼─────────────────  
 1 │ Hank 4.0  
 2 │ Hank 6.0

mean 函数来自 Julia 标准库中的 Statistics 模块:

using Statistics

应用此函数时，需调用 combine 函数：

gdf = groupby(all\_grades(), :name)  
combine(gdf, :grade => mean)

|  |  |
| --- | --- |
| name | grade\_mean |
| Sally | 5.25 |
| Bob | 7.25 |
| Alice | 8.5 |
| Hank | 5.0 |

想象一下，如果没有 groupby 和 combine 函数，则需按照下文这样做。 我们必须循环遍历数据以将其分割为多组，然后循环遍历每组以应用函数，**以及** 循环遍历每组以收集最终结果。 因此，split-apply-combine 模式是值得掌握的技术。

### Multiple Source Columns

但如果我们想将一个函数应用到多列数据，该如何操作？

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 |

操作与之前类似：

gdf = groupby(df, :group)  
combine(gdf, [:X, :Y] .=> mean; renamecols=false)

|  |  |  |
| --- | --- | --- |
| group | X | Y |
| A | 1.5 | 5.5 |
| B | 3.5 | 7.5 |

注意到，我们在右箭头 => 前使用了 . 点运算符，这表示 mean 函数将应用到多个列 [:X, :Y]。

要在combine中使用组合函数，一种简单的方法是创建一个函数来执行预期的组合变换。 例如，对于一组数据，在先应用 mean后调用 round 对值取整（即 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 |

## 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.

### In-place operations

Like we explained in Section [3.3.1.1](#sec:function_bang), 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!, and so on. Notice that these functions **do not** return a new DataFrame, 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](#sec:select). 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)

7648

df = responses()  
@allocated select!(df, :id, :q1)

7360

As we can see, select! allocates less than select. So, it should be faster, while consuming less memory.

### 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]

423658

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].

### 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](#sec:csv).

### 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.

### 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 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 data[[17]](#footnote-182). 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:

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.

# 使用 Makie.jl 做数据可视化

Maki-e 来源于日语， 它指的是一种在漆面上撒金粉和银粉的技术。 数据就是我们这个时代的金和银，让我们在屏幕上制作美丽的数据图吧！

*Simon Danisch, Makie.jl 创始人*

[Makie.jl](http://makie.juliaplots.org/stable/index.html) 是高性能，可扩展且跨平台的 Julia 语言绘图系统。 我们认为，它是最漂亮和最通用的绘图包。

与其他绘图包一样，该库的代码分为多个包。 Makie.jl 是绘图前端，它定义了所有创建绘图对象需要的函数。 虽然这些对象存储了绘图所需的全部信息，但还未转换为图片。 因此，我们需要一个 Makie 后端。 默认情况下，每一个后端都将 Makie.jl 中的API都重新导出了，因此只需要安装和加载所需的后端包即可。

目前主要有三个后端实现了 Makie 中定义的所有抽象类型的渲染功能。 第一个后端能够绘制 2D 非交互式的出版物质量级矢量图：CairoMakie.jl。 另一个后端是交互式 2D 和 3D 绘图库 GLFW.jl（支持 GPU），GLMakie.jl。 第三个后端是基于 WebGL 的交互式 2D 和 3D 绘图库 WGLMakie.jl，它运行在浏览器中。[查阅 Makie 文档了解更多](http://makie.juliaplots.org/stable/documentation/backends_and_output/)。

本书将只介绍一些 CairoMakie.jl 和 GLMakie.jl 的例子。

使用任一绘图后端的方法是 using 该后端并调用 activate! 函数。 示例如下：

using GLMakie  
GLMakie.activate!()

现在可以开始绘制出版质量级的图。 但是，在绘图之前，应知道如何保存。 save 图片 fig 的最简单方法是 save("filename.png", fig)。 CairoMakie.jl 也支持保存为其他格式，如 svg 和 pdf。 通过传递指定的参数可以轻松地改变图片的分辨率。 对于矢量格式，指定的参数为 pt\_per\_unit。例如：

save("filename.pdf", fig; pt\_per\_unit=2)

或

save("filename.pdf", fig; pt\_per\_unit=0.5)

对于 png，则指定 px\_per\_unit。 查阅 [后端 & 输出](https://makie.juliaplots.org/stable/documentation/backends_and_output/) 可获得更多详细信息。

另一重要问题是如何可视化输出数据图。 在使用 CairoMakie.jl 时，Julia REPL 不支持显示图片， 所以你还需要 IDE（Integrated Development Environment，集成开发环境），例如支持 png 或 svg 作为输出的 VSCode，Jupyter 或 Pluto。 另一个包 GLMakie.jl 则能够创建交互式窗口，或在调用 Makie.inline!(true) 时在行间显示位图。

## CairoMakie.jl

我们开始绘制的第一张图是标注了散点的直线：

using CairoMakie  
CairoMakie.activate!()

fig = scatterlines(1:10, 1:10)

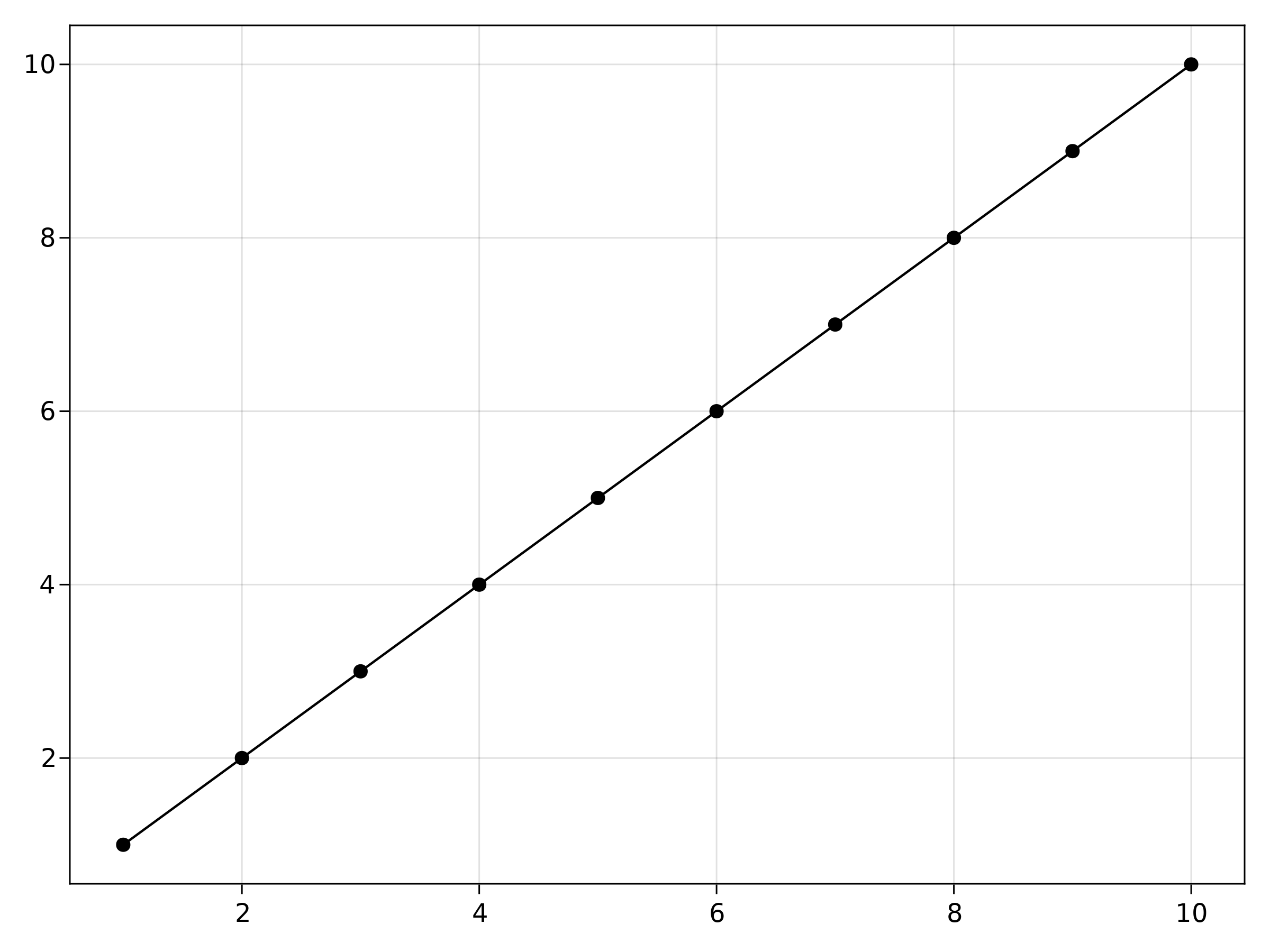


Figure 3: First plot.

注意前面的图采用默认输出样式，因此需要使用轴名称和轴标签进一步调整。

同时注意每一个像 scatterlines 这样的绘图函数都创建了一个 FigureAxisPlot 列表，其中包含 Figure， Axis 和 plot 对象。 这些函数也被称为 non-mutating 方法。 另一方面， mutating 方法（例如 scatterlines!，注意多了 !) 仅返回一个 plot 对象，它可以被添加到给定的 axis 或 current\_figure() 中。

下一个问题是如何改变颜色或标记的类型？ 这可以通过 attributes 实现， 将在下一节讨论。

## 属性

使用 attributes 可以创建自定义的图。 设置属性可以使用多个关键字参数。 每个 plot 对象的 attributes 列表可以通过以下方式查看：

fig, ax, pltobj = scatterlines(1:10)  
pltobj.attributes

Attributes with 14 entries:  
 color => black  
 colormap => viridis  
 colorrange => Automatic()  
 inspectable => true  
 linestyle => nothing  
 linewidth => 1.5  
 marker => Circle{T} where T  
 markercolor => black  
 markercolormap => viridis  
 markercolorrange => Automatic()  
 markersize => 9  
 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

或者调用 pltobject.attributes.attributes 返回对象属性的Dict 。

对于任一给定的绘图函数，都能在 REPL 中以 ?lines 或 help(lines) 的形式获取帮助。Julia将输出该函数的相应属性，并简要说明如何使用该函数。 关于 lines 的例子如下：

help(lines)

lines(positions)  
 lines(x, y)  
 lines(x, y, z)  
  
 Creates a connected line plot for each element in (x, y, z), (x, y) or  
 positions.  
  
 │ Tip  
 │  
 │ You can separate segments by inserting NaNs.  
  
 lines has the following function signatures:  
  
 (Vector, Vector)  
 (Vector, Vector, Vector)  
 (Matrix)  
  
 Available attributes for Lines{T} where T are:  
  
 ambient  
 color  
 colormap  
 colorrange  
 cycle  
 diffuse  
 inspectable  
 lightposition  
 linestyle  
 linewidth  
 nan\_color  
 overdraw  
 shininess  
 specular  
 ssao  
 transparency  
 visible

不仅 plot 对象有属性，Axis 和 Figure 对象也有属性。 例如，Figure 的属性有 backgroundcolor，resolution，font 和 fontsize 以及 figure\_padding。 其中 figure\_padding 改变了图像周围的空白区域，如图 (Figure [4](#fig:custom_plot)) 中的灰色区域所示。 它使用一个数字指定所有边的范围，或使用四个数的元组表示上下左右。

Axis 同样有一系列属性，典型的有 backgroundcolor， xgridcolor 和 title。 使用 help(Axis) 可查看所有属性。

在接下来这张图里，我们将设置一些属性：

lines(1:10, (1:10).^2; color=:black, linewidth=2, linestyle=:dash,  
 figure=(; figure\_padding=5, resolution=(600, 400), font="sans",  
 backgroundcolor=:grey90, fontsize=16),  
 axis=(; xlabel="x", ylabel="x²", title="title",  
 xgridstyle=:dash, ygridstyle=:dash))  
current\_figure()

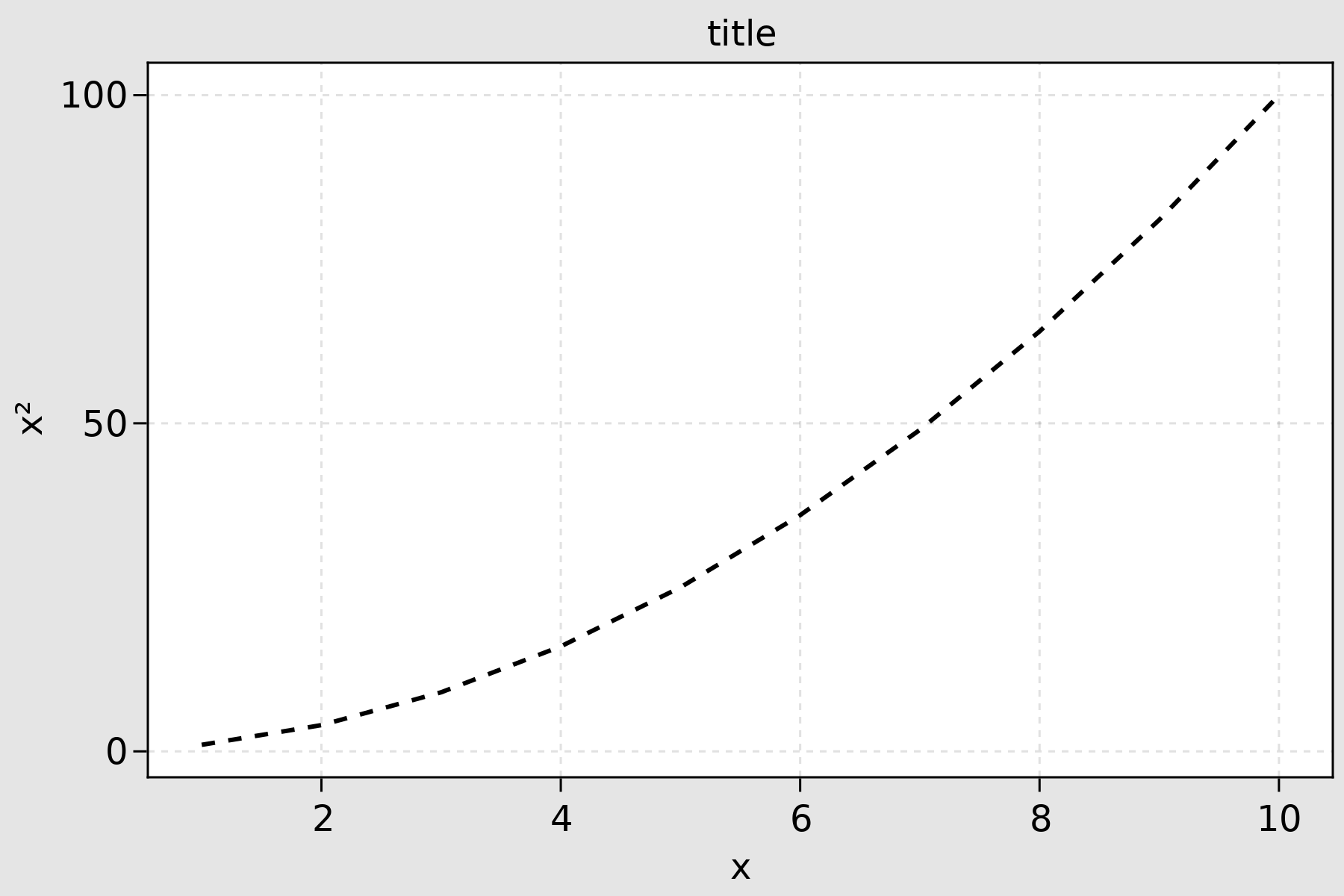


Figure 4: Custom plot.

此例已经包含了大多数用户经常会用到的属性。 或许在图上加一个 legend 会更好，这在有多条曲线时尤为有意义。 所以，向图上 append 另一个 plot object 并且通过调用 axislegend 添加对应的图例。 它将收集所有 plot 函数中的 labels， 并且图例默认位于图的右上角。 本例调用了 position=:ct 参数，其中 :ct 表示图例将位于 center和 top， 如图 Figure [5](#fig:custom_plot_leg) 所示：

lines(1:10, (1:10).^2; label="x²", linewidth=2, linestyle=nothing,  
 figure=(; figure\_padding=5, resolution=(600, 400), font="sans",  
 backgroundcolor=:grey90, fontsize=16),  
 axis=(; xlabel="x", title="title", xgridstyle=:dash,  
 ygridstyle=:dash))  
scatterlines!(1:10, (10:-1:1).^2; label="Reverse(x)²")  
axislegend("legend"; position=:ct)  
current\_figure()

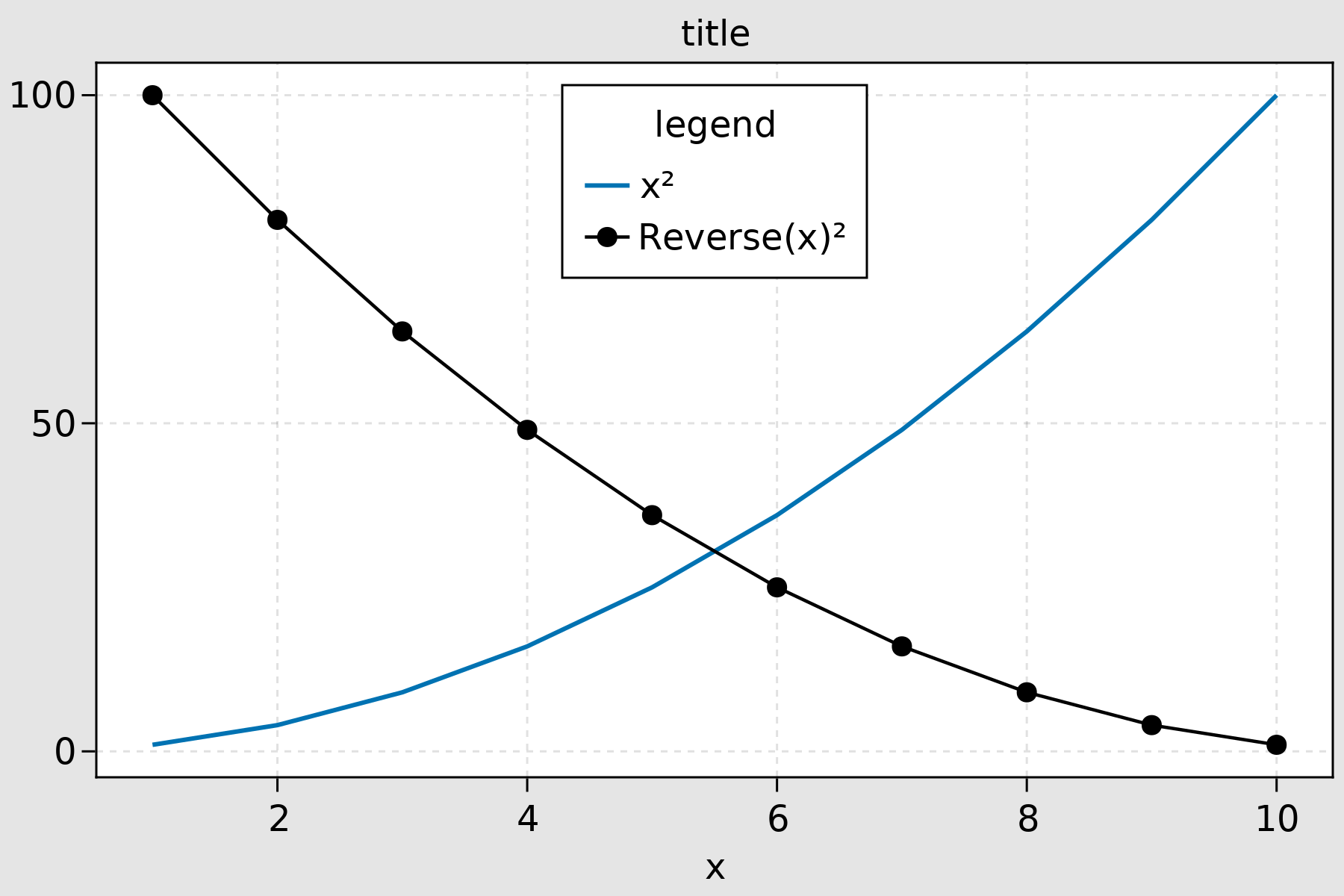


Figure 5: Custom plot legend.

通过组合 left(l), center(c), right(r) 和 bottom(b), center(c), top(t) 还可以再指定其他位置。 例如，使用:lt 指定为左上角。

然而，仅仅为两条曲线编写这么多代码是比较复杂的。 所以，如果要以相同的样式绘制一组曲线，那么最好指定一个主题。 使用 set\_theme!() 可实现该操作，如下所示。

使用 set\_theme!(kwargs)定义的新配置，重新绘制之前的图：

set\_theme!(; resolution=(600, 400),  
 backgroundcolor=(:orange, 0.5), fontsize=16, font="sans",  
 Axis=(backgroundcolor=:grey90, xgridstyle=:dash, ygridstyle=:dash),  
 Legend=(bgcolor=(:red, 0.2), framecolor=:dodgerblue))  
lines(1:10, (1:10).^2; label="x²", linewidth=2, linestyle=nothing,  
 axis=(; xlabel="x", title="title"))  
scatterlines!(1:10, (10:-1:1).^2; label="Reverse(x)²")  
axislegend("legend"; position=:ct)  
current\_figure()  
set\_theme!()  
caption = "Set theme example."

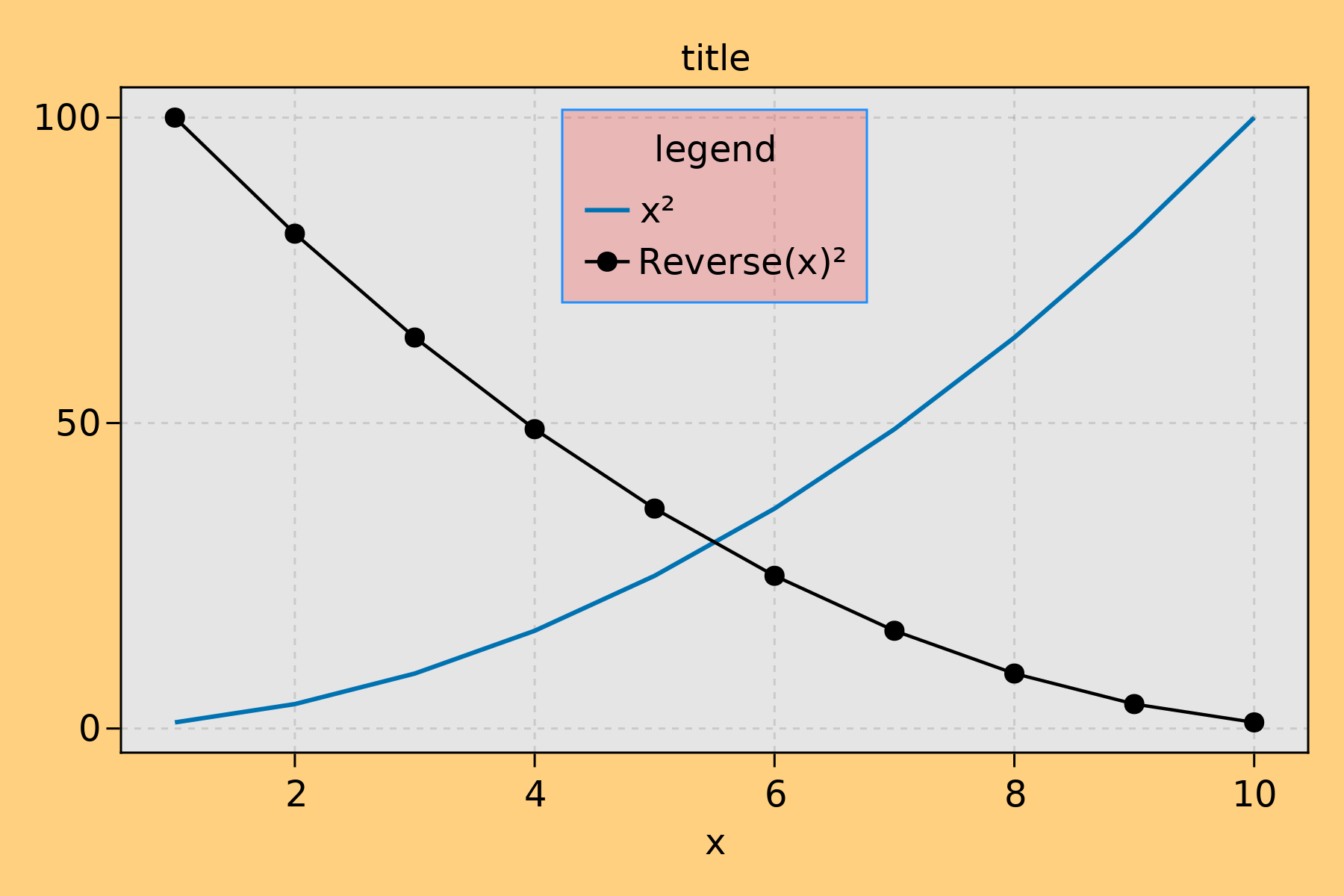


Figure 6: Set theme example.

倒数第二行的 set\_theme!() 会将主题重置到 Makie 的默认设置。 有关 themes 的更多内容请转到 Section [5.3](#sec:themes)。

在进入下节前， 值得先看一个例子：将多个参数所组成的 array 传递给绘图函数来配置属性。 例如，使用 scatter 绘图函数绘制气泡图。

本例随机生成 100 行 3 列的 array ，这些数据满足正态分布。 其中第一列表示 x 轴上的位置，第二列表示 y 轴上的位置，第三列表示与每一点关联的属性值。 例如可以用来指定不同的 color 或者不同的标记大小。气泡图就可以实现相同的操作。

using Random: seed!  
seed!(28)  
xyvals = randn(100, 3)  
xyvals[1:5, :]

5×3 Matrix{Float64}:  
 -0.294668 1.27304 1.20005  
 -0.8177 1.28339 -0.408239  
 -0.936189 1.50032 1.65924  
 -0.334106 0.395313 -1.4814  
 1.81839 0.351304 0.261416

对应的图 Figure [7](#fig:bubble) 如下所示:

fig, ax, pltobj = scatter(xyvals[:, 1], xyvals[:, 2]; color=xyvals[:, 3],  
 label="Bubbles", colormap=:plasma, markersize=15 \* abs.(xyvals[:, 3]),  
 figure=(; resolution=(600, 400)), axis=(; aspect=DataAspect()))  
limits!(-3, 3, -3, 3)  
Legend(fig[1, 2], ax, valign=:top)  
Colorbar(fig[1, 2], pltobj, height=Relative(3 / 4))  
fig  
caption = "Bubble plot."

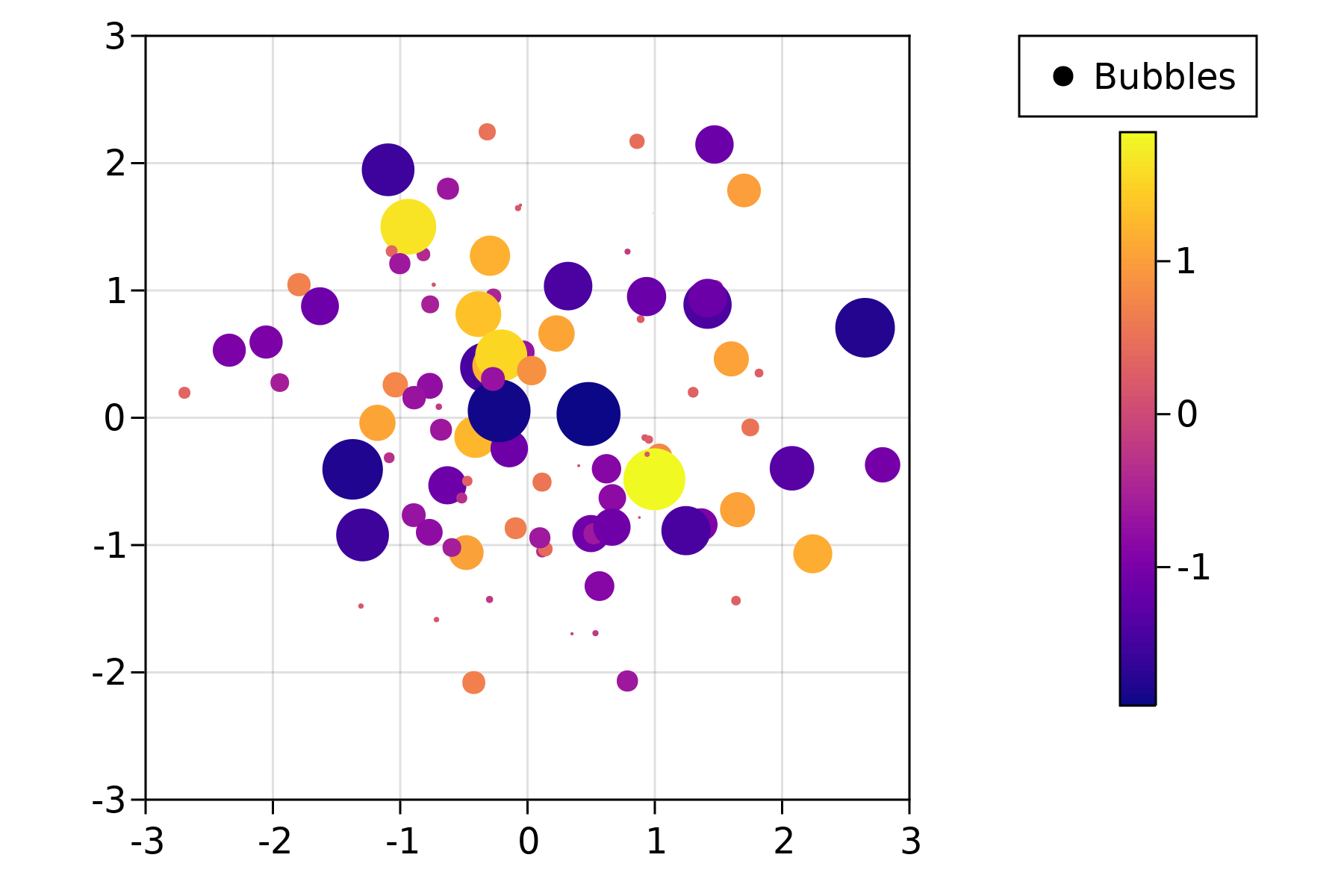


Figure 7: Bubble plot.

为了在图上添加 Legend 和 Colorbar，需将 FigureAxisPlot 元组分解为 fig, ax, pltobj。 我们将在 Section [5.6](#sec:makie_layouts) 讨论有关布局选项的更多细节。

通过一些基本且有趣的例子，我们展示了如何使用Makie.jl，现在你可能想知道：还能做什么？ Makie.jl 都还有哪些绘图函数？ 为了回答此问题，我们制作了一个 *cheat sheet* 如 Figure [8](#fig:cheat_sheet_cairomakie) 所示。 使用 CairoMakie.jl 后端可以轻松绘制这些图。

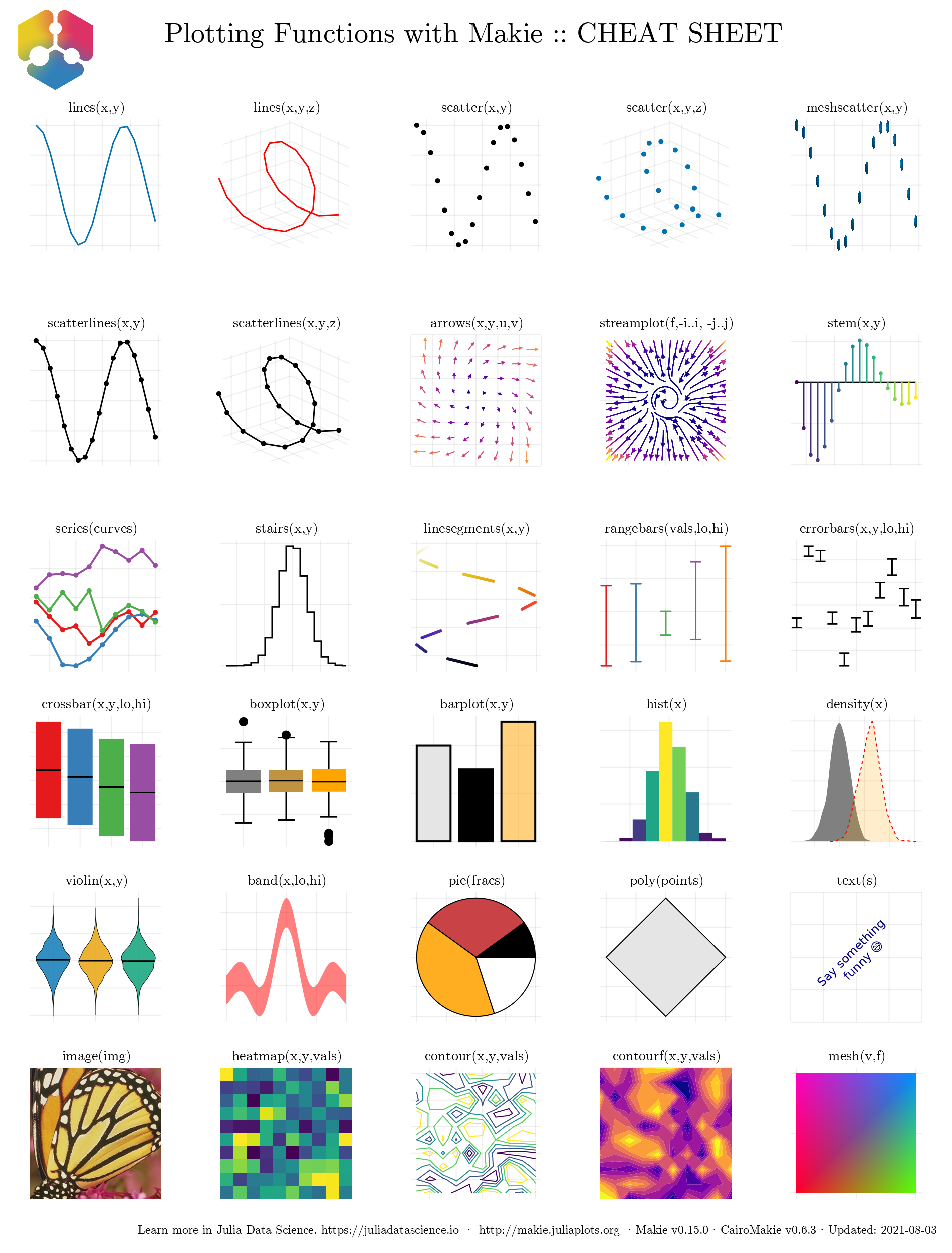


Figure 8: Plotting functions: Cheat Sheet. Output given by Cairomakie.

Figure [9](#fig:cheat_sheet_glmakie) 展示了 GLMakie.jl 的\_cheat sheet\_ ，这些函数支持绘制大多数 3D 图。 这些将在后面的 GLMakie.jl 节进一步讨论。

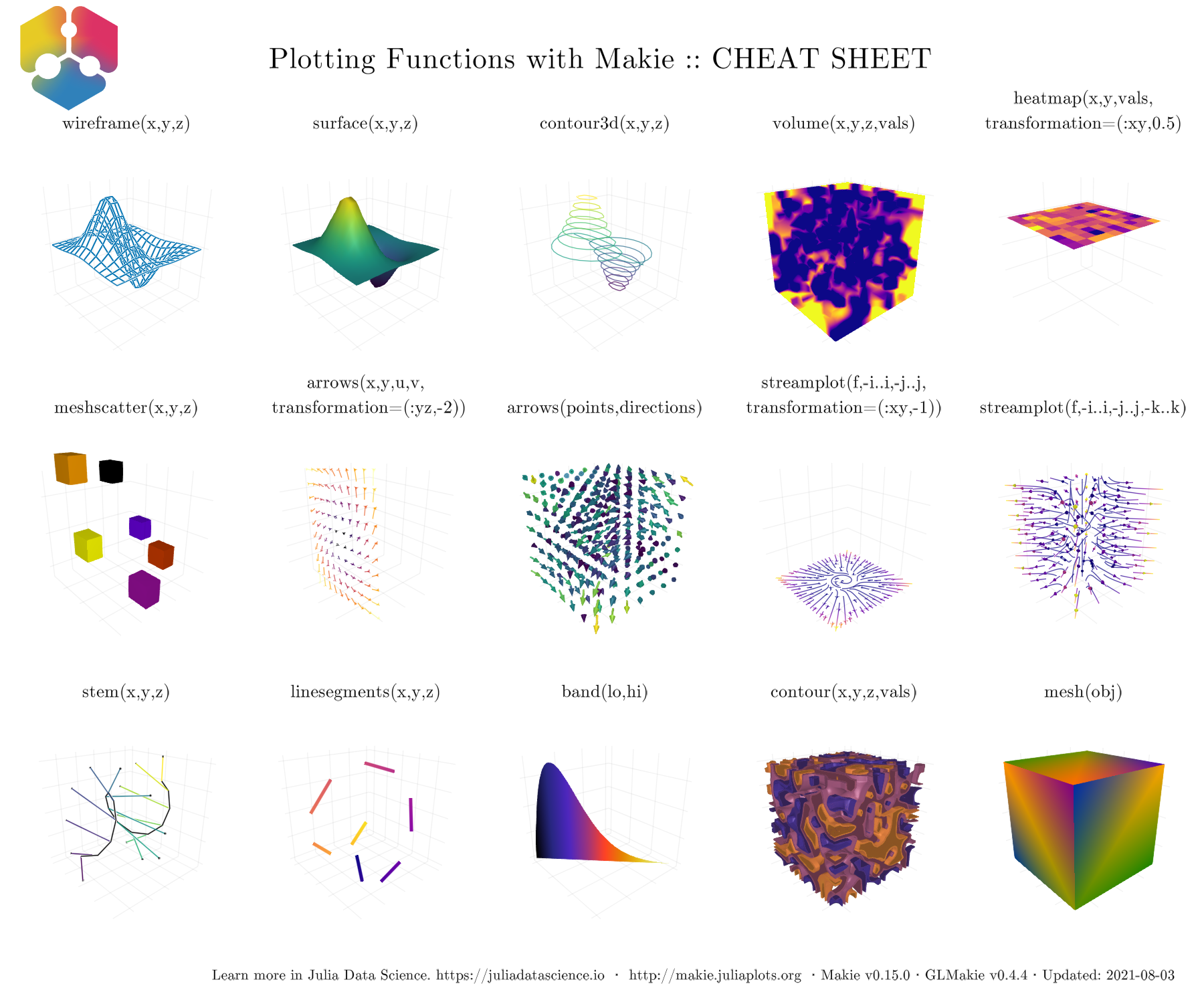


Figure 9: Plotting functions: Cheat Sheet. Output given by GLMakie.

现在，我们已经大致了解到能做什么。接下来应该掉过头来继续研究基础知识。 是时候学习如何改变图的整体外观了。

## 主题

有多种方式可以改变图的整体外观。你可以使用 [预定义主题](http://makie.juliaplots.org/stable/documentation/theming/predefined_themes/index.html) 或自定义的主题。例如，通过 with\_theme(your\_plot\_function, theme\_dark()) 使用预定义的暗色主题。另外，也可以使用 Theme(kwargs) 构建你自己的主题或使用 update\_theme!(kwargs) 更新当前激活的主题。

还可以使用 set\_theme!(theme; kwargs...) 将当前主题改为 theme， 并且通过 kwargs 覆盖或增加一些属性。使用不带参数的 set\_theme!() 即可恢复到之前主题的设置。在下面的例子中，我们准备了具有不同样式的测试绘图函数，以便于观察每个主题的大多数属性。

using Random: seed!  
seed!(123)  
y = cumsum(randn(6, 6), dims=2)

6×6 Matrix{Float64}:  
 1.19027 2.17124 1.2823 0.56489 0.842615 -0.0284417  
 2.04818 1.9727 2.29991 1.52484 3.04876 3.39449  
 1.14265 1.41647 2.00887 1.02933 -0.748397 -0.904251  
 0.459416 0.265187 0.633189 0.893591 -2.03947 0.293544  
 -0.396679 -0.736045 -1.01718 -1.48567 -0.70341 -1.70176  
 -0.664713 -1.50859 -2.24348 -3.12437 -0.810794 -0.743838

本例随机生成了一个大小为 (20,20) 的矩阵，以便于绘制一张热力图（heatmap）。 同时本例也指定了 和 的范围。

using Random: seed!  
seed!(13)  
xv = yv = LinRange(-3, 0.5, 20)  
matrix = randn(20, 20)  
matrix[1:6, 1:6] # first 6 rows and columns

6×6 Matrix{Float64}:  
 -0.410261 0.755685 1.84697 0.0645615 1.53034 0.557182  
 -2.06413 1.2311 0.330232 -0.793936 -1.10552 -2.1084  
 0.0749639 -3.42235 0.392709 2.47305 -1.10597 0.962373  
 0.803344 1.78866 -0.81155 -1.70707 0.00106256 0.297236  
 -1.24842 1.4372 1.11774 -0.952159 -0.0887516 0.0106082  
 -1.43937 1.31755 0.631643 0.261686 -0.402386 0.233161

因此，新绘图函数如下所示：

function demo\_themes(y, xv, yv, matrix)  
 fig, \_ = series(y; labels=["$i" for i = 1:6], markersize=10,  
 color=:Set1, figure=(; resolution=(600, 300)),  
 axis=(; xlabel="time (s)", ylabel="Amplitude",  
 title="Measurements"))  
 hmap = heatmap!(xv, yv, matrix; colormap=:plasma)  
 limits!(-3.1, 8.5, -6, 5.1)  
 axislegend("legend"; merge=true)  
 Colorbar(fig[1, 2], hmap)  
 fig  
end

注意，series 函数的作用是同时绘制多条附带标签的直线图和散点图。另外还绘制了附带 colorbar 的 heatmap。如图所示，有两种暗色主题，一种是 theme\_dark() ，另一种是 theme\_black()。

with\_theme(theme\_dark()) do  
 demo\_themes(y, xv, yv, matrix)  
end  
with\_theme(theme\_black()) do  
 demo\_themes(y, xv, yv, matrix)  
end

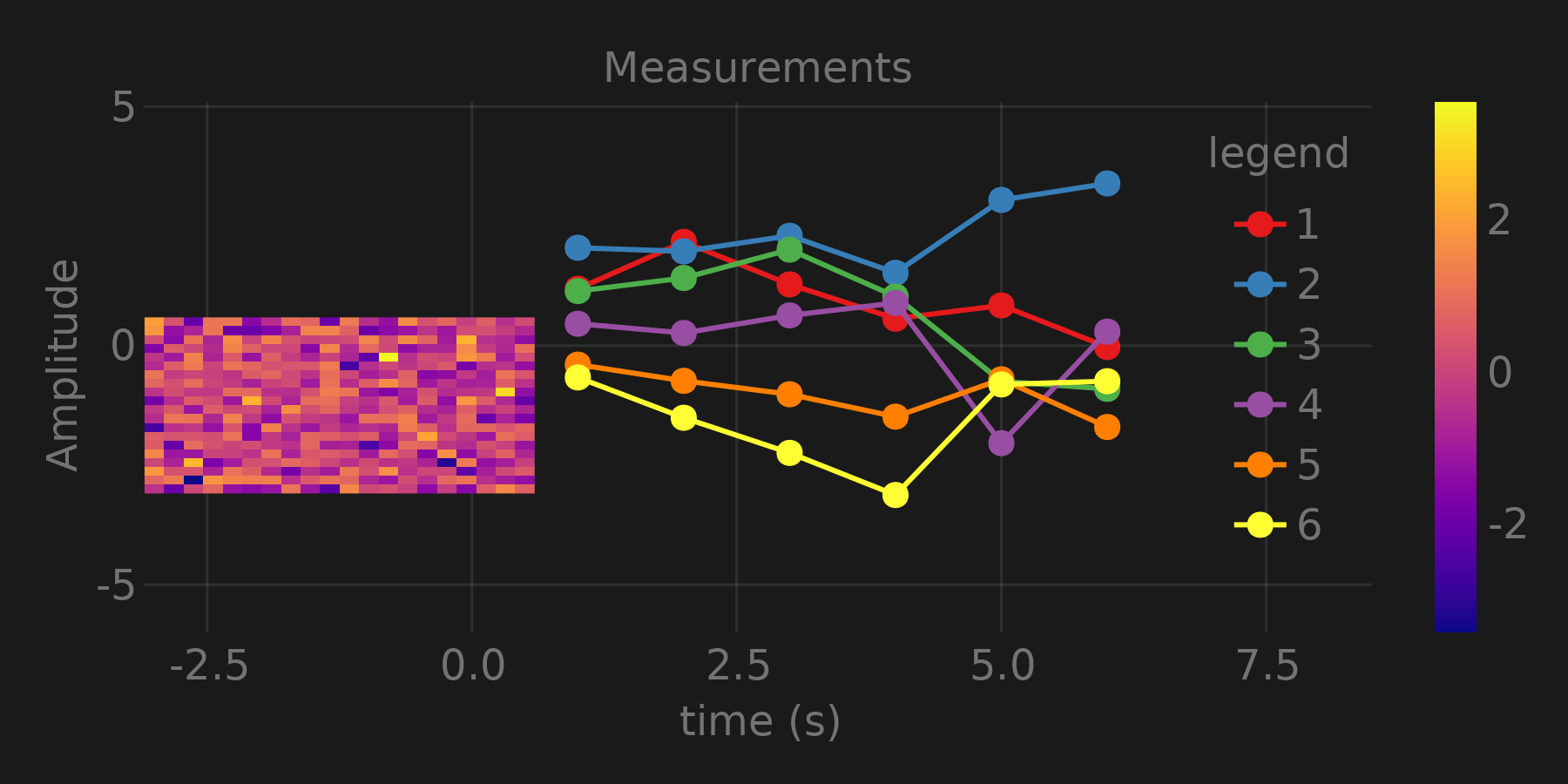


Figure 10: Theme dark.

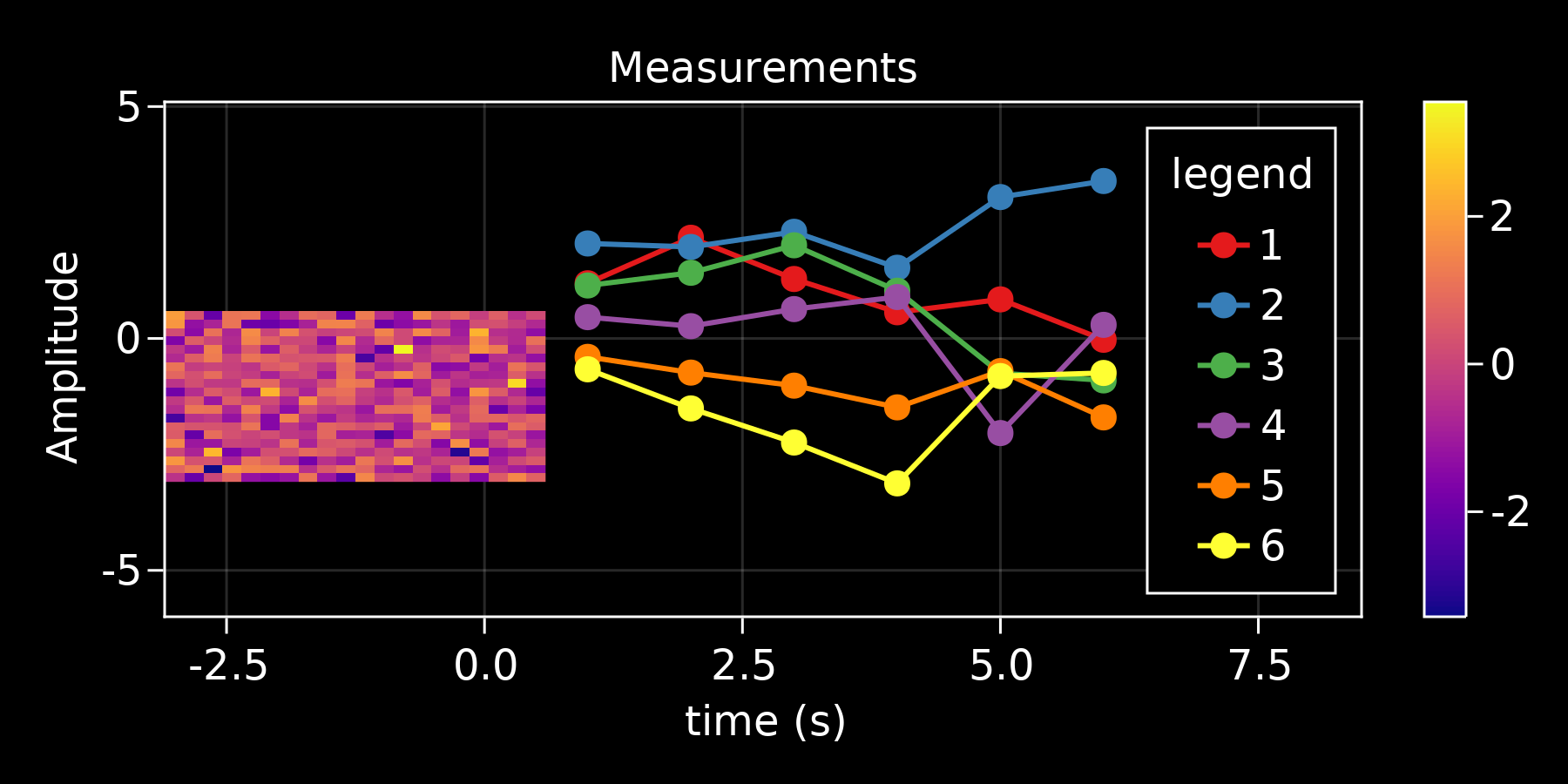


Figure 11: Theme black.

另外有三种白色主题，theme\_ggplot2()，theme\_minimal() 和 theme\_light()。这些主题对于更标准的出版图很有用。

with\_theme(theme\_ggplot2()) do  
 demo\_themes(y, xv, yv, matrix)  
end  
with\_theme(theme\_minimal()) do  
 demo\_themes(y, xv, yv, matrix)  
end  
with\_theme(theme\_light()) do  
 demo\_themes(y, xv, yv, matrix)  
end

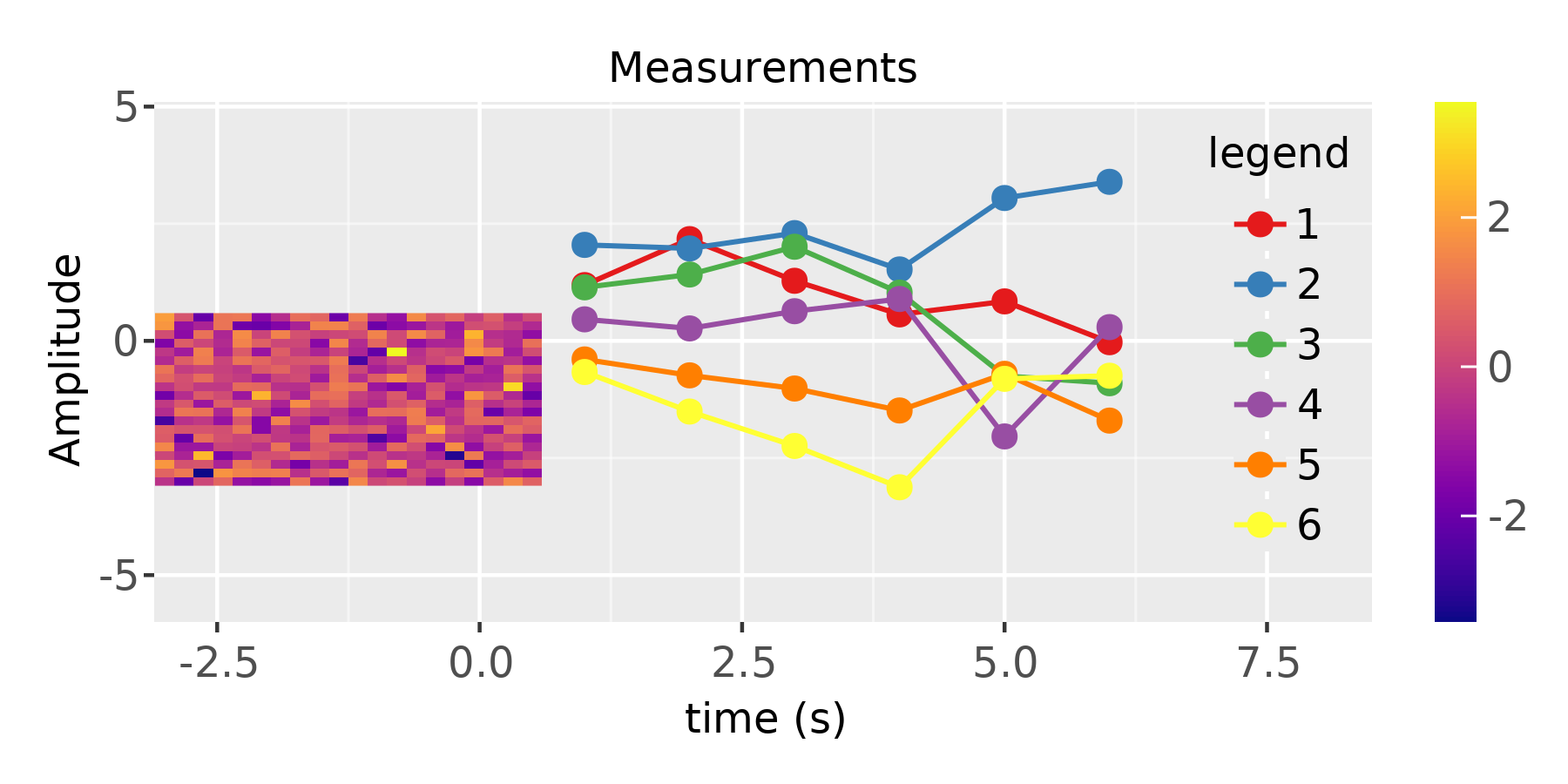


Figure 12: Theme ggplot2.

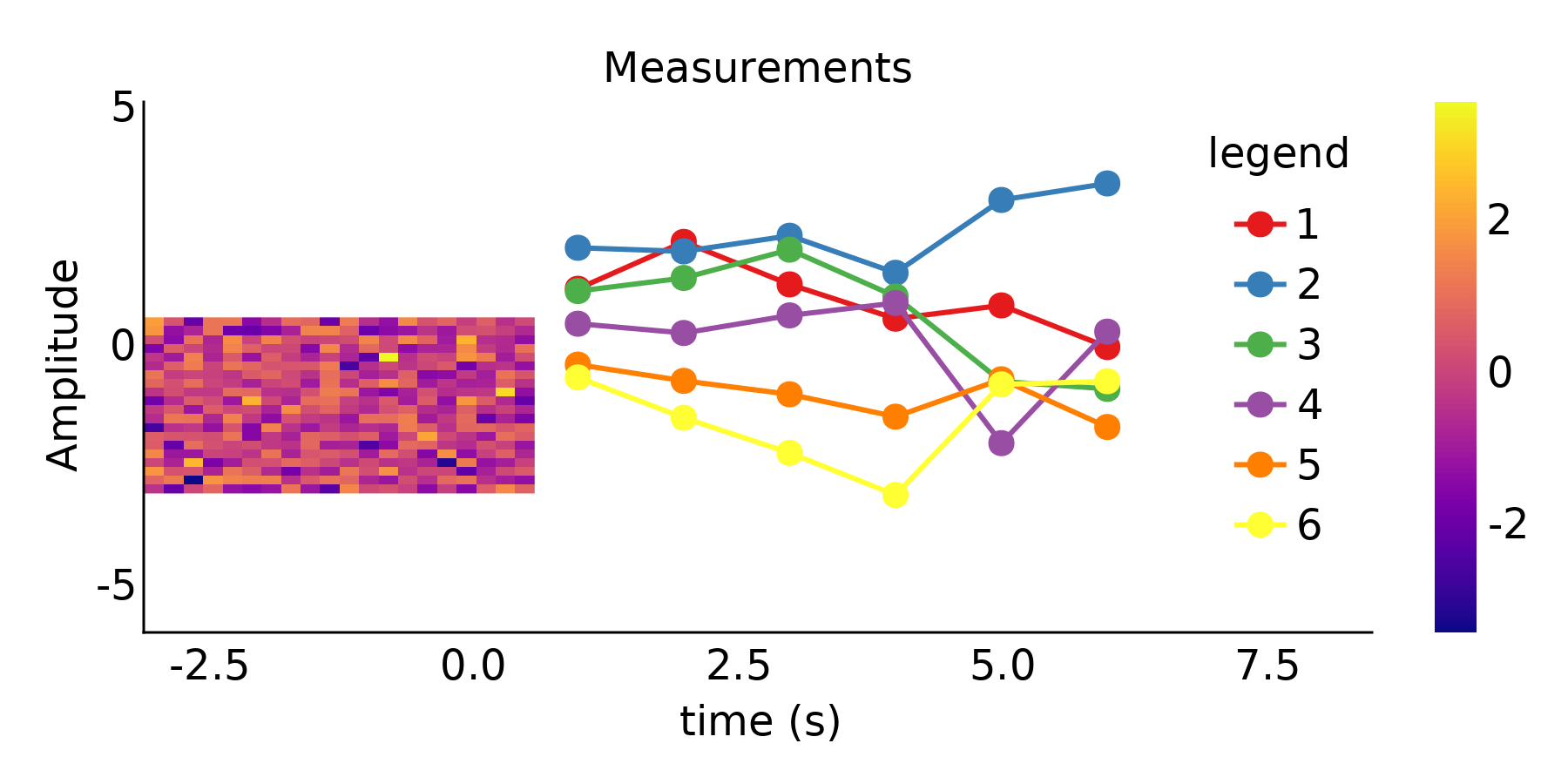


Figure 13: Theme minimal.

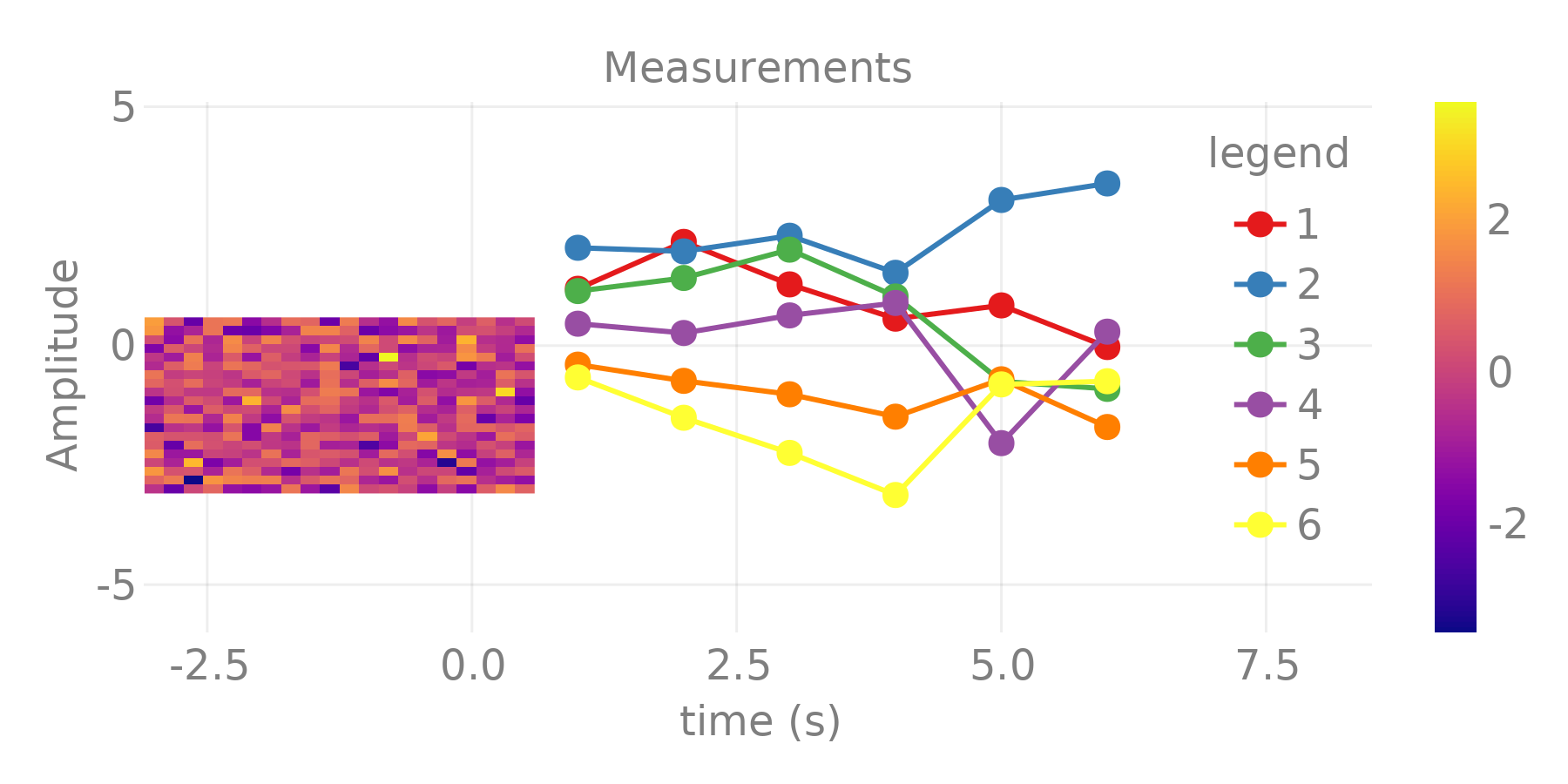


Figure 14: Theme light.

另一种方案是通过使用 with\_theme(your\_plot, your\_theme()) 创建自定义 Theme 。 例如，以下主题可以作为出版质量图的初级模板：

publication\_theme() = Theme(  
 fontsize=16, font="CMU Serif",  
 Axis=(xlabelsize=20, xgridstyle=:dash, ygridstyle=:dash,  
 xtickalign=1, ytickalign=1, yticksize=10, xticksize=10,  
 xlabelpadding=-5, xlabel="x", ylabel="y"),  
 Legend=(framecolor=(:black, 0.5), bgcolor=(:white, 0.5)),  
 Colorbar=(ticksize=16, tickalign=1, spinewidth=0.5),  
)

为简单起见，在接下来的例子中使用它绘制 scatterlines 和 heatmap。

function plot\_with\_legend\_and\_colorbar()  
 fig, ax, \_ = scatterlines(1:10; label="line")  
 hm = heatmap!(ax, LinRange(6, 9, 15), LinRange(2, 5, 15), randn(15, 15);  
 colormap=:Spectral\_11)  
 axislegend("legend"; position=:lt)  
 Colorbar(fig[1, 2], hm, label="values")  
 ax.title = "my custom theme"  
 fig  
end

然后使用前面定义的 Theme，其输出如 (Figure [15](#fig:plot_with_legend_and_colorbar)) 所示。

with\_theme(plot\_with\_legend\_and\_colorbar, publication\_theme())

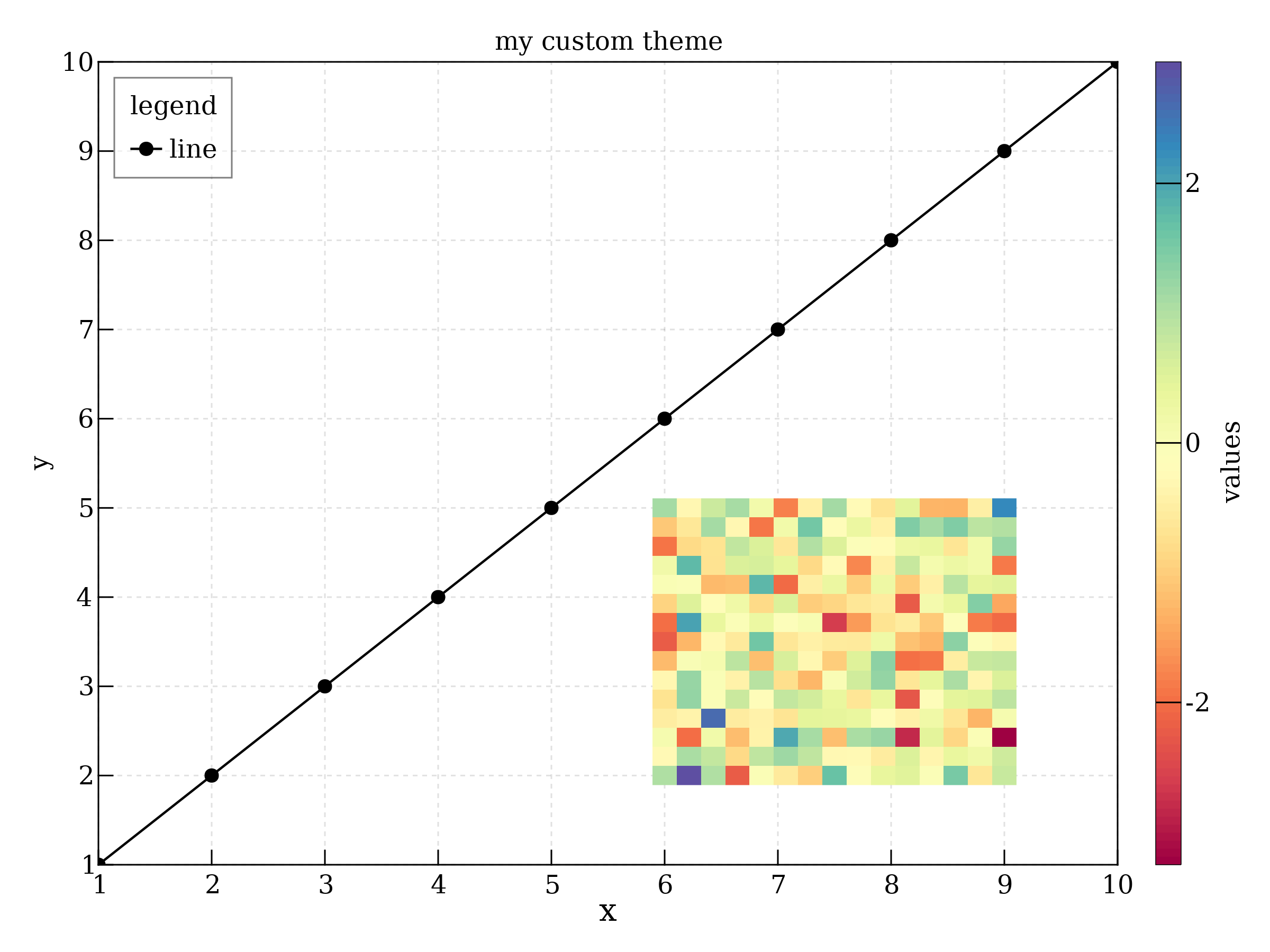


Figure 15: Themed plot with Legend and Colorbar.

如果需要在 set\_theme!(your\_theme)后更改一些设置，那么可以使用 update\_theme!(resolution=(500, 400), fontsize=18)。 另一种方法是给 with\_theme 函数传递额外的参数：

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

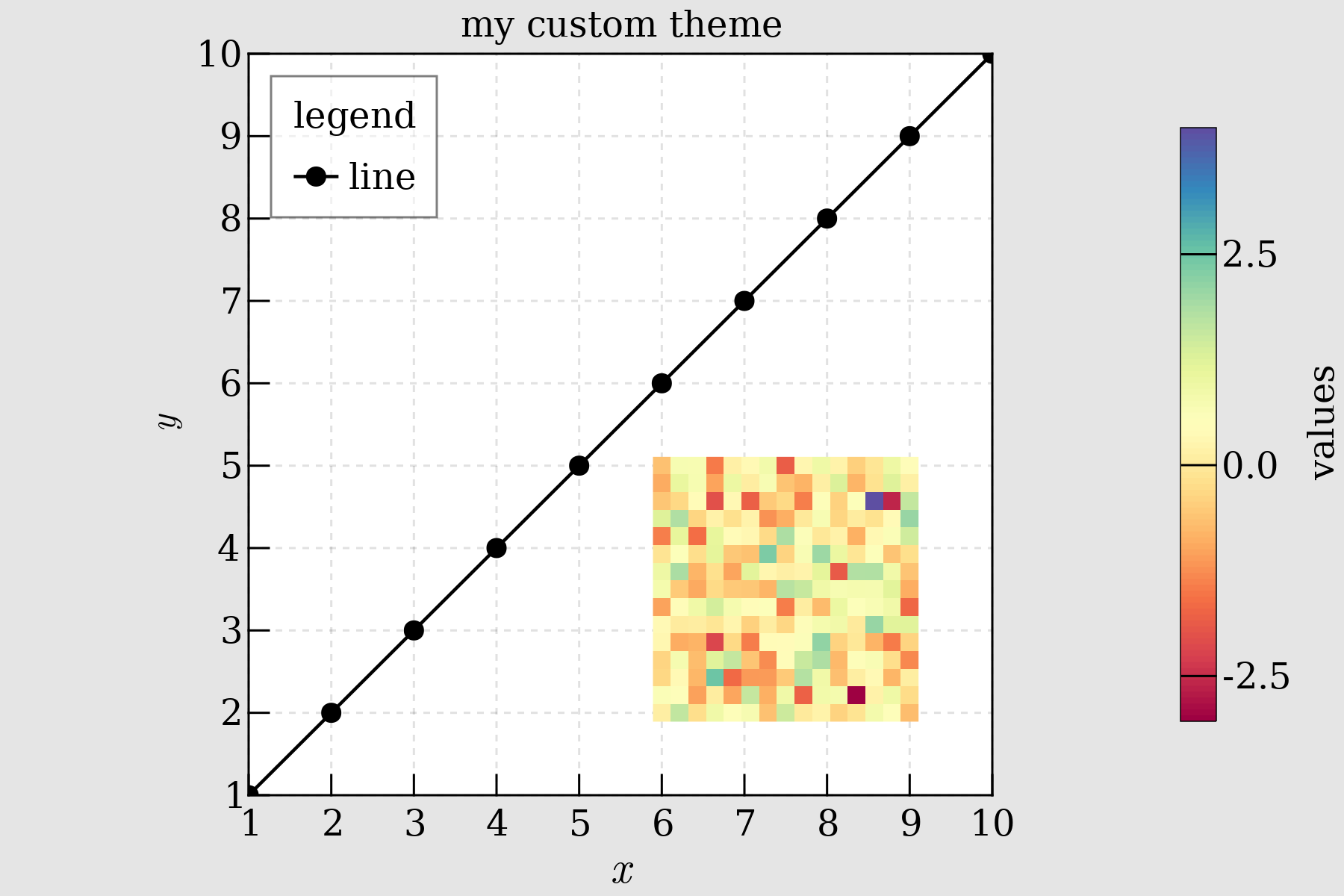


Figure 16: Theme with extra args.

现在，接下来将讨论如何使用 LaTeX 字符串和自定义主题进行绘图。

## 使用 LaTeXStrings.jl

通过调用 LaTeXStrings.jl，Makie.jl 实现了对 LaTeX 的支持：

using LaTeXStrings

一个简单的基础用法例子如下所示 (Figure [17](#fig:latex_strings))，其主要包含用于 x-y 标签和图例的 LaTeX 字符串。

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())

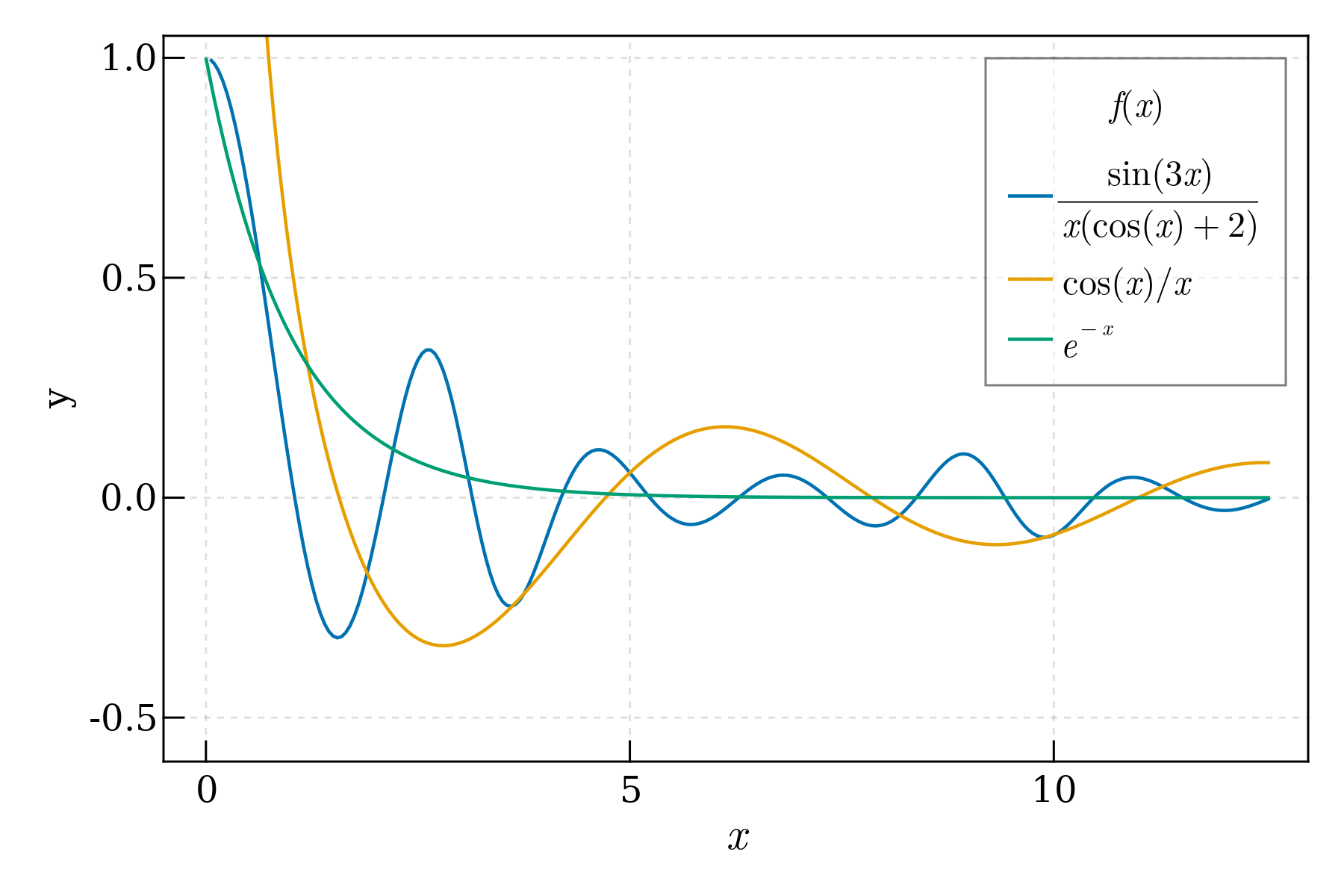


Figure 17: Plot with LaTeX strings.

下面是更复杂的例子，图中的text是一些等式，并且图例编号随着曲线数增加：

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  
multiple\_lines()

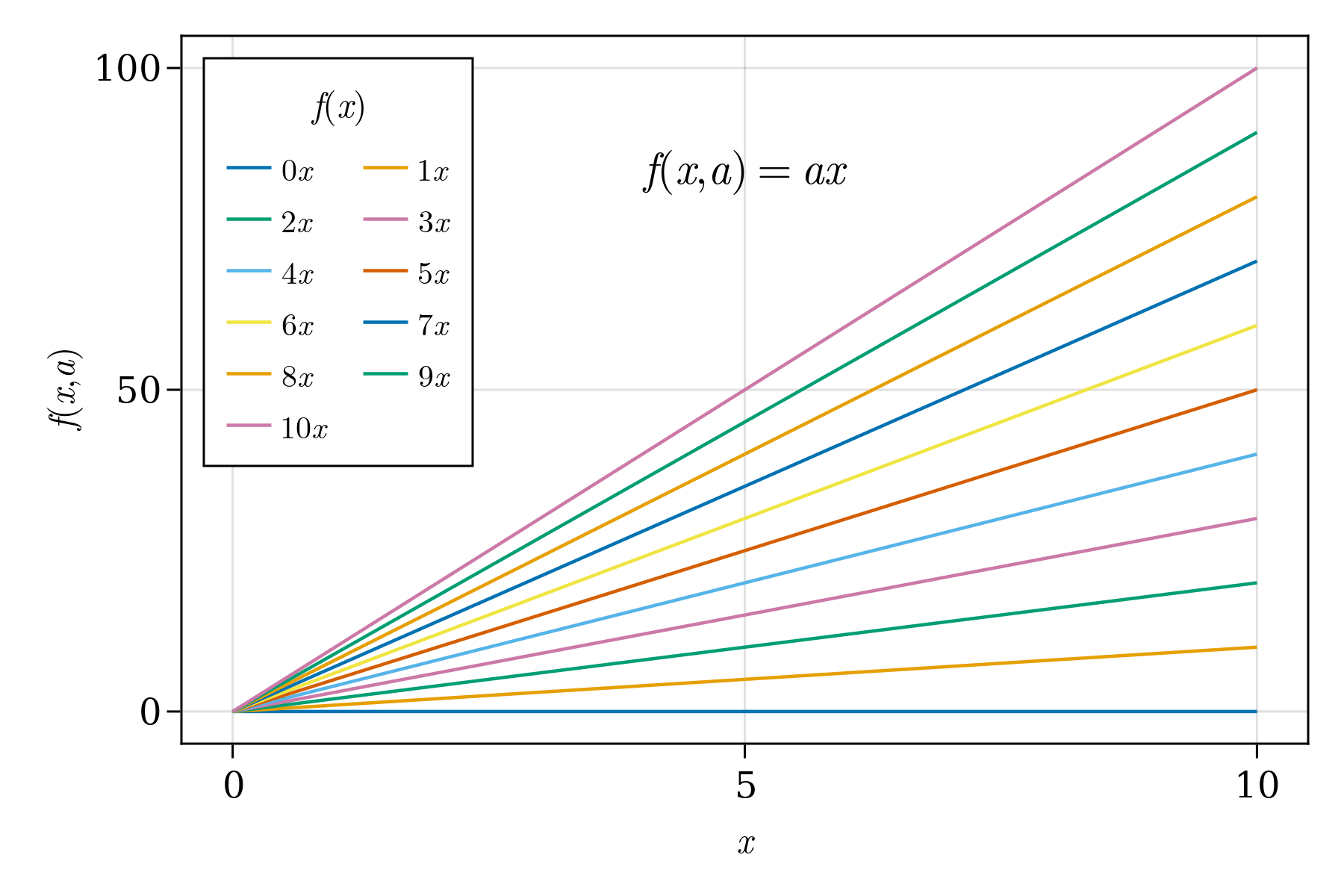


Figure 18: Multiple lines.

但不太好的是，一些曲线的颜色是重复的。 添加标记和线条类型通常能解决此问题。 所以让我们使用 [Cycles](http://makie.juliaplots.org/stable/documentation/theming/index.html#cycles) 来添加标记和线条类型。 设置 covary=true，使所有元素一起循环：

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=latexstring("$(i) x"))  
 scatter!(ax, x, i .\* x; markersize=13, strokewidth=0.25,  
 label=latexstring("$(i) x"))  
 end  
 axislegend(L"f(x)"; merge=true, position=:lt, nbanks=2, labelsize=14)  
 text!(L"f(x,a) = ax", position=(4, 80))  
 set\_theme!() # reset to default theme  
 fig  
end  
multiple\_scatters\_and\_lines()

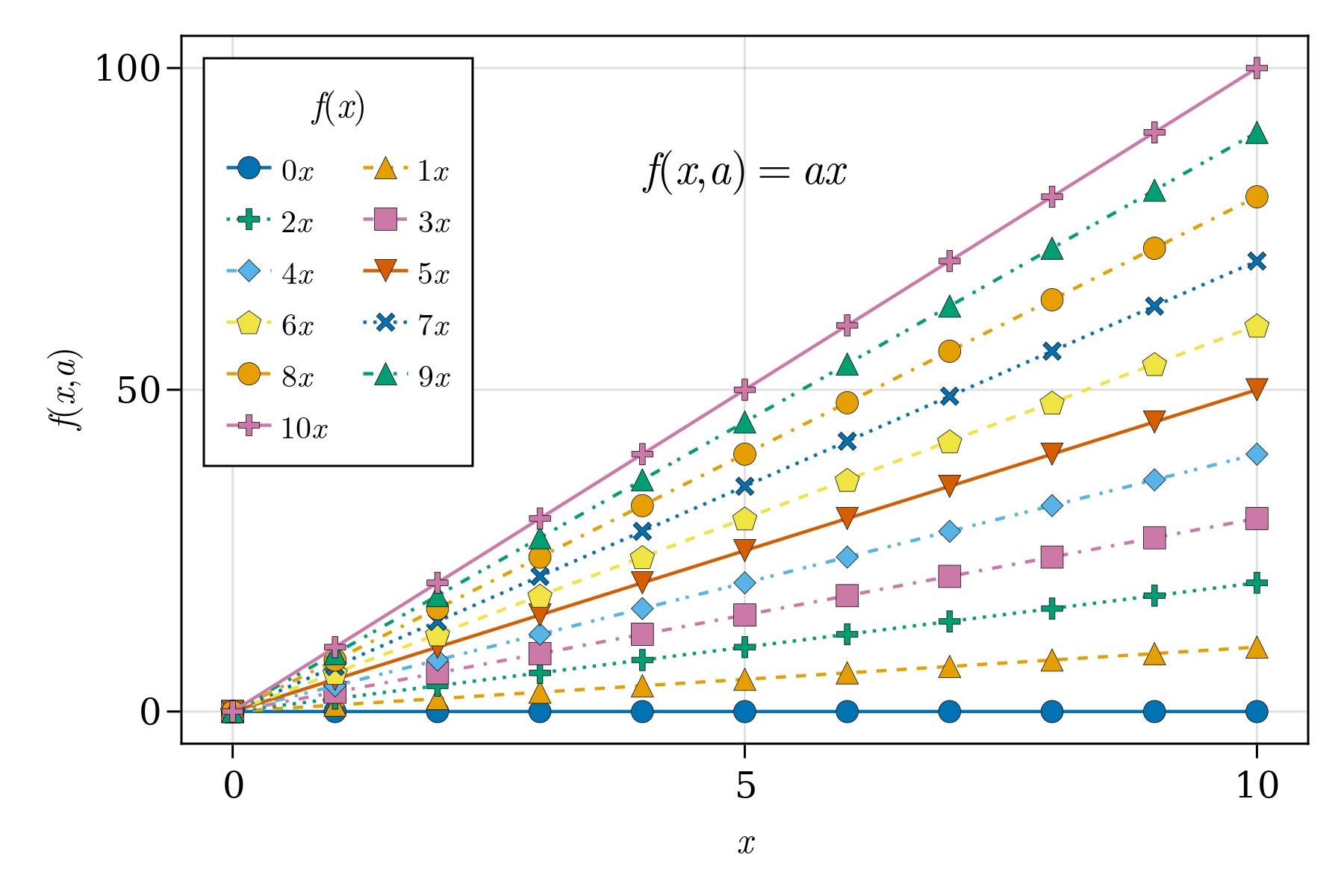


Figure 19: Multiple Scatters and Lines.

一张出版质量的图如上所示。 那我们还能做些什么操作？ 答案是还可以为图定义不同的默认颜色或者调色盘。 在下一节，我们将再次了解如何使用 [Cycles](http://makie.juliaplots.org/stable/documentation/theming/index.html#cycles) 以及有关它的更多信息，即通过添加额外的关键字参数就可以实现前面的操作。

## 颜色和颜色图（Colormap）

在展示结果时，其中重要的一步是为图选择一组合适的颜色或 colorbar。 Makie.jl 支持使用 [Colors.jl](https://github.com/JuliaGraphics/Colors.jl) ，因此你可以使用 [named colors](https://juliagraphics.github.io/Colors.jl/latest/namedcolors/) 而不是传递 RGB 或 RGBA 值。 另外，也可以使用 [ColorSchemes.jl](https://github.com/JuliaGraphics/ColorSchemes.jl) 和 [PerceptualColourMaps.jl](https://github.com/peterkovesi/PerceptualColourMaps.jl) 中的颜色图。 值得了解的是，可以使用 Reverse(:colormap\_name) 反转颜色图 ，也可以通过 color=(:red,0.5) and colormap=(:viridis, 0.5) 获得透明的颜色或颜色图。

下文介绍不同的用例。 接下来使用新的颜色和颜色栏（Colorbar）调色盘来创建自定义主题。

默认情况下， Makie.jl 已经预定义一组颜色，可以循环使用该组颜色。 之前的图因此并未设置任何特定颜色。 覆盖这些默认颜色的方法是，在绘图函数中调用 color 关键字并使用 Symbol 或 String 指定新的颜色。 该操作如下所示：

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 = LinRange(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)  
 fig  
end  
set\_colors\_and\_cycle()

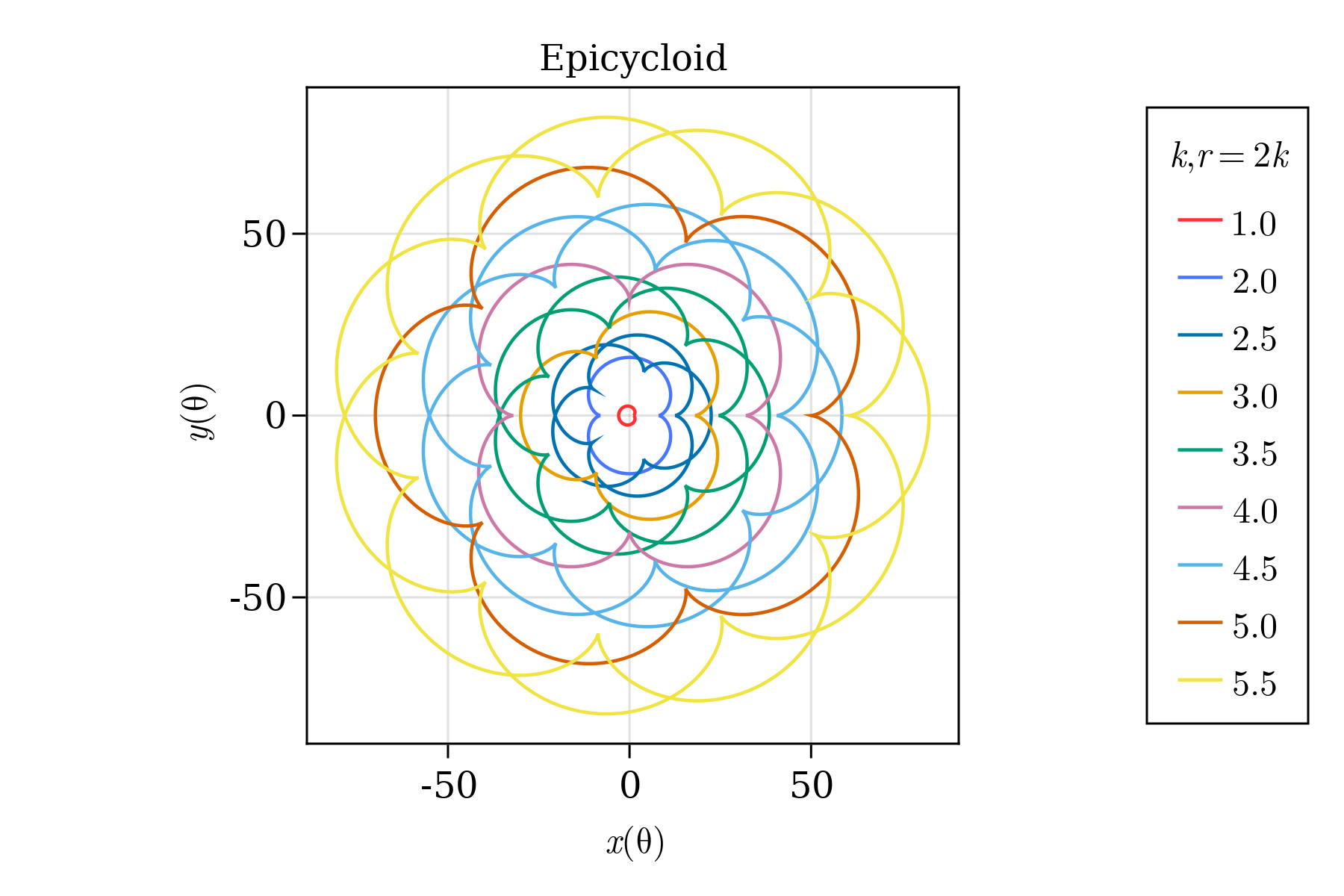


Figure 20: Set colors and cycle.

这里通过color 关键字指定了上例前两条曲线的颜色。 其余使用默认的颜色集。 稍后将学习如何使用自定义颜色循环。

关于颜色图，我们已经非常熟悉用于热力图和散点图的 colormap。下面展示的是，颜色图也可以像颜色那样通过 Symbol 或 String 进行指定。 此外，也可以是 RGB 颜色的向量。 下面是第一个例子，通过 Symbol， String 和分类值的 cgrad 来指定颜色图。 输入 ?cgrad 查看更多信息。

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 colormap Sequential")  
fig

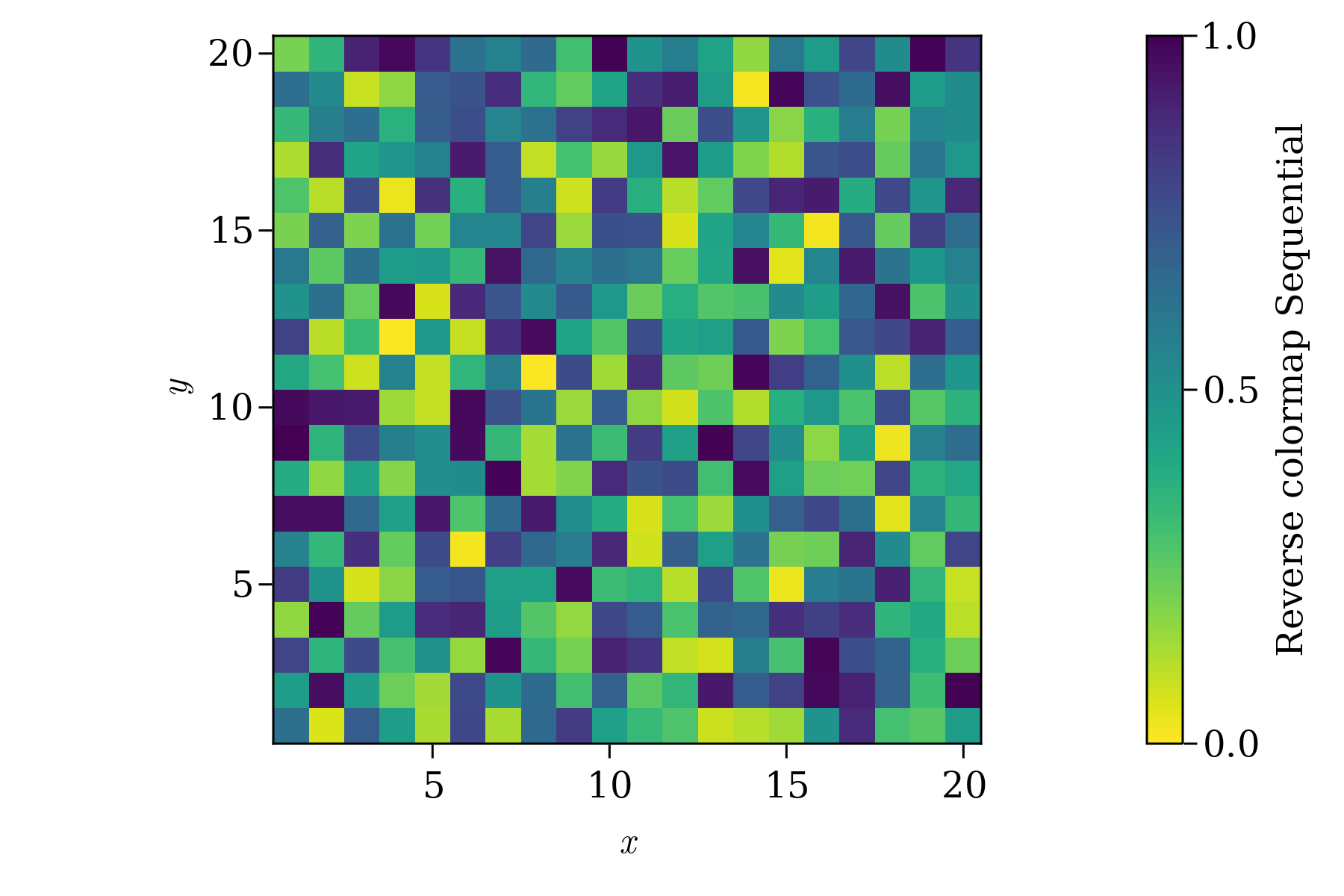


Figure 21: Reverse colormap sequential and colorrange.

当设置 colorrange 后，超出此范围的颜色值会被相应地设置为颜色图的第一种和最后一种颜色。 但是，有时最好自行指定两端的颜色。这可以通过 highclip 和 lowclip 实现：

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); colorrange=(-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")  
fig

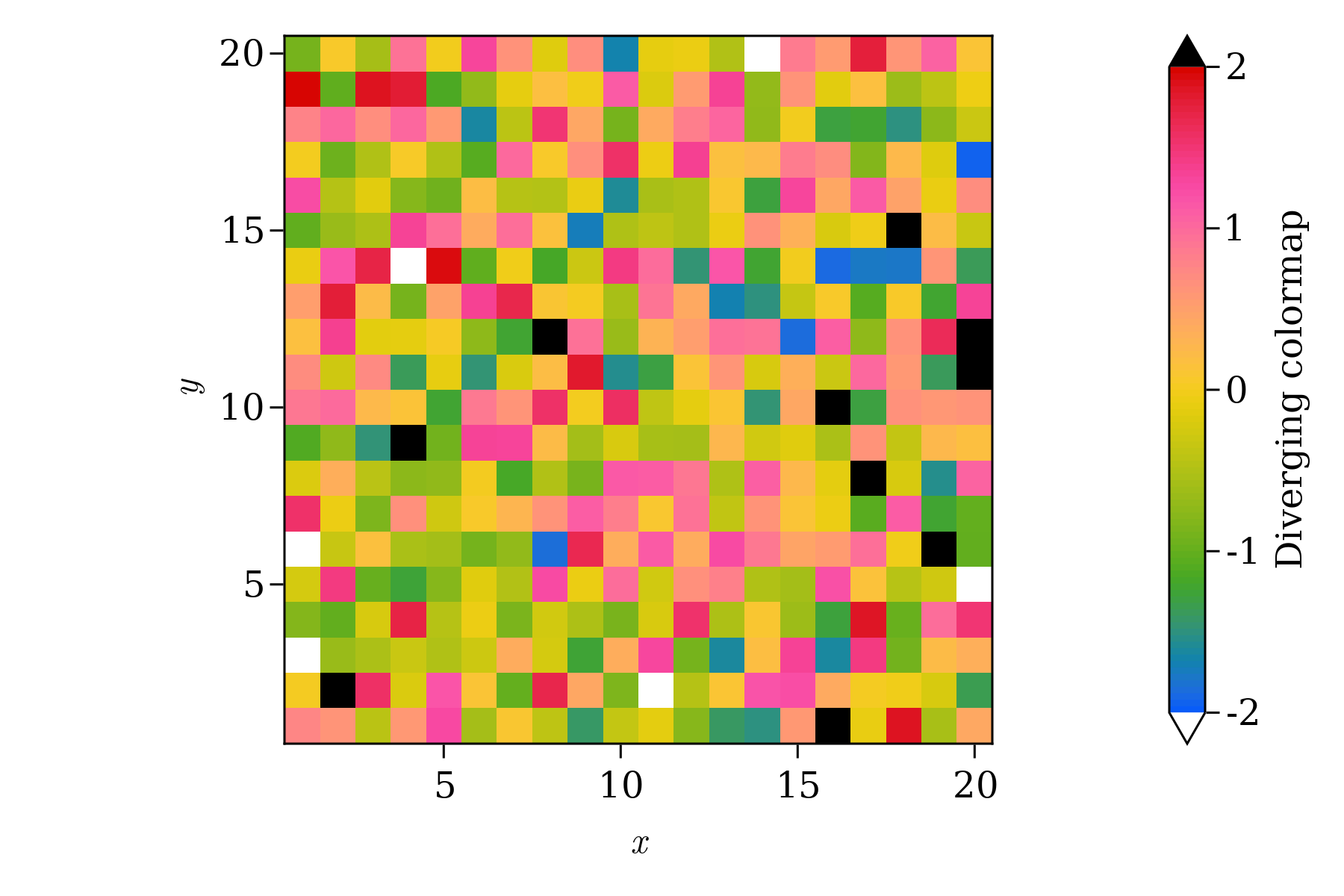


Figure 22: Diverging Colormap with low and high clip.

另外 RGB 向量也是合法的选项。 在下面的例子中， 你可以传递一个自定义颜色图 *perse* 或使用 cgrad 来创建分类值的 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))  
mygrays = ColorScheme([RGB{Float64}(i, i, i) for i in [0.0, 0.5, 1.0]])  
fig, ax, pltobj = heatmap(rand(-1:1, 20, 20);  
 colormap=cgrad(mygrays, 3, categorical=true, rev=true), # cgrad and Symbol, mygrays,  
 axis=axis, figure=figure)  
cbar = Colorbar(fig[1, 2], pltobj, label="Categories")  
cbar.ticks = ([-0.66, 0, 0.66], ["-1", "0", "1"])  
fig

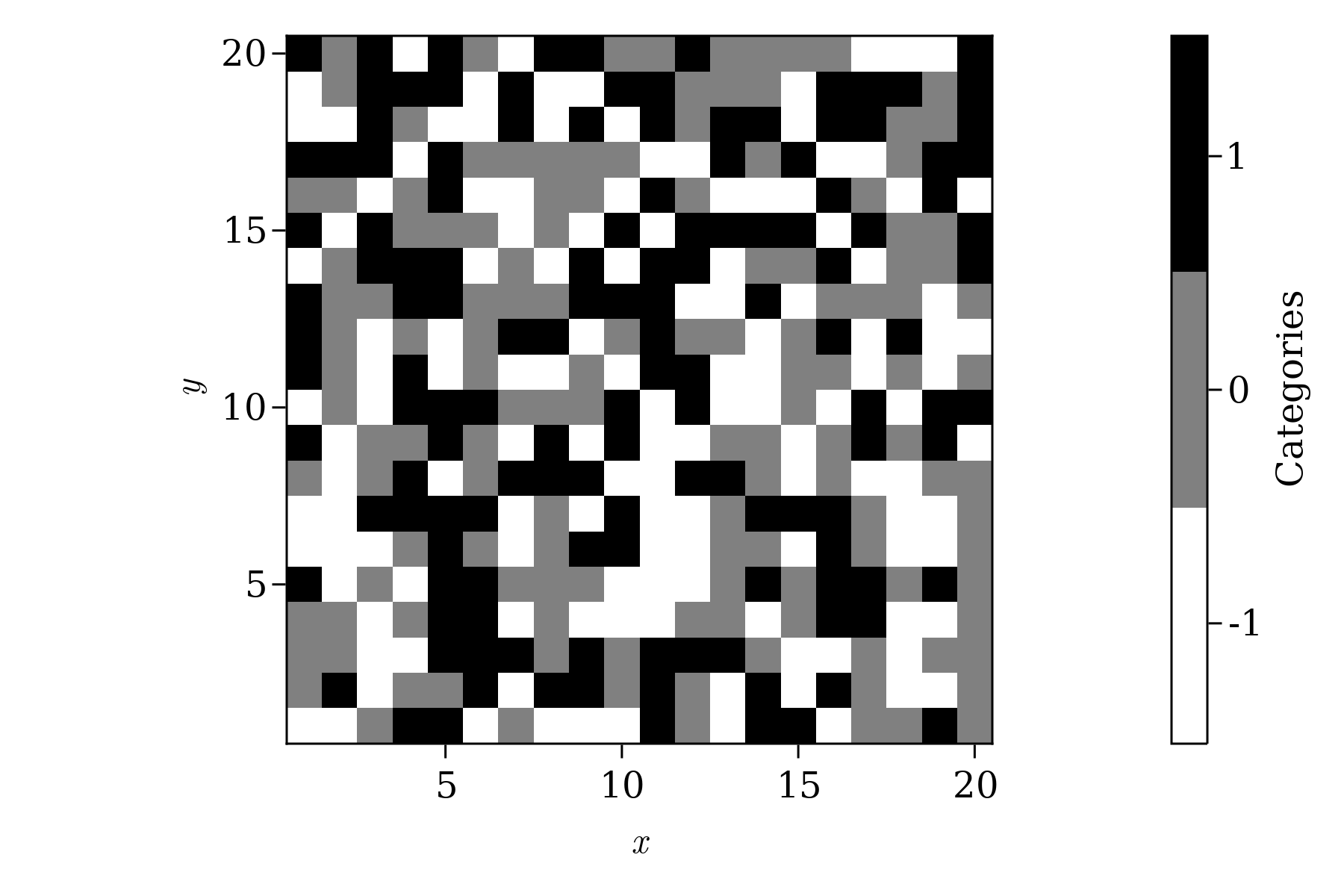


Figure 23: Categorical Colormap.

最后，分类值的颜色栏标签默认不在每种颜色间居中。 添加自定义标签可修复此问题，即 cbar.ticks = (positions, ticks)。 最后一种情况是传递颜色的元组给 colormap，其中颜色可以通过 Symbol， String 或它们的混合指定。 然后将会得到这两组颜色间的插值颜色图。

另外，也支持十六进制编码的颜色作为输入。因此作为示范，下例将在热力图上放置一个半透明的标记。

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=("#C0C0C0", 0.5), markersize=150)  
Colorbar(fig[1, 2], pltobj, label="2 colors")  
fig

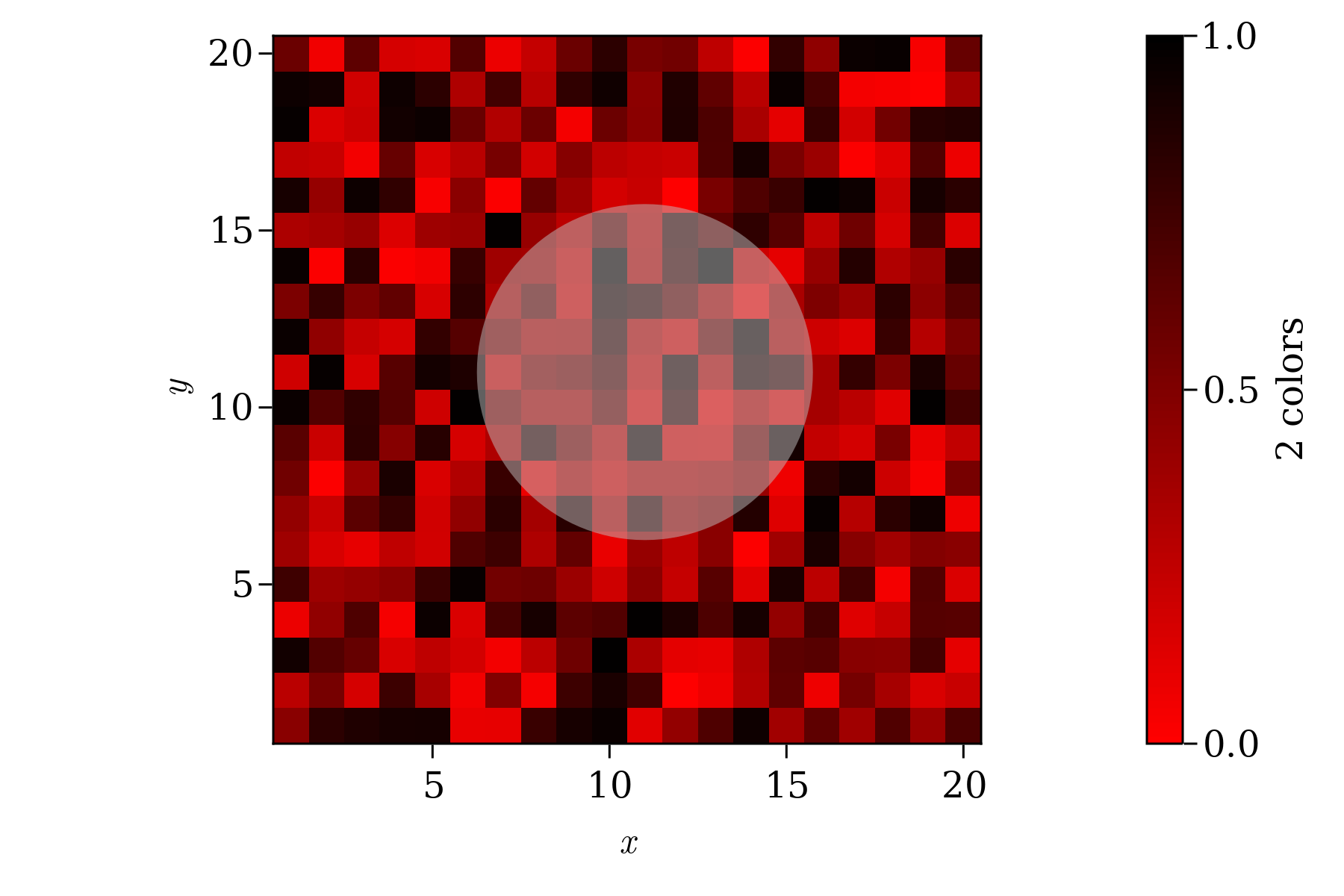


Figure 24: Colormap from two colors.

### 自定义颜色循环

可以通过新的颜色循环定义全局 Theme ，但通常 **不建议** 这样做。 更好的做法是定义新的主题并像上节那样使用它。 定义带有 :color， :linestyle， :marker 属性的新 cycle 和默认的 colormap 。 下面为之前的 publication\_theme 增加一些新的属性。

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) # alltogether  
 my\_markers = [:circle, :rect, :utriangle, :dtriangle, :diamond,  
 :pentagon, :cross, :xcross]  
 my\_linestyle = [nothing, :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, xgridstyle=:dash, ygridstyle=:dash,  
 xtickalign=1, ytickalign=1, yticksize=10, xticksize=10,  
 xlabelpadding=-5, xlabel="x", ylabel="y"),  
 Legend=(framecolor=(:black, 0.5), bgcolor=(:white, 0.5)),  
 Colorbar=(ticksize=16, tickalign=1, spinewidth=0.5),  
 )  
end

然后将它应用到绘图函数中，如下所示:

function scatters\_and\_lines()  
 x = collect(0:10)  
 xh = LinRange(4, 6, 25)  
 yh = LinRange(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())

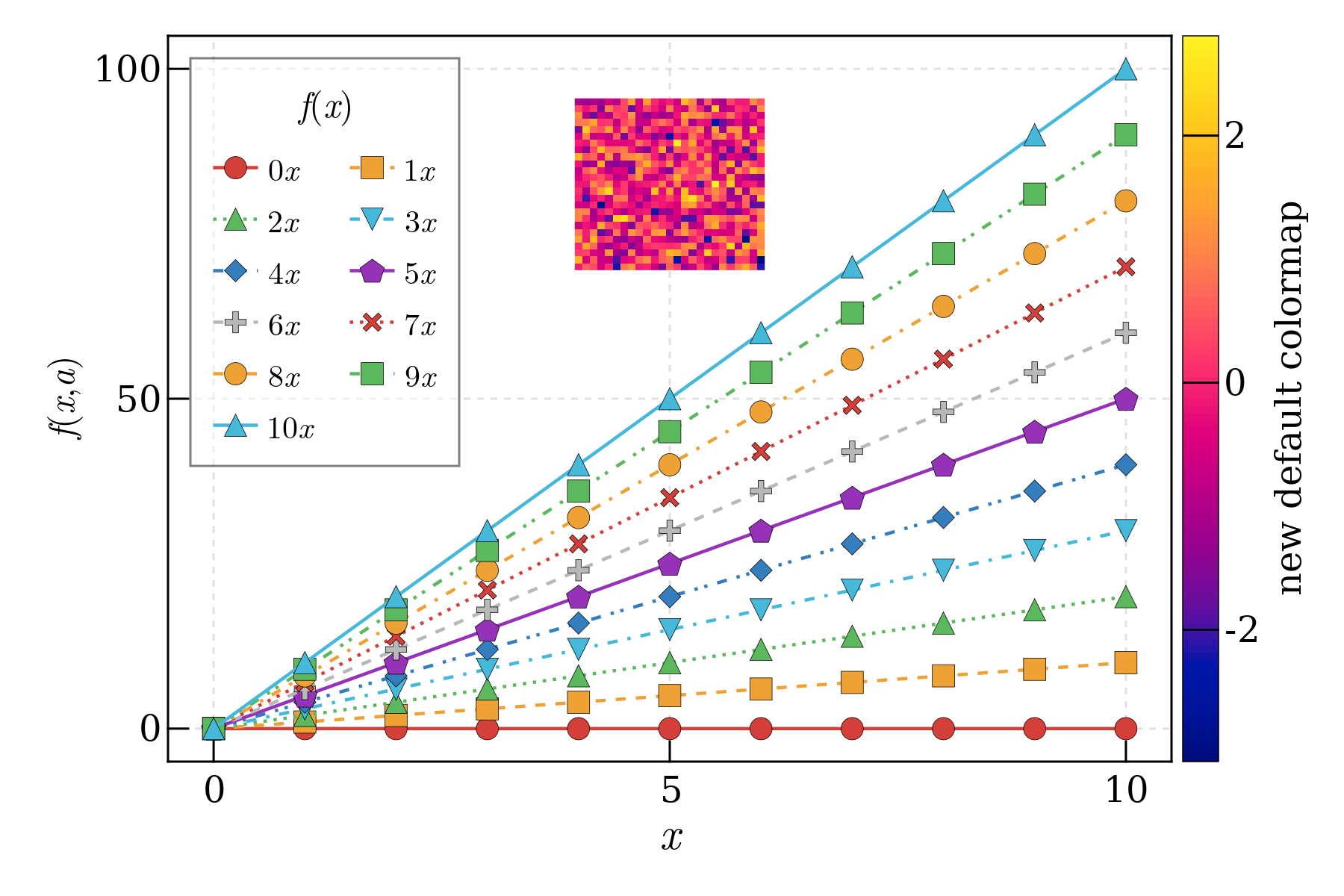


Figure 25: Custom theme with new cycle and colormap.

此时，通过颜色，曲线样式，标记和颜色图，你已经能够 **完全控制** 绘图结果。 下一部分将讨论如何管理和控制 **布局**。

## 布局

一个完整的 **画布/布局** 是由 Figure 定义的，创建后将在其中填充各种内容。 下面将以一个包含 Axis，Legend 和 Colorbar 的简单例子开始。 在这项任务中， 就像 Array/Matrix 那样，可以使用 rows 和 columns 索引 Figure。 Axis 位于 **第 1 行，第 1 列**， 即为 fig[1, 1]。 Colorbar 位于 **第 1 行，第 2 列**， 即为 fig[1, 2]。 另外， Legend 位于 **第 2 行** 和 **第 1 - 2 列**， 即为 fig[2, 1:2]。

function first\_layout()  
 seed!(123)  
 x, y, z = randn(6), randn(6), randn(6)  
 fig = Figure(resolution=(600, 400), backgroundcolor=:grey90)  
 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  
first\_layout()

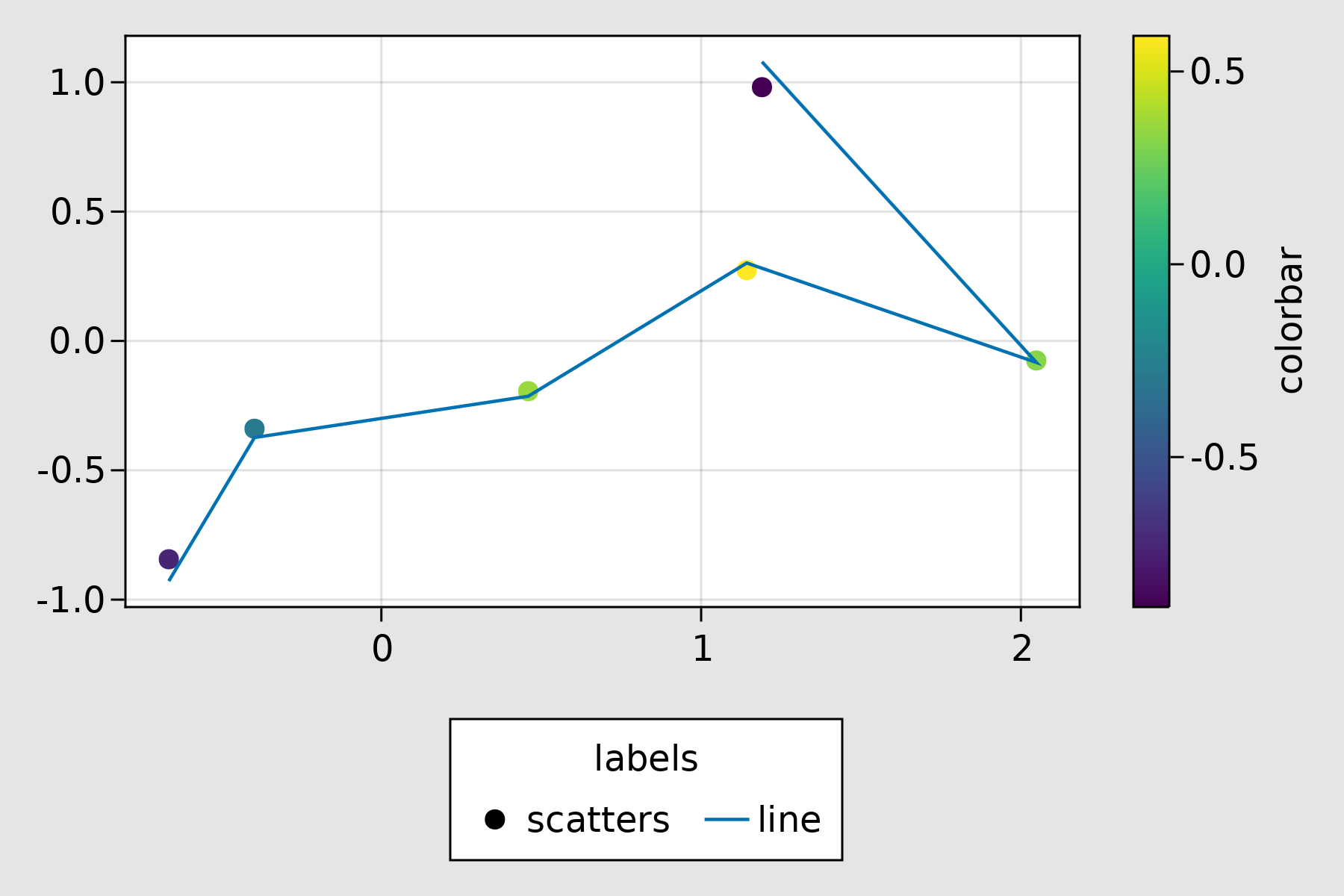


Figure 26: First Layout.

这看起来已经不错了，但能变得更好。可以使用以下关键字和方法来解决图的间距问题：

* figure\_padding=(left, right, bottom, top)
* padding=(left, right, bottom, top)

改变 Legend 或 Colorbar 实际大小的方法为：

* tellheight=true or false
* tellwidth=true or false

**将这些设置为 true 后则需考虑 Legend 或 Colorbar 的实际大小（高或宽）。** 然后这些内容将会相应地调整大小。

可以使用以下方法指定行和列的间距：

* colgap!(fig.layout, col, separation)
* rowgap!(fig.layout, row, separation)

**列间距** （colgap!），如果给定了 col，那么间距将只应用在指定的列。 **行间距** （rowgap!），如果给定了 row，那么间距将只应用在指定的行。

接下来将学习如何将内容放进 **突出部分（protrusion）**，即为 **标题 x 和 y，或 ticks 以及 label** 保留的空间。 实现方法是将位置索引改为 fig[i, j, protrusion]， 其中 *protrusion* 可以是 Left()， Right()，Bottom() 和 Top()，或者是四个角 TopLeft()， TopRight()， BottomRight()，BottomLeft()。 这些选项将在如下的例子中使用：

function first\_layout\_fixed()  
 seed!(123)  
 x, y, z = randn(6), randn(6), randn(6)  
 fig = Figure(figure\_padding=(0, 3, 5, 2), resolution=(600, 400),  
 backgroundcolor=:grey90, 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=(:slateblue1, 0.35))  
 Label(fig[1, 1, Right()], "protrusion", textsize=18,  
 rotation=pi / 2, padding=(3, 3, 3, 3))  
 Label(fig[1, 1, TopLeft()], "(a)", textsize=18, padding=(0, 3, 8, 0))  
 colgap!(fig.layout, 5)  
 rowgap!(fig.layout, 5)  
 fig  
end  
first\_layout\_fixed()

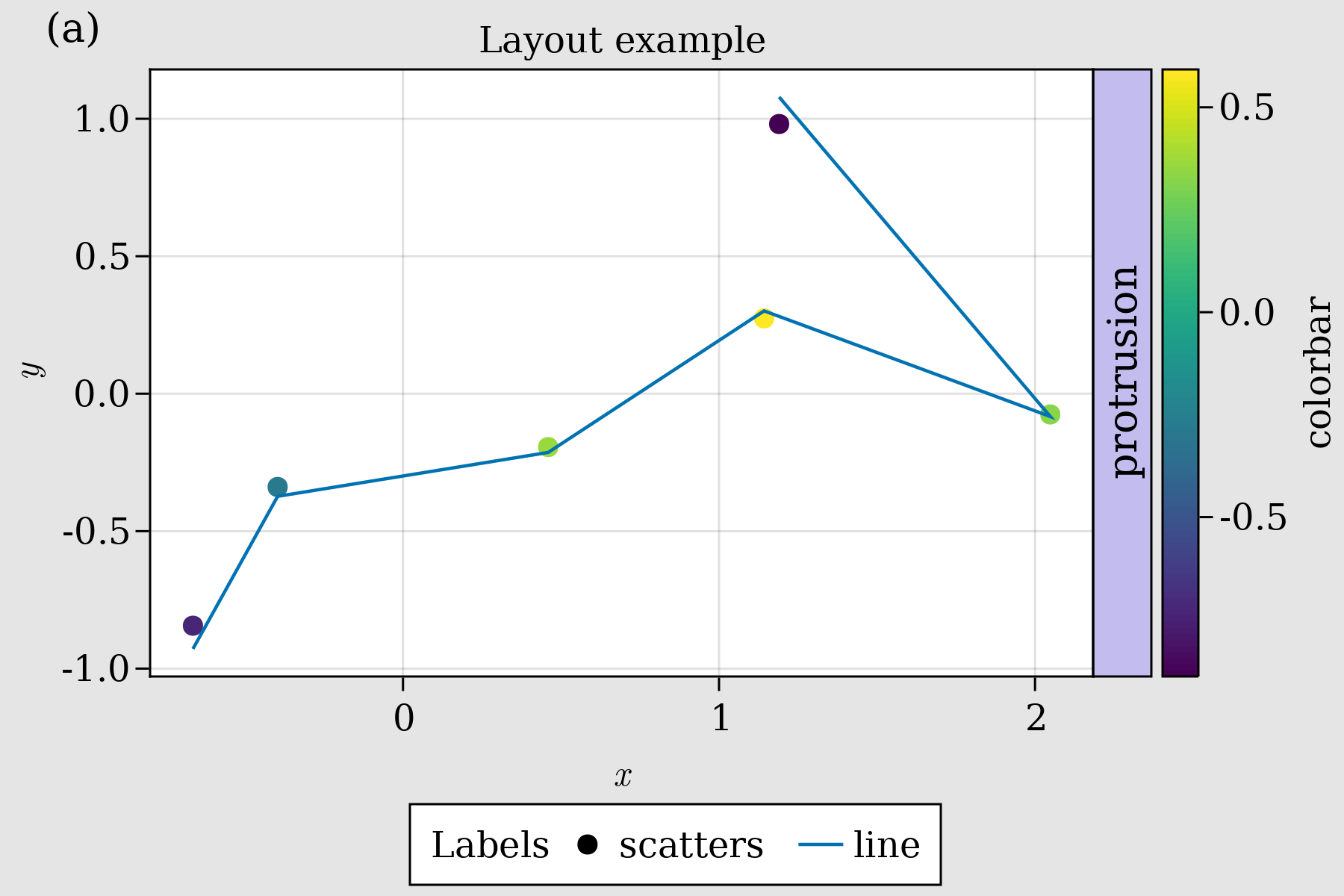


Figure 27: First Layout Fixed.

这里在 TopLeft()添加标签 (a) 可能是不必要的， 因为标签仅在有两个以上的图时有意义。 在接下来的例子中，我们将继续使用之前的工具和一些新工具，并创建一个更丰富、更复杂的图。

可以使用以下函数隐藏图的装饰部分和轴线：

* hidedecorations!(ax; kwargs...)
* hidexdecorations!(ax; kwargs...)
* hideydecorations!(ax; kwargs...)
* hidespines!(ax; kwargs...)

应记住总是可以调用 help 查看能够传递的参数，例如：

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.MakieLayout.hidespines!, T} where T  
 are:

另外，对于 hidedecorations! 有：

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.MakieLayout.hidedecorations!, T}  
 where T are:

对于 **不想隐藏的** 元素，仅需要将它们的值设置为 false，即 hideydecorations!(ax; ticks=false, grid=false)。

同步 Axis 的方式如下：

* linkaxes!， linkyaxes! 和 linkxaxes!

这在需要共享轴时会变得很有用。 另一种获得共享轴的方法是设置 limits!。

使用以下方式可一次性设定limits，当然也能单独为每个方向的轴单独设定：

* limits!(ax; l, r, b, t)，其中 l 为左侧, r 右侧，b 底部， 和 t 顶部。

还能使用 ylims!(low, high) 或 xlims!(low, high)，甚至可以通过 ylims!(low=0) 或 xlims!(high=1) 只设定一边。

例子如下：

function complex\_layout\_double\_axis()  
 seed!(123)  
 x = LinRange(0, 1, 10)  
 y = LinRange(0, 1, 10)  
 z = rand(10, 10)  
 fig = Figure(resolution=(600, 400), font="CMU Serif", backgroundcolor=:grey90)  
 ax1 = Axis(fig, xlabel=L"x", ylabel=L"y")  
 ax2 = Axis(fig, xlabel=L"x")  
 heatmap!(ax1, x, y, z; colorrange=(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", colorrange=(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)", textsize=18, padding=(0, 6, 8, 0))  
 Label(fig[1, 2, TopLeft()], "(b)", textsize=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  
complex\_layout\_double\_axis()



Figure 28: Complex layout double axis.

如上所示， Colorbar 的方向已经变为水平且它的标签也处在其下方。 这是因为设定了 vertical=false 和 flipaxis=false。 另外，也可以将更多的 Axis 添加到 fig 里，甚至可以是 Colorbar 和 Legend，然后再构建布局。

另一种常见布局是热力图组成的正方网格：

function squares\_layout()  
 seed!(123)  
 letters = reshape(collect('a':'d'), (2, 2))  
 fig = Figure(resolution=(600, 400), fontsize=14, font="CMU Serif",  
 backgroundcolor=:grey90)  
 axs = [Axis(fig[i, j], aspect=DataAspect()) for i = 1:2, j = 1:2]  
 hms = [heatmap!(axs[i, j], randn(10, 10), colorrange=(-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]))", textsize=16,  
 padding=(-2, 0, -20, 0)) for i = 1:2, j = 1:2]  
 colgap!(fig.layout, 5)  
 rowgap!(fig.layout, 5)  
 fig  
end  
squares\_layout()

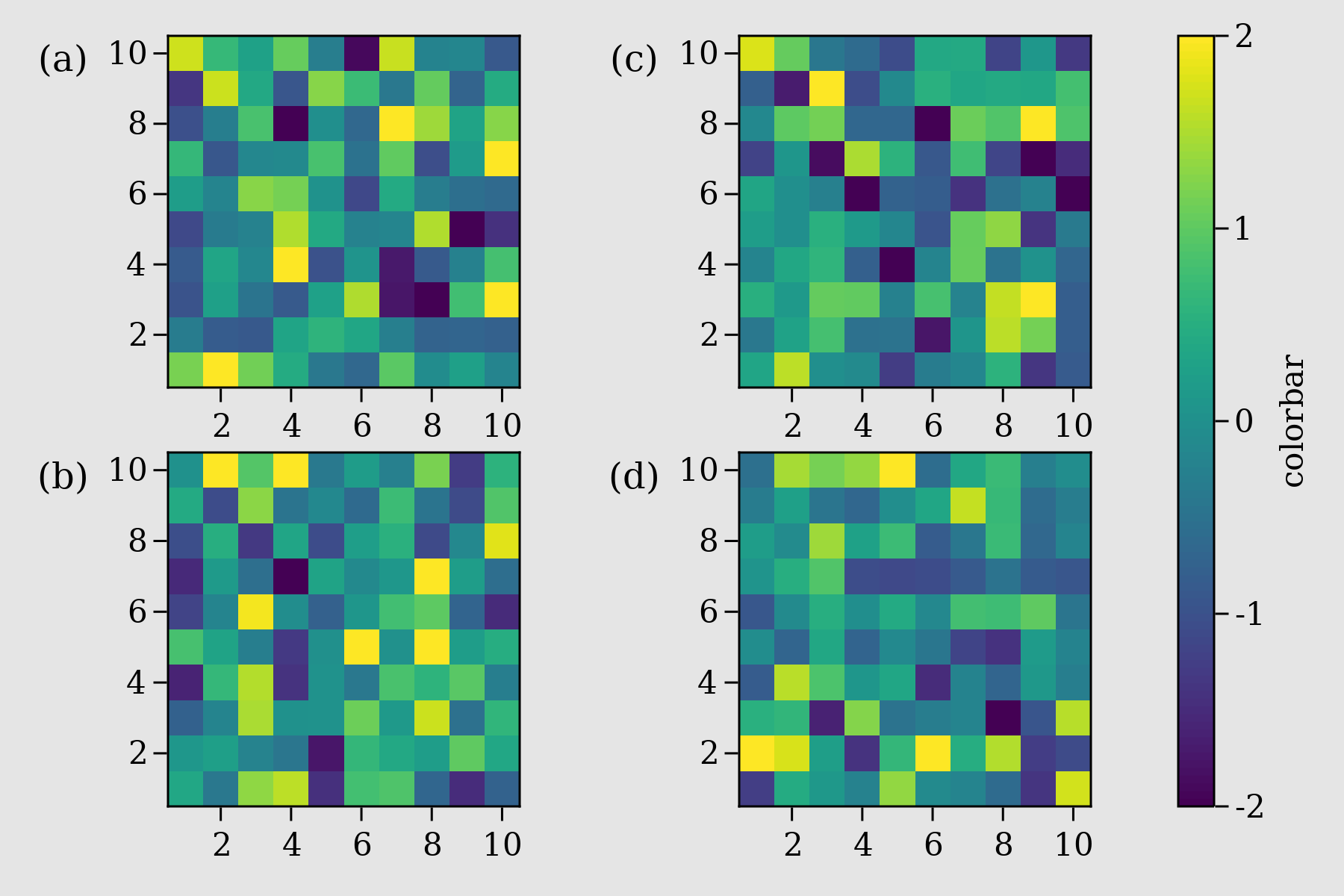


Figure 29: Squares layout.

上图中每一个标签都位于 **突出部分** 并且每一个 Axis 都有 AspectData() 率属性。 图中 Colorbar 位于第三列，并从第一行跨到第二行。

下例将使用称为 Mixed() 的**对齐模式**，这在处理 Axis 间的大量空白区域时很有用，而这些空白区域通常是由长标签导致的。 另外，本例还需要使用 Julia 标准库中的 Dates 。

using Dates

function mixed\_mode\_layout()  
 seed!(123)  
 longlabels = ["$(today() - Day(1))", "$(today())", "$(today() + Day(1))"]  
 fig = Figure(resolution=(600, 400), fontsize=12,  
 backgroundcolor=:grey90, font="CMU Serif")  
 ax1 = Axis(fig[1, 1])  
 ax2 = Axis(fig[1, 2], xticklabelrotation=pi / 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=(:slateblue1, 0.35))  
 Label(fig[2:3, 1:2, Right()], "protrusion", rotation=pi / 2, textsize=14,  
 padding=(3, 3, 3, 3))  
 Label(fig[1, 1:2, Top()], "Mixed alignmode", textsize=16,  
 padding=(0, 0, 15, 0))  
 colsize!(fig.layout, 1, Auto(2))  
 rowsize!(fig.layout, 2, Auto(0.5))  
 rowsize!(fig.layout, 3, Auto(0.5))  
 rowgap!(fig.layout, 1, 15)  
 rowgap!(fig.layout, 2, 0)  
 colgap!(fig.layout, 5)  
 fig  
end  
mixed\_mode\_layout()

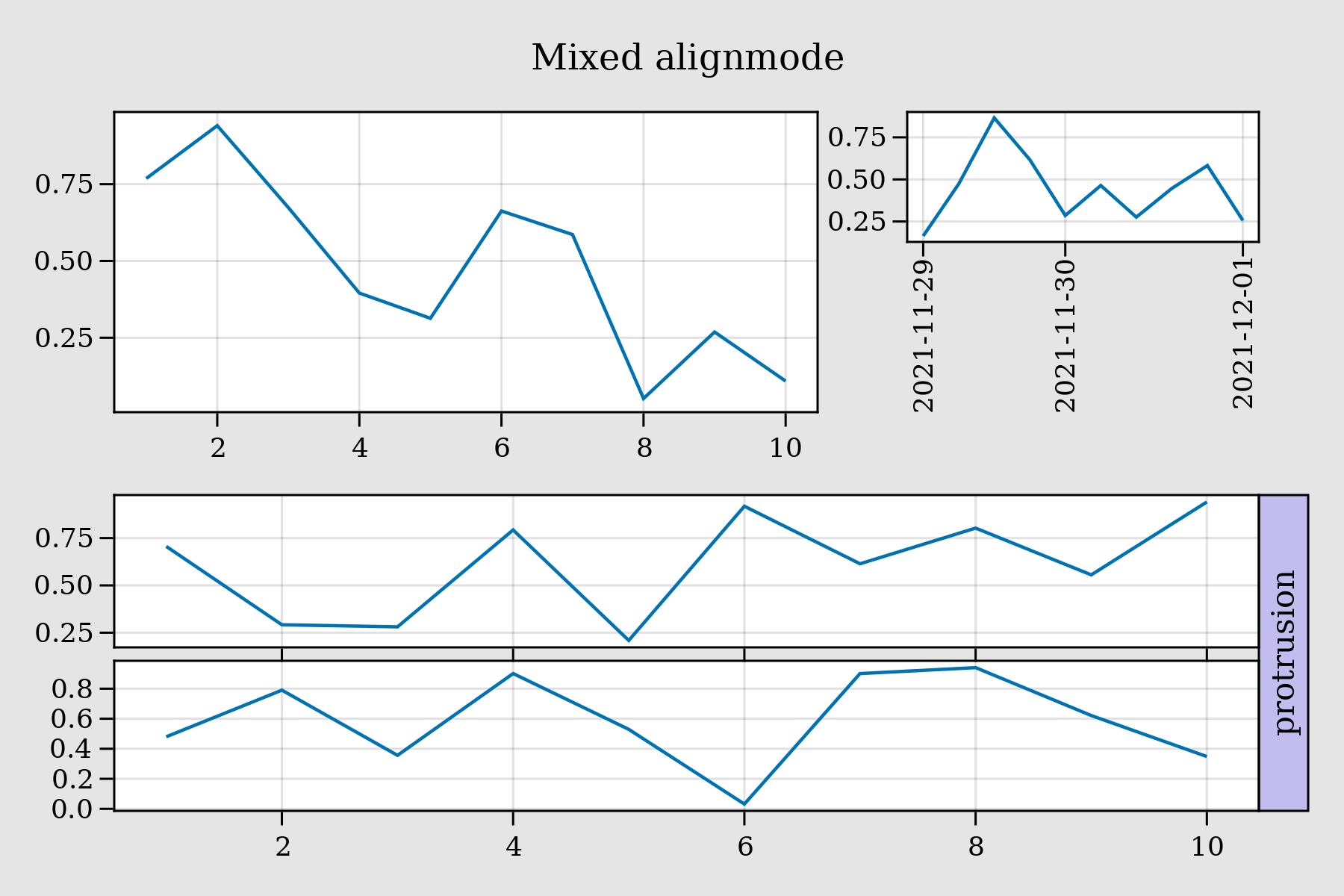


Figure 30: Mixed mode layout.

如上，参数 alignmode=Mixed(bottom=0) 将边界框移动到底部，使其与左侧面板保持对齐。

从上图也可以看到 colsize! 和 rowsize! 如何作用于不同的行和列。 可以向函数传递一个数字而不是 Auto()，但那会固定所有的设置。 另外， 在定义 Axis 时也可以设定 height 或 width，例如 Axis(fig, heigth=50) 将会固定轴的高度。

### 嵌套 Axis (*subplots*)

精准定义一组 Axis (*subplots*) 也是可行的， 可以使用一组 Axis 构造具有多行多列的图。 例如，下面展示了一组较复杂的 Axis：

function nested\_sub\_plot!(fig)  
 color = rand(RGBf0)  
 ax1 = Axis(fig[1, 1], backgroundcolor=(color, 0.25))  
 ax2 = Axis(fig[1, 2], backgroundcolor=(color, 0.25))  
 ax3 = Axis(fig[2, 1:2], backgroundcolor=(color, 0.25))  
 ax4 = Axis(fig[1:2, 3], backgroundcolor=(color, 0.25))  
 return (ax1, ax2, ax3, ax4)  
end

当通过多次调用它来构建更复杂的图时，可以得到：

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  
main\_figure()

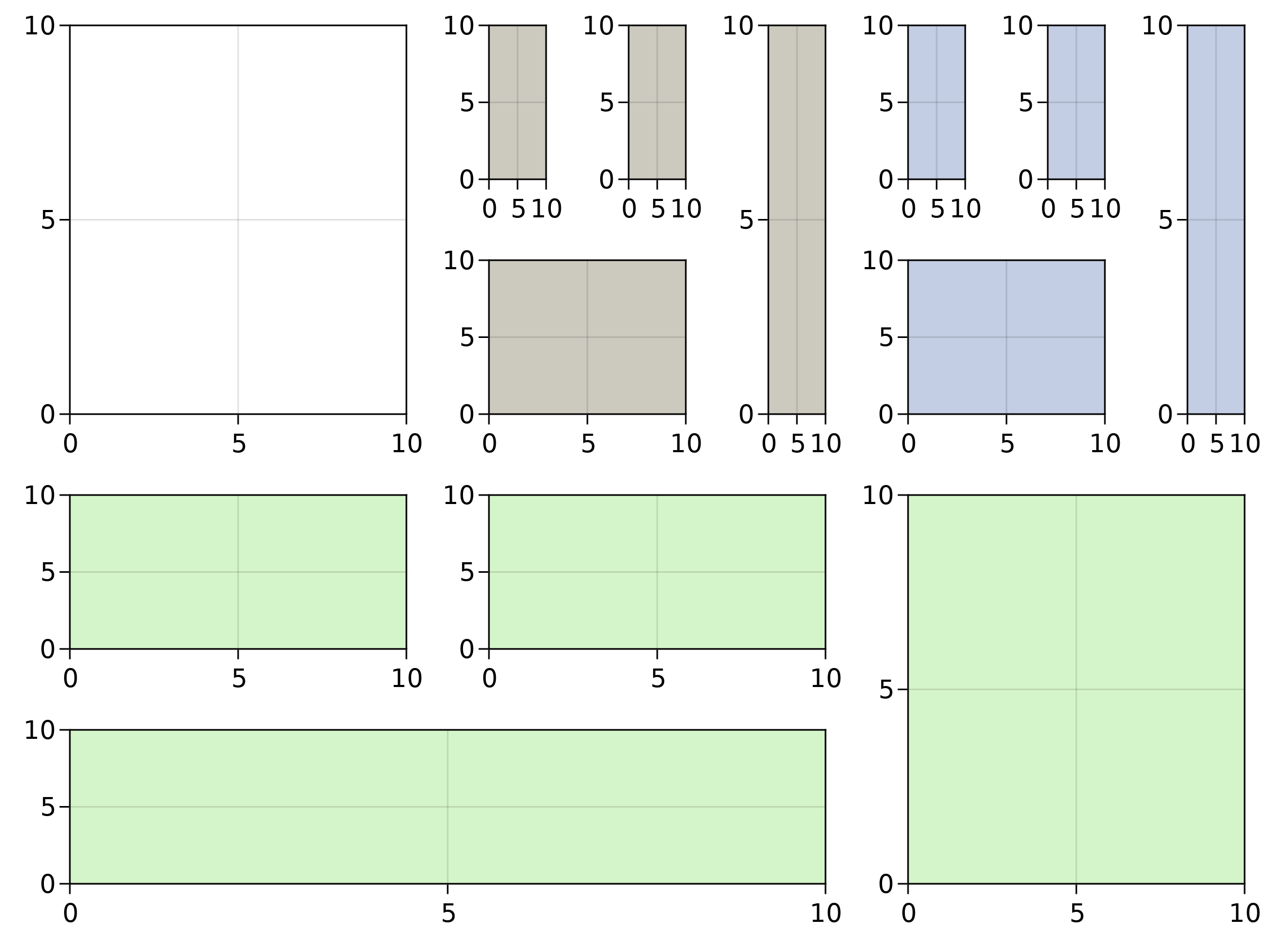


Figure 31: Main figure.

注意，这里可以调用不同的子图函数。 另外，每一个 Axis 都是 Figure 的独立部分。 因此，当在进行 rowgap!或者 colsize! 这样的操作时，你需要考虑是对每一个子图单独作用还是对所有的图一起作用。

对于组合的 Axis (*subplots*) 可以使用 GridLayout()， 它能用来构造更复杂的 Figure。

### 嵌套网格布局

可以使用 GridLayout() 组合子图，这种方法能够更自由地构建更复杂的图。 这里再次使用之前的 nested\_sub\_plot!，它定义了三组子图和一个普通的 Axis：

function nested\_Grid\_Layouts()  
 fig = Figure(backgroundcolor=RGBf0(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[i], grid=false, ticks=false) for i = 1:length(axsc)]  
 colgap!(gc, 5)  
 rowgap!(gc, 5)  
 rowsize!(fig.layout, 2, Auto(0.5))  
 colsize!(fig.layout, 1, Auto(0.5))  
 fig  
end  
nested\_Grid\_Layouts()

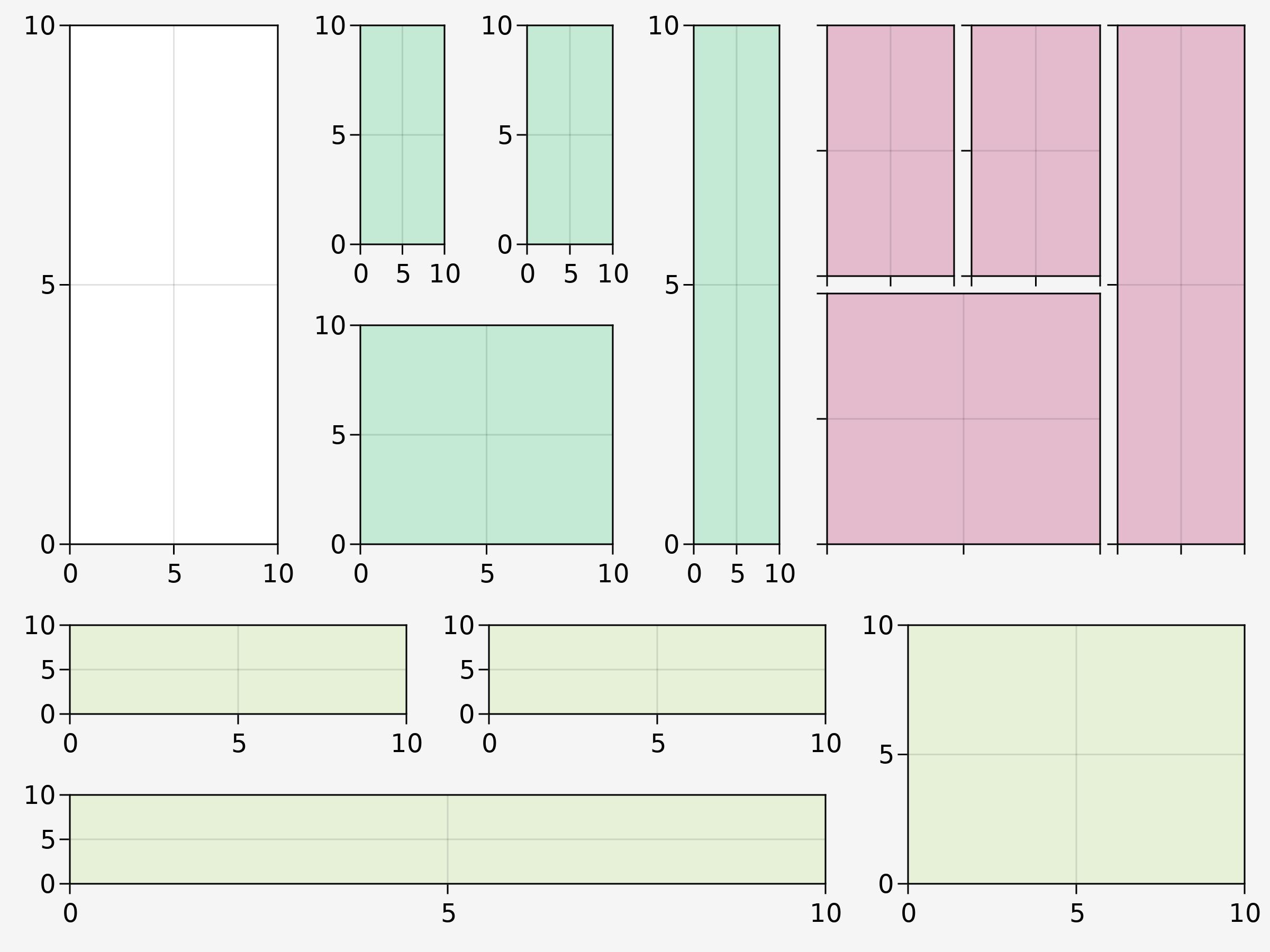


Figure 32: Nested Grid Layouts.

现在，对每一组使用 rowgap! 或 colsize! 将是可行的，并且 rowsize!, colsize! 也能够应用于 GridLayout()。

### 插图

目前，绘制 inset 是一项棘手的工作。 本节展示两种在初始时通过定义辅助函数实现绘制插图的方法。 第一种是定义 BBox，它存在于整个 Figure 空间：

function add\_box\_inset(fig; left=100, right=250, bottom=200, top=300,  
 bgcolor=:grey90)  
 inset\_box = Axis(fig, bbox=BBox(left, right, bottom, top),  
 xticklabelsize=12, yticklabelsize=12, backgroundcolor=bgcolor)  
 # bring content upfront  
 translate!(inset\_box.scene, 0, 0, 10)  
 elements = keys(inset\_box.elements)  
 filtered = filter(ele -> ele != :xaxis && ele != :yaxis, elements)  
 foreach(ele -> translate!(inset\_box.elements[ele], 0, 0, 9), filtered)  
 return inset\_box  
end

然后可以按照如下方式轻松地绘制插图：

function figure\_box\_inset()  
 fig = Figure(resolution=(600, 400))  
 ax = Axis(fig[1, 1], backgroundcolor=:white)  
 inset\_ax1 = add\_box\_inset(fig; left=100, right=250, bottom=200, top=300,  
 bgcolor=:grey90)  
 inset\_ax2 = add\_box\_inset(fig; left=500, right=600, bottom=100, top=200,  
 bgcolor=(:white, 0.65))  
 lines!(ax, 1:10)  
 lines!(inset\_ax1, 1:10)  
 scatter!(inset\_ax2, 1:10, color=:black)  
 fig  
end  
figure\_box\_inset()

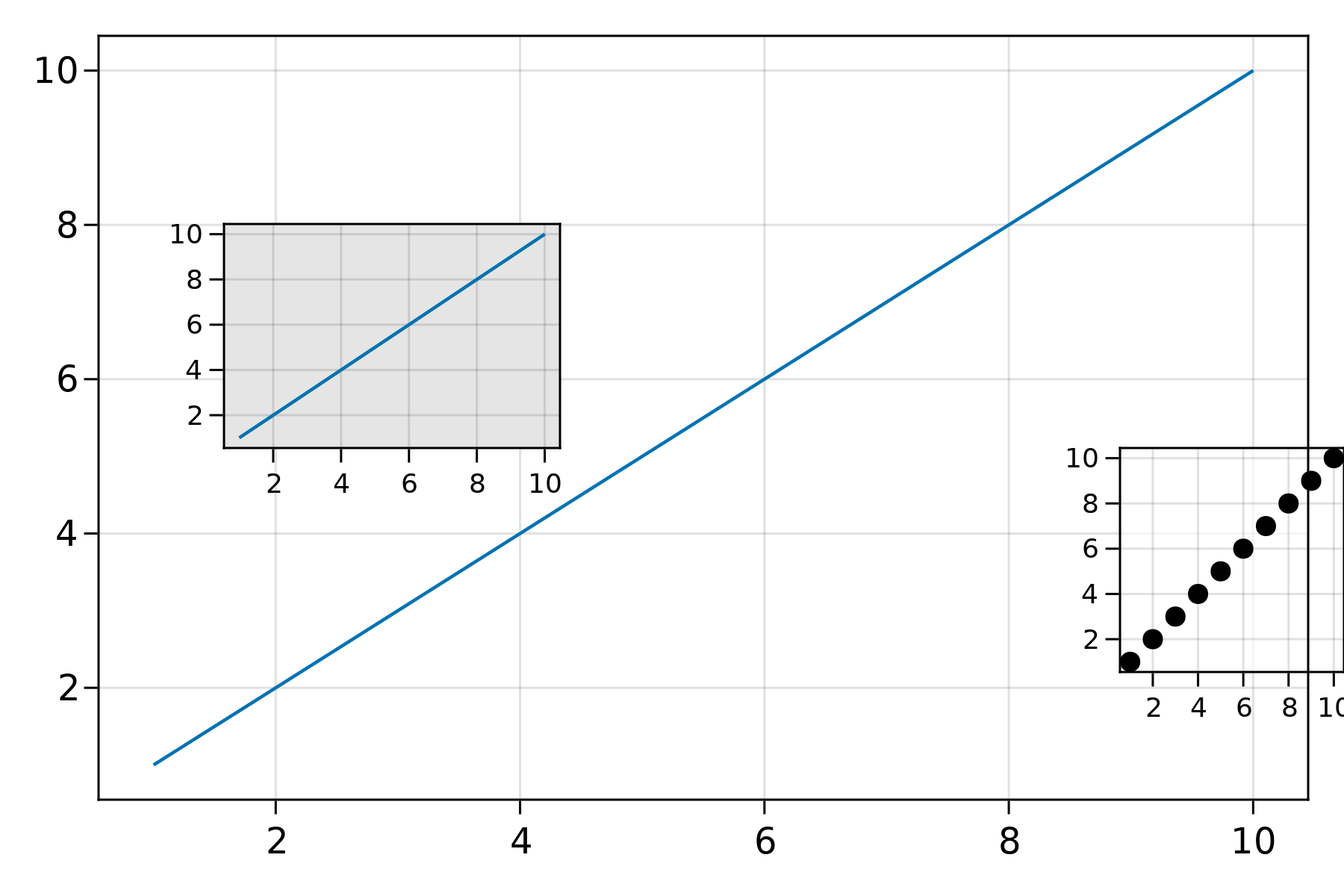


Figure 33: Figure box inset.

其中 Box 的尺寸受到 Figure中 resolution 参数的约束。 注意，也可以在 Axis 外绘制插图。 另一种绘制插图的方法是，在位置fig[i, j]处定义一个新的 Axis，并且指定 width， height， halign 和 valign。 如下面的函数例子所示：

function add\_axis\_inset(; pos=fig[1, 1], halign=0.1, valign=0.5,  
 width=Relative(0.5), height=Relative(0.35), bgcolor=:lightgray)  
 inset\_box = Axis(pos, width=width, height=height,  
 halign=halign, valign=valign, xticklabelsize=12, yticklabelsize=12,  
 backgroundcolor=bgcolor)  
 # bring content upfront  
 translate!(inset\_box.scene, 0, 0, 10)  
 elements = keys(inset\_box.elements)  
 filtered = filter(ele -> ele != :xaxis && ele != :yaxis, elements)  
 foreach(ele -> translate!(inset\_box.elements[ele], 0, 0, 9), filtered)  
 return inset\_box  
end

在下面的例子中，如果总图的大小发生变化，那么将重新缩放灰色背景的 Axis。 同时 **插图** 要受到 Axis 位置的约束。

function figure\_axis\_inset()  
 fig = Figure(resolution=(600, 400))  
 ax = Axis(fig[1, 1], backgroundcolor=:white)  
 inset\_ax1 = add\_axis\_inset(; pos=fig[1, 1], halign=0.1, valign=0.65,  
 width=Relative(0.3), height=Relative(0.3), bgcolor=:grey90)  
 inset\_ax2 = add\_axis\_inset(; pos=fig[1, 1], halign=1, valign=0.25,  
 width=Relative(0.25), height=Relative(0.3), bgcolor=(:white, 0.65))  
 lines!(ax, 1:10)  
 lines!(inset\_ax1, 1:10)  
 scatter!(inset\_ax2, 1:10, color=:black)  
 fig  
end  
figure\_axis\_inset()

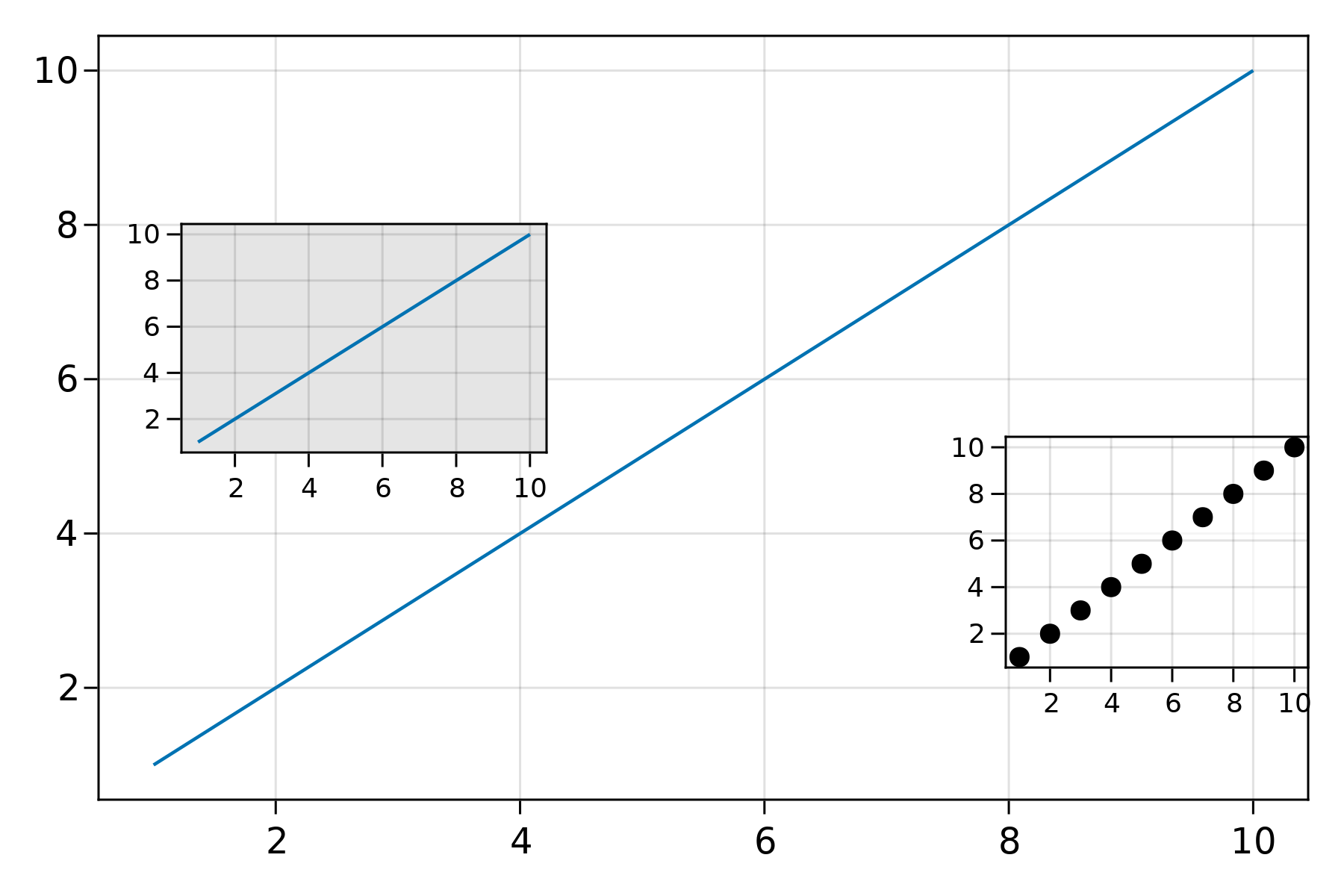


Figure 34: Figure axis inset.

以上包含了 Makie 中布局选项的大多数常见用例。 现在，让我们接下来使用 GLMakie.jl 绘制一些漂亮的3D示例图。 ## GLMakie.jl {#sec:glmakie}

CairoMakie.jl supplies 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 GLMakie.jl might be helpful, since it uses [OpenGL](http://www.opengl.org/) as a backend that adds interactivity 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.

### 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 first one markers don’t scale in the axis directions, but in the later they do because they are actual geometries in 3D space. See the next example:

using GLMakie  
GLMakie.activate!()

function scatters\_in\_3D()  
 seed!(123)  
 xyz = randn(10, 3)  
 x, y, z = xyz[:, 1], xyz[:, 2], xyz[:, 3]  
 fig = Figure(resolution=(1600, 400))  
 ax1 = Axis3(fig[1, 1]; aspect=(1, 1, 1), perspectiveness=0.5)  
 ax2 = Axis3(fig[1, 2]; aspect=(1, 1, 1), perspectiveness=0.5)  
 ax3 = Axis3(fig[1, 3]; aspect=:data, perspectiveness=0.5)  
 scatter!(ax1, x, y, z; markersize=50)  
 meshscatter!(ax2, x, y, z; markersize=0.25)  
 hm = meshscatter!(ax3, x, y, z; markersize=0.25,  
 marker=FRect3D(Vec3f(0), Vec3f(1)), color=1:size(xyz)[2],  
 colormap=:plasma, transparency=false)  
 Colorbar(fig[1, 4], hm, label="values", height=Relative(0.5))  
 fig  
end  
scatters\_in\_3D()

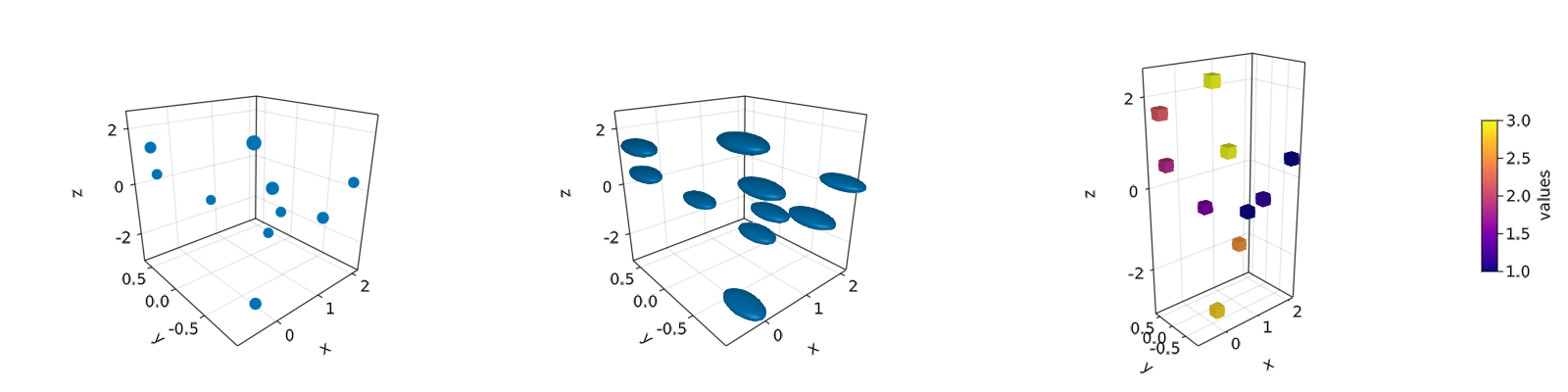


Figure 35: Scatters in 3D.

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)  
 xyz = randn(10, 3)  
 x, y, z = xyz[:, 1], xyz[:, 2], xyz[:, 3]  
 fig = Figure(resolution=(1600, 400))  
 ax1 = Axis3(fig[1, 1]; aspect=(1, 1, 1), perspectiveness=0.5)  
 ax2 = Axis3(fig[1, 2]; aspect=(1, 1, 1), perspectiveness=0.5)  
 ax3 = Axis3(fig[1, 3]; aspect=:data, perspectiveness=0.5)  
 lines!(ax1, x, y, z; color=1:size(xyz)[2], linewidth=3)  
 scatterlines!(ax2, x, y, z; markersize=50)  
 hm = meshscatter!(ax3, x, y, z; markersize=0.2, color=1:size(xyz)[2])  
 lines!(ax3, x, y, z; color=1:size(xyz)[2])  
 Colorbar(fig[2, 1], hm; label="values", height=15, vertical=false,  
 flipaxis=false, ticksize=15, tickalign=1, width=Relative(3.55 / 4))  
 fig  
end  
lines\_in\_3D()

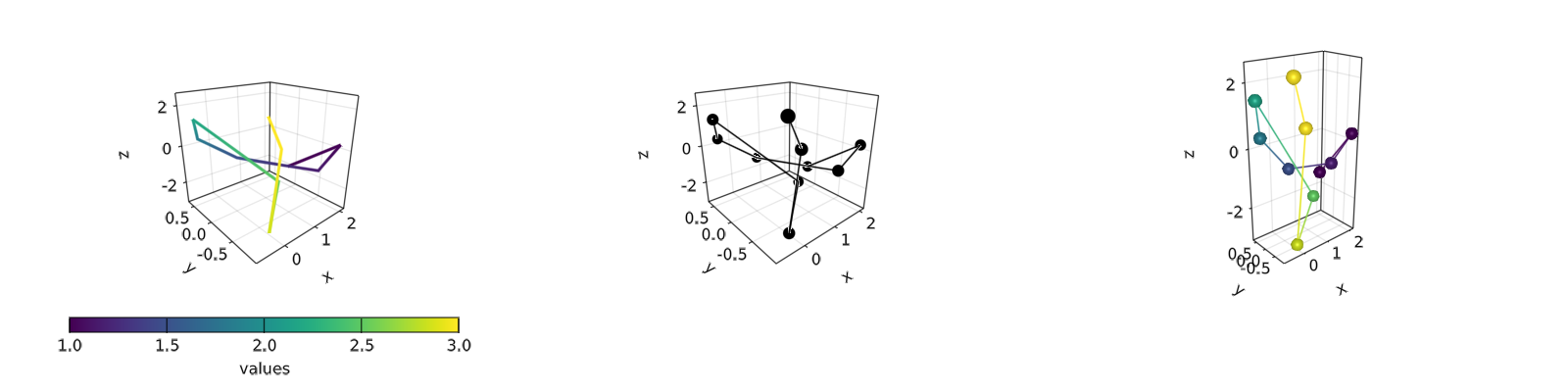


Figure 36: Lines in 3D.

Plotting a surface is also easy to do as well as a wireframe and contour lines in 3D.

### Surfaces, wireframe, contour, contourf and contour3d

To show these cases we’ll use the following peaks function:

function peaks(; n=49)  
 x = LinRange(-3, 3, n)  
 y = LinRange(-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=(1600, 400), fontsize=26)  
 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  
plot\_peaks\_function()

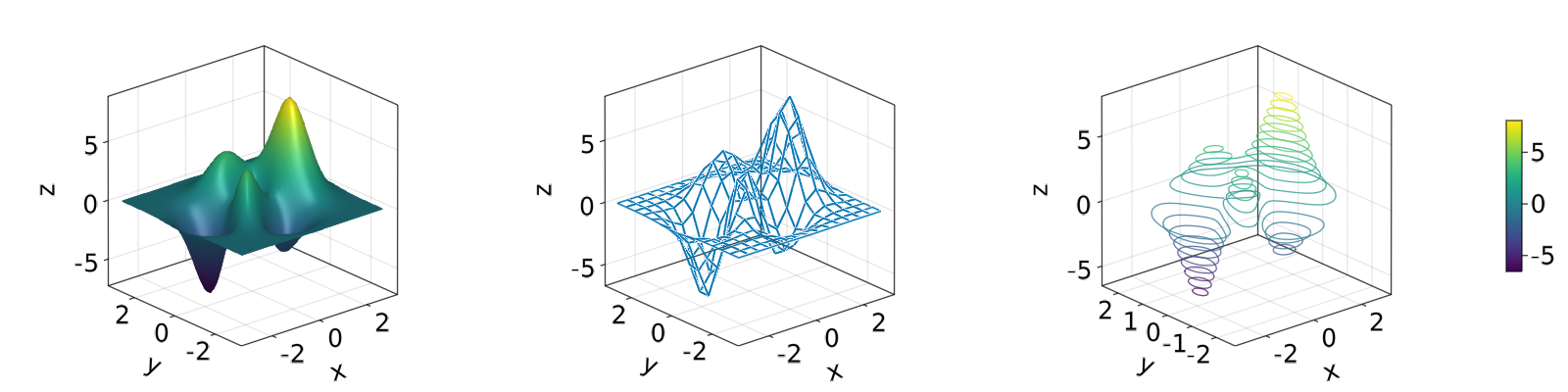


Figure 37: Plot peaks function.

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=(1600, 400), fontsize=26)  
 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  
heatmap\_contour\_and\_contourf()

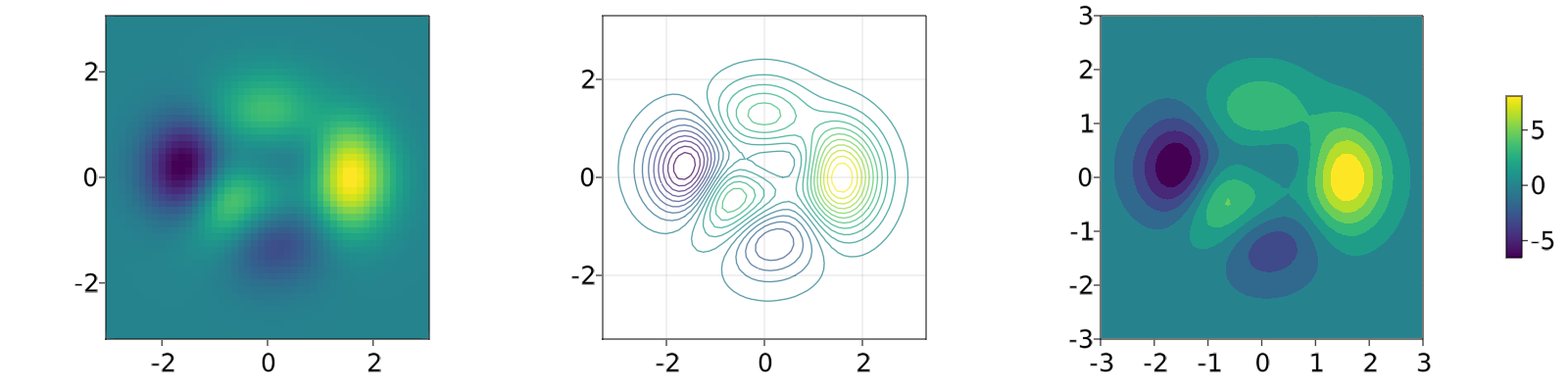


Figure 38: Heatmap contour and contourf.

Additionally, by changing Axis to an Axis3, these plots will be automatically be in the x-y plane:

function heatmap\_contour\_and\_contourf\_in\_a\_3d\_plane()  
 x, y, z = peaks()  
 fig = Figure(resolution=(1600, 400), fontsize=26)  
 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  
heatmap\_contour\_and\_contourf\_in\_a\_3d\_plane()

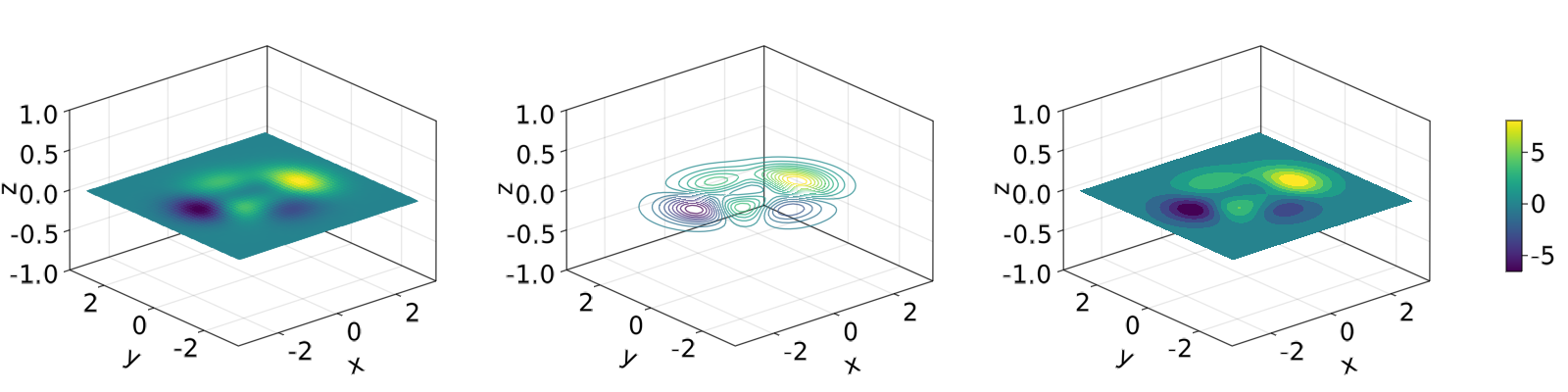


Figure 39: Heatmap contour and contourf in a 3d plane.

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=pi / 6, xzpanelcolor=(:black, 0.75),  
 perspectiveness=0.5, yzpanelcolor=:black, zgridcolor=:grey70,  
 ygridcolor=:grey70, xgridcolor=:grey70)  
 ax2 = Axis3(fig[1, 3]; aspect=(1, 1, 1), elevation=pi / 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)  
 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  
mixing\_surface\_contour3d\_contour\_and\_contourf()

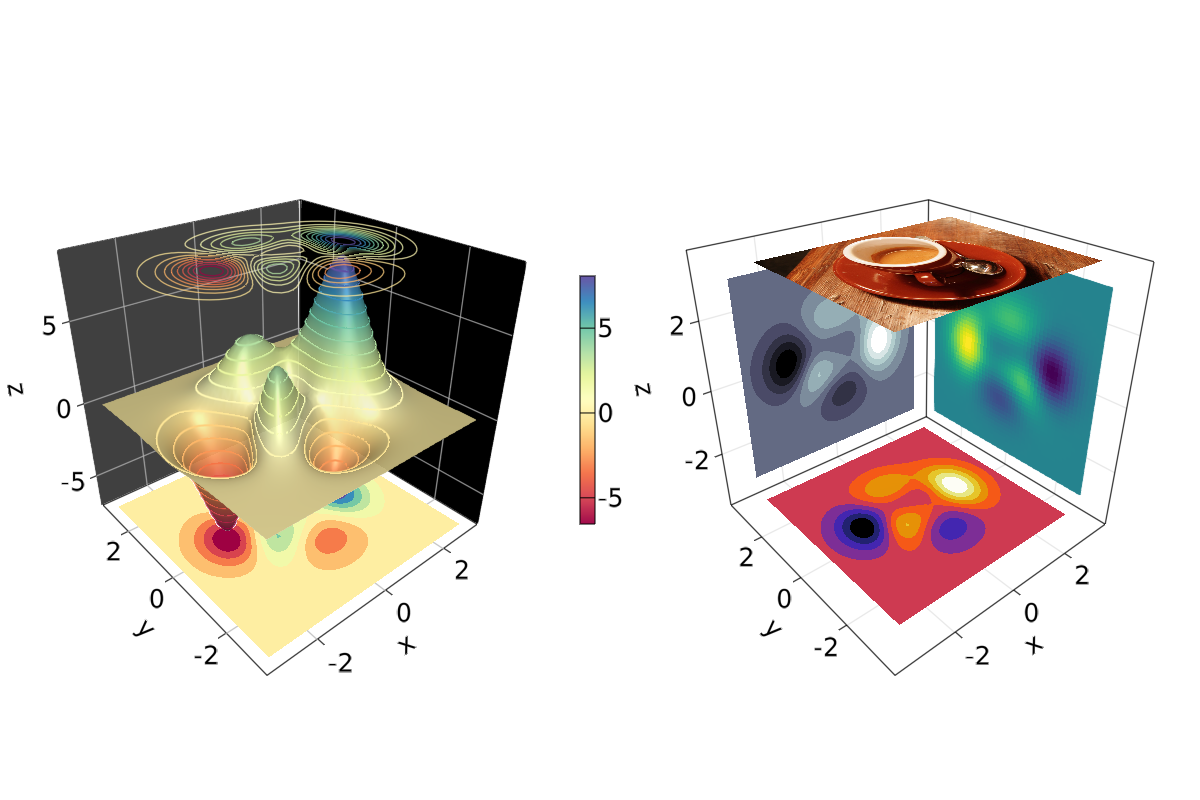


Figure 40: Mixing surface, contour3d, contour and contourf.

Not bad, right? From there is clear that any heatmap’s, contour’s, contourf’s or image can be plotted into any plane.

### 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 below[[18]](#footnote-283):

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[1, i]; aspect=(1, 1, 1), perspectiveness=0.5) for i = 1:2]  
 arrows!(axs[1], ps, ns, color=lengths, arrowsize=Vec3f0(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  
arrows\_and\_streamplot\_in\_3d()

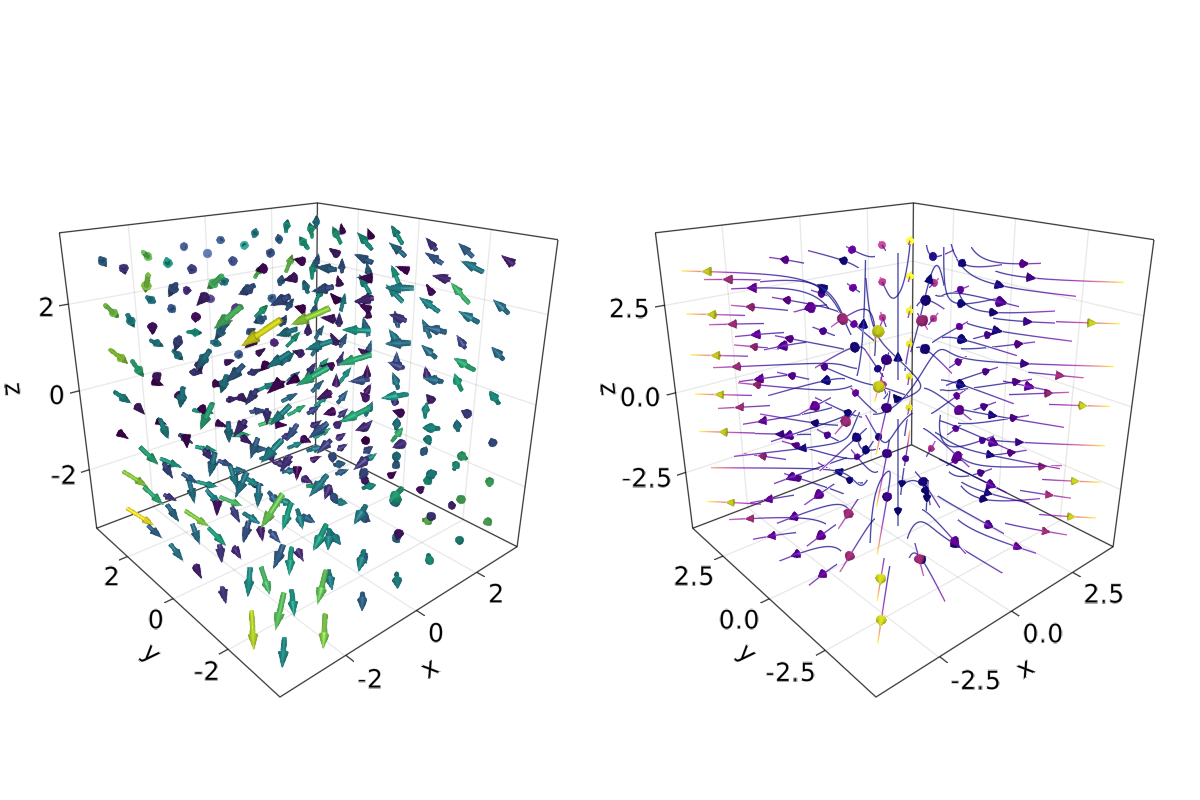


Figure 41: Arrows and streamplot in 3d.

Other interesting examples are a mesh(obj), a volume(x, y, z, vals), and a contour(x, y, z, vals).

### 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 tracing](https://en.wikipedia.org/wiki/Ray_tracing_(graphics)) to simulate a wide variety of optical effects. See the next examples:

using GeometryBasics

function mesh\_volume\_contour()  
 # mesh objects  
 rectMesh = FRect3D(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=(1600, 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  
mesh\_volume\_contour()

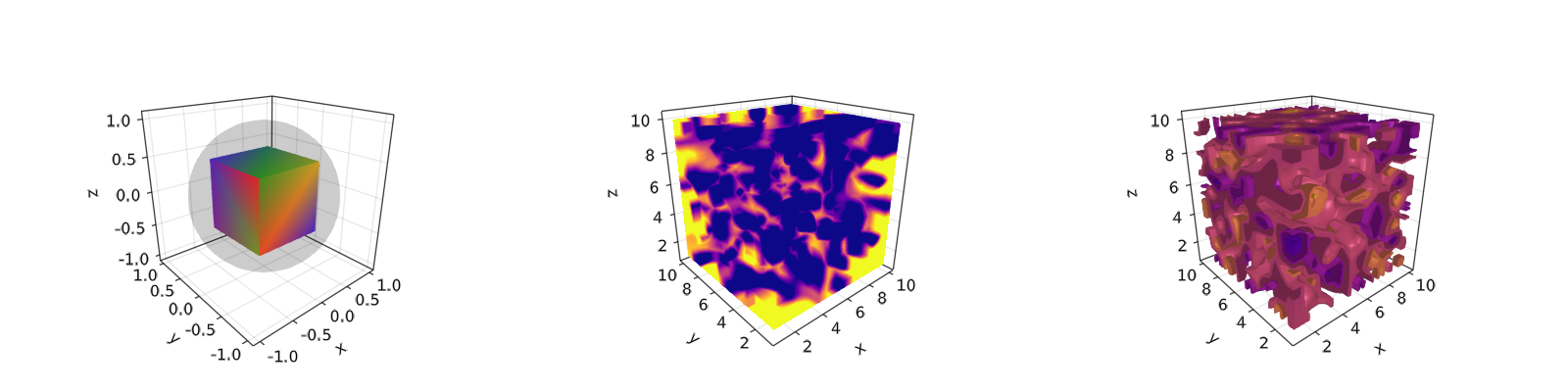


Figure 42: Mesh volume contour.

Note that here we are plotting two meshes in the same axis, one transparent sphere and a cube. So far, we have covered most of the 3D use-cases. Another example is ?linesegments.

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 1:2.5:20 for j in 1:2.5:10 for k in 1:2.5:4]  
cmap = get(colorschemes[:plasma], LinRange(0, 1, 50))  
colorsPlane = cmap[rand(1:50,50)]  
rectMesh = FRect3D(Vec3f(-1, -1, 2.1), Vec3f(22, 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()  
 fig = with\_theme(theme\_dark()) do  
 fig = Figure(resolution=(1200, 800))  
 ax1 = Axis3(fig[1, 1]; aspect=:data, perspectiveness=0.5, azimuth=0.72)  
 ax2 = Axis3(fig[1, 2]; aspect=:data, perspectiveness=0.5)  
 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  
grid\_spheres\_and\_rectangle\_as\_plate()

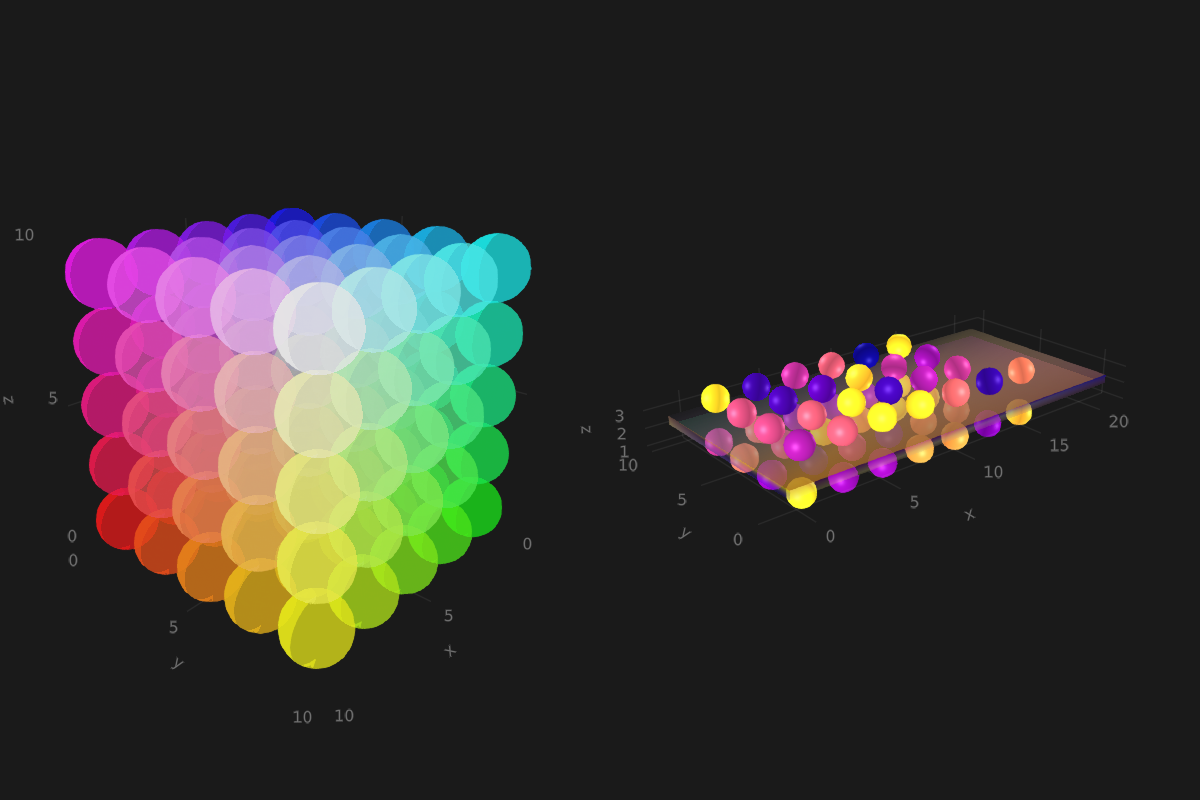


Figure 43: Grid spheres and rectangle as plate.

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 do implement which in turn could be used for plotting a 3D histogram. See our next example, where we are using again our 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 are used to specified our boxes size. 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 = FRect3D(Vec3f0(-0.5, -0.5, 0), Vec3f0(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 = FRect3D(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  
histogram\_or\_bars\_in\_3d()

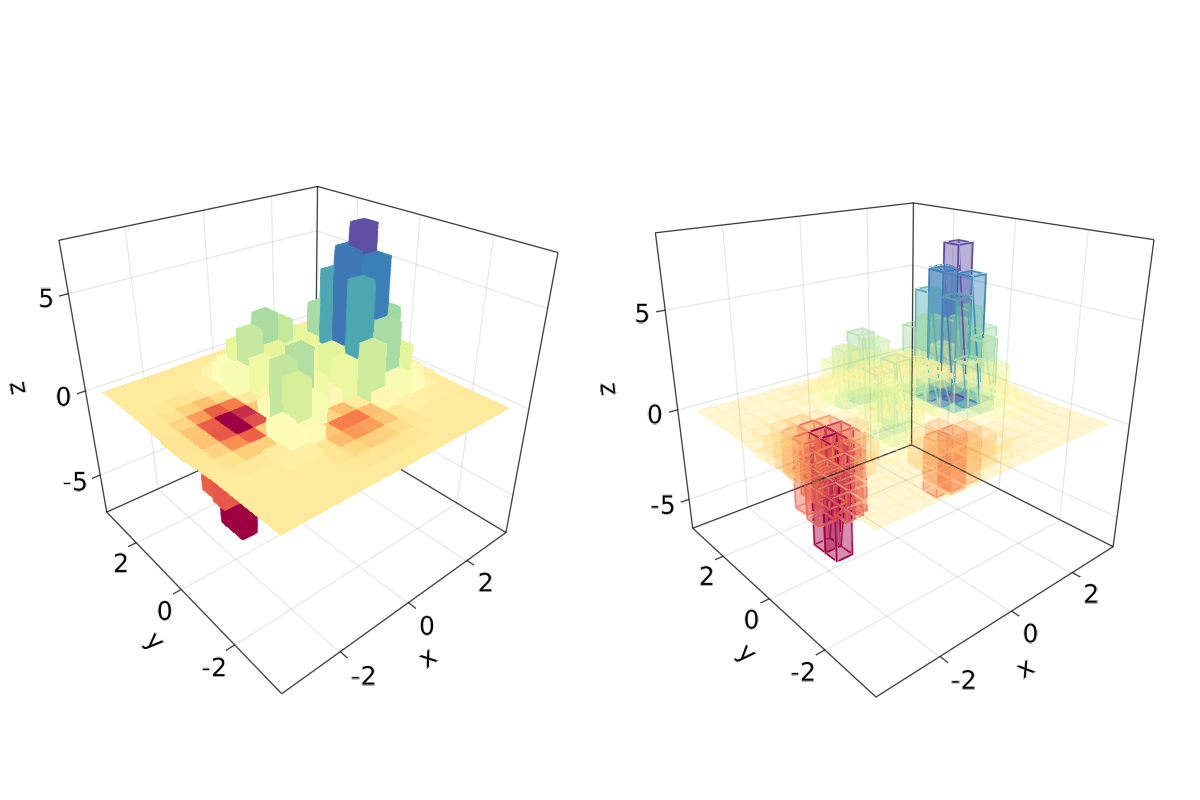


Figure 44: Histogram or bars in 3d.

Note, that you can also call lines or wireframe over a mesh object.

### 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 = LinRange(-3, 3, 10)  
 lower = [Point3f(i, -i, 0) for i in LinRange(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=pi/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  
filled\_line\_and\_linesegments\_in\_3D()

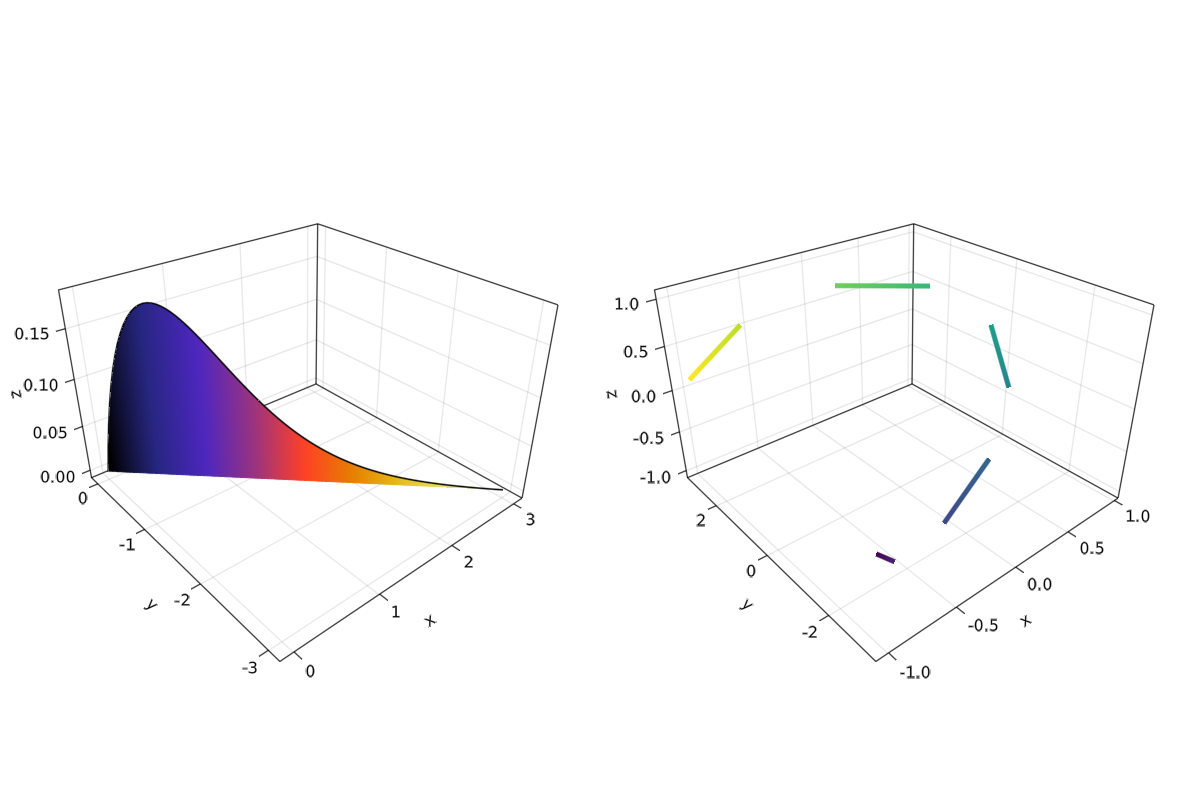


Figure 45: Filled line and linesegments in 3D.

Finally, our journey doing 3D plots has come to an end. You can combine everything we exposed here to create amazing 3D images!

# Appendix

## Packages Versions

This book is built with Julia 1.6.4 and the following packages:

Books 1.1.4  
CSV 0.9.11  
CairoMakie 0.6.6  
CategoricalArrays 0.10.2  
ColorSchemes 3.15.0  
Colors 0.12.8  
DataFrames 1.2.2  
Distributions 0.25.34  
FileIO 1.11.2  
GLMakie 0.4.7  
GeometryBasics 0.4.1  
ImageMagick 1.2.2  
LaTeXStrings 1.3.0  
Makie 0.15.3  
QuartzImageIO 0.7.4  
Reexport 1.2.2  
StatsBase 0.33.13  
TestImages 1.6.2  
XLSX 0.7.8

Build: 2021-11-30 6:6 UTC

## 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.

### Julia Style Guide

Firstly, we attempt to stick to the conventions from the [Julia Style Guide](https://docs.julialang.org/en/v1/manual/style-guide/). Most importantly, we write functions not scripts (see also Section [1.3](#sec:engineering)). Furthermore, we use naming conventions consistent with Julia base/, meaning:

* Use camelcase for modules: module JuliaDataScience, struct MyPoint. (Note that camelcase 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.

### BlueStyle

The [Blue Style Guide](https://github.com/invenia/BlueStyle) 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.

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).

### 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](#ref-jump2021using)). 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](#ref-pep8)).

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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1. 1 exabyte (EB) = 1,000,000 terabyte (TB). [↑](#footnote-ref-20)
2. no C++ or FORTRAN API calls. [↑](#footnote-ref-34)
3. and sometimes milliseconds. [↑](#footnote-ref-36)
4. numba, or even Rcpp or cython? [↑](#footnote-ref-37)
5. have a look at some deep learning libraries in GitHub and you’ll be surprised that Python is only 25%-33% of the codebase. [↑](#footnote-ref-38)
6. this is mostly a Python ecosystem problem, and while R doesn’t suffer heavily from this, it’s not blue skies either. [↑](#footnote-ref-39)
7. or with little effort necessary. [↑](#footnote-ref-40)
8. sometimes even faster than C. [↑](#footnote-ref-42)
9. a petaflop is one thousand trillion, or one quadrillion, operations per second. [↑](#footnote-ref-45)
10. LLVM stands for **L**ow **L**evel **V**irtual **M**achine, you can find more at the LLVM website (<http://llvm.org>). [↑](#footnote-ref-49)
11. if you like to learn more about how Julia is designed you should definitely check [Bezanson et al.](#ref-bezanson2017julia) ([2017](#ref-bezanson2017julia)). [↑](#footnote-ref-51)
12. please note that the Julia results depicted above do not include compile time. [↑](#footnote-ref-53)
13. or, that the memory address pointers to the elements in the column are stored next to each other [↑](#footnote-ref-111)
14. it is easier because first and last also work on many other collections, so you need to remember less. [↑](#footnote-ref-114)
15. 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>). [↑](#footnote-ref-155)
16. thanks to Sudete on Discourse (<https://discourse.julialang.org/t/pull-dataframes-columns-to-the-front/60327/4>) for this suggestion. [↑](#footnote-ref-162)
17. 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. [↑](#footnote-ref-182)
18. we are using the LinearAlgebra module from Julia’s standard library. [↑](#footnote-ref-283)