

A Reproducible Research Compendium

cf. list of contributors at

<https://github.com/rr-mrc-bsu/reproducible-research/graphs/contributors>

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Chapter 1

A ‘Living Book’ - aims and scope

This book is a little different from your usual statistics foliant - it is written entirely using **Markdown** and rendered to HTML, PDF, and EPUB publishing formats using the R package **bookdown**. Its entire Markdown source code is publicly available on GitHub.com at <https://github.com/rr-mrc-bsu/reproducible-research>. A pre-build version is hosted as static html website using **GitHub pages** at <https://rr-mrc-bsu.github.io/reproducible-research/>. This structure allows to easily discuss changes using GitHub issues <https://github.com/rr-mrc-bsu/reproducible-research/issues>, organize further development using milestones and projects, contribute corrections or even entire chapters by creating pull requests, and to manage editions by GitHub releases. It also means that everybody - and yes, that does include you - can become a contributor by creating pull requests in the GitHub repository. Since the contents are thus evolving over time as long as there are active contributors to the project, the book is ‘living’.

The overall purpose of the *Reproducible Research Compendium* is threefold:

1. Provide a platform for discussing aims and objectives as well as best practices for reproducible research with a clear focus on applications in biostatistics.
2. Build-up a lasting compendium for knowledge sharing around various issues and methods for coping with them that may broadly be subsumed under the term ‘reproducible research’.
3. The book project itself acts as a learning-by-doing example for its contributors with the goal of anybody participating becoming knowlegable about organizing collaborative open-source [mostly coding] projects.

We are committed to making the contribution process as easy as possible while at the same time requiring contributors to comply with a set of best-practices for open online collaborative coding. To ease the transition, see chapter 2. Please do feel free to post any question, suggestions, or feedback via the GitHub issue system!

1.1 Other resources

Interest in reproducibility for quantitative (and qualitative!) research is rapidly increasing. The perspectives are probably almost as diverse, if not more diverse, than the number of scientific fields. While many techniques and tools might be applicable across quantitative fields, definitions, conventions, and implementation details may vary widely. Before continuing with our take on the subject, we would therefore like to point out similar projects and resources. Please let us know if you feel that we should include your project here!

- **The Turing Way:** <https://github.com/alan-turing-institute/the-turing-way>, an initiative by the Alan Turing national institute for data science and artificial intelligence.

[statement on sharing citing policy our license?]

1.2 Our definition of ‘Reproducible Research’

At the core of the scientific method stands the idea that evidence gathered from experience can be used to refute hypotheses. By eliminating all hypotheses not compatible with the experimental data, the remaining explanation (alternative hypotheses) must be accepted.

In order to convince fellow scientists - and ultimately the society at large - of ones findings, experiments must be replicable in the sense that anybody interested in validating the results could set up the same or a similar experiment, again collect data, and - agreeing on the methods used - would need to reach the same qualitative conclusions. Obviously, replicability of results remains a promise up to the point that somebody actually attempts to do so. Often, replication studies are not realistic due to the high associated costs. Just think about the effort of building an entirely new particle accelerator like CERN just to replicate its findings! In medical research replication already plays a major role in the approval of new drugs since the FDA usually requires convincing evidence from two independently conducted randomized clinical trials to approve a new substance [REFERENCE].

An important caveat in the notion of replication is the fact that one needs to agree on the methods before being truly able to replicate results by collecting new data. Since nowadays most analyses of empirical data require relatively complex statistical methods which in turn rely on numerical computation on a computer system, just describing the exact method of getting from the input data to the analysis results - be it figures, numbers, tables - is daunting. Anybody with experience in computer-based analyses is familiar with the fact that these are essentially chaotic: Even the smallest change (missed comma in script) may lead to a catastrophic error or even worse, altered results without raising an error! A necessary but not sufficient prerequisite of replicability is thus reproducibility of results, i.e., the capability to get the exact same results from the exact same inputs. This might sound like the most natural and self-evident thing but in practice merely reproducing the results in many scientific papers is not possible [REFS].

These considerations lead us to the same schematic definition of reproducibility as put forward in The Turing Way.

[TODO: nice table graph here]

We feel that reproducibility of scientific results should be the bare minimum standard to strive for and want to collaboratively explore and advocated techniques, tools, and best-practises for getting there.

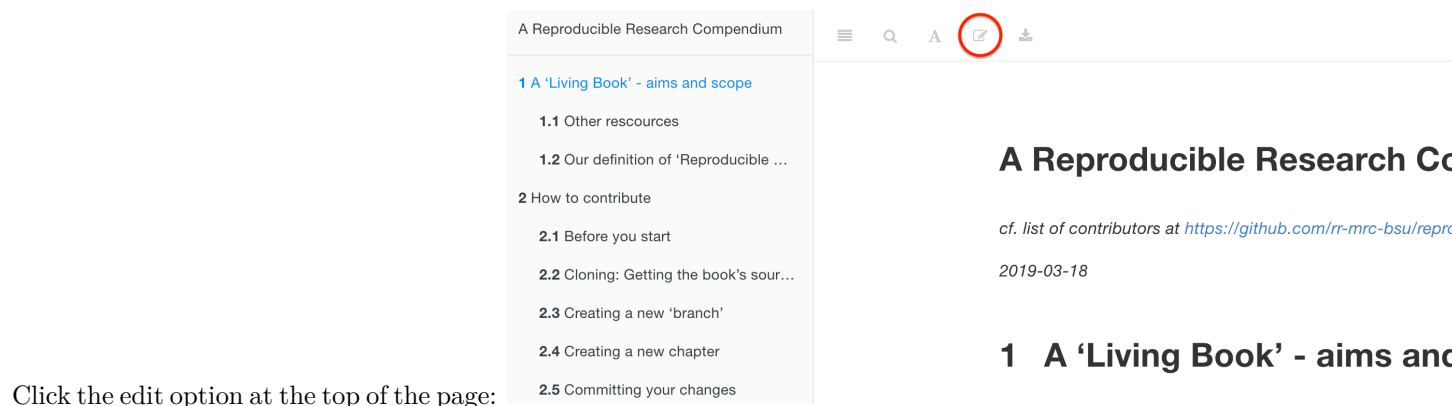
Chapter 2

How to contribute

This book is a collaborative effort. Therefore, an important aspect is that it enables people to contribute. This chapter is a hands-on tutorial on how to contribute.

2.1 The easy way (online)

The easiest way to contribute is to visit the book website at <https://rr-mrc-bsu.github.io/reproducible-research/> and click on the chapter you would like to edit.



The screenshot shows the website 'A Reproducible Research Compendium'. On the left sidebar, the menu item '2 How to contribute' is highlighted. In the top navigation bar, the 'edit this file' icon (a pencil inside a circle) is circled in red. The main content area shows the title 'A Reproducible Research Compendium' and a list of contributors.

Click the edit option at the top of the page:



The screenshot shows the GitHub source code editor for the file 'A Reproducible Research Compendium'. The file has 126 lines (100 sloc) and is 6.29 KB. The code is a YAML frontmatter for a book, including fields for title, author, date, site, documentclass, bibliography, bibio-style, link-citations, and description.

Which will take you to GitHub. From here, click the 'edit this file' option:

This will open the source markdown in the browser, which you can directly edit. Once you have made changes, add a short description of the changes at the bottom of the editing page and select 'Commit changes'.

A pull request will be opened and a fellow contributor will check your changes before they are published on the book website!

2.2 The proper way (using git)

2.2.1 Before you start

In the following, we assume that you are working on a Linux or MacOS machine. The instructions are similar for Windows users, but we do not discuss the details here. Using an open source operating system, such as Linux, is preferable because it avoids licensing barriers.

A great way to get started with Linux is Ubuntu and the easiest way to install it on an existing Windows or MacOS machine might be via a virtual machine. Detailed instructions on how to do so can be found [here](#).

2.2.2 Cloning: Getting the book's source code

The book is compiled from a collection of R markdown files which is a special text file format that allows to combine code and text within the same file as well as basic markup¹. The motivation behind markdown is to separate the content entirely from the layout and stick to an absolute minimum number of markups (e.g. headings, enumeration, hyperlinks) to be able to compile the document to as many different output formats as possible. The actual compilation will be done in ‘pandoc’ and will be explained later [ref].

A very important pillar of reproducibility is version control, i.e., some mechanism to keep track of changing files over time and enabling roll-backs to previous versions. We refer to [ref: version control chapter] for more details on version control, why it is so important in reproducible research and how to implement it. For now, we will just focus on how to install and use a specific program, **git**, to obtain the source code for the book and make changes to it. Assuming that you have a Linux (we will assume an Ubuntu installation) or MacOS system running, you will need to install the version control system git [link to chapter]. The easiest way to do this is via the command line package manager ‘apt’ on Linux (‘homebrew’ is the equivalent for MacOS).

On **Linux**, open a terminal window and execute the command

```
sudo apt -y install git
```

On **MacOS**, the following command will prompt git installation if it is not already installed

```
git --version
```

This will download and install all required packages from the official repository.

You may now ‘clone’ the online repository of the book from its GitHub.com website: <https://github.com/rr-mrc-bsu/reproducible-research>. Here ‘cloning’ does exactly what it says: it downloads an exact copy of the entire source code including its complete history of previous changes to your local computer to work on.

Assuming that you have opened a terminal window and that the working directory is your home directory ‘~’, you can clone the repository by invoking

```
git clone https://github.com/rr-mrc-bsu/reproducible-research.git
```

This will create a new folder ‘reproducible-research’ in your current working directory and download all necessary files. You should then change the working directory to the new folder via

¹Markups are simple meta information on text such as ‘this is a headline’ etc. If you are familiar with LaTeX you are already a markup professional since LaTeX supports a huge number of different markup expressions. HTML is also a markup language.


```
cd reproducible-research
```

Note that the source code only needs to be cloned **once**. After you have a local copy of the source code, you should ensure that this is kept up to date by ‘pulling’ from the remote master branch. This ensures that you are editing the most up-to-date version of the project.

The following command copies the remote master branch to your local device (this is not needed if you have just cloned the source code)

```
git pull origin master
```

2.2.3 Creating a new ‘branch’

Branches are different variants of the source code that may exist in parallel. A major feature of git is to make it possible to bring these branches together.

By default your git repository will now be on its ‘master’ branch.

You may verify that via

```
git status
```

It is important to check that you are never working on the master branch. For this project, we have invoked a branch protection rule so you are not able to work on the local master and then push directly to the remote master. Instead, you must first create a branch for editing and then push back to the remote, before opening a pull request to merge with the remote master.

The master branch is special in that it is usually considered the current ‘best’ variant of a project. For most small projects, a single master branch might be sufficient but things do get a bit hairy when many people could potentially change this common master branch at the same time. For this book project, each time the master branch in the online repository changes, the entire book is recompiled and published at <https://rr-mrc-bsu.github.io/reproducible-research/>. Therefore, the book contributing guidelines require that no changes are made directly to the master branch. Instead, all work is done on separate feature branches, for example on ‘my-cool-new-chapter’ if you want to add a new chapter.

To create this branch you run the following git commands

```
git branch my-cool-new-chapter
git checkout my-cool-new-chapter
```

This creates the new branch and checks it out (activates it). All changes that you now make to files in the directory only affect the version of the book associated with your local branch ‘my-cool-new-chapter’ (after you commit them, that is).

Of course, you can always check that you are on your new branch using

```
git status
```

2.2.4 Creating a new chapter

You may now add a new chapter simply by placing a new numbered .Rmd file in the top level of the book projects directory, e.g. the new file could be called ‘99-my-cool-new-chapter.Rmd’. Do feel free to browse the other chapters of the book already present to learn more about the R markdown syntax used to write

the book. Note that although R markdown relies on R to compile the files, the contents of the file may not contain any R code at all. For more details on R markdown see [link chapter].

Once the new chapter file is created and you added some content you should check whether the altered book still compiles without errors. This is critically important for any piece of source code since even small changes might break the entire thing. Since you will not be able to incorporate your changes in the online version of the book without passing some automated checks, you may just as well check that everything is working locally before attempting to add your changes online.

To compile the book you will need R and some packages. The easiest way to install everything is again via the command line.

Linux users should invoke

```
sudo apt-get install r-base r-base-dev
Rscript -e 'install.packages("bookdown")'
```

Whilst MacOS users should use the following, which installs XCode CLT and homebrew prior to the installation of R (if XCode and/or homebrew are already installed you will see a message warning and you can skip these steps)

```
xcode-select --install
/usr/bin/ruby -e "$(curl -fsSL https://raw.githubusercontent.com/Homebrew/install/master/install)"
brew install r
Rscript -e 'install.packages("bookdown")'
```

You may then attempt to build the new book with your new chapter by invoking the build script

```
bash _build.sh
```

which essentially runs the R command

```
bookdown::render_book("index.Rmd")
```

to build the book and cleans up afterwards. You should now see a new folder ‘_book/’ and be able to open ‘_book/index.html’ in your browser. This just opens the newly build version of the book locally. Make sure that everything is as you want it to be.

The complete documentation for **bookdown** can be found at <https://bookdown.org/yihui/bookdown/>.

2.2.5 Committing your changes

Next you will want to ‘commit’ your changes to your local ‘my-cool-new-chapter’ branch. Committing means that you store your changes in the git repository thus creating a snapshot in time that you may always return to irrespective of any further changes to the repository.

The repository should be configured in such a way as to ignore the _book/ folder that you created since this is just output. You can therefore simply add all changes and commit them with a short description of what you did

```
git add -A
git commit -m "added cool new chapter"
```

The complete documentation for **bookdown** can be found at <https://bookdown.org/yihui/bookdown/>.

2.2.6 Publishing your changes

Changes to the master branch in the online repository are organized as pull requests. This is a feature on GitHub.com that allows you to publicly propose merging a branch back to master. Usually this is straightforward to do since the master branch will change very slowly (cf. [ref merge conflicts]). The pull request will then have to be reviewed by at least one other collaborator to the repository before you are able to actually merge the changes into the master branch - only at that point are they actually integrated in the published book.

To do so, you first have to be a contributor to the project [TODO: explain how to do that without being a contributor / how to become one]. Next, you will need to push your local branch to the online repository via

```
git push -u origin my-cool-new-chapter
```

Switch to a browser and open <https://github.com/rr-mrc-bsu/reproducible-research>. In the top/middle you then need to switch from the '<> Code' tab to the pull requests tab. Create a new pull request by clicking on the button. This opens a panel where you can define your pull request. A pull request always proposes to merge one branch onto another. In our case we want to merge 'my-cool-new-chapter' onto 'master'. That means that we leave the 'base:' branch master as it stands by default. However, in the drop-down menu for 'compare:' you can now select your new branch. Note that the arrow between the two already indicates that the 'compare:' branch is supposed to be merged onto the 'base:' branch. In the panel below you will then see a git diff, i.e., a listing of all the differences between the two branches (gree: additions, red: deletions). Since you only added new stuff in this example and the master (probably) did not change between you downloading the latest copy of the repository and creating your changes, there are no merge conflicts. Confirm by clicking on 'create pull request'.

This will first create the pull request and the immediately trigger a build script on the continuous integration system Travis [reference to continuous integration]. The continuous integration system will spin up a virtual machine in the cloud, install all required software, download the repository and check whether the build script will still run without errors after merging your pull request. This process will take a few minutes and once it is completed the status of the build will be shown in your pull request. Even if the build script ran perfectly fine on your local machine the Travis build might fail if you introduced new dependencies without altering the Travis build configuration. For normal changes (only editing .Rmd files), the build should work without any errors. The advantage of having a CI system is that anybody reviewing your changes will immediately know that your pull request did not introduce any breaking changes and that the book can still be compiled on the default minimal build system defined in the travis.yml file.

Once another contributor has reviewed your changes and approved them, you are then free to merge your pull request. Only this last action will actually change the master branch of the repository. This change will again trigger a build on Travis, this time for the newly merged master branch. Since the pull request was already checked, there should not be any further problems. Additionally, any build of the master branch will also execute the `_deploy.sh` script which will take the compiled book and push the output to the gh-pages branch of the repository. This branch is special in that it only contains the generated output and not the corresponding source code. GitHub.com offers the possibility of hosting static html pages free of charge via GitHub pages and the project is configured such that the contents of the gh-pages branch (feel free to inspect it) are used to populate the GitHub pages homepage of the project. This means that the version of the book displayed at <https://rr-mrc-bsu.github.io/reproducible-research/> should automatically corresponds to the version obtained from the last commit to the repositories master branch.

Chapter 3

Version control

the turing way: https://github.com/alan-turing-institute/the-turing-way/blob/master/chapters/version_control.md

Chapter 4

Literate Programming

[TODO]

Chapter 5

Build automation

Large projects can be a pain to manage. Small changes may break your software, or may deem your previously obtained analysis results useless. Build automation refers to a collection of tools that attempt to automate steps in your workflow, thereby simplifying your the whole process. Many processes may be automated, but here we will mainly discuss build automation using Makefiles.

5.1 Makefiles

Most research projects consist of several different connected components. For example, the end product might be a manuscript, which depends on intermediate components such as a data analysis script and an R package. In this case, the manuscript depends on the data analysis script, which in turn depends on the R package. Such a hierarchy implies that every time a file changes, all files downstream in the hierarchy should be updated as well. In the previous example, we might adjust a function in the R package, which might change the outcome of the data analysis, and as a result, we'd have to re-run the data analysis script. The outcome of the data analysis might change the manuscript, so we'd have to re-compile that as well. In large projects, this quickly becomes tedious and difficult to maintain by hand. Luckily there is software available to streamline this process.

Consider the more complicated example in Figure 5.1 with the following corresponding project directory:

```
./
  rpackage
    DESCRIPTION
    functions.R
  code
    analysis.R
    simulation.R
  docs
    manuscript.Rnw
    presentation.Rnw
    refs.bib
  README.md
```

[to do: make diagram with DiagrammeR]

Re-running, -building, and -compiling all the files after we made a change to the anyone of the intermediate files would be a tedious task. Ideally, we would like to have a command that re-runs/compiles/builds the different files everytime an upstream change is made. This is exactly what the GNU software Make does. Make works through a Makefile, a file that describes how a target file, depends on its dependencies, and

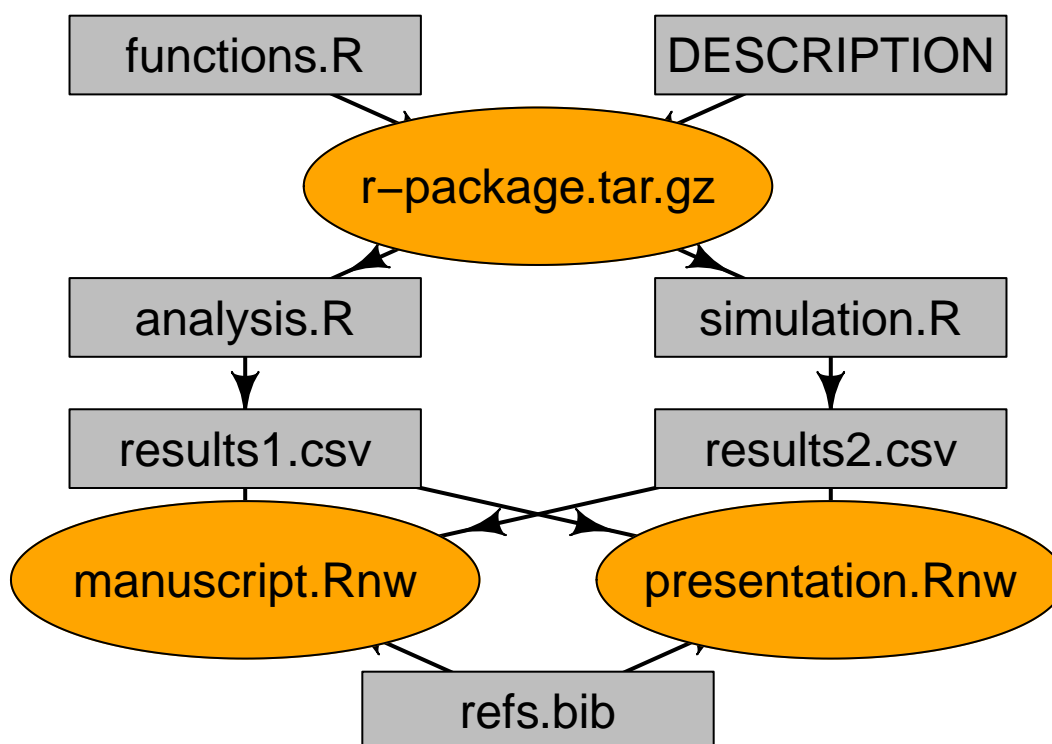


Figure 5.1: Example project workflow

how these in turn on their dependencies, and so on. If a Makefile is run, a file is compiled if any of its dependencies has changed since the last time the file was compiled. In other words, the Makefile starts at the top of the hierarchy and updates a file if its creation time is older than the creation time of its dependencies. In our example in Figure 5.1, if we make a change to the `functions.R` file, we trigger the recompilation of the `r-package.tar.gz` file, which in turn triggers a rerunning of the `analysis.R` and `simulation.R` scripts, and so on, until all files are up to date again.

[add example Makefile]

Chapter 6

Dependency management

Reproducible research, in the narrow sense in which it is defined in this book, ultimately means that an entire analysis - however complicated - can be repeated at the push of a button (or the command line equivalent: typing ‘make’) to yield the exact same figures, tables, files, or reports when applied to the exact same data. In mathematical terms, one could go as far as requiring that an analysis must act as a function on data: there may very well be two data sets that produce the same output but the same input data must always produce the same analysis results. The core tools for achieving this are certainly literate programming, which allows to closer integrate documentation and code from a documentation-first perspective, and any form of build automation/workflow management system (GNU make, snakemake, CWL, etc.).

It is certainly worthwhile to take a step back here and reflect on the complexity of the approach that was put forward so far. None of the steps suggested is excessively complex or requires a particularly deep understanding of ‘the command line’ but in combination a sizeable stack of software dependencies has piled up:

1. On the base layer, there is the operating system itself.
2. The analysis is conducted by interacting with the operating system, ideally, via some form of terminal and shell.
3. Next, a workflow management system or build system like GNU make, snakemake, or CWL-runner should be used to ‘tie everything together’
4. Version control software (usually git) is required to ensure integrity of the project
5. Usually some form of output is to be produced and the most reliable way to preserve digital documents at the moment seems to be .pdf. Note that changes in html/browser support may lead to different depiction of the same html file over the years! To create this output one will typically rely on some form of literate programming which has further dependencies. In the case of Rmarkdown and pdf output that would be R + pandoc + LaTeX.
6. Finally, the analysis itself will require even more complex software (R packages, python modules). In a scientific context there might also be bleeding edge software with no stable release at all, which needs to be build from source.

All in all, this software stack is incredibly complex even for the simplest of analyses! Over time, each of these component layers might change/be updated at different pace or the development might simply cease. This situation can be pictured as a completed analysis being a delicate skyscraper: the moment it is finished it starts to slowly crumble away. [picture leaning tower of pisa] Even if all all scripts and report files were preserved exactly in the state they were in when the analysis was conducted, the slowly evolving software ecosystem around them will still change over time and it might very well be that the exact same code would produce different results, or much more likely, simply stop working at some point.

It is thus not enough to simply maintain a versioned repository of all analysis scripts. Rather, complete reproducibility also requires a perfect snapshot of the software environment at the time of execution to be preserved for future execution - a time capsule of code if you will. A good first step in this direction

is certainly to report as many version numbers of software used as possible. This approach, however, is cumbersome, error prone and ultimately futile since users are typically not even aware of the plethora of low level software they implicitly rely on. A better approach would be to define explicitly the computing environment required for the intended computation and to preserve an exact ‘image’ of this environment which can then be replicated at a later point in time to re-run the analysis in its original environment.

6.1 Example problem

Consider the toy example in <https://github.com/rr-mrc-bsu/containerization-example>. This example repository is built around a single R Markdown report (`r-and-python.Rmd`) highlighting how R and python can be integrated in a single report. While this is still a fairly simple project in terms of dependencies (no custom source dependencies) it is complex enough to highlight the benefits of a containerized analysis.

Let’s sort through the individual files and folder one by one. Any well-organized repository should contain `README.md`, `LICENSE`, and `.gitignore` files. Their respective roles are described in the git chapter [write chapter, REFERENCE].

The `.travis.yml` configuration file contains the configuration of the continuous integration system (here: Travis-CI) linked to the repository. Continuous integration services allow automatic builds/checks of the code in a repository and greatly facilitate quality checking of new pull requests. To avoid a lengthy configuration file, the folder `.travis` contains further scripts which are referenced from the actual Travis configuration file. For details on continuous integration, see chapter 7.

The `Makefile` and the `Snakemake` files are explained in more detail in chapter ???. These files can be used to organize complex workflows using either GNU make (in simpler cases) or snakemake (more sophisticated, cluster integration). We will discuss how these two common workflow automation systems can be used together with containers at the end of this chapter in section 6.4.

The folder `mnist` contains prepared data from the classical mnist digital handwritten data set.

The R Markdown file `r-and-python.Rmd` and the `docker` folder are the elements of the example repository most important to the contents of this chapter. The R Markdown file `r-and-python.Rmd` contains an example analysis using python and tensorflow + keras to do the heavy lifting for training a deep neural network to classify the mnist example data (in digits 0 to 9). Some data wrangling and plotting is done using R though. Both R and python sessions interoperate using the `reticulate` package. To learn more about the language agnostic nature of R Markdown and especially python/R interoperability, see [write chapter, REFERENCE]. The analysis thus has a non-trivial set of dependencies in both R and python packages/modules, which we will manage by using a custom docker container. The build instructions for this container are specified in the `docker` folder which contains a build script `docker/build` and a `dockerfile`. We will return to this folder in section 6.2.1. Before learning more about containers, it is a good idea to have a rough understanding of so called ‘virtual machines’.

6.2 Virtual machines and containers

Virtual machines are (software) emulations of entire computer systems. As such they allow running various guest operating systems from within a single host system, e.g., Linux within Windows or vice versa. To achieve this, a virtual machine acts as an intermediate layer between the host system (and its hardware) and the guest operating system. i.e., all low-level operations of the guest system are mapped through the virtual machine and the host operating system to the host hardware. A common software for running virtual machines is VirtualBox which can, e.g., be used to run an Ubuntu linux from within a Windows system. When using virtual machines for reproducible research, care should be taken to make the process of creating the virtual machine as transparent as possible. Command line tools like Vagrant are much better suited for these use cases. We strongly discourage setting up a full-fledged Ubuntu system within VirtualBox

and installing required software manually from within the virtual machine since this process is itself not reproducible. A virtual machine created in this way may render a particular piece of code reproducible but can itself not easily be recreated to the exact same specifications.

Instead, the reproducible research community is mainly embracing containers to create portable computing environments. For our purposes, containers can be seen as a more lightweight alternative to virtual machines. Snakemake [write chapter, REFERENCE], for instance, supports running workflows where individual steps are executed in their respective individual containers.

In a nutshell, we may see container images as lightweight portable pieces of software which can be used to spawn container instances thus creating a **portable computing environment** by simply distributing the respective container image file.

If all dependencies of a particular analysis or an individual step in a larger workflow are contained in a container image, these dependencies will be available in any instance spawned from the image. An excellent video explaining the concept of a container in more detail is:

- Ben Corrie, ‘what is a container?’: <https://www.youtube.com/watch?v=EnJ7qX9fkU>

By far the most common container software is Docker.

6.2.1 Docker

Docker constitutes the de-facto standard in terms of container software and hugely contributed to popularizing the concept of containerization in recent years. As most of the tools discussed in this book, Docker was never designed with reproducibility in mind but rather to enable the fast spinning-up of lightweight application containers to handle web-services etc. (‘micro virtualization’).

Since it is the de-facto standard, Docker is very well documented and the docker community edition is an open source project and available free of charge. The company behind Docker also runs an online repository, Docker Hub, for docker images which can be seen as the GitHub/GitLab equivalent for docker images. Docker Hub can be used free of charge and thus enables the storage and sharing of custom container images via the world wide web.

A major drawback of Docker is, that it was never intended as a user-space application but mainly as a tool for server administrators. As such it requires root access to operate. While this is fine for building containers from so called **dockerfiles** (cf. **docker/dockerfile** in the example repository), the execution of an analysis should not require root access of the user. This is especially important when computations are conducted on shared resource like HPC systems where users do not have root access.

6.2.2 Singularity

Only relatively recently, the singularity container software was introduced to address this issue. Singularity was created exactly with HPC systems and reproducibility in science in mind (see this video). It does not require root access to run (but to build container images!) and thus enables HPC users to locally build container images which they can then use to run analyses on a high-performance cluster. A guiding principle in the development of singularity was to maintain compatibility with docker containers, i.e., singularity can be used to run standard docker containers. Since singularity is still rather a niche product, community help for docker is much easier to get online, and dockerhub is arguably the safest (and cheapest) place to store and distribute container images we still propose to use Docker for building the actual container images.

6.3 The dockerfile

A `dockerfile` contains the ‘recipe’ for building a docker container image. The complete reference of the syntax of dockerfiles can be found [here](#). For our purposes, only a few commands will suffice to set up a docker container that contains all dependencies needed to render the Rmarkdown file `r-and-python.Rmd` of the example project. In fact, the entire contents of `docker/dockerfile` boil down to:

```
FROM rocker/verse:latest

MAINTAINER Kevin Kunzmann kevin.kunzmann@mrc-bsu.cam.ac.uk

# update apt
RUN sudo apt-get update

# install python and required packages
RUN sudo apt-get install -y python3-pip python3-dev python3-tk
RUN sudo pip3 install -U pip
RUN sudo pip3 install numpy matplotlib tensorflow

# install required R packages
RUN R -e "install.packages('reticulate')"
```

Only three statements are used.

1. The `FROM` statement indicates the basis of the container. This allows to build on existing containers which may then be modified or extended to save time and storage space since images are composed of individual layers. By re-using previous layers with `FROM` the respective layer must only be saved once per container repository. Here, the container is derived from the latest version of `rocker/verse`, a relatively large container consisting of a stable debian linux system with R, Rstudio, the tidyverse packages, and all software required to render Rmarkdownr reports (LaTeX) pre-installed.
2. The `MAINTAINER` field simply contains an email address to complain to.
3. The `RUN` statement can be used to execute commands inside the container during the build. Here we use it to update the distribution package manager before installing the R package `reticulate` which enables interoperability between R and python before installing python and the required modules.

We will now build the container image locally. To that end, clone the example repository to your local filesystem (cf. [TODO; REFERENCE GIT]).

```
git clone https://github.com/rr-mrc-bsu/containerization-example
```

Next, install docker, `cd` to the docker subfolder of the example repository and build the container via

```
cd containerization-example/docker
sudo docker build --no-cache -t mycontainer .
```

Note that you do require root access to build the container! This command will trigger the build process (and take a while). Afterwards, a success message is displayed together with a unique sha256 hash value for the container image. This hash value can later be used to uniquely identify a particular version of a container (similar to git commit hashes, cf. ???). Should you have a Docker Hub account you could then push the image by

```
docker push yourname/mycontainer
```

These are essentially the steps executed in the `docker/build` script. Without making an image publicly available on dockerhub, the image is only available locally. Note that having access to the image (or at least its exact hash) is extremely important to guarantee reproducibility. Simply rebuilding the image from the same dockerfile at a later timepoint will almost always result in a slightly different image when the build is configured to use the most recent package sources and versions of the software required. To avoid this,

one may take steps to specify the software versions explicitly in the dockerfile but this never guarantees reproducible builds due to the many uncontrollable external dependencies. Still, keeping the dockerfile is important, since it may be seen as a guide as to how a similar computing environment can be set up manually at a later timepoint. Even if there are reasons not to use singularity to re-run an analysis, as good dockerfile might be the best way to specify software dependencies.

[TODO link to continuous integration for dockerfiles]

Switch back to the top level of the containerization example folder now.

```
cd ..
```

A major advantage of singularity over docker over virtual machines is the ease with which singularity enables execution of commands **inside of a docker container instance** but **within the host file system**, i.e., in contrast to docker, one does not need to manually mount a particular directory when starting a container but simply may invoke

```
singularity exec docker://kkmann/rr-containerization-example touch test
```

to execute the command `touch test` in an instance of the publicly built container image but **within the host filesystem**. This means that after executing the line in a shell, a new file ‘test’ should have been created in the current working directory. The touch command, however, was not executed in the host system but within the container! This example is obviously useless since `touch` is just as well available in the host shell but it immediately demonstrates the ease of using singularity with the host file system!

6.4 Containers and workflow management

6.4.1 GNU make

A much more useful application in our context is executing GNU make in a container! This means that we can render the Rmarkdown file in our container by

```
singularity exec docker://kkmann/rr-containerization-example make
```

Since all dependencies are pre-installed in the container image, this command only depends on the version of singularity and the exact container image. To query the exact sha256 hash value, use `docker images`

```
docker images --digest | grep containerization
```

which will list the locally available corresponding container images and their exact hash values. To re-use a particular version, one may then invoke, e.g.,

```
singularity exec docker://kkmann/rr-containerization-example@sha256:5225e53f934d749bf3017f140e5169b0d2e...
```

6.4.2 Snakemake

Snakemake is a much more powerful tool when it comes to complex workflows since it supports cluster execution and more flexible rule definitions (cf chapter [TODO, REFERENCE]). It is also designed with reproducibility in mind and thus allows to run either specific rules or an entire workflow using singularity. The contents of the `Snakefile` in the containerization-example folder are

```
singularity:
    "docker://kkmann/rr-containerization-example@sha256:17414f63929b0283f82e70ded3ca9cd9b61f37e13fe3d10..."

rule build_report:
    input:
        "r-and-python.Rmd"
```

```

output:
  "r-and-python.html"
shell:
  """
  Rscript -e "rmarkdown::render(\"{input}\")"
  """

```

The first line specifies the singularity container to use. Here, the publicly available image from dockerhub is used with a particular hash value. One could just as well point to a local image as well though. Such a global singularity parameter will run every rule of the workflow in the same default container. It is also possible to specify custom containers on a per-rule basis by specifying the `singularity` parameter of the rule.

```

rule build_report:
  input:
    "r-and-python.Rmd"
  output:
    "r-and-python.html"
  singularity:
    "docker://kkmann/rr-containerization-example@sha256:17414f63929b0283f82e70ded3ca9cd9b61f37e13fe"
  shell:
    """
    Rscript -e "rmarkdown::render(\"{input}\")"
    """

```

This will override potential global singularity container settings (cf. [REFERENCING SINGULARITY CHAPTER]).

6.5 Containerization vs. package managers

The approach to dependency management presented in this chapter might be considered a bit overpowered for some use cases. The main reason why we chose to demonstrate what we consider the ‘gold-standard’ of dependency management over more language/environment specific approaches is to showcase how simple it actually is. As long as you are capable of running a few simple commands in a Linux command line you are good to go. The container-based approach to dependency management is also the most generic in that it is capable of managing arbitrary dependencies - as long as your computing environment can be set up on a Linux operating system you are good to go! It does not matter which (or even how many different) programming languages you use, how much messy custom research software you need. As long as you are able to install it to a plain Linux system there is no environment that cannot be mapped to a container (or several!). Still, for completeness’ sake, a few different, potentially more accessible methods for partial dependency management will be discussed as ‘honorable mentions’ in the following.

6.5.1 R only - wrap everything up in a package

In case your entire workflow is R-based, it might be worthwhile to write an R package for your analysis. This essentially relies on R’s package management system to resolve dependencies (in this case: R packages only). An R analysis package tends to not contain much code in the `R/` folder, but rather encapsulates any analyses in vignettes. [TODO: elaborate on this idea, example repository]

6.5.2 R only - packrat

[TODO]

6.6 Caveats

Depending on your perspective, there are a few restrictions to a container-based dependency management approach.

1. **Licensing:** Reproducibility and the open-source philosophy are closely connected in that true reproducibility requires the software dependencies to be openly available. If the required dependencies cannot be installed in a container that may be distributed openly, results will not be reproducible by everybody. For instance, while the SAS system for statistical analyses can be used inside containers, licensing and license costs may be a major obstacle in doing so.
2. **Containers are Linux based:** The effective restriction to open-source software also restricts the choice of container operating systems. In practice, containers are almost exclusively Linux based. In case of, e.g., Windows dependencies, this means that the less flexible approach via virtual machines might be required to encapsulate the analysis environment.

While these restrictions might be seen as caveats, in fact, they can also be seen as an encouragement to conducting research in a more open (as in open-source-software-based) way.

Chapter 7

Continuous Integration

Did you ever wonder what the green/yellow/red ‘badges’ in some Readme.md files on, e.g., GitHub.com actually mean? How are they created, what are they for and why should you care?

This section will hopefully shed light on the meaning of some of these badges (those referring to a ‘build status’) and you will learn how to use these techniques for your own repositories. The key term here is ‘continuous integration’ (CI) which refers to a concept in software development where all working copies (in git one would refer to branches) of a project are frequently integrated into the mainline (in git terms: the master branch). The rationale being that frequent/continuous integration prevents diverging development branches. Since the philosophy of git is to create feature branches for small, contained changes of master which are to be merged back as soon as possible, CI and git are a natural fit.

In practice, however, frequent changes to master are dangerous. After all, the master branch should maintain the last at least working if not stable version of the project that other feature branches can be started from. It is thus crucial to prevent erroneous changes to be merged into the master branch too often. This means that CI requires some kind of automated quality checks that pre-emptively check for new bugs/problems before a pull request from a feature branch on master is executed. It is this particular aspect of CI that is most interesting to collaborative work on scientific coding projects - being able to automatically run checks/tests on pull requests proposing changes to the master branch of the project.

[Random thought: we should have an example repository for demonstrating the different states of PRs etc. instead of just including pictures. Readers could then inspect the ‘frozen’ repository directly and see the PRs etc.!]

To enable this kind of feature on GitHub, a cloud-based farm or build servers is required where users can run build scripts in virtual machines and retrieve reports on the build status (0 worked, 1 failed). It is these build-statuses that the green/yellow/red badges report visually (yellow/grey being a pending build)! There are multiple companies offering these services (within reasonable bounds) for free for public repositories and as of 2018 the free academic account for GitHub also enables free builds using TravisCI for private repositories. It must be stressed though that, since everything is running in the cloud, the same constraints as for storing data on GitHub servers apply to downloading or processing data in build scripts for CI services. [point to Jenkins as on-premise solution]

The obvious setting to use automated builds in is package development. This is by far the most common application and the current tools are definitely geared towards that use case. We will later discuss how to extend the scope to non-package situations. For instance, the repository containing the source code for this book also uses TravisCI for build automation even though it is not an R-package itself.

Chapter 8

Metadata

- what is metadata?
- indexing and search engines?
- long term storage/accessibility

8.1 FAIR principle

[todo]

8.2 Digital Object Identifiers - DOI

[todo]

8.3 Zenodo.org

[todo]

Chapter 9

R package development

[R]{www.r-project.org} is one the most popular software among statisticians. It provides a very powerful environment for statistical computing and data visualization. It is now common to create R packages that accompany research papers and implement novel statistical methods. These packages are then made publicly available on [CRAN]{cran.r-project.org}, personal websites or the journal website. Sharing implementations of recent methodological development facilitates uptake by the research community. It is also increasingly used to check reproducibility of published results. This chapter treats of R package development with an emphasis on continuous integration and unit testing.

9.1 Continuous integration

9.2 Unit testing

9.3 Documentation

Chapter 10

Python package development

10.1 Continuous integration

I agree, Kevin, we should some content.

10.2 Unit testing

10.3 Documentation