

rang: Reconstructing reproducible R computational environments

Chung-hong Chan

David Schoch

A complete declarative description of the computational environment is often missing when researchers share their materials. Without such description, software obsolescence and missing system components can jeopardize computational reproducibility in the future, even when data and computer code are available. The R package rang is a complete solution for generating the declarative description for other researchers to automatically reconstruct the computational environment at a specific time point. The reconstruction process, based on Docker, has been tested for R code as old as 2001. The declarative description generated by rang satisfies the definition of a reproducible research compendium and can be shared as such. In this contribution, we show how rang can be used to make otherwise unexecutable code, spanning from fields such as computational social science and bioinformatics, executable again. We also provide instructions on how to use rang to construct reproducible and shareable research compendia of current research. The package is currently available from CRAN (<https://cran.r-project.org/web/packages/rang/index.html>) and GitHub (<https://github.com/chainsawriot/rang>).

Background

“In some cases the polarization estimation will not work ... This is NOT a problem in the method, it is entirely dependent on the numpy version (and even the OS’s). If you have different versions of numpy or even the same version of numpy on a different OS configuration, different networks will fail randomly... [F]or instance, the 109th Congress will fail, but will work entirely normally on a different numpy version, which will fail on a different Congress network.”

~ excerpt of [this README file](#)

Other than bad programming practices (Trisovic et al. 2022), the main computing barrier to computational reproducibility is the failure to reconstruct the computational environment like the one used by the original researchers. This task looks trivially simple. But as computer

science research has shown, this task is incredibly complex (Abate et al. 2015; Dolstra, Löh, and Pierron 2010). In the realm of a usual scripting language such as R ¹, that pertains four aspects: a) operating system, b) system components such as `libxml2`, c) the exact R version, and d) what and which version of the installed R packages. We will call them Component A, B, C, D in the following sections. Any change in these four components can possibly affect the execution of any shared computer code. For example, the lack of the system component `libxml2` can impact whether the R package `xml2` can be installed on a Linux system. If the shared computer code requires the R package `xml2`, then the whole execution fails.

In reality, the impact of Component A is relatively weak as mainstream, open source programming languages and their software libraries are usually cross platform. In modern computational research, Linux is the de-facto operating system in high performance computing environments (e.g. Slurm). Instead, the impact of Components B, C, and D is much higher. Component D is the most volatile among them all as there are many possible combinations of R packages and versions. Software updates with breaking changes (even in a dependency) might render existing shared code using those changed features not executable or not producing the same result anymore. Also, software obsolescence is commonplace, especially since academic software is often not well maintained due to lack of incentives (Merow et al. 2023).

The DevOps (software development and IT operations) community is also confronted with this problem. The issue is usually half-jokingly referred to as “it works on my machine”-problem (Valstar, Griswold, and Porter 2020, a software works on someone’s local machine but is not working anymore when deployed to the production system, indicates the software tacitly depends on the computational environment of the local machine). A partial solution to this problem from the DevOps community is called *containerization*. In essence, to containerize is to develop and deploy the software together with all the libraries and the operating system in an OS-level virtualization environment. In this way, software dependency issues can be resolved inside the isolated virtualized software environment and independent of what is installed on the local computer. Docker is a popular choice in the DevOps world for containerization.

To build a container, one needs to write a plain text declarative description of the required computational environment. Inside this declarative description, it should pin down all four Components mentioned above. For Docker, it is in the form of a plain text file called `Dockerfile`. This `Dockerfile` is then used as the recipe to build a Docker image, where the four Components are assembled. Then, one can launch a container with the built Docker image.

There has been many papers written on how containerization solutions such as Docker can be helpful also to foster computational reproducibility of science (e.g. Nüst and Hinz 2019; Peikert and Brandmaier 2021; Boettiger and Eddelbuettel 2017). Although tutorials are available (e.g. Nüst and Hinz 2019), providing a declarative description of the computational environment in the form of Dockerfile is far from the standard code sharing practice. This might be due to a lack of (DevOps) skills of most scientists to create a Dockerfile (Kim, Poline, and Dumas

¹In this paper, we will focus on R, a popular programming language used frequently in various computational fields (e.g. computational social science, bioinformatics).

2018). But there are many tools available to automate the process (e.g. Nüst and Hinz 2019). The case in point described in this paper, **rang**, is one of them. We argue that **rang** is the only easy-to-use solution available that can pin down and restore all four components without the reliance on any commercial service such as MRAN.

Existing solutions

renv (Ushey 2022) (and its derivatives such as **jetpack** and its predecessor **packrat**) takes a similar approach to Python’s **virtualenv** and Ruby’s **Gem** to pin down the exact version of R packages using a “lock file”. Other solutions such as **checkpoint** (Ooi, de Vries, and Microsoft 2022) depend on the availability of The Microsoft R Application Network (MRAN, a time-stamped daily backup of CRAN), which will be shut down on July 1st, 2023. **groundhog** (Simonsohn and Gruson 2023) used to depend on MRAN but has a plan to switch to their home-grown R package repository. These solution can effectively pin down Component C and D. But they can only restore component D. Also, for solutions depending on MRAN, there is a limit on how far back this reproducibility can go, since MRAN can only go back as far as September 17, 2014. Additionally, it only covers CRAN packages.

containerit (Nüst and Hinz 2019) takes the current state of the computational environment and documents it as a Dockerfile. **containerit** makes the assumption that Component A has a weak influence on computational reproducibility and therefore defaults to Linux-based Rocker images. In this way, it fixes Component A. But **containerit** does not pin down the exact version of R packages. Therefore, it can pin down components A, B, C, but only a part of component D. **dockta** is another containerization solution that can potentially pin down all components due to the fact that MRAN is used. But it also suffers from the same limitations mentioned above.

It is also worth mentioning that MRAN is not the only archival service. Posit also provides a free (*gratis*) time-stamped daily backup of CRAN and Bioconductor (a series of repositories of R package for bioinformatics and computational biology) called Posit Public Package Manager (<https://packagemanager.rstudio.com/client/#/repos/2/packages/>). It can goes as far back as October 10, 2017.

These solutions are better for prospective usage, i.e. using them now to ensure the reproducibility of the current research for future researchers. **rang** mostly targets retrospective usage, i.e. using **rang** to reconstruct historical R computational environments for which the declarative descriptions are not available. One can think of **rang** as an archaeological tool. In this realm, we could not find any existing solution targeting R specifically which does not currently depend on MRAN.

Structure of this paper

In Section 2, we will explain how to use **rang**. In Section 3, **rang** is used to enable the reproducibility of published literature (with increasing sophistication). However, one can still use **rang** for prospective usage and arguably can ensure a longer term computational reproducibility than other solutions. In Section 4, **rang** is used to create an executable research compendium with Docker and Make (Baker 2020).

Basic usage

There are two important functions of **rang**: **resolve()** and **dockerize()**.

resolve() queries various web services from the r-hub project of the R Consortium for information about R packages at a specific time point that is necessary for reconstructing a computational environment, e.g. (deep) dependencies (Component D), R version (Component C), and system requirements (Component B). For instance, if there was a computational environment constructed on 2020-01-16 (called “snapshot date”) with the several natural language processing R packages, **resolve()** can be used to resolve all the dependencies of these R packages. Currently, **rang** supports CRAN, Bioconductor, GitHub, and local packages.

```
library(rang)
graph <- resolve(pkgs = c("openNLP", "LDavis", "topicmodels", "quanteda"),
                 snapshot_date = "2020-01-16")
graph
```

The resolved result is an S3 object called **rang**. The information contained in a **rang** object can then be used to construct a computational environment in a similar manner as **containerit**, but with the packages and R versions pinned on the snapshot date. Then, the function **dockerize()** is used to generate the **Dockerfile** and other scripts in the **output_dir**.

```
dockerize(graph, output_dir = "docker")
```

For $R \geq 3.1$, the images from the Rocker project are used (Boettiger and Eddelbuettel 2017). For $R < 3.1$ but $\geq 1.3.1$, a custom image based on Debian is used. As of writing, **rang** does not support $R < 1.3.1$, i.e. snapshot date earlier than 2001-08-31 (which is 13 years earlier than all solutions depending on MRAN). There are two features of **dockerize()** that are important for future reproducibility.

1. By default, the container building process downloads source packages from their sources and then compiles them. This step depends on the future availability of R packages on CRAN (which is extremely likely to be the case in the near future, given the continuous

availability since 1997-04-23)², Bioconductor, and Github. However, it is also possible to cache (or archive) the source packages now. The archived R packages can then be used instead during the building process. The significance of this step in terms of long-term computational reproducibility will be discussed in Section 4.

```
dockerize(graph, output_dir = "docker", cache = TRUE)
```

2. It is also possible to install R packages in a separate library during the building process to isolate all these R packages from the main library.

```
dockerize(graph, output_dir = "docker", cache = TRUE,  
          lib = "anotherlibrary")
```

For the sake of completeness, the instructions for building and running the Docker container on Unix-like systems are included here.

```
cd docker  
## might need to sudo  
docker build -t rang .  
## interactive environment  
docker run --rm --name "rangtest" -ti rang
```

Project scanning

The first argument of `resolve()` is processed by a separate function called `as_pkgrefs()`. For interoperability, `rang` supports the “package references” standard³ used also in other packages such as `renv` (Ushey 2022). It is mostly used for converting “shorthands” (e.g. `xml2` and `S4Vectors`) to package references (e.g. `cran::xml2` and `bioc::S4Vectors`).

When `as_pkgrefs()` is applied to a single path of a directory, it scans all relevant files (`DESCRIPTION`, R scripts and R Markdown files) for all R packages used (based on `renv::dependencies()`). How it works is demonstrated in three of the following examples below. But an important caveat is that it can only scan CRAN and Bioconductor packages.

²<https://stat.ethz.ch/pipermail/r-announce/1997/000001.html>

³https://r-lib.github.io/pkgdepends/reference/pkg_refs.html

Case Studies

The following are some examples of how **rang** can be used to make shared, but otherwise unexecutable, R code runnable again. The examples were drawn from various fields spanning from political science, psychological science, and bioinformatics.

quanteda JOSS paper

The software paper of the text analysis R package **quanteda** was published on 2018-10-06 (Benoit et al. 2018). In the paper, the following R code snippet is included.

```
library("quanteda")
# construct the feature co-occurrence matrix
examplefcm <-
tokens(data_corpus_irishbudget2010, remove_punct = TRUE) %>%
tokens_tolower() %>%
tokens_remove(stopwords("english"), padding = FALSE) %>%
fcm(context = "window", window = 5, tri = FALSE)
# choose 30 most frequency features
topfeats <- names(topfeatures(examplefcm, 30))
# select the top 30 features only, plot the network
set.seed(100)
textplot_network(fcm_select(examplefcm, topfeats), min_freq = 0.8)
```

On 2023-02-08, this code snippet is not executable with the current version of **quanteda** (3.2.4). It is possible to install the “period appropriate” version of **quanteda** (1.3.4) using **remotes** on the current version of R (4.2.2). And indeed, the above code snippet can still be executed.

```
remotes::install_version("quanteda", version = "1.3.4")
```

The issue is that installing **quanteda** 1.3.4 this way installs the latest dependencies from CRAN. **quanteda** 1.3.4 uses a deprecated (but not yet removed) function of **Matrix** (**as(<dgTMatrix>, "dgCMatrix")**). If this function were removed in the future, the above code snippet would not be executable anymore.

Using **rang**, one can query the version of **quanteda** on 2018-10-06 and create a Docker container with all the “period appropriate” dependencies. Here, the **rstudio** Rocker image is selected.

```
library(rang)
graph <- resolve(pkgs = "quanteda",
                 snapshot_date = "2018-10-06",
```

```
os = "ubuntu-18.04")
dockerize(graph, output_dir = "quanteda_docker",
image = "rstudio")
```

The above code snippet can be executed with the generated container without any problem (Figure 1).

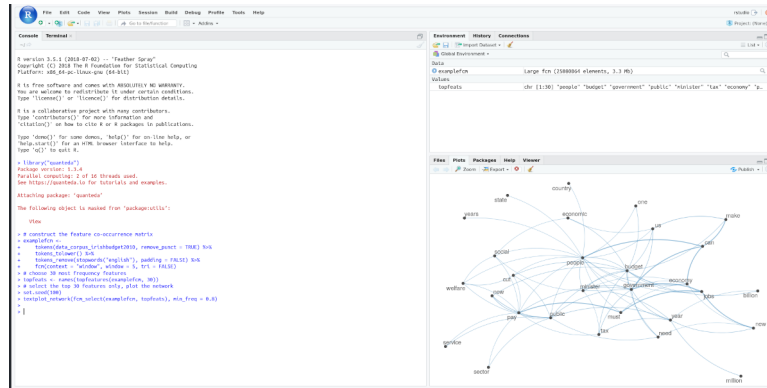


Figure 1: The code snippet running in a R 3.5.1 container created with rang

Psychological Science

Crüwell et al. (2023) evaluate the computational reproducibility of 14 articles published in *Psychological Science*. Among these articles, the paper by Hilgard et al. (2019) has been rated as having “package dependency issues”.

All data and computer code are available from GitHub with the last commit on 2019-01-17⁴. The R code contains a list of R packages used in the project as `library()` statements, including an R package on GitHub that is written by the main author of that paper. However, we identified one package (`compute.es`) that was not written in those `library()` statements but used with the namespace operator, i.e. `compute.es::tes()`. This undocumented package can be detected by `renv::dependencies()`, which is the provider of the scanning function of `rang`.

Based on the above information, one can run `resolve()` to obtain the dependency graph of all R packages on 2019-01-17.

```
## scan all packages
r_pkgs <- as_pkgrefs("vvg-2d4d")
## replace cran:hilgard with Github
```

⁴<https://github.com/Joe-Hilgard/vvg-2d4d>

```
r_pkgs[r_pkgs == "cran::hilgard"] <- "Joe-Hilgard/hilgard"
graph <- resolve(r_pkgs, snapshot_date = "2019-01-17")
```

When running `dockerize()`, one can take advantage of the `materials_dir` parameter to transfer the shared materials from Hilgard et al. (2019) into the Docker image.

```
dockerize(graph, "hilgard", materials_dir = "vvg-2d4d", cache = TRUE)
```

We then built the Docker and launch a Docker container. For this container, we changed the entry point from R to bash so that the container goes to the Linux command shell instead.

```
cd hilgard
docker build -t hilgard .
docker run --rm --name "hilgardcontainer" --entrypoint bash -ti hilgard
```

Inside the container, the materials are located in the `materials` directory. We used the following shell script to test the reproducibility of all R scripts.

```
cd materials
rfiles=(0_data_aggregation.R 1_data_cleaning.R 2_analysis.R 3_plotting.R)
for i in ${rfiles[@]}
do
  Rscript $i
  code=$?
  if [ $code != 0 ]
  then
    exit 1
  fi
done
```

All R scripts ran fine inside the container and the figures generated are the same as the ones in Hilgard et al. (2019).

Political Analysis

The study by Trisovic et al. (2022) evaluates the reproducibility of R scripts shared on Data-verse. They found that 75% of R scripts cannot be successfully executed. Among these failed R scripts is an R script shared by Beck (2019).

This R script has been “rescued” by the author of the R package **groundhog** (Simonsohn and Gruson 2023), as demonstrated in a blog post ⁵. We were wondering if **rang** can also be used to “rescue” the concerned R script. The date of the R script, as indicated on Dataverse, is 2018-12-12. This date is used as the snapshot date.

```
## as_pkgrefs is automatically run in this case
graph <- resolve("nathaniel", snapshot_date = "2018-12-12")
dockerize(graph, output_dir = "nat", materials_dir = "nathaniel")

cd nat
docker build -t nat .
docker run --rm --name "natcontainer" --entrypoint bash -ti nat
```

Inside the container

```
cd materials
Rscript fn_5.R
```

The same file can thus also be “rescued” by **rang**.

Recover a removed R package: **maxent**

The R package **maxent** introduces a machine learning algorithm with a small memory footprint and was available on CRAN until 2019. A software paper was published by the original authors in 2012 (Jurka 2012). The R package was also used in some subsequent automated content analytic papers (e.g. Lörcher and Taddicken 2017). Despite the covert editing of the package by a staffer of CRAN ⁶, the package was removed from CRAN in 2019 ⁷. We attempted to install the second last (the original submitted version) and last (with covert editing) versions of **maxent** on R 4.2.2. Both of them didn’t work.

Using **rang**, we are able to reconstruct a computational environment with R 2.15.0 (2012-03-30) to run all code snippets published in Jurka (2012) ⁸. For removed CRAN packages, we strongly recommend querying the Github read-only mirror of CRAN instead (<https://github.com/cran>). It is because in this way, the resolved system requirements have a higher chance of being correct.

⁵<http://datacolada.org/100>

⁶<https://github.com/cran/maxent/commit/9d46c6aad27a1f41a78907b170ddd9a586192be9>

⁷https://cran-archive.r-project.org/web/checks/2019/2019-03-05_check_results_maxent.html

⁸On an interesting historical side note: The original paper reported —based on a benchmark— that “the algorithm is very fast; **maxent** uses only 135.4 megabytes of RAM and finishes in 53.3 seconds.” On a modest computer in 2023 with a dockerized R 2.15.0, the benchmark finishes in 4 seconds.

```
maxent <- resolve("cran/maxent", "2012-06-10")
dockerize(maxent, "maxentdir", cache = TRUE)
```

Recover a removed R package: `ptproc`

The software paper of the R package `ptproc` was published in 2003 and introduced multidimensional point process models (Peng 2003). But the package has been removed from CRAN for over a decade (at least). The only release on CRAN was on 2002-10-10. The package is still listed in the “Handling and Analyzing Spatio-Temporal Data” CRAN Task View ⁹ despite being uninstallable without modification on any modern R system (see below). As of writing, the package, as a tarball file (tar.gz), is still downloadable from the original author’s website ¹⁰.

Even with this over-a-decade removal and new packages with similar functionalities have been created, there is evidence that `ptproc` is still being sought for. As late as 2017, there are blog posts on how to install the long obsolete package on modern versions of R ¹¹. The package is extremely challenging to install on a modern R system because the package was written before the introduction of name space management in R 1.7.0 (Tierney 2003). In other words, the available tarball file from the original author’s website does not contain a `NAMESPACE` file as all other modern R packages do.

The oldest version of R that `rang` can support, as of writing, is R 1.3.1. `rang` is probably the only solution available that can support the 1.x series of R (i.e. before 2004-10-04). Similar to the case of `maxent` above, a Dockerfile to assemble a Docker image with `ptproc` installed can be generated with two lines of code.

```
graph <- resolve("ptproc", snapshot_date = "2004-07-01")
dockerize(graph, "~/dev/misc/ptproc", cache = TRUE)
```

Suppose we have an R script, extracted from Peng (2003), called “peng.R” like this:

```
require(ptproc)

set.seed(1000)
x <- cbind(runif(100), runif(100), runif(100))
hPois.cond.int <- function(params, eval.pts, pts = NULL, data = NULL, TT = NULL) {
  mu <- params[1]
```

⁹<https://cran.r-project.org/web/views/SpatioTemporal.html>

¹⁰<https://www.biostat.jhsph.edu/~rpeng/software/>

¹¹<https://blog.mathandpencil.com/installing-ptproc-on-osx> and <https://tomaxent.com/2017/03/16/Installing-ptproc-on-Ubuntu-16-04-LTS/>

```

    if(is.null(TT))
      rep(mu, nrow(eval.pts))
    else {
      vol <- prod(apply(TT, 2, diff))
      mu * vol
    }
  }
}
ppm <- ptproc(pts = x, cond.int = hPois.cond.int, params = 50,
              ranges = cbind(c(0,1), c(0,1), c(0,1)))
fit <- ptproc.fit(ppm, optim.control = list(trace = 2), method = "BFGS")
summary(fit)

```

One can integrate **rang** into a BASH script to completely automate the batch execution of the above R script.

```

Rscript -e "require(rang); dockerize(resolve('ptproc', '2004-07-01'),
'pengdocker', cache = TRUE)"
docker build -t pengimg ./pengdocker
## launching a container in daemon mode -d
docker run -d --rm --name "pengcontainer" -ti pengimg
docker cp peng.R pengcontainer:/peng.R
docker exec pengcontainer R CMD BATCH peng.R
docker exec pengcontainer cat peng.Rout
docker cp pengcontainer:/peng.Rout peng.Rout
docker stop pengcontainer

```

The file **peng.Rout** contains the execution results of the script from inside the Docker container. As the random seed was preserved by the original author (Peng 2003), the above BASH script can perfectly reproduce the analysis ¹².

Recover a removed Bioconductor package

Similar to CRAN, packages can also be removed over time from Bioconductor. The Bioconductor package **Sushi** has been deprecated by the original authors and is removed from Bioconductor version 3.16 (2022-11-02). **Sushi** is a data visualization tool for genomic data and was used in many online tutorials and scientific papers, including the original paper announcing the package by the original authors (Phanstiel et al. 2014).

¹²It is also important to note that the random number generator (RNG) of R has been changed several times over the course of the development. In this case, we are using the same generation of RNG as Peng (2003).

`rang` has native support for Bioconductor packages since version 0.2. We obtained the R script "PaperFigure.R" from the Github repository of Sushi ¹³, which generates the figure in Phanstiel et al. (2014). Similar to the above case of `ptproc`, we made a completely automated BASH script to run "PaperFigure.R" and get the generated figure out of the container (Figure 2). We made no modification to "PaperFigure.R".

```
Rscript -e "require(rang); dockerize(resolve('Sushi', '2014-06-05'),
'sushidocker', no_rocker = TRUE, cache = TRUE)"
docker build -t sushiimg ./sushidocker
docker run -d --rm --name "sushicontainer" -ti sushiimg
docker cp PaperFigure.R sushicontainer:/PaperFigure.R
docker exec sushicontainer mkdir vignettes
docker exec sushicontainer R CMD BATCH PaperFigure.R
docker cp sushicontainer:/vignettes/Figure_1.pdf sushi_figure1.pdf
docker stop sushicontainer
```

Preparing research compendia with long-term computational reproducibility

The above six examples show how powerful `rang` is to reconstruct tricky computational environments which have not been completely declared in the literature. Although we position `rang` mostly as an archaeological tool, we think that `rang` can also be used to prepare research compendia of current research. We can't predict the future but research compendia generated by `rang` would probably have long-term computational reproducibility.

To demonstrate this point, we took the recent paper by Oser et al. (2022). This paper was selected because 1) the paper was published in *Political Communication*, a high impact journal that awards Open Science Badges; 2) shared data and R code are available; and most importantly, 3) the shared R code is well-written. In the repository of this paper, we based on the materials shared by Oser et al. (2022) and prepared a research compendium that should have long-term computational reproducibility. The research compendium is similar to the Executable Compendium suggested by the Turing way.

The preparation of the research compendium is easy as `rang` can scan a materials directory for all R packages used ¹⁴.

¹³<https://github.com/PhanstielLab/Sushi/blob/master/vignettes/PaperFigure.R>

¹⁴We detected a minor issue in the code base that an undeclared Github package is used. But it can be easily solved, as in the Psychological Science example above.

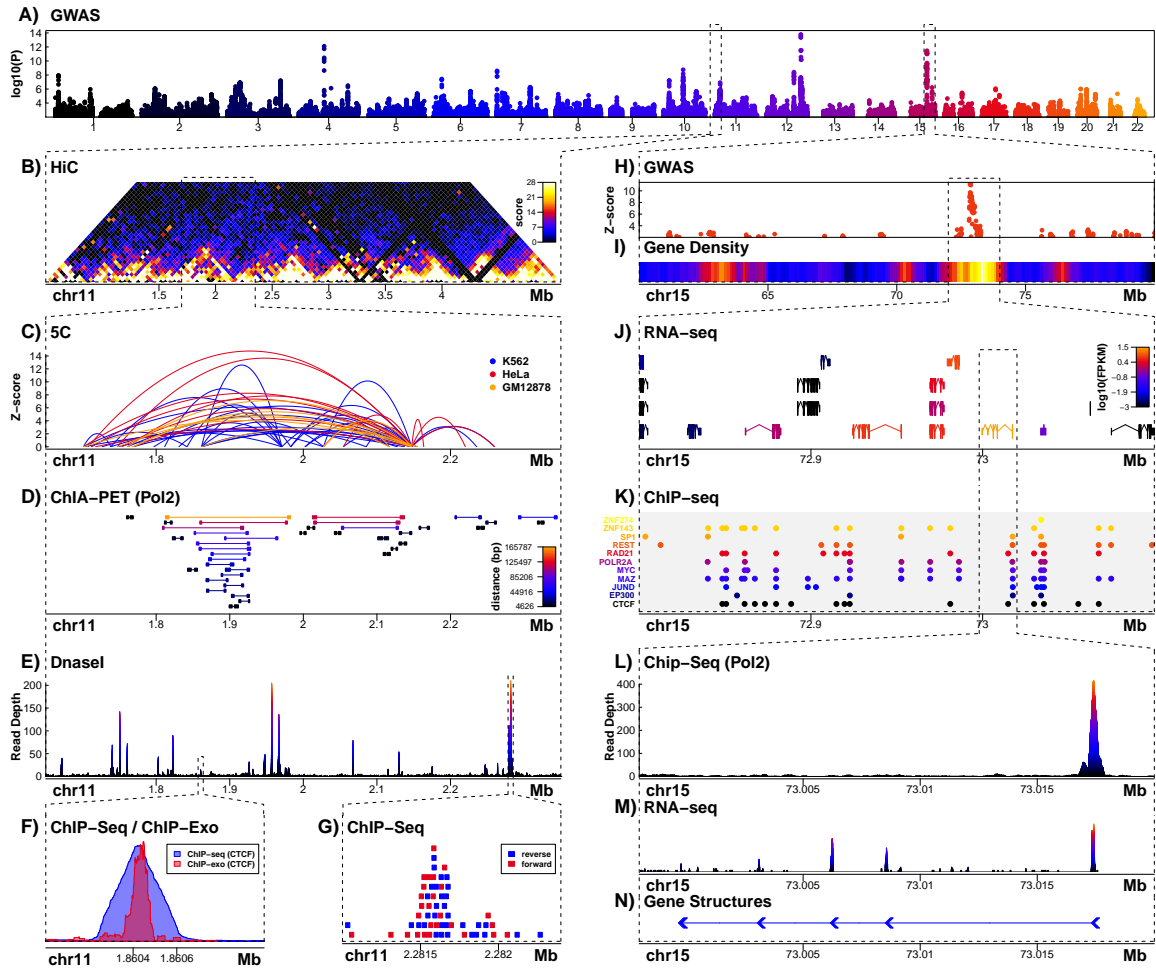


Figure 2: The figure from the batch execution of PaperFigure.R inside a Docker container generated by rang

```

require(rang)
## meta-analysis is the directory of all shared materials
cran_pkgs <- as_pkgrefs("meta-analysis")

## dmetar is an undeclared github package: MathiasHarrer/dmetar
cran_pkgs[cran_pkgs == "cran:dmetar"] <- "MathiasHarrer/dmetar"
x <- resolve(cran_pkgs, "2021-08-11", verbose = TRUE)
##print(x, all_pkgs = TRUE)
dockerize(x, "oserdocker", materials_dir = "meta-analysis", cache = TRUE)

```

The above R script is saved as `oser.R`. The central piece of the executable compendium is the Makefile.

```

output_file=reproduced.html
r_cmd = "rmarkdown::render('materials/README.Rmd', output_file = '${output_file}')"
handle=oser
local_file=${handle}_README.html

all: resolve build render
    echo "finished"
resolve:
    Rscript ${handle}.R
build: ${handle}docker
    docker build -t ${handle}img ${handle}docker
render:
    docker run -d --rm --name "${handle}container" -ti ${handle}img
    docker exec ${handle}container Rscript -e ${r_cmd}
    docker cp ${handle}container:/materials/${output_file} ${local_file}
    docker stop ${handle}container
export:
    docker save ${handle}img | gzip > ${handle}img.tar.gz
rebuild: ${handle}img.tar.gz
    docker load < ${handle}img.tar.gz

```

With this Makefile, one can create the Dockerfile with `make resolve`, build the Docker image with `make build`, render the RMarkdown file inside the container with `make render`, export the built Docker image with `make export`, and rebuild the exported Docker image with `make rebuild`.

The structure of the entire executable compendium looks like this:

```
Makefile
oser.R
meta-analysis/
README.md
oserdocker/
osering.tar.gz
```

In this executable compendium, only the first four elements are essential. The directory `oserdocker` (116 MB) contains cached R packages, a Dockerfile, and a verbatim copy of the directory `meta-analysis/` to be transferred into the Docker image. That can be regenerated by running `make resolve`. However, having this directory preserved insures against the situations that some R packages used in the project were no longer available or any of the information providers used by `rang` for resolving the dependency relationships were not available. (Or in the rare circumstance of `rang` is no longer available.)

`osering.tar.gz` (667 MB) is a backup copy of the Docker image. This can be regenerated by running `make export`. Preserving this file insures against all the situations mentioned above, but also the situations of Docker Hub and the software repositories used by the dockerized operating system being not available. When `osering.tar.gz` is available, it is possible to run `make rebuild` and `make render` even without internet access (provided that Docker and `make` have been installed before). Of course, there is still an extremely rare situation where Docker (the program) itself is no longer available ¹⁵. However, it is possible to convert the image file for use on other containerization solutions such as Singularity ¹⁶, if Docker is really not available anymore.

Sharing of research artifacts less than 1G is not as challenging as it used to be. Zenodo, for example, allows the sharing of 50G of files. Therefore, sharing of the last two components of the executable compendium prepared with `rang` is at least possible on Zenodo. However, for data repositories with more restrictions on data size, sharing the executable compendium without the last two parts could be considered sufficient. For that, run `make` will make the default target `all` and generate all the things needed for reproducing the analysis inside a container.

The above `Makefile` is general enough that one can reuse it by just modifying how the R scripts (the `r_cmd` variable) in the `materials` directory are executed. This can be a starting point of a standard executable compendium format.

¹⁵We can't imagine a world without `Make`, a tool that has been available since 1976.

¹⁶https://docs.sylabs.io/guides/3.0/user-guide/singularity_and_docker.html

Concluding remarks

This paper presents **rang**, a solution to (re)construct R computational environments based on Docker. As the six examples in Section 3 show, **rang** can be used archaeologically to rerun old code, many of them not executable without the analytic and reconstruction processes facilitated by **rang**. These retrospective use cases demonstrate how versatile **rang** is. **rang** is also helpful for prospective usage, as demonstrated in Section 4 whereby an executable compendium is created.

There are still many features that we did not mention in this paper. **rang** is built with interoperability in mind. As of writing, **rang** is interoperable with existing R packages such as **renv** and R built-in `sessionInfo()`. Also, the **rang** object can be used for network analysis with R packages such as **igraph**.

Computational reproducibility is a complex topic and as in all of these complex topic, there is no silver bullet (Canon and Younge 2019). All solutions have their trade-offs. The (re)construction process based on **rang** takes notably more time than other solutions because all packages are compiled from source. **rang** trades computational efficiency of this often one-off (re)constructing process for correctness, backward compatibility and independence from any commercial backups of software repositories such as MRAN. There are also other limitations. In the Vignette of **rang** (<https://cran.r-project.org/web/packages/rang/vignettes/faq.html>), we list all of these limitations as well as possible mitigation.

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