An R Autograder for PrairieLearn

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This version was compiled on March 17, 2020

We describe how we both use and extend the PrairieLearn framework by taking advantage of its built-in support for external auto-graders. By using a custom Docker container, we can match our course requirements perfectly. Moreover, by relying on the flexibility of the interface we can customize our Docker container. A specific extension for unit testing is described which creates context-dependent differences between student answers and reference solutions providing a more comprehensive response at test time.

Context

We describe the motivation, design and use of an autograder for the R language within the PrairieLearn system (Zilles \textit{et al.}, 2018). PrairieLearn is in use at the University of Illinois at Urbana-Champaign, where it is also being developed, and other campuses to support fully automated computer-based testing of homework, quizzes and examples for undergraduate and graduate students. We use it to support the topics course \textsc{STAT} 430 “Data Science and Control” at test time.

As documented, PrairieLearn supports external graders, and we are providing one such grader for the R language and system. Our implementation follows \textit{KISS principles}, and is sufficiently safe and robust for deployment. Our approach uses two key insights. First, testing student submissions is close to unit testing code—and we benefit from relying on a very clever, small and nimble test framework package, \texttt{tinytest} (\textit{van der Loo}, 2019). Second, the PrairieLearn decision to allow external graders under a ‘bring your own container’ scheme allows us to regroup all our requirements in a simple Docker container—extending a base container from the Rocker Project (Boettiger and Eddelbuettel, 2017)—we provision and control.

PrairieLearn

PrairieLearn (Zilles \textit{et al.}, 2018) is an online problem-driven learning system for creating homeworks and tests that enables automated code evaluation as well as more traditional question types (like multiple choice questions) for both homework assignments as well as exams. It is built to be flexible, and enables grading to happen however the instructor wishes using Docker. PrairieLearn comes with many easy ways of adding randomization to questions, and a custom set of HTML tags that makes writing questions easy.

Direct PrairieLearn Integration

The integration between different components is designed to be simple and flexible. Data is exchanged by configuration text files in the JSON format (which is discussed below). At its core, this involves only two files (which we describe next) that are made available in the top-level directory of the contributed grader as shown the following listing:

```r
fs::dir_tree("r_autograder")
# r_autograder
# |-- pltest.R
# |-- run.sh
```

\texttt{run.sh}. The first file, \texttt{run.sh}, shown in Appendix 1, is more-or-less unchanged from the \texttt{run.sh} file in the PrairieLearn example course which invokes the file \texttt{pltest.R} discussed next. It sets up a number of environment variables reflecting the PrairieLearn setup. It also copies files in place, adjusts modes (more on that below when we discuss security), calls the evaluation script discussed next, and assembles the result.

\texttt{pltest.R}. The second file is the actual test runner for PrairieLearn under R, and is shown in Appendix 2.

For a given question, essentially three things happen:

\textit{Extract Metadata from Tests}. The displayed title of each available test, and the available points per test, are extracted from the question’s test files themselves. This is performed by the helper function \texttt{plr::get_question_details()} which is given the default test directory used in our layout: "/grade/tests/tests".\(^1\) Our implementation is inspired by the doxygen and roxygen2 tag use for documentation and is most appropriate: metadata for each tests is stored with test. This allows for quick iteration during development as test files can simply be renamed to be deactivated without worrying about conflicting metadata.

\textit{Run the Tests}. The actual test predicates are being run using the \texttt{tinytest} package and its function \texttt{run_test_dir()} traversing a directory (more on that below). The result is then converted into a data.frame object. We discuss the \texttt{tinytest} framework in more detail below.

\textit{Merge and Post-Process}. The two data.frame objects (metadata and test results) are merged using the names of each test file as the key. Then points are calculated and the resulting object is written as a JSON file for PrairieLearn to consume.

Test Framework

\texttt{tinytest} is an appropriately light-weight test framework without further dependencies. As stated in the opening of its vignette:

The purpose of \textit{unit testing} is to check whether a function gives the output you expect, when it is provided with certain input.

This is precisely what checking student answers amounts to. Given the context of a question, students provide code, typically as a function, which we can test given inputs—and compare to a reference answer and its output. Our framework does just that.

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Two of the key insights of \texttt{tinytest} are:

\(^1\)Earlier or alternate approaches use an explicit file \texttt{points.json}; we find it more suitable to define this on the fly given the test files.
Within the testing framework, questions are a key component. In general, each question is organized in its own directory. Questions may then be grouped by directory name for assignments, exams or quizzes comprising a set of such questions.

For each question used in our autograder, the directory layout is as shown in the next figure.

![Directory Structure](image-url)

There are two mandatory top-level files:

First, `info.json` which contains all the relevant data for this question, including course which grader to use. As discussed above, this file controls which of several graders is used.

```json
{
    "uid": "32A968E04-0A4C-497A-91D2-18BC4FE98047",
    "title": "Fibonacci Sequence 2.0",
    "topic": "Functions",
    "tags": ["code", "v3", "barbehe2", "deddel", "balamut2", "stat430dspm", "Fa19", "autograder"],
    "type": "v3",
    "singleVariant": true,
    "gradingMethod": "External",
    "externalGradingOptions": {
        "enabled": true,
        "image": "stat430/pl",
        "serverFilesCourse": ["r_autograder/"]
    },
    "timeout": 5
}
```

We note that this points specifically to

- a top-level directory (such as the one shown above),
- an entry-point script (as discussed above)
- a container to run the evaluations in.

Second, `question.html` which defines the display shown to the student. PrairieLearn now allows for markdown to describe the central part, and can reference external files such as the file `initial_code.R` listed here too. `initial_code.R` provides the stanza of code shown in the Ace editor component (and the file name is specified in `question.html`).

Then, the `tests/` directory contains the test infrastructure. By our convention, `tests/ans.R` is the reference answer. This file is set to mode 0600 to ensure the student code can never read it.

```r
# Reference answer to find nth term in the # Fibonacci sequence using non-recursive methods fib <- function(n) {
  out <- rep(1, n)
  if (n >= 3)
    for (i in 3:n)
      out[i] <- out[i-1] + out[i-2]
  return(out)
}
```

The subdirectory `tests/tests/` then contains one or more `unit` tests or, in our case, question validations. The first question sources the file, evaluates \( F(1) \) and compares to the expected answer, 1. (Other test questions then check for other values as shown below; several test predicates could also be present in a single test file but we are keeping it simple here.)

```r
## @title Test F(1)
## @score 2
defile <- "/grade/student/fib.R"
v <- plr::source_and_eval_safe(file, fib(1), "ag")
expect_equal(v, 1)
```

Of note is our use of a function from the helper package `plr` (Eddelbuettel and Barbehenn, 2019a). As the same code fragment would be repeated across numerous question files, it makes sense to regroup this code in a (simple) function. At its core are the `system()` call, made as the autograde user `ag`, and the subsequent evaluation of the supplied expression. We take full advantage of the lazy evaluation that makes R so powerful: `fib(1)` is not evaluated by the caller but rather in the context of the caller—after sourcing the corresponding file. We also make the file to sourced visible to the ag user. All other files remain inaccessible thanks for their mode of 0600.

Another key aspect is the use of `eval_safe()` from the `unix` package (Ooms, 2019b). As we are effectively running as root inside a container, we have the ability to lower to permission to those of another user, here `ag`.

```r
## roxygen2 documentation omitted here, see repo source_and_eval_safe <- function(file, expr, 
   uid=NULL) {
  if (!is.null(uid) &&
    class(uid) == "character")
    uid <- unix::user_info(uid)$uid
  if (!file.exists(file)) return(invisible(NULL))
  oldmode <- file.mode(file)
  Sys.chmod(file, mode="0664")
  invisible(system("source_and_eval_safe", file, expr))
  rwsyscall("chmod", oldmode, file)
}
```
source(file)

res <- unix::eval_safe(expr, uid=uid)
Sys.chmod(file, mode=oldmode)
res
}

We omit the second question which is largely identical to the first, but tests \( F(2) \) for the expected answer of \((1,1)\).

The third file uses randomization to prevent students from hardcoding an answer to \( F(n) \) for a given knowable value \( n \).

```r
# @title Test F(n) for random n
# @score 2

library(tinytest)
using(ttdo)

n <- sample(3:20, 1)

file <- "/grade/student/fib.R"
student <- plr::source_and_eval_safe(file, fib(n), "ag")

source("/grade/tests/ans.R")
correct <- fib(n)

expect_equivalent_with_diff(student, correct)
```

It also shows another key feature: our use of the `diffobj` package. We use a very small add-on package `ttdo` (an acronym for ‘tinytest-diffobj’) we created utilizing the extensions mechanism of `tinytest` in order to provide more specific feedback in the test results. The `ttdo` package is separate from our `plr` package because of its potential use in contexts other than PrairieLearn.

Figure 1 shows a screenshot resulting from providing an answer that returns a content of 1 no matter the input. This passes \( F(1) \), fails \( F(2) \) and fails \( F(n) \) for \( n >= 3 \). The screenshot displays the effect of the colorized difference between the received answer and the expected answer for the latter two questions.

**Container**

PrairieLearn allows for external containers. We use this feature to deploy a custom container based on the `r-ubuntu` container from the Rocker Project (Boettiger and Eddelbuettel, 2017). This container is setup with access to the “Personal Package Archive” (PPA) by Michel Rutter which provides a considerable subset of the tinytest-diffobj package we created utilizing the extensions mechanism (when compared to bespoke custom solutions not relying on more widely-used components).

Similarly, by relying on widely-used and tested components such as the Rocker Project containers as a base, along with provided Ubuntu binaries, the risk of inadvertent breakage is minimized as well (when compared to bespoke custom solutions not relying on more widely-used components).

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2 See the brief description at the top of https://CRAN.R-Project.org/bin/linux/ubuntu for more details.

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**Security Aspects**

R is a very flexible language that is somewhat difficult to sandbox as it allows computation on the language. Some approaches do exist—the RAppArmor package (Ooms, 2019a) wraps around one of the two prevalent approaches for Linux is a candidate given that we match the installation requirements by being on Debian/Ubuntu systems.

Here, however, we opted for a more basic approach. All files copied in by `run.sh` are set to be owned by the root user with no read, write or execution rights set for groups or others. The one exception is the uploaded file containing the to-be-evaluated student code. This file is then `source()`-ed in a lower-priority process owned by the autograde user `ag`, and the supplied function is evaluated with a given argument. We use the `unix` package (Ooms, 2019b) for this, taking advantage of the fact that inside a container we are running as the superuser permitting us to lower permissions. In other words, the one execution that could expose secrets (of the untrusted code submitted by the student) is the one running with the lowest possible permissions of the `ag` user with all other files being “locked-away” and readable only by the root user.

Concretely, our function `plr::source_and_eval_safe()` shown above relies on the function `unix::eval_safe()` which takes care of the (system-specific) details of process permission control. In addition, we also minimize file permission changes. A sibbling function `plr::eval_safe_as()` works similarly on an R expression rather than file.

**Summary**

The PrairieLearn system (Zilles et al., 2018) permits large-scale and automated testing and grading of quizzes, exercises and tests as used in university educated. It is designed as an open and extensible system.

We have created a custom autograding container for the R language to both take advantage of the excellent PrairieLearn system,
and extends its facilities by using a unit testing framework which allows for further customization. Our plr package (Eddelbuettel and Barbehenn, 2019a) for R autograding with PrairieLearn deploys the tinytest system (van der Loo, 2019) for unit testing. It also extends it via the ttdo package (Eddelbuettel and Barbehenn, 2019b) which permits the creation of highly-informative diff objects produced by the diffobj package (Gaslam, 2019) which can be deployed directly in the dataflow based on JSON objects used by PrairieLearn.

References
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Zilles C, West M, Mussulman D, Bretl T (2018). “Making testing less trying: Lessons learned from operating a computer-based testing facility.” In Proceedings of the 2018 Frontiers in Education Conference (FIE 2018). URL http://lagrange.mechse.illinois.edu/pubs/ZiWeMuBr2018/ZiWeMuBr2018.pdf.
Appendix 1: run.sh.

```bash
#!/bin/bash

#### INIT

# the directory where the file pertaining to the job are mounted
JOB_DIR="/grade/

# the other directories inside it
STUDENT_DIR="${JOB_DIR}student/
AG_DIR="${JOB_DIR}serverFilesCourse/r_autograder/
TEST_DIR="${JOB_DIR}tests/
OUT_DIR="${JOB_DIR}results/

# where we will copy everything
MERGE_DIR="${JOB_DIR}run/

# where we will put the actual student code - this depends on what the autograder expects, etc
BIN_DIR="${MERGE_DIR}bin/"

## now set up the stuff so that our run.sh can work
echo "[init] making directories"
mkdir ${MERGE_DIR} ${BIN_DIR} ${OUT_DIR}

## making the test directory root:root and stripping group and others
## this will prevent the restricted user from snooping
chown -R root:root ${TEST_DIR}
chmod -R go-rwx ${TEST_DIR}

## under 'tinytest' artefacts are created where the tests are running
## so let the 'ag' user own the directory to write files, run mkdir, ...

# [init] setting up tests directory for 'ag' user
chown ag:ag ${TEST_DIR} tests

echo "[init] copying content"
cp ${STUDENT_DIR}* ${BIN_DIR}
cp ${AG_DIR}* ${MERGE_DIR}
cp -r ${TEST_DIR}* ${MERGE_DIR}
chown ag:ag ${MERGE_DIR} tests

#### RUN

cd ${MERGE_DIR}

# we evaluate student code inside the test functions as a limited user called ag
# see the R package plr in the stat430dspm repo for details of the implementation

echo "[run] starting autograder"

Rscript pltest.R

if [ ! -s results.json ]; then
    # Let's attempt to keep everything from dying completely
    echo -n '{"succeeded": false, "score": 0.0, "message": "Catastrophic failure! ' > results.json
    echo 'Contact course staff and have them check the logs for this submission."}' >> results.json
fi

echo "[run] autograder completed"

# get the results from the file
cp ${MERGE_DIR}/results.json '/grade/results/results.json'
echo "[run] copied results"
```
Appendix 2: pltest.R

## Simple-yet-good enough runner for R questions
## Alton Barbehenn and Dirk Eddelbuettel, Aug/Sep 2019

message_to_test_result <- function(msg, mxpts=100) {
  data.frame(
    name = "Error",
    max_points = mxpts,
    points = 0,
    output = msg$message
  )
}

result <- tryCatch({
  ## Set seed for control over randomness (change every day)
  set.seed(as.integer(Sys.Date()))

  ## Directory with test files
  tests_dir <- "/grade/tests/tests"

  ## Get question information on available points and displayed title
  question_details <- plr::get_question_details(tests_dir)

  ## Run tests in the test directory
  cat("[pltest] about to call tests from", getwd(), 
       "\n")
  test_results <- as.data.frame(tinytest::run_test_dir(tests_dir, verbose = FALSE))

  ## Aggregate test results and process NAs as some question may have exited
  res <- merge(test_results, question_details, by = "file", all = TRUE)
  ## Correct answers get full points, other get nothing
  res$points <- ifelse(!is.na(res$result) & res$result==TRUE, res$max_points, 0)
  ## For false answers we collate call and diff output (from diffobj::diffPrint)
  res$output <- ifelse(!is.na(res$result) & res$result==FALSE,
                        paste(res$call, res$diff, sep = "\n"), "")

  score <- sum(res$points) / sum(res$max_points)  # total score

  ## Columns needed by PL
  res <- res[, c("name", "max_points", "points", "output")]

  ## output
  list(tests = res, score = score, succeeded = TRUE)
},
  warning = function(w) list(tests = message_to_test_result(w), score = 0, succeeded = FALSE),
  error = function(e) list(tests = message_to_test_result(e), score = 0, succeeded = FALSE) 
)

## Record results as the required JSON object
jsonlite::write_json(result, path = "results.json", auto_unbox = TRUE, force = TRUE)
Appendix 3: Dockerfile for stat430/pl container.

# Image used for PrairieLearn external grading of R questions
# as well as general support of STAT 430 Data Science Programming Methods

# Alton Barbehenn and Dirk Eddelbuettel, 2019

# Before we based our image on prairielearn/centos7-python,
# and that worked, but it was harder to maintain and a lot
# than we needed. Now we're using rocker/tidyverse as our
# base because it's more focused and solves the prerequisites
# for us, along with providing many useful R packages.

FROM rocker/r-ubuntu:18.04

# From prairielearn/centos7-python: Needed to properly handle UTF-8
ENV PYTHONIOENCODING=UTF-8

# Install required libraries -- using prebuild binaries where available
RUN apt-get update
&&
apt-get install -y

  git \\
  r-cran-data.table \\
  r-cran-devtools \\
  r-cran-doparallel \\
  r-cran-dygraphs \\
  r-cran-foreach \\
  r-cran-fs \\
  r-cran-future.apply \\
  r-cran-gh \\
  r-cran-git2r \\
  r-cran-igraph \\
  r-cran-memoise \\
  r-cran-microbenchmark \\
  r-cran-png \\
  r-cran-rcpparmadillo \\
  r-cran-rex \\
  r-cran-rsqlite \\
  r-cran-runif \\
  r-cran-shiny \\
  r-cran-stringdist \\
  r-cran-testthat \\
  r-cran-tidyverse \\
  r-cran-tinytest \\
  r-cran-xts \\
  sqlite3 \\
sudo

# Install additional R packages from CRAN (on top of the ones pre-built as r-cran-*)
RUN install.r bench diffobj flexdashboard lintr ttdo unix

# Install plr -- for now (?) from GH; also install visualTest
RUN installGitHub.r stat430dspm/plr MangoTheCat/visualTest

RUN useradd ag \\
  && mkdir /home/ag \\
  && chown ag:/home/ag \\
  && echo "[user]" > /home/ag/.gitconfig \\
  && echo " name = Autograding User" >> /home/ag/.gitconfig \\
  && echo " email = ag@nowhere" >> /home/ag/.gitconfig \\
  && chown ag:/home/ag/.gitconfig