Pre-compiled binary packages provide a convenient way of efficiently distributing software that has been adopted by most Linux package management systems. However, the heterogeneity of the Linux ecosystem, combined with the growing number of R extensions available, poses a scalability problem. As a result, efforts to bring binary R packages to Linux have been scattered, and lack a proper mechanism to fully integrate them with R's package manager. This work reviews past and present of binary distribution for Linux, and presents a path forward by showcasing the ‘cran2copr’ project, an RPM-based proof-of-concept implementation of an automated scalable binary distribution system with the capability of building, maintaining and distributing thousands of packages, while providing a portable and extensible bridge to the system package manager.

1 Introduction

R has become an essential tool, language, and environment for working with data. One of the reasons for its success can be attributed to the Comprehensive R Archive Network (CRAN), a network of mirrored sites (Fox, 2009). It offers (at present) over 17,000 packages in a way that ensures quality, interoperability, and, last but not least, installability. R has also gone to great length to abstract away the notion of the underlying operating system (OS). While users on a particular OS may stress minor idiosyncratic aspects of the user interface (such as clipboard copying between applications), both R code and how users operate with R is essentially entirely portable between systems.

Among the aforementioned 17,000 add-on packages extending R, one particular commonality is the use of compiled code. This has several advantages such as better performance for heavy computations as well as possibly a tighter integration via the internals of R, but also direct access to a wide variety of system and application libraries. To this end, R provides official interfaces to Fortran, Java and C, and thus effectively to any compiled language that can generate a C interface, such as C++, Rust or Go. Currently, more than 24% of CRAN packages use compiled code, and another 57% have at least one hard dependency (Depends or Imports) that uses compiled code. In other words, if we install a random package from CRAN, we have about a 81% chance of requiring compilation, directly or indirectly. Moreover, as Fig. 1 suggests, packages requiring direct compilation are much more common among the most widely used packages: up to 50% of the most popular packages (according to the number of downloads) directly use compiled code.

It should be noted that these performance advantages that make the package attractive to the developer (and of course also to its users) may come at a “hidden” yet high cost for the users. Installation of R packages from source becomes more expensive (both in terms of time and computational resources), and requires an appropriate toolchain to be installed. Traditionally, Linux distributions have taken proper care of this second aspect by providing a sufficient set of tools via the system package manager, while Windows and macOS systems require extra steps and add-ons. The availability of a single and relatively stable toolchain and system libraries allowed CRAN to build the necessary infrastructure to distribute binary packages for these systems, easing the burden on a large portion of the user base. On the other hand, CRAN never provided Linux binaries (except for some early experimental builds for Debian), likely due to the fragmentation of Linux distributions leading to a smaller market share, combined with the fact that Linux users have historically been regarded as “power” users. As a consequence, Linux users likely continue to spend considerable time and CPU cycles on source installations.

Acknowledging that hard numbers are difficult to come by, anecdotal evidence suggests that, still nowadays, the majority of users deploy R—and write packages for R—on either Windows
Figure 1: Percentage of packages that require direct or indirect compilation by popularity, measured by percentile of downloads from RStudio’s CRAN logs for January 2021.

or macOS (Stack Overflow, 2020). On the other hand, the Linux OS is very widely deployed on “cloud” computing instances. And although Windows and macOS are gaining better support on new continuous integration and deployment (CI/CD) platforms, Linux proliferated sooner and faster, in part thanks to its early support for OS-level virtualization (i.e., container technologies such as Docker). It can then be argued that portability and the widespread adoption of CI services had a hand in an almost invisible usage increase on operating systems on which users may not be working directly. As a result, we can conclude that binary distribution for Linux would benefit a substantial portion of both package installations and users that are not necessarily accustomed to this platform. Although binary distribution is necessarily tied to a specific toolchain—therefore imposing specific settings that might not be according to the user’s preference—it greatly helps data scientists in getting whole groups of packages (such as the \textit{tidyverse}, or the geospatial stack) quickly deployed in their systems.

2 Past and present

Binary package distribution faces a number of challenges. Here, we identify and discuss four of them from the Linux perspective: OS support, dependency management, scalability and integration.

OS support Cross-distribution incompatibilities can be a major source of concern for binary packages. In the Linux ecosystem, this issue becomes more dramatic as the matrix of possible configurations grows: there are several families of distributions, supported by different package binary formats; different distributions per family, with different philosophies about naming conventions and update cycles; and, finally, there are several supported versions per distribution at any given time too.

Dependency management Once a package has been successfully built, it must be distributed along with the same set of dependencies used for the build process. This is not limited to other R packages, but it is particularly important for code that links against external libraries and interfaces. No portable solution for providing or querying system dependencies reliably exists. Static linking and embedded libraries are popular ways to overcome both OS support and dependency management issues, especially since the development of packaging technologies such as Flatpak (Flatpak Community, 2021), Snap (Snap Team, 2021) or AppImage (AppImage Community, 2021). However, these techniques may be better suited for monolithic
graphical applications, rather than for complex projects such as the R ecosystem with its built-in extension mechanism.

**Scalability** CRAN has experimented an impressive growth over its lifetime (Fox and Leanage, 2016). Building and distributing binary packages at scale means handling the enormous complexity of versions and dependencies in an automated way for thousands of packages.

**Integration** CRAN’s integrated support for Windows and macOS binaries entails a friendly experience for the user, who can install thousands of packages from the R command line using the built-in `install.packages`. On Linux, however, package management has a different model in which specialized system tools require administrative privileges and maintain the integrity of the software stack.

CRAN itself hosted at least some Linux binaries at its very beginning (Hornik, 1997). Since then, most Linux distributions provide at least the R system and interpreter in their official repositories, and may also maintain various subsets of add-on packages. This task is extremely time-consuming for maintainers, because it typically requires a per-package peer-review for the initial inclusion, and then the application of a stringent set of policies and standards. Consequently, these subsets are commonly very limited, and package versions tend to lag behind.

In order to improve upon official repositories, several projects have over time tried to tackle these challenges with varying degrees of success. A short list of these attempts follows.

**cran2deb (take one)** Albrecht Gebhard wrote a first fully automated conversion of CRAN packages into Debian binaries using Perl in the early 2000s, which lead to subsequent work summarised in a useR! presentation (Eddelbuettel et al., 2007).

**cran2deb (take two)** Charles Blundell, as a Google Summer of Code student and during a subsequent academic year, rewrote this in R with a SQL backend, which one of us later ran for a while peaking at around 6k or 7k CRAN packages—until it sadly broke while being presented at CRAN headquarters in Vienna (Eddelbuettel and Blundell, 2009).

**debian-r** Don Armstrong had a parallel setup during his PhD studies with up to 10k packages, but then the RAID system broke (Armstrong, 2015).

**c2d4u** During this time, Michael Rutter has (essentially singlehandedly) grown a ‘cran2deb’ offshoot on Ubuntu and its Launchpad build and hosting system to about 4.7k packages across three releases (Rutter, 2011, 2021).

**CRAN2OBS** Independently of the work described here, a parallel (and long-running) effort has focused on an automated system for turning CRAN packages into RPM binaries for the SUSE Linux distribution at scale, with an impressive CRAN coverage of over 16k packages as of August 2021 (Steuer, 2020). This initiative demonstrates the capabilities of the openSUSE Build Service (OBS) (OBS Team, 2021), which is designed to be cross-distribution. Hence, the successful demonstration of the use of the OBS opens the door for future work which may consolidate efforts and result in a unified service relying on a pan-distribution build service.

All these distribution-based solutions, either via official or contributed repositories, inherently provide dependency management as well as a tight integration with the OS. Another collateral advantage of using system repositories is that package installations are shared across users, so it is easier for a system administrator to maintain a consistent and updated stack of packages. However, although ‘cran2deb’ and ‘CRAN2OBS’ constitute a step forward towards scalable distribution, the lack of integration constitutes a major drawback, especially for casual Linux users.

Although the need for better integration of (binary) package installations directly from R was also expressed occasionally (Gil Bellosta, 2010), it was not until recently when new projects started to focus on this challenge. Particularly, RStudio’s Public Package Manager (RStudio, 2020), based on the proprietary product RSPM (RStudio Package Manager), stands out as the most comprehensive solution to date. RSPM works by providing a drop-in replacement for CRAN mirrors that serves Linux users pre-compiled packages via `install.packages` (when available) with impressive breadth of cross-platform coverage, yet no (formal) dependency support. Thus, the Linux community benefits—under RStudio’s terms of use—from binary installations of CRAN packages, but many of such installations may be fragile and break unless the user installs the required system dependencies in a second (manual) step. And although RSPM alleviates the task of discovering such dependencies for each supported distribution via a dedicated (yet heuristic) database, the process of installing system dependencies involves administrative rights and still remains a separate workflow outside R, which ultimately hinders full integration.
Table 1: Main challenges of binary package distribution and degree of achievement for different projects. A checkmark denotes fulfillment, while a bullet indicates partial fulfillment.

| Official repos  | cran2deb | CRAN2OBS | RSPM | cran2copr |
|-----------------|----------|----------|------|-----------|
| OS support      | •        | •        | ✓    | ✓         | ●        |
| Dependencies    | ✓        | ✓        | ✓    | ✓         |          |
| Scalability     | ●        | ✓        | ✓    | ✓         |          |
| Integration     |          | ●        | ✓    | ✓         | ✓        |

3 cran2copr: RPM distribution of CRAN packages at scale

In this context, the ‘cran2copr’ project (Ucar, 2020a) was created as an initiative under the umbrella of the Fedora Project that aims at distributing all packages on CRAN via a separate RPM repository (Ucar, 2020c), with full dependency management, automatic daily synchronization and seamless integration with the R console. It consists of a Copr project for building and distributing packages; the CoprManager package for the integration, and standalone R tooling around the Copr API for automation. Building on the experience of previous projects, ‘cran2copr’ shares the advantages of distribution-based solutions and solves the remaining major challenges of binary distribution for Linux: scalability and integration (see Table 1 for a comparison).

3.1 A primer

This section briefly demonstrates the user workflow. The following commands enable the project’s Copr repository, and install the CoprManager utility on Fedora 32:

```bash
$ sudo dnf install 'dnf-command(copr)'
$ sudo dnf copr enable iucar/cran
$ sudo dnf install R-CoprManager
```

From this point on, no further administrative tasks are required. Package installations are carried out through R’s standard `install.packages` function, which transparently delegates in the system package manager. In the event that a certain R package is not available in the Copr repository, CoprManager also provides an automatic fallback mechanism, and `install.packages` continues the installation directly from CRAN.

This is how the installation looks like for a package included in the project (`units`) and another that is currently not (`gifski`). As can be seen, the request for `units` is transparently intercepted and installed in binary form from the Copr repository, including its system dependencies; `gifski`, on the other hand, is pulled directly from CRAN in standard source form.

```
install.packages(c("gifski", "units"))
```

```bash
#> Installing packages as root...
#> (1/3): R-CRAN-units-0.6.7-3.fc32.x86_64.rpm 5.2 MB/s | 787 kB 00:00
#> (2/3): R-CRAN-Rcpp-1.0.5-2.fc32.x86_64.rpm 2.0 MB/s | 2.0 MB 00:00
#> (3/3): udunits2-2.2.26-6.fc32.x86_64.rpm 420 kB/s | 617 kB 00:01
#> Preparing         : 1/1
#> Installing        : udunits2-2.2.26-6.fc32.x86_64 1/3
#> Installing        : R-CRAN-Rcpp-1.0.5-2.fc32.x86_64 2/3
#> Installing        : R-CRAN-units-0.6.7-3.fc32.x86_64 3/3
#> Running scriptlet: R-CRAN-units-0.6.7-3.fc32.x86_64 3/3
#> Verifying         : R-CRAN-Rcpp-1.0.5-2.fc32.x86_64 1/3
#> Verifying         : R-CRAN-units-0.6.7-3.fc32.x86_64 2/3
#> Verifying         : udunits2-2.2.26-6.fc32.x86_64 3/3
#>
#> * DONE (gifski)
```
There is no integration with `remove.packages` by default, which will only remove packages installed in the user library. Removing system packages is still possible through the `CoprManager` API:

```r
CoprManager::remove_copr("units")
```

```r
#> Remove system packages as root...
#> Preparing : 1/1
#> Erasing : R-CRAN-units-0.6.7-3.fc32.x86_64 1/3
#> Erasing : R-CRAN-Rcpp-1.0.5-2.fc32.x86_64 2/3
#> Erasing : udunits2-2.2.26-6.fc32.x86_64 3/3
#> Running scriptlet: udunits2-2.2.26-6.fc32.x86_64 3/3
#> Verifying : R-CRAN-Rcpp-1.0.5-2.fc32.x86_64 1/3
#> Verifying : R-CRAN-units-0.6.7-3.fc32.x86_64 2/3
#> Verifying : udunits2-2.2.26-6.fc32.x86_64 3/3
```

As another advantage, it can be noted that the system package manager automatically removes dependencies that are not required by any other package. Finally, the integration can be disabled, so that `install.packages` only installs from CRAN:

```r
CoprManager::disable()
install.packages("units")
```

```r
#> Installing package into ‘/home/user/R/x86_64-redhat-linux-gnu-library/4.0’
#> (as ‘lib’ is unspecified)
#> trying URL ‘https://cloud.r-project.org/src/contrib/Rcpp_1.0.5.tar.gz’
#> trying URL ‘https://cloud.r-project.org/src/contrib/units_0.6-7.tar.gz’
#> [...]```

Only that now the installation from source fails, because the required `udunits2` library is not available.

### 3.2 Building and maintaining thousands of binary packages

The ‘cran2copr’ project is based on Fedora Copr, a platform to build and manage contributed package repositories based on the Copr Buildsystem (Copr Team, 2020). Copr projects publish standard RPM repositories that are readily available through `dnf`’s `copr` command, as shown in the previous section. The build system supports several RPM-based distributions and a wide range of architectures (either natively or through virtualization). As a result, Copr projects are able to build and distribute binary packages for several versions of a number of distributions (currently, Fedora, CentOS, Mageia, openSUSE, OpenMandriva and Oracle Linux) and multiple architectures (currently, i386, x86_64, aarch64, armhf, ppc64le and s390x).

This project leverages the Copr infrastructure to manage thousands of packages and builds with a set of standalone R scripts around the Copr API. The workflow for building a package is as follows. A single-file SPEC (a “recipe” for building an RPM package) is auto-generated from a standard template, the package’s DESCRIPTION file, and a list of (non-R) system dependencies (see the next subsection for further details). Then, it is uploaded to the Copr Buildsystem via its API, and no further local processing is required. Note that SPECs are committed to the project’s repository for the purposes of caching and keeping a history of changes, but this step is not required.

Using this SPEC, the Copr Buildsystem automatically fetches the sources of the package to build the intermediate source RPM, and then spawns build tasks for all the configured chroots (combinations of Linux distribution, version and architecture). Builds are always carried out in a fresh isolated environment consisting on a minimal set of packages. This strategy, along with the automatic execution of the standard set of RPM checks, has proved to be useful to detect a whole new class of installation issues that go unnoticed on CRAN. ¹ Once binary packages are built, they are automatically signed and included in the exported RPM repository for each chroot.

In contrast to previous open projects, ‘cran2copr’ is completely stateless and requires no complex setup, making it very easy to automate via CI/CD services. In fact, we take advantage of GitHub Actions (GitHub’s integrated CI system) to perform updates on a schedule: everyday at 00:00

¹Just to mention some of them, by examining build failures, we have found undeclared dependencies, incorrect versioning of dependencies, and a number of security issues, such as pre- and post-installation downloads, incorrect execution flag in files, or the inclusion of the buildroot path in installed files. This has led to many upstream reports to package maintainers as well as CRAN maintainers and R developers.
UTC, the CRAN database is fetched and compared against the Copr repository to remove archived packages and submit updated SPECs for building.

Another key challenge to maintaining thousands of binary packages is the need to perform mass rebuilds due to breaking changes (e.g., in a new version of R, or in system libraries). The Copr Buildsystem exposes a batching functionality that makes this process straightforward. First, a simple iterative algorithm takes the CRAN database and derives a list of lists of packages, so that each batch only requires packages from the previous batch. Second, builds for each package are requested via the Copr API, indicating the batch identifier and the dependency on the previous batch. Typically, a single mass rebuild is required for each Fedora release, and it is performed in the rawhide branch after the official mass rebuild is carried out per release schedule.

Finally, to be able to scale to CRAN’s current size, a number of design decisions were made to accommodate some limitations of traditional packaging (Fedora Community, 2021):

- Package names, versions and license strings are copied from DESCRIPTION files unmodified, and files under the installation directory are not explicitly listed.
- Packages are built as-is, without unbundling any included third-party libraries.
- To ensure compatibility with the official repositories, the /usr/local prefix is used for package installation. Thus, all R packages are installed under /usr/local/lib/R/library.

Currently, ‘cran2copr’ maintains almost the whole CRAN (over 17.5k packages as of August 2021), except for a few hundred packages (out of about 17,000) due to various reasons. For example, Bioconductor (Gentleman et al., 2004) is not supported at present. Thus, CRAN packages that require (Depends or Imports) Bioconductor packages are excluded. Packages that require unsupported system dependencies are excluded too. Several cases fall under this category, such as packages that depend on proprietary libraries available on CRAN, or packages that require an Internet connection at installation time. For instance, this is the case with gifski shown in the previous section, as well as with other Rust-based packages. These are excluded because enabling repository-wide Internet connection is a security risk, and Copr still lacks support for this option on a per-package basis.

Despite these limitations, as Copr—which is under heavy development—grows in capabilities and resources, ‘cran2copr’ will be able to improve even further to bring binary distribution of R packages to more distributions and architectures.

3.3 A note about SystemRequirements

As established by the Writing R Extensions manual (R Core Team, 2021), “dependencies external to the R system should be listed in the SystemRequirements field”. This usually includes the need for specific libraries (such as the units package in our example above, which requires the udunits2 library) as well as programs (such as a compiler, pandoc, specific LaTeX classes...), and it is therefore an essential part of the SPEC generation process. However, the complete lack of standardization of this field, together with the fact that sometimes packages are accepted on CRAN with undeclared dependencies, makes manual intervention unavoidable.

There have been previous attempts to formalize these requirements, but we opted for maintaining our separate database of system requirements to better distinguish between build- and run-time requirements, thus minimizing the footprint for the builder as well as for the final user. This database was initially bootstrapped by scraping the SystemRequirements field from the DESCRIPTION file for all packages on CRAN, and curated by hand. Maintenance consists in examining build failures from time to time, and manually updating the database accordingly.

Although some automation may be possible by parsing the SystemRequirements field with some clever regular expression (to our knowledge, ‘CRAN2OBS’ takes this approach), such methods are doomed to failure in the long run. Any long-term solution to this problem would probably involve the commitment of CRAN to help standardize, enforce and maintain such a database of system requirements.

3.4 Integrating rootless binary installation on Linux

The last challenge that previous projects always lacked was a transparent integration with the R console. Recently, RStudio’s RSPM system partially achieved this goal, but at a cost: a complete decoupling from the system repositories. The unified package management on Linux, central to

\[\text{https://github.com/r-hub/sysreqsdb}\] as does RStudio’s system requirements for R packages at \[\text{https://github.com/rstudio/r-system-requirements}\].
automatic dependency management, seems to irrevocably require specific tools and administrative privileges.

To overcome this issue, CoprManager integrates a system service written in Python that exposes a D-Bus interface. The D-Bus (Pennington et al., 2020), or Desktop Bus, is a convenient and mature abstraction that is omnipresent in modern Linux environments. It provides inter-process communication (IPC) through a remote procedure call (RPC) mechanism handled by the D-Bus daemon, which starts and stops registered services and manages messages for them.

When CoprManager is installed and enabled, it traces the `install.packages` function and forwards the requested packages over this interface. The system service receives the names of the R packages and translates them to the proper names in the system repositories (e.g., `units` to `r-cran-units`). With the necessary privileges to talk to the system package manager, it requests the installation and reports the progress to the R session. Finally, if a package is not found, it is returned to the unprivileged R session, so that `install.packages` can continue the installation from CRAN (or other repositories).

This mechanism bridges the gap between robust package management through system repositories and the user-friendliness of R’s `install.packages`. Moreover, it can be easily extended to support fine-grained permission management through D-Bus policies or Polkit to, e.g., enable just a subset of users or packages.

4 bspm: Bridge to System Package Manager

The experience with ‘cran2copr’ allowed us to distill the main features of CoprManager into the bspm package (Ucar, 2020b). This is an extensible cross-distribution solution that provides other projects, such as ‘cran2deb’, with the previously missing integration layer. In fact, the most recent versions of CoprManager are built from bspm’s sources as a “branded” version specifically targeted to the ‘cran2copr’ project. Moreover, bspm implements further enhancements that enable the same integration in other major use cases beyond desktop environments. Already existing examples for both Debian and Ubuntu uses of bspm are working with containers, CI/CD workflows, and direct use via a littler (Eddelbuettel and Horner, 2021) wrapper.

4.1 Extensible cross-distribution support

Cross-distribution support is achieved by exposing a standardized interface in the underlying Python service. This interface comprises three calls:

- **discover**: Receives no input, and explores the system repositories to find the list of prefixes required to map R package names to system package names (e.g., `units` to `r-cran-units` for Ubuntu/Debian) via a set of heuristics. This mapping—as well as an optional exclusion list—can also be preset by an administrator to enforce a particular subset of packages.
- **install / remove**: Both receive a list of R package names, and try to install/remove them from the system repositories using the previous mapping. Errors from non-existent packages are caught, and those R package names are returned to the R session. This provides a fallback mechanism within the `install.packages` integration, which transparently continues the installation from source.

D-Bus-mediated calls to the Python service also report the identifier (PID) of the calling process, so that progress can be injected into the R session via its standard error file descriptor. These three functions are prototypes and need to be implemented for each specific system package manager. Currently, bspm implements connectors to the two major package managers, dnf (for the .rpm-based distributions, and apt for the .deb-based ones), covering a large portion of the Linux ecosystem.

4.2 Beyond the desktop environment

The bspm package was conceived with the primary goal of providing full integration with the R console in a desktop environment setup, as well as in multi-tenant server deployments. In these environments, bspm provides unprivileged R sessions with a secure and standardized mechanism to request binary package installations to a privileged service. However, there are other important use cases in which the D-Bus interface is not available. Instead, cloud deployments, as well as CI/CD systems, generally consist of minified headless containers based on Docker or a similar virtualization technology, either running as root or as an unprivileged user with access to sudo. In
such scenarios, bsom works transparently by directly calling the bridge interface without the need for an intermediate service.

bsom is used by container images by the Rocker Project (Boettiger and Eddelbuettel, 2017), a widely-used suite of Docker images with customized R environments for particular tasks. Specifically, the r-bsom images leverage a simple setup via a r-cran-bsom binary package for either Debian (using the ‘testing’ distribution) or Ubuntu (using the two most recent LTS releases). The ‘r-ci’ project (Eddelbuettel, 2021) utilises this setup with its bsom-driven delivery of pre-build binaries under full dependency control in a portable script that provides flexible and lightweight CI use at GitHub Actions, Travis, and Azure Pipelines.

5 Summary and future work

This paper reviews the history of the distribution of binary R packages for Linux and presents ‘cran2copr’, an RPM-based proof-of-concept implementation of an automated scalable binary distribution system. Our solution not only demonstrates the feasibility of building, maintaining and distributing thousands of binary packages—potentially for multiple Linux distributions and multiple architectures—but also provides a portable and extensible bridge to the system package manager, thus providing both full dependency resolution and integration with the R console via bsom.

The huge success of the RSPM repositories currently kindly provided for free by RStudio to the R community is one of the most clear indicators of the importance of binary package distribution for Linux. This work makes the case for future community-driven cross-distribution developments based on modern open-source build systems like Copr, discussed here, or the more general OBS. Build systems present several advantages to current CRAN infrastructure, such as isolation and scaling, which would enhance the quality of packages by exposing them to more stringent checks as well as a wider and more realistic set of environments. But more importantly, artifacts from the building process would be automatically gathered into a consistent (possibly, multi-architecture) set of contributed repositories that would benefit the R community as a whole.

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