REPORT ON OpenDreamKit DELIVERABLE D3.8
Continuous integration platform for multi-platform build/test.

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1. Introduction

In this report we look at what some OpenDreamKit-affiliated projects have achieved in the areas of continuous integration and multi-platform building and testing.

Continuous integration (CI) in software development is a process whereby work performed by one or more developers on a software project is regularly merged together into a single, central software repository (referred to as the 'mainline'), and the software built and tested with success or failure of the build reported quickly back to the developers of the project. This helps to ensure that individual developers' changes do not conflict with each other or otherwise "break the build", and provides rapid feedback when breaking changes are introduced into the mainline. Both the process, and the associated tools (e.g. automated continuous integration servers) are an essential part of the day-to-day work of developers on those projects that use it.

Modern CI requires server infrastructure. At the very least one server is needed to both perform software builds and serve (usually through a web-based UI) reports back to developers so that they are kept regularly up-to-date on the "health" of the build. For some projects – especially those that support multiple software platforms – continuous integration infrastructure can involve a whole fleet of hardware systems, each of which perform builds and tests of the software and report results back to a central server which collates them into a single multi-platform build report for developers to examine. Unsurprisingly, as the CI needs of a project grow, so too does the size of its CI infrastructure, and the time, financial resources, and expertise required to maintain it.

The SAGE project, being quite large both in terms of number of contributors and in terms of overall code base (and by extension the length of time required to build the software and run its test suite) has non-trivial CI needs, and to address this it has, over time, amassed a small multi-platform fleet of build machines as part of its "buildbot" infrastructure (based on the Buildbot[1] CI software framework), as well as expertise needed to maintain that infrastructure. One of the original aims of this deliverable was to see if other projects under the OpenDreamKit umbrella could benefit from using Sage's buildbots, and thus achieve better multi-platform CI. Additionally, we would look into widening the set of platforms supported by Sage's buildbot infrastructure – in particular adding Windows builds to coincide with Sage's newfound Windows support (see D3.7: "One-click install SAGE distribution for Windows with Cygwin 32bits and 64bits").

In practice, the needs of the OpenDreamKit community as a whole with respect to multi-platform CI, and in particular the need for a "common infrastructure" for CI, did not align with

[1] `https://buildbot.net/`

our original expectations, for reasons that are enumerated in the following sections. Nevertheless, significant achievements were made by OpenDreamKit projects in the area of CI, and there are lessons learned that we are communicating through this report with plans for future cross-pollination on the subject. Our experiences have also taught us that although there is not a one-size-fits-all solution to CI, there remains a clear need in the community for easier access to multi-platform build and development infrastructure, especially for non-free operating systems such as Windows and macOS.

2. Changes in scope of the deliverable

In the last five years there has been a rise in free (especially for open source) cloud-based continuous integration services that integrate closely with source code hosting platforms like GitHub and GitLab. This has precipitated both an increase in use of CI as a best practice in the software community, though conversely a decrease in the need for self-hosted and self-managed CI infrastructure such as Sage's buildbots.

Although free-for-open-source cloud-based services were in use before the start of OpenDreamKit[2], there has been an explosion in the number of services, including among others Travis CI, CircleCI, AppVeyor, and now Microsoft has entered the field with its new version of Visual Studio Team Services (VSTS). For example, by their own estimate[3]in 2016 Travis CI was in use by nearly a third of active GitHub projects. Without the existence of these free services, most projects – especially smaller ones – would not have the resources to maintain CI infrastructure even if they wanted to[4].

Another advantage of services that integrate with GitHub is that it enables a particular type of continuous integration sometimes referred to as "advisory CI". This contrasts with traditional CI, wherein all developers on a project are allowed to push changes to a central version control system, and the CI system builds from that shared "mainline". So, if a developer pushes a change that breaks the code, the code is "broken" for all other developers on the project (even if a correctly functioning CI system should catch the bug fairly quickly).

However, in distributed, open source projects like those hosted on GitHub or GitLab, one does not want to give just anyone permission to push changes to the mainline. Instead, most developers submit a *pull request* – a change proposal that is not immediately merged into the mainline, but which a project administrator can merge into the mainline after it has been reviewed and deemed acceptable and sufficiently stable. Advisory CI can help immensely in determining when a proposed pull request is "sufficiently stable". Under this model the CI framework builds the version of the code in the pull request *as though* it were the project's mainline (without ever changing the real mainline) and then attempts to build the code and run its test suite in isolation from any other pending changes to the code. If this works, then one can have reasonable confidence (after a manual code review, and acceptance of the change on its merits) that the change is safe to include in the mainline. This is not a silver bullet: it is possible that two mutually independent pull requests can pass through the CI system on their own, but conflict with each other in a way that is only apparent after they have been merged into the mainline. In this case one has the traditional CI problem of a "broken build". But this scenario is relatively uncommon, especially in well-structured projects.

[2]The popular Travis CI service saw rapid growth in 2012: `https://blog.travis-ci.com/2012-12-17-numbers/`

[3]`https://blog.travis-ci.com/2016-07-28-what-we-learned-from-analyzing-2-million-travis-builds/`

[4]Travis CI has also become popular for the use case of automated deployment of non-software projects such as static websites and (as demonstrated in D2.7: "Community-curated indexing tool (open source)") Jupyter notebook galleries.

Therefore, between the relative ease of setting up free continuous integration systems for use on one's project, and the added convenience of advisory CI that integrates directly with the project's issue tracker, there is relatively little demand for self-managed CI infrastructure such as that used for Sage. However, there is still the question – anticipated by the original proposal for this deliverable – of multi-platform continuous integration. In fact, this is also reasonably well-covered by free CI services. While most services provide building and testing of software on Linux distributions, some also have fleets of different non-free OSes (e.g. Travis CI supports builds on macOS, while AppVeyor is popular for its Windows support). For projects wishing to achieve some multi-platform support – especially across those three major OSes – they can do so by configuring a combination of CI services for the project, and many projects do just this.

In practice though, multi-platform CI has not had as much demand as we anticipated. Most mathematical software projects do not have a great deal of system-specific code, and are mostly numerical in nature (e.g. C++ libraries such as LinBox and Givaro). These have relatively little need for multi-platform testing. While platform-specific issues can still arise in such software, it is not always typical enough to merit the extra overhead of multi-platform testing. When platform-specific issues do arise, it is more common for them to occur when building the project, rather than at run time. To this end, the Sage project is already providing implicit cross-platform build testing for many projects; see the next section for details.

2.1. Sage remains a special case

In the case of Sage, it is still useful for now to have the self-managed infrastructure due to the unique nature of Sage and the fact that it includes an entire software distribution. Its builds can take a very long time and run up against limits imposed by the free services. It is also useful to test Sage across a wider number of platforms than those offered by the popular free CI providers due to the likelihood of platform-specific build issues across its more than 150 dependencies.

It is also worth noting that being a software distribution comprising so many components, Sage is providing implicit cross-platform build and runtime testing of OpenDreamKit-affiliated projects and dozens of other mathematical software systems. While Sage's test suite does not provide full test coverage for its dependent packages, it does exercise most of them extensively. In particular, Sage tests all its dependencies at the system integration level (such as interaction between multiple processes, and running multi-threaded computations); these are the areas where the most platform-specific challenges arise, as opposed to purely numerical and mathematical code. In fact, the process of porting Sage to Windows, and running Sage's tests on Windows (D3.7: "One-click install Sage distribution for Windows with Cygwin 32bits and 64bits") has led to the discovery and fixing of these kinds of system-level issues in software such as GAP, ECL, and PARI/GP among others.

A remaining challenge for Sage is obtaining more machines that can run builds of Sage on non-free operating systems. For macOS testing we currently have one "official" machine: a Mac mini donated personally by Sage's release manager Volker Braun. For Windows we currently have a few VMs running on the OpenStack infrastructure provided by Université Paris-Sud. However, we have found the performance of Windows VMs on Linux hosts to be wanting, and difficult to improve. Although we will continue using this infrastructure for the foreseeable future, we are investigating the purchasing of some dedicated hardware to run a Windows build server natively.

That said, there were also areas for improvement identified with Sage's existing CI practices, especially with regard for its relatively unreliable home-grown advisory CI system. It was also realized that the now wide availability of Docker as a tool for CI could be leveraged to both improve Sage's CI practices, and make Sage development easier. This work is discussed further in the next section.

3. Continuous integration achievements of OpenDreamKit projects

3.1. Sage

The Sage project had traditionally employed two distinct CI systems, the Buildbot and Sage's own development, the patchbot[5].

3.1.1. *Buildbot and patchbot.* Sage's Buildbot runs as a non-advisory CI system on a wide variety of platforms. It builds Sage and runs its test suite for every change that gets accepted into the mainline of the Sage code. Its main purpose is not to be an advisory tool for developers but to catch problems and incompatibilities of Sage or its dependencies, in particular on more obscure platforms that dependent projects often do not test for. Due to the vast range of platforms covered, the Buildbot can not realistically be turned into an advisory CI system as it is not conceivable to provision and administer the number of machines that would be necessary to run Sage's test suite at every stage of a test that gets proposed by a developer.

Therefore, the Sage community at some point developed its own patchbot system which runs Sage's test suite at every stage of a proposed change. Anybody can run a patchbot on their private computer, typically a Linux system. These patchbots will then look for proposed changes to Sage, run Sage's test suite, and report findings back to a central server. It is worth noting that the patchbot system predates most of the currently popular CI systems.

The patchbot system comes with a number of issues: It is not nearly as polished as the professional offerings which means that its workings can often be confusing and that it also requires continuous maintenance and development from the Sage community and by those that run the patchbots on their private machines. The fact that it is running on private machines means that due to load, connectivity issues, and other temporary issues on these machines, the patchbots are very frequently reporting false positive errors. This noise can be very frustrating as it makes the patchbot system unreliable and in particular harder to understand for new contributors. Finally, due to limitations of the patchbot architecture, not all types of changes can be tested, in particular it can not test changes that involve dependent software packages. This can be frustrating as testing such changes is often the most time consuming task for developers and it would be particularly nice to give such tasks away to a CI system.

3.1.2. *Modern CI with GitLab CI and CircleCI.* To fix these issues we were looking at best pratices that would give the Sage community fast, reproducible, reliable CI with minimal maintenance and continuous development necessary to keep the CI working for everybody. We settled for GitLab CI, a modern open-source CI system, and CircleCI, a popular closed-source system. Which one to use is up to each developer. For simplicity we focus on GitLab CI here. GitLab CI typically uses Docker containers as its backend (but it can also be based on many other technologies.) These containers are essentially virtual machines that can be hosted in a central location but also on private computers. Unlike in the patchbot systems, Docker containers are standardized and isolated so that there is usually no issue of false positives.

GitLab CI now runs a "pipeline" for every change proposed by a developer.

This pipeline goes in stages. In the setup for Sage, the first stage builds several flavors of Docker container which contain a built version of Sage. The second stage runs tests on these containers. Finally the Docker containers from the first stage are made publicly available.

It should be noted that the first stage is where most complications for Sage arise. Building Sage takes several hours on most machines, so a lot of effort went into speeding this up in a sane and reproducible way to about 10 minutes. Also, we try to make the resulting Docker containers as small as possible. This speeds up the whole CI pipeline and also makes it easier for developers to download these containers; in typical cases they only have to download a few MB to get a hold of the Docker container.

[5] `https://github.com/sagemath/sage-patchbot`

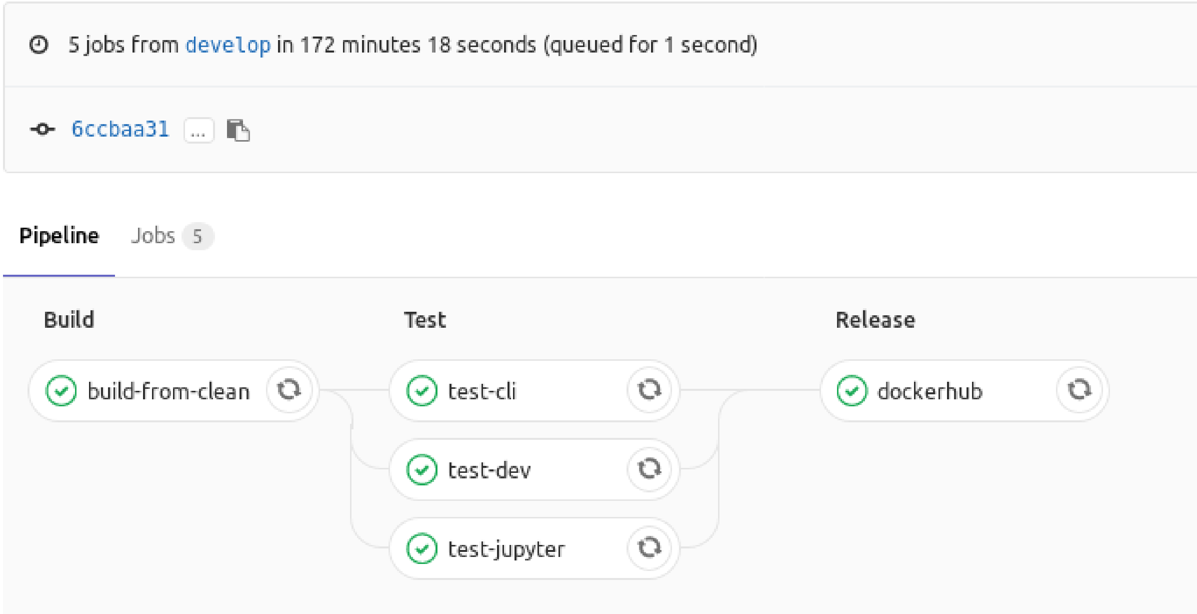


FIGURE 1. An example build pipeline for Sage on GitLab. Demonstrates multiple pipeline jobs including building Sage, testing it, and publishing the build as a Docker image.

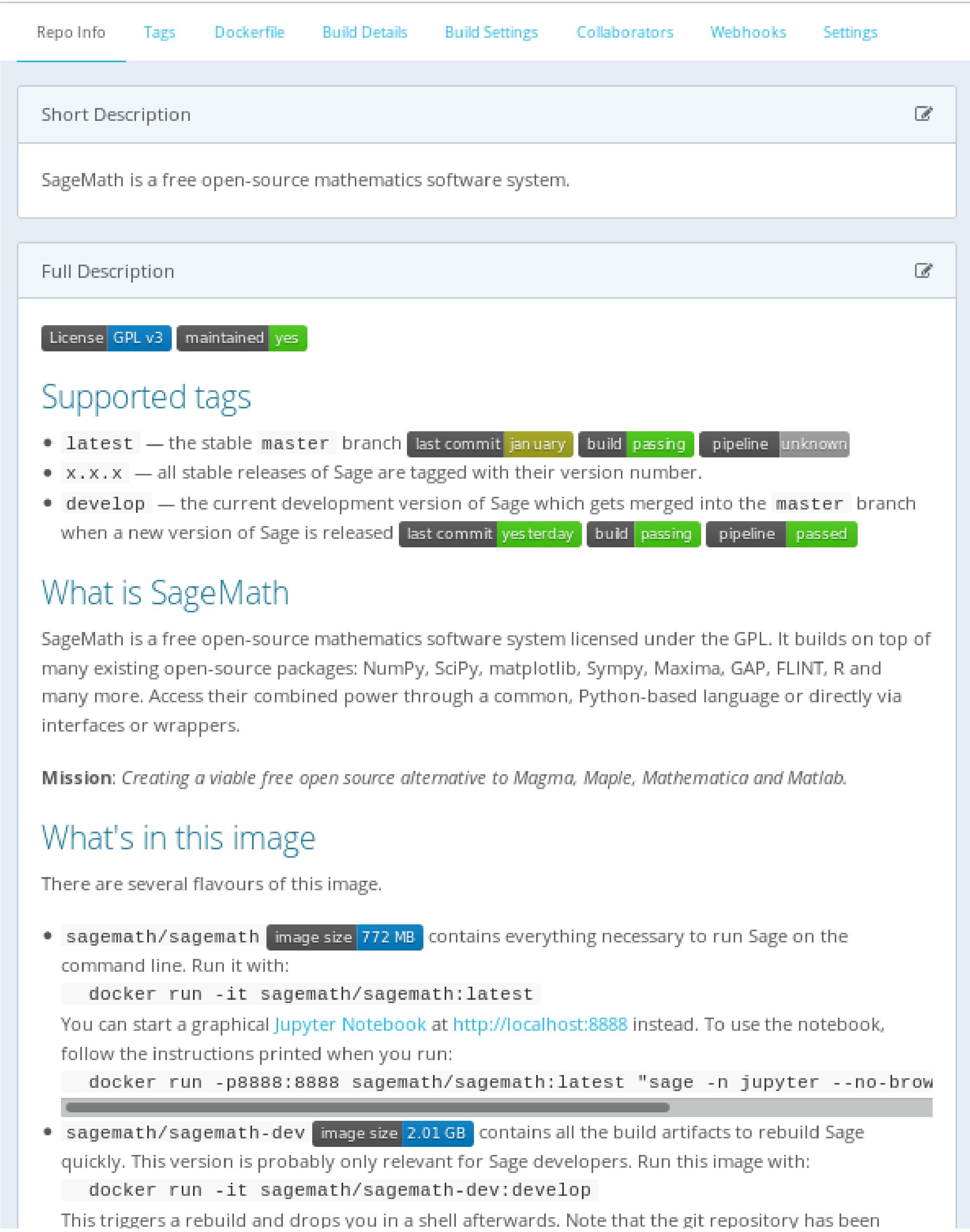
3.1.3. *Use Cases of Docker Containers.* Having these Docker containers readily available as a by-product of our CI turned out to be very valuable (see Figure 2).

It means that recent stable & unstable versions of Sage are automatically made available for anybody to work with, without the need of having to understand how to build Sage on their machine.

Sage developers can use these to reproduce and understand issues reported by the CI system simply by downloading the container and running the Sage version contained in that container.

Projects that depend on Sage can use these Docker containers for their own CI needs and run their tests based on these containers. Without such Docker containers, most such projects would refrain from using CI as setting up Sage in a CI system appeared to be too complicated.

Sage (and projects depending on Sage) can link to these containers through mybinder.org to make different versions of their systems available through public web interfaces. This means that anybody can easily experiment with the latest unreleased features in a web browser without having to go through any local installation.



Repo Info Tags Dockerfile Build Details Build Settings Collaborators Webhooks Settings

Short Description

SageMath is a free open-source mathematics software system.

Full Description

License GPL v3 maintained yes

Supported tags

- `latest` — the stable `master` branch last commit january build passing pipeline unknown
- `x.x.x` — all stable releases of Sage are tagged with their version number.
- `develop` — the current development version of Sage which gets merged into the `master` branch when a new version of Sage is released last commit yesterday build passing pipeline passed

What is SageMath

SageMath is a free open-source mathematics software system licensed under the GPL. It builds on top of many existing open-source packages: NumPy, SciPy, matplotlib, Sympy, Maxima, GAP, FLINT, R and many more. Access their combined power through a common, Python-based language or directly via interfaces or wrappers.

Mission: *Creating a viable free open source alternative to Magma, Maple, Mathematica and Matlab.*

What's in this image

There are several flavours of this image.

- `sagemath/sagemath` image size 772 MB contains everything necessary to run Sage on the command line. Run it with:
  `docker run -it sagemath/sagemath:latest`
  You can start a graphical Jupyter Notebook at http://localhost:8888 instead. To use the notebook, follow the instructions printed when you run:
  `docker run -p8888:8888 sagemath/sagemath:latest "sage -n jupyter --no-brow`
- `sagemath/sagemath-dev` image size 2.01 GB contains all the build artifacts to rebuild Sage quickly. This version is probably only relevant for Sage developers. Run this image with:
  `docker run -it sagemath/sagemath-dev:develop`
  This triggers a rebuild and drops you in a shell afterwards. Note that the git repository has been

FIGURE 2. The DockerHub landing page for Sage's Docker images, including up-to-date build status read from the GitLab pipeline.

3.2. GAP

GAP has a mechanism for user contributions in the form of packages, which may be submitted for refereeing and for the redistribution with GAP. They extend the functionality of the system and may implement mathematical algorithms, provide mathematical databases, interfaces to other systems or enhancements of the system's infrastructure such as tools for debugging and profiling, and building documentation.

Packages are developed and released independently of the core GAP system. They should be properly integrated into GAP to not to break the functionality of the system or any other package. On the other hand, changes in GAP are only permitted to have a disruptive effect on package functionality in a major release, and we aim to identify such situations in advance and resolve them in cooperation with package authors. Hence continuous integration facilities in GAP are designed to suit the following primary goals:

- checking pull requests which propose changes to the core GAP system
- checking for new versions of GAP packages redistributed with GAP; retrieving and storing them, and combining them for testing and redistribution
- running package integration tests which check that GAP packages redistributed with GAP do not break the functionality of the core GAP system
- wrapping and testing GAP releases
- testing official package releases for their readiness for the next GAP release
- testing package development versions for their compatibility with the GAP development version

This is supported by the following infrastructure:

- Jenkins CI[6] instance at the University of St Andrews, providing Linux, macOS and Windows nodes (available only within St Andrews network due to security restrictions)
- Travis CI accounts to test builds on Linux (both on native Travis CI infrastructure and on Docker containers for GAP; we also used macOS builds in the past, but then they were disabled due to reliability and performance issues):
  - for the core GAP system: `https://travis-ci.org/gap-system/`
  - for GAP packages: `https://travis-ci.org/gap-packages/`
- Codecov[7] accounts:
  - for the core GAP system: `https://codecov.io/gh/gap-system/gap`
  - for GAP packages: `https://codecov.io/gh/gap-packages/`
- AppVeyor account to test builds on Windows under Cygwin: `https://ci.appveyor.com/project/gap-system/gap`
- A collection of Docker containers with various configurations available from Docker Hub: `https://hub.docker.com/r/gapsystem/`

All links to critical CI builds are collected together at `https://github.com/gap-system/gap-distribution`.

The core GAP system tests use Travis CI and AppVeyor to check every pull request submitted to the main GAP repository on both Linux and Windows, and to publish code coverage reports to Codecov. In the last 6 months, code coverage on Travis CI increased from 70% to 75%, mainly due to new tests added by our external collaborator Max Horn (University of Gießen). In addition to that, several extended tests are performed on Jenkins, as they are more time consuming.

GAP package authors are advised to provide with each package a short test suite, which may be used to check that a package works as expected, together with metadata which informs GAP how to run that test suite. Such tests are run regularly as a part of the standard GAP test suite.

[6] Another popular framework for self-hosted CI services; `https://jenkins.io/`

[7] A specialized supplement to CI systems for hosting code coverage reports – that is, measures of how well a project's test suite tests or "covers" lines of code and different code branches; `https://codecov.io/`

Since Jenkins CI outputs are not accessible outside St Andrews, we use a two-tier approach: new versions of GAP packages are picked up and tested internally on the Jenkins CI instance in St Andrews; approved versions are then published to be used in all further tests of GAP (core system and package integration tests) on Travis CI, and to run standard tests of GAP packages in a way making their output available to their authors. These builds use Docker containers for the latest GAP release and for the two release branches of the GAP repository.

For more comprehensive testing, we provide a standard Travis CI and Codecov setup for GAP packages, available in the EXAMPLE package `https://github.com/gap-packages/example`. It has been adopted and customised by most of the GAP packages developed on GITHUB (see their list at `https://gap-packages.github.io/`). Furthermore, there are tools for creating and publishing packages, primarily developed by our external collaborator Max Horn: PACKAGEMAKER[8], RELEASETOOLS[9] and GITHUBPAGESFORGAP[10]. All these measures facilitate interaction between contributors to packages and the core GAP system, improve reliability of our software and help to keep regular release cycles.

The following table shows the dynamics of the number of packages redistributed with GAP, number of authors involved in them, and adoption of standard tests by packages included in selected GAP releases in 2012–2018.

GAP release	Number of of packages	Number of authors	Have standard regression tests
4.5.4 (06/2012)	99	129	46
4.5.7 (12/2012)	105	130	47
4.6.2 (02/2013)	106	133	58
4.7.2 (12/2013)	114	140	51
4.7.6 (11/2014)	115	151	53
4.7.9 (11/2015)	119	158	57
4.8.2 (02/2016)	131	167	69
4.8.6 (11/2016)	131	171	69
4.8.9 (12/2017)	132	186	73
4.9.1 (05/2018)	134	186	85
4.9.3 (to appear)	140	187	91

3.3. **Cysignals**

The Cysignals project[11] has been using Travis CI[12] for continuous integration on Linux practically since its inception (see D4.1: “Python/Cython bindings for PARI and its integration in Sage”). In Spring of 2018 we made initial progress towards adding native Windows support to Cysignals[13] as well as continuous integration for both native Windows and Cysignals on Cygwin using AppVeyor[14], the initial results of which have been promising. The process of adding Cygwin testing on AppVeyor even exposed new Cygwin-specific bugs with Cysignals that had not been previously caught.

However, multi-platform testing still remains an interesting problem for Cysignals in particular. The low-level details of Cysignals are such that its functionality can depend heavily on the underlying operating system kernel (even different versions of the Linux kernel). As such, one would like to be able to test against different kernels. Because most CI services – including Travis CI – are using container-based technology, this means that even testing different OS

[8] `https://github.com/gap-system/PackageMaker`
[9] `https://github.com/gap-system/ReleaseTools`
[10] `https://github.com/gap-system/GitHubPagesForGAP`
[11] `https://cysignals.readthedocs.io/en/latest/`
[12] `https://travis-ci.org/sagemath/cysignals`
[13] `https://github.com/sagemath/cysignals/pull/76`
[14] `https://github.com/sagemath/cysignals/pull/95`

platforms via containers is not entirely helpful, because all containers running on the system host system are using the same underlying kernel. Another problem is that although Travis CI supports build configurations using macOS, it does not support this by default for Python-based projects without employing various unsupported workarounds.

Thus, an area for future work might be to try using GitLab's CI framework and providing our own build runner machines (possibly even reusing the existing one from Sage's buildbot fleet) to test Cysignals against more OS platforms with a wider range of OS kernels than we might test otherwise.

4. Conclusion

There does not appear to be a one-size-fits all solution for continuous integration. Massive, complex projects like Sage, projects with many third-party contributed components such as GAP, projects with low-level system integrations like Cysignals, and everything in-between have different needs. Between that fact, and the advancements in free-for-open-source cloud-hosted CI providers, the idea of uniting OpenDreamKit projects under a single CI platform (whether Buildbot as used by Sage, or something else) would not have been practical or effective.

What does remain clear – and is a commonality between the projects mentioned in this report in particular, as well as others, is the need for easy access to "hardware" infrastructure with which one can easily spin up a virtual machine on which to install some operating system one does not have immediate access to. In the case of non-free OSes, this includes a need for easy to obtain Windows licenses for running Windows VMs and, in the case of macOS, specialized hardware as well, as Apple's licensing is extremely restrictive when it comes to virtualization. It should be noted that this need is not strictly for the use case of continuous integration, but also for building software releases for multiple platforms, investigation by developers of platform-specific bugs, and new development to improve multi-platform support in general. For example, the author has personally experienced frustration with obtaining access to a macOS machine in order to investigate macOS-specific bugs in Sage, having not procured an Apple machine for personal use.

The current situation is such that individual developers must find ways to access these kinds of computing resources, and the ease of doing so may depend on the level of institutional resources available to them. At Université Paris-Sud we have found it easy to create and access VMs of free UNIX-like operating systems, but had to put several days of FTEs into getting a Windows VM up and running on that platform, with mixed results. And this provides us no help for macOS. Meanwhile the build machines for GAP hosted at St Andrews meet the project's needs for CI, but are not accessible outside the St Andrews firewall and are thus not easily accessible to GAP developers at other institutions. In both cases, some effort is required by the community to maintain their build hardware infrastructure, which this work might be more efficiently handed off to experts working in dedicated computing centers.

For example, we are discussing the possibility of getting in touch with EGI and seeing if we might be able to use EGI-provided resources for a multi-platform cloud environment specifically for use by open source mathematics projects. Ideally we would want this to be provided in such a way that it isn't restricted to projects that are strictly European by nature (or maybe at the most have some European grant or contributors associated with it). Or at the very least, we would want to be able to easily create server infrastructure for a given project which can then be shared as needed with other trusted developers of that project. However, the exact nature of such an arrangement remains an open question to be resolved.

been checked for correctness at the time of submission of the deliverable, but there is no guarantee implied that they will remain valid.