
Developer's Guide

Release 9.7

The Sage Development Team

Sep 20, 2022

CONTENTS

1	Git and Trac for Sage development	3
1.1	First Steps with Git	3
1.1.1	Setting Up Git	3
1.1.2	Sage Development Process	4
1.2	Using Git with Trac	9
1.2.1	The Sage Trac Server	9
1.2.2	Using Git with the Sage Trac Server	14
1.2.3	Tips and References	21
1.2.4	Advanced Git	25
1.2.5	Distributed Development	31
1.2.6	Optional: Using the Git-Trac Command	36
2	Writing Code for Sage	45
2.1	Setting up your workspace	45
2.1.1	Configuring text editors and IDEs for use with Sage	45
2.1.2	Gitpod	45
2.2	General Conventions	46
2.2.1	Python Code Style	46
2.2.2	Files and Directory Structure	47
2.2.3	Learn by copy/paste	48
2.2.4	Headings of Sage Library Code Files	48
2.2.5	Documentation Strings	49
2.2.6	Running Automated Doctests	63
2.2.7	General Coding Style Regarding Whitespace	64
2.2.8	Global Options	64
2.2.9	Miscellaneous minor things	65
2.3	The reviewer's check list	65
2.4	Running Sage's tests	67
2.4.1	Running Sage's doctests	67
2.5	Testing on multiple platforms	91
2.5.1	Testing on multiple platforms	91
2.6	Additional development and testing tools	111
2.6.1	Additional development and testing tools	111
2.7	Contributing to Manuals and Tutorials	116
2.7.1	The Sage Manuals	116
2.8	Sage Coding Details	119
2.8.1	Coding in Python for Sage	119
2.8.2	Coding in Cython	129
2.8.3	Using External Libraries and Interfaces	131
2.9	Packaging the Sage Library	143

2.9.1	Packaging the Sage Library	143
2.10	Packaging Third-Party Code	151
2.10.1	Packaging Third-Party Code	151
3	Indices and tables	169
	Bibliography	171
	Index	173

Everybody who uses Sage is encouraged to contribute something back to Sage at some point. You could:

- Add examples to the documentation
- Find bugs or typos
- Fix a bug
- Implement a new function
- Contribute a useful tutorial for a mathematical topic
- Translate an existing document to a new language
- Create a new class, create a fast new C library, etc.

This document tells you what you need to know to do all the above, from reporting bugs to modifying and extending Sage and its documentation. We also discuss how to share your new and modified code with other Sage users around the globe.

Here are brief overviews of each part; for more details, see the extended table of contents below. No matter where you start, good luck and welcome to Sage development!

- **Trac server:** all changes go through [the Sage Trac server](#) at some point. It contains bug reports, upgrade requests, changes in progress, and those already part of Sage today. [Click here](#) for more information.

Importantly, you will need to [create a trac account](#) in order to contribute.

- **Source code:** You need your own copy of Sage's source code to change it. [Go there](#) to get it and for instructions to build it.

If you have never worked on software before, pay close attention to the [prerequisites to compile](#) on your system.

As an easy way to get started, you can run and edit Sage's code and contribute your changes using [Gitpod](#), a free online development environment based on VS Code. It will launch a pre-made workspace with all dependencies and tools installed so that you can start contributing straight away. Start by [going to Gitpod](#), and read [our Gitpod guidelines](#) to learn more.

- **Conventions:** read our [conventions and guidelines](#) for code and documentation.

For everything related to manuals, tutorials, and languages, [click here](#).

- **Git (revision control):** To share changes with the Sage community, you will need to learn about revision control; we use the software Git for this purpose.
 - [How to install it?](#)
 - [How to configure it for use with Trac?](#)
 - [Here is](#) an overview of our development flow.

GIT AND TRAC FOR SAGE DEVELOPMENT

1.1 First Steps with Git

Sage uses git for version control.

1.1.1 Setting Up Git

To work on the Sage source code, you need

- a working git installation, see *Installing Git*.
- configure git to use your name and email address for commits, see *Your Name and Email*.

The *Tips and References* chapter contains further information about git that might be useful to some but are not required.

Installing Git

First, try git on the command line. Most distributions will have it installed by default if other development tools are installed. If that fails, use the following to install git:

Debian / Ubuntu `sudo apt-get install git-core`

Fedora `sudo yum install git-core`

Windows (Cygwin) Install the Cygwin package git. Do not attempt to use native Windows installations of git.

Windows (WSL) We strongly recommend to install the package using the Linux distribution's package manager. Native Windows installations of git may also work, but there are possible pitfalls.

macOS Install the Xcode Command Line Tools.

Some further resources for installation help are:

- [Section 1.5 of the git book](#)
- [The git homepage](#) for the most recent information.
- [Github install help pages](#)

Your Name and Email

The commit message of any change contains your name and email address to acknowledge your contribution and to have a point of contact if there are questions in the future; filling it in is required if you want to share your changes. The simplest way to do this is from the command line:

```
[user@localhost ~] git config --global user.name "Your Name"
[user@localhost ~] git config --global user.email you@yourdomain.example.com
```

This will write the settings into your *git configuration file* with your name and email:

```
[user]
  name = Your Name
  email = you@yourdomain.example.com
```

Of course you'll need to replace `Your Name` and `you@yourdomain.example.com` with your actual name and email address.

1.1.2 Sage Development Process

This section is a concise overview of the Sage development process. In it, we will see how to make changes to the Sage source code and record them in the git revision control system.

We also have a handy [one-page “cheat sheet”](#) of commonly used git commands that you can print out and leave on your desk. We have some [recommended references and tutorials](#) as well.

In the following sections on *The Sage Trac Server* and *Using Git with Trac* we will look at communicating these changes back to the Sage project. All changes to Sage source code have to go through the [Sage Trac development server](#).

As an alternative to using the Trac server directly, you can fork and create a Merge Request (MR) at [GitLab](#) which will automatically fetch your code and open a ticket on our trac server.

Pull Requests (PR) on GitHub are currently not supported by the SageMath project.

Configuring Git

One way or another, git is what Sage uses for tracking changes. So first, open a shell (for instance, Terminal on Mac) and check that git works:

```
[user@localhost]$ git
usage: git [--version] [--help] [-C <path>] [-c name=value]
...
The most commonly used git commands are:
  add          Add file contents to the index
...
  tag          Create, list, delete or verify a tag object signed with GPG

'git help -a' and 'git help -g' lists available subcommands and some
concept guides. See 'git help <command>' or 'git help <concept>'
to read about a specific subcommand or concept.
```

Don't worry about the giant list of subcommands. You really only need a handful for effective development, and we will walk you through them in this guide. If you got a “command not found” error, then you don't have git installed. Now is the time to install it; see [Setting Up Git](#) for instructions.

Because we also track who does changes in Sage with git, you must tell git how you want to be known. This only needs to be done once:

```
[user@localhost]$ git config --global user.name "Your Name"
[user@localhost]$ git config --global user.email you@yourdomain.example.com
```

If you have multiple accounts / computers use the same name on each of them. This name/email combination ends up in commits, so do it now before you forget!

Obtaining and Compiling the Sage Source Code

Obviously one needs the Sage source code to develop. You can use your local installation of Sage, or (to start from scratch) download it from GitHub which is a public read-only mirror (=faster) of our internal git repository:

```
[user@localhost ~]$ git clone https://github.com/sagemath/sage.git
Cloning into 'sage'...
[...]
Checking connectivity... done.
```

This creates a directory named `sage` containing the sources for the current stable and development releases of Sage. You next need to switch to the `develop` branch (latest development release):

```
[user@localhost ~]$ cd sage
[user@localhost sage]$ git checkout develop
```

Next, compile Sage, following the instruction in the file `README.md` in `SAGE_ROOT`. Additional details can be found in the [section on installation from source](#) in the Sage installation guide. If you wish to use conda-forge, see the [section on conda](#).

Note: macOS allows changing directories without using exact capitalization. Beware of this convenience when compiling for macOS. Ignoring exact capitalization when changing into `SAGE_ROOT` can lead to build errors for dependencies requiring exact capitalization in path names.

For the experts, note that the repository at git.sagemath.org is where development actually takes place.

Branching Out

In order to start modifying Sage, we want to make a *branch* of Sage. A branch is a copy (except that it doesn't take up twice the space) of the Sage source code where you can store your modifications to the Sage source code and which you can upload to trac tickets.

To begin with, type the command `git branch`. You will see the following:

```
[user@localhost sage]$ git branch
* develop
  master
```

The asterisk shows you which branch you are on. Without an argument, the `git branch` command displays a list of all local branches with the current one marked by an asterisk.

It is easy to create a new branch; first make sure you are on the branch from which you want to branch out. That is, if you are not currently on the `develop` branch, type the command `git checkout develop`:

```
[user@localhost sage]$ git checkout develop
Switched to branch 'develop'
Your branch is up-to-date with 'origin/develop'.
```

Then use the `git branch` command to create a new branch, as follows:

```
[user@localhost sage]$ git branch last_twin_prime
```

Also note that `git branch` creates a new branch, but does not switch to it. For this, you have to use `git checkout`:

```
[user@localhost sage]$ git checkout last_twin_prime
Switched to branch 'last_twin_prime'
```

Now if you use the command `git branch`, you will see the following:

```
[user@localhost sage]$ git branch
  develop
* last_twin_prime
  master
```

Note that unless you explicitly upload (“push”) a branch to a remote git repository, the branch is a local branch that is only on your computer and not visible to anyone else.

To avoid typing the new branch name twice you can use the shortcut `git checkout -b my_new_branch` to create and switch to the new branch in one command.

The History

It is always a good idea to check that you are making your edits on the version that you think you are on. The first one shows you the topmost commit in detail, including its changes to the sources:

```
[user@localhost sage]$ git show
```

To dig deeper, you can inspect the log:

```
[user@localhost sage]$ git log
```

By default, this lists all commits in reverse chronological order.

- If you find your branch to be in the wrong place, see the [Reset and Recovery](#) section.
- Many programs are available to help you visualize the history tree better. `tig` is a very nice text-mode such tool.

Editing the Source Code

Once you have your own branch, feel free to make any changes as you like. *Subsequent chapters* of this developer guide explain how your code should look like to fit into Sage, and how we ensure high code quality throughout.

`Status` is probably the most important git command. It tells you which files changed, and how to continue with recording the changes:

```
[user@localhost sage]$ git status
On branch last_twin_prime
Changes not staged for commit:
```

(continues on next page)

(continued from previous page)

```
(use "git add <file>..." to update what will be committed)
(use "git checkout -- <file>..." to discard changes in working directory)
```

```
modified:    some_file.py
modified:    src/sage/primes/all.py
```

Untracked files:

```
(use "git add <file>..." to include in what will be committed)
```

```
src/sage/primes/last_pair.py
```

no changes added to commit (use "git add" and/or "git commit -a")

To dig deeper into what was changed in the files you can use:

```
[user@localhost sage]$ git diff some_file.py
```

to show you the differences.

Rebuilding Sage

Once you have made any changes you of course want to build Sage and try out your edits. As long as you only modified the Sage library (that is, Python and Cython files under `src/sage/...`) you just have to run:

```
[user@localhost sage]$ ./sage -br
```

to rebuild the Sage library and then start Sage. This should be quite fast. If you made changes to *third-party packages*, then you have to run

```
[user@localhost sage]$ make build
```

as if you were *installing Sage from scratch*. However, this time only packages which were changed (or which depend on a changed package) will be recompiled, so it should be much faster than compiling Sage the first time.

Note: If you have *pulled a branch from trac*, it may depend on changes to third-party packages, so `./sage -br` may fail. If this happens (and you believe the code in this branch should compile), try running `make build`.

Rarely there are conflicts with other packages, or with the already-installed older version of the package that you changed, in that case you do have to recompile everything using:

```
[user@localhost sage]$ make distclean && make build
```

Also, don't forget to run the tests (see *Running Sage's doctests*) and build the documentation (see *The Sage Manuals*).

Note: If you switch between branches based on different releases, the timestamps of modified files will change. This triggers recythonization and recompilation of modified files on subsequent builds, whether or not you have made any additional changes to files. To minimize the impact of switching between branches, install `ccache` using the command

```
[user@localhost sage]$ ./sage -i ccache
```

Recythonization will still occur when rebuilding, but the recompilation stage first checks whether previously compiled files are cached for reuse before compiling them again. This saves considerable time rebuilding.

Commits (Snapshots)

Whenever you have reached your goal, a milestone towards it, or just feel like you got some work done you should *commit* your changes. A commit is just a snapshot of the state of all files in the *repository* (the program you are working on).

Unlike with some other revision control programs, in git you first need to *stage* the changed files, which tells git which files you want to be part of the next commit:

```
[user@localhost sage]$ git status
# On branch my_branch
# Untracked files:
#   (use "git add <file>..." to include in what will be committed)
#
#       src/sage/primes/last_pair.py
nothing added to commit but untracked files present (use "git add" to track)

[user@localhost sage]$ git add src/sage/primes/last_pair.py
[user@localhost sage]$ git status
# On branch my_branch
# Changes to be committed:
#   (use "git reset HEAD <file>..." to unstage)
#
#       new file:   src/sage/primes/last_pair.py
#
```

Once you are satisfied with the list of staged files, you create a new snapshot with the `git commit` command:

```
[user@localhost sage]$ git commit
... editor opens ...
[my_branch 31331f7] Added the very important foobar text file
1 file changed, 1 insertion(+)
 create mode 100644 foobar.txt
```

This will open an editor for you to write your commit message. The commit message should generally have a one-line description, followed by an empty line, followed by further explanatory text:

```
Added the last twin prime
```

```
This is an example commit message. You see there is a one-line
summary followed by more detailed description, if necessary.
```

You can then continue working towards your next milestone, make another commit, repeat until finished. As long as you do not `git checkout` another branch, all commits that you make will be part of the branch that you created.

1.2 Using Git with Trac

To contribute back your changes to Sage source code to the project, you will need a ticket on the [Sage trac server](#).

1.2.1 The Sage Trac Server

Sometimes you will only want to work on local changes to Sage, for your own private needs. However, typically it is beneficial to share code and ideas with others; the manner in which the [Sage project](#) does this (as well as fixing bugs and upgrading components) is in a very collaborative and public setting on [the Sage Trac server](#) (the Sage bug and enhancement tracker).

The purpose of the Sage trac server is to

1. Provide a place for discussion on issues and store a permanent record.
2. Provide a repository of source code and all proposed changes.
3. Link these two together.

There is also a [wiki](#) for more general organizational web pages, like Sage development workshops.

Thus if you find a bug in Sage, if you have new code to submit, want to review new code already written but not yet included in Sage, or if you have corrections for the documentation, you should post on the trac server. Items on the server are called *tickets*, and anyone may search or browse the tickets. For a list of recent changes, just visit the [Sage trac timeline](#).

Obtaining an Account

If you do not have an account on GitHub yet, choose a user name and [create an account](#).

Using your GitHub account, you can log in to:

- [the Sage trac server](#), so that you can open tickets and participate in discussions on existing tickets.
On the Sage trac server, click the link “GitHub Login” in the top right corner and follow the prompts.
Within the Sage trac server, your GitHub user name will be prefixed with the letters gh- (which stand for “GitHub”).
- GitLab, where the mirror repository [sagemath/sage](#) accepts Merge Requests.
In GitLab, click the button “Sign in / Register” in the top right corner, and then use the button “Sign in with GitHub” and follow the prompts.

Users with legacy sage-trac accounts (account names not starting with “gh-”) should use the Login link. Do not to use GitHub login, as it will be treated as a separate user from their original account (unless you actively prefer to switch).

Reporting Bugs

If you think you have found a bug in Sage, here is the procedure:

- Search through our Google groups for postings related to your possible bug (it may have been fixed/reported already):
 - [sage-devel](#): <https://groups.google.com/group/sage-devel>
 - [sage-support](#): <https://groups.google.com/group/sage-support>

Similarly, you can search *The Sage Trac Server* to see if anyone else has opened a ticket about your bug.

- If you do not find anything, and you are not sure that you have found a bug, ask about it on [sage-devel](#). A bug report should contain:
 - An explicit and **reproducible example** illustrating your bug (and/or the steps required to reproduce the buggy behavior).
 - The **version** of Sage you run, as well as the version of the optional packages that may be involved in the bug.
 - Describe your **operating system** as accurately as you can and your architecture (32-bit, 64-bit, ...).
- You might be asked to open a new ticket. In this case, follow the [Guidelines for Opening Tickets](#).

Thank you in advance for reporting bugs to improve Sage in the future!

Guidelines for Opening Tickets

In addition to bug reports (see [Reporting Bugs](#)), you should also open a ticket if you have some new code that makes Sage a better tool. If you have a feature request, start a discussion on [sage-devel](#) first, and then if there seems to be general agreement that you have a good idea, open a ticket describing the idea.

- Do you already have a **trac account**? If not, [click here](#).

Before opening a new ticket, consider the following points:

- Make sure that nobody else has opened a ticket about the same or closely related issue.
- It is much better to open several specific tickets than one that is very broad. Indeed, a single ticket which deals with lots of different issues can be quite problematic, and should be avoided.
- Be precise: If foo does not work on OS X but is fine on Linux, mention that in the title. Use the keyword option so that searches will pick up the issue.
- The problem described in the ticket must be solvable. For example, it would be silly to open a ticket whose purpose was “Make Sage the best mathematical software in the world”. There is no metric to measure this properly and it is highly subjective.
- For bug reports: the ticket’s description should contain the information described at [Reporting Bugs](#).
- If appropriate, provide URLs to background information or [sage-devel](#) conversation relevant to the problem you are reporting.

When creating the ticket, you may find useful to read [The Ticket Fields](#).

Unless you know what you are doing, leave the milestone field to its default value.

The Ticket Fields

When you open a new ticket or change an existing ticket, you will find a variety of fields that can be changed. Here is a comprehensive overview (for the ‘status’ field, see [The Status of a Ticket](#)):

- **Reported by:** The trac account name of whoever created the ticket. Cannot be changed.
- **Owned by:** Trac account name of owner, by default the person in charge of the Component (see below). Generally not used in the Sage trac.
- **Type:** One of **enhancement** (e.g. a new feature), **defect** (e.g. a bug fix), or **task** (rarely used).
- **Priority:** The priority of the ticket. Keep in mind that the “blocker” label should be used very sparingly.
- **Milestone:** Milestones are usually goals to be met while working toward a release. In Sage’s trac, we use milestones instead of releases. Each ticket must have a milestone assigned. If you are unsure, assign it to the current milestone.

- **Component:** A list of components of Sage, pick one that most closely matches the ticket.
- **Keywords:** List of keywords. Fill in any keywords that you think will make your ticket easier to find. Tickets that have been worked on at Sage days NN (some number) after have sdNN as keyword.
- **Cc:** List of trac user names to Cc (send emails for changes on the ticket). Note that users that enter a comment are automatically subscribed to email updates and don't need to be listed under Cc.
- **Merged in:** The Sage release where the ticket was merged in. Only changed by the release manager.
- **Authors:** Real name of the ticket author(s). Set this field only if you intend to provide code.
- **Reviewers:** Real name of the ticket reviewer(s).
- **Report Upstream:** If the ticket is a bug in an upstream component of Sage, this field is used to summarize the communication with the upstream developers.
- **Work issues:** Issues that need to be resolved before the ticket can leave the "needs work" status.
- **Branch:** The Git branch containing the ticket's code (see [Branching Out](#)). It is displayed in green color, unless there is a conflict between the branch and the latest beta release (red color). In this case, the branch should be merged or rebased.
- **Dependencies:** Does the ticket depend on another ticket? Sometimes, a ticket requires that another ticket be applied first. If this is the case, put the dependencies as a comma-separated list (#1234, #5678) into the "Dependencies:" field.
- **Stopgaps:** See [Stopgaps](#).

The Status of a Ticket

The status of a ticket appears right next to its number, at the top-left corner of its page. It indicates who has to work on it.

- **new** – the ticket has only been created (or the author forgot to change the status to something else).
If you intend to work on the code yourself, put your name in the Authors field, or leave a comment to say so. It could avoid having two persons doing the same job.
- **needs_review** – the code is ready to be peer-reviewed. If the code is not yours, then you can review it. See [The reviewer's check list](#).
- **needs_work** – something needs to be changed in the code. The reason should appear in the comments.
- **needs_info** – somebody has to answer a question before anything else can happen. It should be clear from the comments.
- **positive_review** – the ticket has been reviewed, and the release manager will close it.

The status of a ticket can be changed using a form at the bottom of the ticket's page. Leave a comment explaining your reasons whenever you change it.

Stopgaps

When Sage returns wrong results, two tickets should be opened:

- A main ticket with all available details.
- A “stopgap” ticket (e.g. [trac ticket #12699](#))

This second ticket does not fix the problem but adds a warning that will be printed whenever anyone uses the relevant code. This, until the problem is finally fixed.

To produce the warning message, use code like the following:

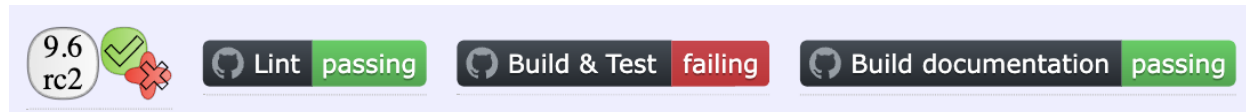
```
from sage.misc.stopgap import stopgap
stopgap("This code contains bugs and may be mathematically unreliable.",
        TICKET_NUM)
```

Replace `TICKET_NUM` by the ticket number for the main ticket. On the main trac ticket, enter the ticket number for the stopgap ticket in the “Stopgaps” field (see *The Ticket Fields*). Stopgap tickets should be marked as blockers.

Note: If mathematically valid code causes Sage to raise an error or crash, for example, there is no need for a stopgap. Rather, stopgaps are to warn users that they may be using buggy code; if Sage crashes, this is not an issue.

Working on Tickets

If you manage to fix a bug or enhance Sage you are our hero. See *Sage Development Process* for making changes to the Sage source code, uploading them to the Sage trac server, and finally putting your new branch on the trac ticket.



After pushing a branch to a ticket, the ticket will show badges linking to results of automated tests that run on the patchbot and other tests that run on GitHub Actions.

- The Patch buildbot will automatically test your ticket. See [trac ticket #wiki/patchbot](#) for more information about its features and limitations. Make sure that you look at the log, especially if the patch buildbot did not give you the green blob.
- A [linting workflow](#) runs on all pushes to a branch on Trac. It checks that the code of the current branch adheres to the style guidelines using *Pycodestyle* (in the *pycodestyle-minimal* configuration) and *Relint*.

In order to see details when it fails, you can click on the badge and then select the most recent workflow run.

- The [incremental build and test workflow](#) on GitHub Actions builds Sage for the current branch (incrementally on top of an installation of the `develop` branch) and runs the test. Note that in contrast to the patchbot, the ticket branch is not merged into the current beta version.

Details are again available by clicking on the badge.

The automatic workflow runs on a container based on `ubuntu-focal-standard`. To request a run of the workflow on a different platform, you can issue a [workflow_dispatch](#). You can select any of the platforms for which a [prebuilt container image](#) exists.

- The [build documentation workflow](#) on GitHub Actions builds the HTML documentation for the current branch.

If you click on the badge, you get the HTML output of the successful run. The idea is to use this to easily inspect changes to the documentation without the need to locally rebuild the docs yourself. If the doc build fails, you

can go to the [Actions tab](#) of [sagemath/sagetrac-mirror repo](#) and choose the particular branch to see what went wrong.

The following are some other relevant issues:

- Every bug fixed should result in a doctest.
- This is not an issue with defects, but there are many enhancements possible for Sage and too few developers to implement all the good ideas. The trac server is useful for keeping ideas in a central place because in the Google groups they tend to get lost once they drop off the first page.
- If you are a developer, be nice and try to solve a stale/old ticket every once in a while.
- Some people regularly do triage. In this context, this means that we look at new bugs and classify them according to our perceived priority. It is very likely that different people will see priorities of bugs very differently from us, so please let us know if you see a problem with specific tickets.

Reviewing and Closing Tickets

Tickets can be closed when they have positive review or for other reasons. To learn how to review, please see [The reviewer's check list](#).

Only the Sage release manager will close tickets. Most likely, this is not you nor will your trac account have the necessary permissions. If you feel strongly that a ticket should be closed or deleted, then change the status of the ticket to *needs review* and change the milestone to *sage-duplicate/invalid/wontfix*. You should also comment on the ticket, explaining why it should be closed. If another developer agrees, he sets the ticket to *positive review*.

A related issue is re-opening tickets. You should refrain from re-opening a ticket that is already closed. Instead, open a new ticket and provide a link in the description to the old ticket.

Reasons to Invalidate Tickets

One Issue Per Ticket: A ticket must cover only one issue and should not be a laundry list of unrelated issues. If a ticket covers more than one issue, we cannot close it and while some of the patches have been applied to a given release, the ticket would remain in limbo.

No Patch Bombs: Code that goes into Sage is peer-reviewed. If you show up with an 80,000 lines of code bundle that completely rips out a subsystem and replaces it with something else, you can imagine that the review process will be a little tedious. These huge patch bombs are problematic for several reasons and we prefer small, gradual changes that are easy to review and apply. This is not always possible (e.g. coercion rewrite), but it is still highly recommended that you avoid this style of development unless there is no way around it.

Sage Specific: Sage's philosophy is that we ship everything (or close to it) in one source tarball to make debugging possible. You can imagine the combinatorial explosion we would have to deal with if you replaced only ten components of Sage with external packages. Once you start replacing some of the more essential components of Sage that are commonly packaged (e.g. Pari, GAP, lisp, gmp), it is no longer a problem that belongs in our tracker. If your distribution's Pari package is buggy for example, file a bug report with them. We are usually willing and able to solve the problem, but there are no guarantees that we will help you out. Looking at the open number of tickets that are Sage specific, you hopefully will understand why.

No Support Discussions: The trac installation is not meant to be a system to track down problems when using Sage. Tickets should be clearly a bug and not "I tried to do X and I couldn't get it to work. How do I do this?" That is usually not a bug in Sage and it is likely that `sage-support` can answer that question for you. If it turns out that you did hit a bug, somebody will open a concise and to-the-point ticket.

Solution Must Be Achievable: Tickets must be achievable. Many times, tickets that fall into this category usually ran afoul to some of the other rules listed above. An example would be to "Make Sage the best CAS in the world". There is no metric to measure this properly and it is highly subjective.

The Release Process

The Sage Release Manager uses the following procedure to make releases, as of 2022.

Beta Release Stage: For preparing a new beta release or the first release candidate, all positively reviewed tickets with the forthcoming release milestone are considered. Tickets that have unmerged dependencies are ignored. The Release Manager merges tickets in batches of 10 to 20 tickets, taking the ticket priority into account. If a merge conflict of a ticket to the Release Manager's branch occurs, the ticket is set back to "needs work" status by the Release Manager, and the list of the tickets already merged to the Release Manager's branch is posted. The author of the ticket needs to identify conflicting tickets in the list, make merge commits and declare them as dependencies, before setting back to "positive review" status. Each batch of merged tickets then undergoes integration testing. If problems are detected, a ticket will be set back to "needs work" status and unmerged. When a batch of tickets is ready, the Release Manager closes these tickets and proceeds to the next batch. After a few batches, a new beta release is tagged, pushed to the `develop` branch on the main git repository, and announced on `sage-release`.

Release Candidate Stage: After the first release candidate has been made, the project is in the release candidate stage, and a modified procedure is used. Now **only tickets with a priority set to "blocker" are considered**. Tickets with all other priorities, including "critical", are ignored. Hence if a ticket is important enough to merit inclusion in this stage, it should be set to "blocker".

Blocker Tickets: The goal of the release process is to make a stable release of high quality. Be aware that there is a risk/benefit trade-off in merging a ticket. The benefit of merging a ticket is the improvement that the ticket brings, such as fixing a bug. However, any code change has a risk of introducing unforeseen new problems and thus delaying the release: If a new issue triggers another release candidate, it delays the release by 1-2 weeks. Hence developers should use "blocker" priority sparingly and should indicate the rationale on the ticket. Though there is no one fixed rule or authority that determines what is appropriate for "blocker" status,

- Tickets introducing new features are usually not blockers – unless perhaps they round out a set of features that were the focus of development of this release cycle.
- Tickets that make big changes to the code, for example refactoring tickets, are usually not blockers.

Final Release: If there is no blocker ticket for the last release candidate, the Release Manager turns it to the final release. It is tagged with the release milestone, and announced on `sage-release`.

1.2.2 Using Git with the Sage Trac Server

Now we continue our introduction to git from *Sage Development Process*. We discuss how to push your local changes to a remote repository so that your changes can be reviewed for inclusion in Sage.

In the following, we assume that you are in the source directory of Sage (`SAGE_ROOT`), obtained either from a source tarball or by cloning a Sage git repository such as <https://github.com/sagemath/sage.git>, as described in the [README](#). In either case, this source directory is actually the main worktree of a local git repository.

Using the following command, we can see which remote repository or repositories are associated with this local repository:

```
[user@localhost sage]$ git remote -v
origin      https://github.com/sagemath/sage.git (fetch)
origin      https://github.com/sagemath/sage.git (push)
```

Git authentication through SSH

In order to push changes securely to a remote repository, git uses public-key cryptography. This section will show you how to set up the necessary cryptographic keys for Secure Shell (SSH).

Checking whether you have already have suitable SSH keys

Follow the instructions in <https://docs.gitlab.com/ee/user/ssh.html#see-if-you-have-an-existing-ssh-key-pair>.

Generating your SSH Keys

If you don't have suitable SSH keys yet, you can create a key pair with the `ssh-keygen` tool.

Follow either the detailed instructions at <https://docs.gitlab.com/ee/user/ssh.html#generate-an-ssh-key-pair> or the following brief instructions:

```
[user@localhost ~]$ ssh-keygen
Generating public/private rsa key pair.
Enter file in which to save the key (/home/user/.ssh/id_rsa):
Enter passphrase (empty for no passphrase):
Enter same passphrase again:
Your identification has been saved in /home/user/.ssh/id_rsa.
Your public key has been saved in /home/user/.ssh/id_rsa.pub.
The key fingerprint is:
ce:32:b3:de:38:56:80:c9:11:f0:b3:88:f2:1c:89:0a user@localhost
The key's randomart image is:
+--[ RSA 2048 ]-----+
|    . . . .    |
|    . .        |
|    .o+        |
| o o+o.        |
|E + . .S       |
|+o . . o.      |
| . o  +.o      |
|      oB       |
|      o+..     |
+-----+
```

This will generate a new random private RSA key in the `.ssh` folder in your home directory. By default, they are

`~/.ssh/id_rsa` Your private key. Keep safe. **Never** hand it out to anybody.

`~/.ssh/id_rsa.pub` The corresponding public key. This and only this file can be safely disclosed to third parties.

The `ssh-keygen` tool will let you generate a key with a different file name, or protect it with a passphrase. Depending on how much you trust your own computer or system administrator, you can leave the passphrase empty to be able to login without any human intervention.

Linking your Public Key to your Trac Account

In order to push your code directly to a branch on the git repository `trac.sagemath.org`, the Sage trac server needs to know your public key. You can upload it in the preferences, that is

1. Go to <https://trac.sagemath.org>
2. Log in with your trac username/password
3. Click on “Preferences”
4. Go to the “SSH Keys” tab
5. Paste the content of your public key file (e.g. `~/.ssh/id_rsa.pub`)
6. Click on “Save changes”

Note that this does **not** allow you to ssh into any account on trac, it is only used to authenticate you to the gitolite installation on trac. You can test that you are being authenticated correctly by issuing some basic gitolite commands, for example:

```
[user@localhost ~]$ ssh git@trac.sagemath.org info
hello user, this is git@trac running gitolite3 (unknown) on git 1.7.9.5

R W      sage
[user@localhost ~]$ ssh git@trac.sagemath.org help
hello user, this is gitolite3 (unknown) on git 1.7.9.5

list of remote commands available:

    desc
    help
    info
    perms
    writable
```

Adding your Public Key for authentication on another server

If you have an account on a lab or department computer that allows you to log in remotely via SSH, you can now also use your SSH keys to log in. Just copy the **public** key file (ending in `.pub`) to `~/.ssh/authorized_keys` on the remote computer and make sure that the file is only read/writeable by yourself. Voila, the next time you ssh into that machine you don't have to provide your password.

The git repository `trac.sagemath.org`

The Sage trac server is another git repository for the Sage source tree, it is served via the ssh protocol. To add it as a remote repository to your local git repository, use these commands:

```
[user@localhost sage]$ git remote add trac https://github.com/sagemath/sagetrac-mirror.
↪git -t master
[user@localhost sage]$ git remote set-url --push trac git@trac.sagemath.org:sage.git
```

Instead of `trac` you can use any other name you want, of course. To verify that it is set up correctly:

```
[user@localhost sage]$ git remote -v
origin      https://github.com/sagemath/sage.git (fetch)
origin      https://github.com/sagemath/sage.git (push)
trac        https://github.com/sagemath/sagetrac-mirror.git (fetch)
trac        git@trac.sagemath.org:sage.git (push)
```

It is perfectly fine to have multiple remote repositories for git, think of them as bookmarks. You can then use `git pull` to get changes and `git push` to upload your local changes using:

```
[user@localhost sage]$ git <push|pull> trac [ARGS]
```

Note: In the command above we set up the remote to only track the `master` branch on the trac server (the `-t master` option). This avoids clutter by not automatically downloading all branches ever created. But it also means that you will not fetch everything that is on trac by default, and you need to explicitly tell git which branch you want to get from trac. See the [Checking Out Tickets](#) section for examples.

Note that write operations (push) use the ssh protocol (specified by the `git@` part). For this to work, you need to have a trac account and to set up your ssh public key as described in [Trac authentication through ssh](#). Authentication is necessary if you want to upload anything to ensure that it really is from you.

The above instructions set up the remote to perform read-only operations (fetch) using HTTPS from a mirror of the trac repository instead. The mirror is faster and more reliable than our git server. However, this configuration is not recommended if you use VS Code as an IDE.

If you want to use ssh only for both fetch and push, use the following commands instead:

```
[user@localhost sage]$ git remote add trac git@trac.sagemath.org:sage.git -t master
[user@localhost sage]$ git remote -v
origin      https://github.com/sagemath/sage.git (fetch)
origin      https://github.com/sagemath/sage.git (push)
trac        git@trac.sagemath.org:sage.git (fetch)
trac        git@trac.sagemath.org:sage.git (push)
```

Checking Out Tickets

Trac tickets that are finished or in the process of being worked on can have a git branch attached to them. This is the “Branch:” field in the ticket description. The branch name is generally of the form `u/user/description`, where `user` is the name of the user who made the branch and `description` is some free-form short description (and can include further slashes).

If you want to work with the changes in that remote branch, you must make a local copy. In particular, git has no concept of directly working with the remote branch, the remotes are only bookmarks for things that you can get from/to the remote server. Hence, the first thing you should do is to get everything from the trac server’s branch into your local repository. This is achieved by:

```
[user@localhost sage]$ git fetch trac u/user/description
remote: Counting objects: 62, done.
remote: Compressing objects: 100% (48/48), done.
remote: Total 48 (delta 42), reused 0 (delta 0)
Unpacking objects: 100% (48/48), done.
From trac.sagemath.org:sage
* [new branch]      u/user/description -> FETCH_HEAD
```

The `u/user/description` branch is now temporarily (until you fetch something else) stored in your local git database under the alias `FETCH_HEAD`. In the second step, we make it available as a new local branch and switch to it. Your local branch can have a different name, for example:

```
[user@localhost sage]$ git checkout -b my_branch FETCH_HEAD
Switched to a new branch 'my_branch'
```

creates a new branch in your local git repository named `my_branch` and modifies your local Sage filesystem tree to the state of the files in that ticket. You can now edit files and commit changes to your local branch.

Pushing Your Changes to a Ticket

To add your local branch to a trac ticket, you should first decide on a name on the Sage trac repository.

For read/write permissions on git branches, see [Note on Branch Names](#)

In order to avoid name clashes, you can use `u/your_username/a_description_of_your_branch` (the description can contain slashes, but no spaces). Then:

- **Fill** the Branch field of the trac ticket with that name.
- **Push** your branch to trac with either:

```
[user@localhost sage]$ git push --set-upstream trac HEAD:u/user/description
```

if you started the branch yourself and do not follow any other branch, or use:

```
[user@localhost sage]$ git push trac HEAD:u/user/description
```

if your branch already has an upstream branch.

Here, `HEAD` means that you are pushing the most recent commit (and, by extension, all of its parent commits) of the current local branch to the remote branch.

The Branch field on the trac ticket can appear in red/green. See [The Ticket Fields](#) to learn what it means.

Getting Changes

A common task during development is to synchronize your local copy of the branch with the branch on trac. In particular, assume you downloaded somebody else's branch and made some suggestions for improvements on the trac ticket. Now the original author incorporated your suggestions into his branch, and you want to get the added changesets to complete your review. Assuming that you originally got your local branch as in [Checking Out Tickets](#), you can just issue:

```
[user@localhost sage]$ git pull trac u/user/description
From trac.sagemath.org:sage
 * branch          u/user/description -> FETCH_HEAD
Updating 8237337..07152d8
Fast-forward
 src/sage/tests/cmdline.py      | 3 ++-
 1 file changed, 2 insertions(+), 1 deletions(-)
```

where now `user` is the other developer's trac username and `description` is some description that he chose. This command will download the changes from the originally-used remote branch and merge them into your local branch. If you haven't published your local commits yet then you can also rebase them via:

```
[user@localhost sage]$ git pull -r trac u/user/description
From trac.sagemath.org:sage
 * branch          u/user/description -> FETCH_HEAD
First, rewinding head to replay your work on top of it...
Applying: my local commit
```

See *Merging and Rebasing* section for an in-depth explanation of merge vs. rebase.

So far, we assumed that there are no conflicts. It is unavoidable in distributed development that, sometimes, the same location in a source file is changed by more than one person. Reconciling these conflicting edits is explained in the *Conflict Resolution* section.

Updating Master

The `master` branch can be updated just like any other branch. However, your local copy of the master branch should stay **identical** to the trac master branch.

If you accidentally added commits to your local copy of `master`, you must delete them before updating the branch.

One way to ensure that you are notified of potential problems is to use `git pull --ff-only`, which will raise an error if a non-trivial merge would be required:

```
[user@localhost sage]$ git checkout master
[user@localhost sage]$ git pull --ff-only trac master
```

If this pull fails, then something is wrong with the local copy of the master branch. To switch to the correct Sage master branch, use:

```
[user@localhost sage]$ git checkout master
[user@localhost sage]$ git reset --hard trac/master
```

Merging and Rebasing

Sometimes, a new version of Sage is released while you work on a git branch.

Let us assume you started `my_branch` at commit B. After a while, your branch has advanced to commit Z, but you updated `master` (see *Updating Master*) and now your git history looks like this (see *The History*):

```
      X---Y---Z my_branch
      /
A---B---C---D master
```

How should you deal with such changes? In principle, there are two ways:

- **Rebase:** The first solution is to **replay** commits X,Y,Z atop of the new master. This is called **rebase**, and it rewrites your current branch:

```
git checkout my_branch
git rebase -i master
```

In terms of the commit graph, this results in:

```
      X'--Y'--Z' my_branch
      /
A---B---C---D master
```

Note that this operation rewrites the history of `my_branch` (see [Rewriting History](#)). This can lead to problems if somebody began to write code atop of your commits X, Y, Z. It is safe otherwise.

Alternatively, you can rebase `my_branch` while updating master at the same time (see [Getting Changes](#)):

```
git checkout my_branch
git pull -r master
```

- **Merging** your branch with master will create a new commit above the two of them:

```
git checkout my_branch
git merge master
```

The result is the following commit graph:

```
      X---Y---Z---W my_branch
      /       /
A---B---C-----D master
```

- **Pros:** you did not rewrite history (see [Rewriting History](#)). The additional commit is then easily pushed to the git repository and distributed to your collaborators.
- **Cons:** it introduced an extra merge commit that would not be there had you used rebase.

Alternatively, you can merge `my_branch` while updating master at the same time (see [Getting Changes](#)):

```
git checkout my_branch
git pull master
```

In case of doubt use merge rather than rebase. There is less risk involved, and rebase in this case is only useful for branches with a very long history.

Finally, **do nothing unless necessary**: it is perfectly fine for your branch to be behind master. You can always merge/rebase if/when your branch's name appears in red on its trac page (see [The Ticket Fields](#)), or when you will really need a feature that is only available in the current master.

Merge Tools

Simple conflicts can be easily solved with git only (see [Conflict Resolution](#))

For more complicated ones, a range of specialized programs are available. Because the conflict marker includes the hash of the most recent common parent, you can use a three-way diff:

```
[alice@laptop]$ git mergetool
```

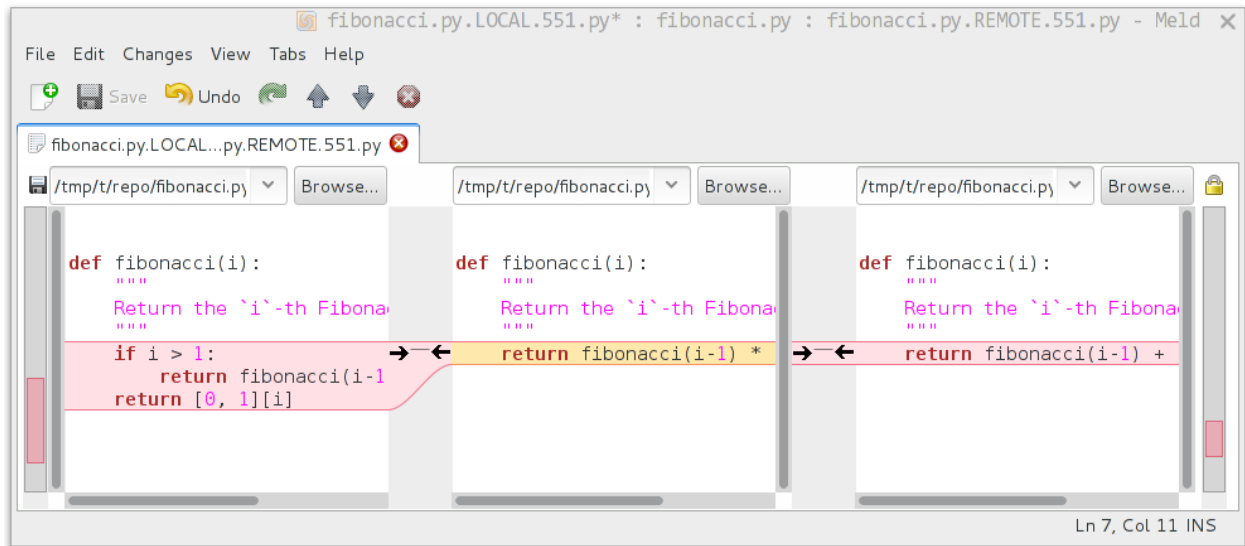
```
This message is displayed because 'merge.tool' is not configured.
See 'git mergetool --tool-help' or 'git help config' for more details.
'git mergetool' will now attempt to use one of the following tools:
meld opendiff kdiff3 [...] merge araxis bc3 codecompare emerge vimdiff
Merging:
fibonacci.py
```

(continues on next page)

(continued from previous page)

```
Normal merge conflict for 'fibonacci.py':
{local}: modified file
{remote}: modified file
Hit return to start merge resolution tool (meld):
```

If you don't have a favourite merge tool we suggest you try [meld](#) (cross-platform). The result looks like the following screenshot.



The middle file is the most recent common parent; on the right is Bob's version and on the left is Alice's conflicting version. Clicking on the arrow moves the marked change to the file in the adjacent pane.

1.2.3 Tips and References

This chapter contains additional material about the git revision control system. See [Setting Up Git](#) for the minimal steps needed for Sage development.

Configuration Tips

Your personal git configurations are saved in the `~/.gitconfig` file in your home directory. Here is an example:

```
[user]
  name = Your Name
  email = you@yourdomain.example.com

[core]
  editor = emacs
```

You can edit this file directly or you can use git to make changes for you:

```
[user@localhost ~] git config --global user.name "Your Name"
[user@localhost ~] git config --global user.email you@yourdomain.example.com
[user@localhost ~] git config --global core.editor vim
```

Aliases

Aliases are personal shortcuts for git commands. For example, you might want to be able to shorten `git checkout` to `git co`. Or you may want to alias `git diff --color-words` (which gives a nicely formatted output of the diff) to `git wdiff`. You can do this with:

```
[user@localhost ~] git config --global alias.ci "commit -a"
[user@localhost ~] git config --global alias.co checkout
[user@localhost ~] git config --global alias.st "status -a"
[user@localhost ~] git config --global alias.stat "status -a"
[user@localhost ~] git config --global alias.br branch
[user@localhost ~] git config --global alias.wdiff "diff --color-words"
```

The above commands will create an alias section in your `.gitconfig` file with contents like this:

```
[alias]
  ci = commit -a
  co = checkout
  st = status -a
  stat = status -a
  br = branch
  wdiff = diff --color-words
```

Editor

To set the editor to use for editing commit messages, you can use:

```
[user@localhost ~] git config --global core.editor vim
```

or set the *EDITOR* environment variable.

Merging

To enforce summaries when doing merges (`~/ .gitconfig` file again):

```
[merge]
  log = true
```

Or from the command line:

```
[user@localhost ~] git config --global merge.log true
```

Fancy Log Output

Here is an alias to get a fancy log output; it should go in the alias section of your `.gitconfig` file:

```
lg = log --graph --pretty=format:'%Cred%h%Creset -%C(yellow)%d%Creset %s %Cgreen(%cr)
%C(bold blue)[%an]%Creset' --abbrev-commit --date=relative
```

Using this `lg` alias gives you the changelog with a colored ascii graph:

```
[user@localhost ~] git lg
* 6d8e1ee - (HEAD, origin/my-fancy-feature, my-fancy-feature) NF - a fancy file (45
↳ minutes ago) [Matthew Brett]
* d304a73 - (origin/placeholder, placeholder) Merge pull request #48 from hhuuggoo/
↳ master (2 weeks ago) [Jonathan Terhorst]
| \
| * 4aff2a8 - fixed bug 35, and added a test in test_bugfixes (2 weeks ago) [Hugo]
| /
* a7ff2e5 - Added notes on discussion/proposal made during Data Array Summit. (2 weeks
↳ ago) [Corran Webster]
* 68f6752 - Initial implementation of AxisIndexer - uses 'index_by' which needs to be
↳ changed to a call on an Axes object - this is all very sketchy right now. (2 weeks
↳ ago) [Corr
* 376adbd - Merge pull request #46 from terhorst/master (2 weeks ago) [Jonathan
↳ Terhorst]
| \
| * b605216 - updated joshu example to current api (3 weeks ago) [Jonathan Terhorst]
| * 2e991e8 - add testing for outer ufunc (3 weeks ago) [Jonathan Terhorst]
| * 7beda5a - prevent axis from throwing an exception if testing equality with non-axis
↳ object (3 weeks ago) [Jonathan Terhorst]
| * 65af65e - convert unit testing code to assertions (3 weeks ago) [Jonathan Terhorst]
| * 956fbab - Merge remote-tracking branch 'upstream/master' (3 weeks ago) [Jonathan
↳ Terhorst]
| | \
| | /
```

Tutorials and Summaries

There are many, many tutorials and command summaries available online.

Beginner

- [Try Git](#) is an entry-level tutorial you can do in your browser. If you are unfamiliar with revision control, you will want to pay close attention to the “Advice” section toward the bottom.
- [Git magic](#) is an extended introduction with intermediate detail.
- The [git parable](#) is an easy read explaining the concepts behind git.
- [Git foundation](#) expands on the [git parable](#).
- Although it also contains more advanced material about branches and detached head and the like, the visual summaries of merging and branches in [Learn Git Branching](#) are really quite helpful.

Advanced

- [Github help](#) has an excellent series of how-to guides.
- The [pro git book](#) is a good in-depth book on git.
- [Github Training](#) has an excellent series of tutorials as well as videos and screencasts.
- The [git tutorial](#).
- [Git ready](#) is a nice series of tutorials.
- [Fernando Perez' git page](#) contains many links and tips.
- A good but technical page on [git concepts](#)
- [Git svn crash course](#): git for those of us used to [subversion](#)

Summaries/Cheat Sheets

- A [git cheat sheet](#) is a page giving summaries of common commands.
- The [git user manual](#).

Git Best Practices

There are many ways of working with git; here are some posts on the rules of thumb that other projects have come up with:

- [Linus Torvalds on git management](#)
- [Linus Torvalds on linux git workflow](#). Summary: use the git tools to make the history of your edits as clean as possible; merge from upstream edits as little as possible in branches where you are doing active development.

Manual Pages Online

You can get these on your own machine with (e.g) `git help push` or (same thing) `git push --help`, but, for convenience, here are the online manual pages for some common commands:

- `git add`
- `git branch`
- `git checkout`
- `git clone`
- `git commit`
- `git config`
- `git diff`
- `git log`
- `git pull`
- `git push`
- `git remote`
- `git status`

1.2.4 Advanced Git

This chapter covers some advanced uses of git that go beyond what is required to work with branches. These features can be used in Sage development, but are not really necessary to contribute to Sage. If you are just getting started with Sage development, you should read *Sage Development Process* and *Using Git with the Sage Trac Server* instead.

Detached Heads and Reviewing Tickets

Each commit is a snapshot of the Sage source tree at a certain point. So far, we always used commits organized in branches. But secretly the branch is just a shortcut for a particular commit, the head commit of the branch. But you can just go to a particular commit without a branch, this is called “detached head”. If you have the commit already in your local history, you can directly check it out without requiring internet access:

```
[user@localhost sage]$ git checkout a63227d0636e29a8212c32eb9ca84e9588bbf80b
Note: checking out 'a63227d0636e29a8212c32eb9ca84e9588bbf80b'.
```

You are in 'detached HEAD' state. You can look around, make experimental changes and commit them, and you can discard any commits you make in this state without impacting any branches by performing another checkout.

If you want to create a new branch to retain commits you create, you may do so (now or later) by using `-b` with the checkout command again. Example:

```
git checkout -b new_branch_name
```

HEAD is now at a63227d... Szekeres Snark Graph constructor

If it is not stored in your local git repository, you need to download it from the trac server first:

```
[user@localhost sage]$ git fetch trac a63227d0636e29a8212c32eb9ca84e9588bbf80b
From ssh://trac/sage
 * branch                a63227d0636e29a8212c32eb9ca84e9588bbf80b -> FETCH_HEAD
[user@localhost sage]$ git checkout FETCH_HEAD
HEAD is now at a63227d... Szekeres Snark Graph constructor
```

Either way, you end up with your current HEAD and working directory that is not associated to any local branch:

```
[user@localhost sage]$ git status
# HEAD detached at a63227d
nothing to commit, working directory clean
```

This is perfectly fine. You can switch to an existing branch (with the usual `git checkout my_branch`) and back to your detached head.

Detached heads can be used to your advantage when reviewing tickets. Just check out the commit (look at the “Commit:” field on the trac ticket) that you are reviewing as a detached head. Then you can look at the changes and run tests in the detached head. When you are finished with the review, you just abandon the detached head. That way you never create a new local branch, so you don’t have to type `git branch -D my_branch` at the end to delete the local branch that you created only to review the ticket.

Update Branch to Latest SageMath Version (and Minimizing Recompilation Time)

- You have a compiled and working new SageMath version `n`, and
- you want to work on a branch `some_code` which is based on some old SageMath version `o`
- by updating this branch from version `o` to `n`
- with only recompiling changed files (and not all touched files from `o` to `n`),
- then continue reading this section.

Introduction

When developing, quite frequently one ends up with a branch which is not based on the latest (beta) version of SageMath.

Note: Continue working on a feature based on an old branch is perfectly fine and usually there is no need to merge in this latest SageMath version.

However sometimes there is a need for a merge, for example

- if there are conflicts with the latest version or
- one needs a recent feature or
- simply because the old SageMath version is not available on your machine any longer.

Then merging in the latest SageMath version has to be done.

Merge in the Latest SageMath Version

(This is the easy way without minimizing the recompilation time.)

Suppose we are on our current working branch `some_code` (branch is checked out). Then

```
git merge develop
```

does the merging, i.e. we merge the latest development version into our working branch.

However, after this merge, we need to (partially) recompile SageMath. Sometimes this can take ages (as many files are touched and their timestamps are renewed) and there is a way to avoid it.

Minimize the Recompilation Time

Suppose we are on some new SageMath (e.g. on branch `develop`) which was already compiled and runs successfully, and we have an “old” branch `some_code`, that we want to bring onto this SageMath version (without triggering unnecessary recompilations).

We first create a new working tree in a directory `new_worktree` and switch to this directory:

```
git worktree add new_worktree
cd new_worktree
```

Here we have a new copy of our source files. Thus no timestamps etc. of the original repository will be changed. Now we do the merge:

```
git checkout some_code
git merge develop
```

And go back to our original repository:

```
git checkout develop
cd ..
```

We can now safely checkout `some_code`:

```
git checkout some_code
```

We still need to call

```
make
```

but only changed files will be recompiled.

To remove the new working tree simply use

```
rm -r new_worktree
```

Why not Merging the Other Way Round?

Being on some new SageMath (e.g. on branch `develop`) which runs successfully, it would be possible to merge in our branch `some_code` into `develop`. This would produce the same source files and avoid unnecessary recompilations. However, it makes reading git's history very unpleasant: For example, it is hard to keep track of changes etc., as one cannot simply pursue the first parent of each git commit (`git log --first-parent`).

Reset and Recovery

Git makes it very hard to truly mess up. Here is a short way to get back onto your feet, no matter what. First, if you just want to go back to a working Sage installation you can always abandon your working branch by switching to your local copy of the `master` branch:

```
[user@localhost sage]$ git checkout master
```

As long as you did not make any changes to the `master` branch directly, this will give you back a working Sage.

If you want to keep your branch but go back to a previous commit you can use the `reset` command. For this, look up the commit in the log which is some 40-digit hexadecimal number (the SHA1 hash). Then use `git reset --hard` to revert your files back to the previous state:

```
[user@localhost sage]$ git log
...
commit eafaedad5b0ae2013f8ae1091d2f1df58b72bae3
Author: First Last <user@email.com>
Date:   Sat Jul 20 21:57:33 2013 -0400

    Commit message
...
[user@localhost sage]$ git reset --hard eafae
```

Warning: Any *uncommitted* changes will be lost!

You only need to type the first couple of hex digits, git will complain if this does not uniquely specify a commit. Also, there is the useful abbreviation `HEAD~` for the previous commit and `HEAD~n`, with some integer `n`, for the `n`-th previous commit.

Finally, perhaps the ultimate human error recovery tool is the `reflog`. This is a chronological history of git operations that you can undo if needed. For example, let us assume we messed up the `git reset` command and went back too far (say, 5 commits back). And, on top of that, deleted a file and committed that:

```
[user@localhost sage]$ git reset --hard HEAD~5
[user@localhost sage]$ git rm sage
[user@localhost sage]$ git commit -m "I shot myself into my foot"
```

Now we cannot just checkout the repository from before the reset, because it is no longer in the history. However, here is the `reflog`:

```
[user@localhost sage]$ git reflog
2eca2a2 HEAD@{0}: commit: I shot myself into my foot
b4d86b9 HEAD@{1}: reset: moving to HEAD~5
af353bb HEAD@{2}: checkout: moving from some_branch to master
```

(continues on next page)

(continued from previous page)

```
1142feb HEAD@{3}: checkout: moving from other_branch to some_branch
...
```

The `HEAD@{n}` revisions are shortcuts for the history of git operations. Since we want to rewind to before the erroneous `git reset` command, we just have to reset back into the future:

```
[user@localhost sage]$ git reset --hard HEAD@{2}
```

Rewriting History

Git allows you to rewrite history, but be careful: the SHA1 hash of a commit includes the parent's hash. This means that the hash really depends on the entire content of the working directory; every source file is in exactly the same state as when the hash was computed. This also means that you can't change history without modifying the hash. If others branched off your code and then you rewrite history, then the others are thoroughly screwed. So, ideally, you would only rewrite history on branches that you have not yet pushed to trac.

As an advanced example, consider three commits A, B, C that were made on top of each other. For simplicity, we'll assume they just added a file named `file_A.py`, `file_B.py`, and `file_C.py`

```
[user@localhost]$ git log --oneline
9621dae added file C
7873447 added file B
bf817a5 added file A
5b5588e base commit
```

Now, let's assume that the commit B was really independent and ought to be on a separate ticket. So we want to move it to a new branch, which we'll call `second_branch`. First, branch off at the base commit before we added A:

```
[user@localhost]$ git checkout 5b5588e
Note: checking out '5b5588e'.
```

You are in 'detached HEAD' state. You can look around, make experimental changes and commit them, and you can discard any commits you make in this state without impacting any branches by performing another checkout.

If you want to create a new branch to retain commits you create, you may do so (now or later) by using `-b` with the checkout command again. Example:

```
git checkout -b new_branch_name

HEAD is now at 5b5588e... base commit
[user@localhost]$ git checkout -b second_branch
Switched to a new branch 'second_branch'
[user@localhost]$ git branch
  first_branch
* second_branch
[user@localhost]$ git log --oneline
5b5588e base commit
```

Now, we make a copy of commit B in the current branch:

```
[user@localhost]$ git cherry-pick 7873447
[second_branch 758522b] added file B
1 file changed, 1 insertion(+)
create mode 100644 file_B.py
[user@localhost]$ git log --oneline
758522b added file B
5b5588e base commit
```

Note that this changes the SHA1 of the commit B, since its parent changed! Also, cherry-picking *copies* commits, it does not remove them from the source branch. So we now have to modify the first branch to exclude commit B, otherwise there will be two commits adding file_B.py and our two branches would conflict later when they are being merged into Sage. Hence, we first reset the first branch back to before B was added:

```
[user@localhost]$ git checkout first_branch
Switched to branch 'first_branch'
[user@localhost]$ git reset --hard bf817a5
HEAD is now at bf817a5 added file A
```

Now we still want commit C, so we cherry-pick it again. Note that this works even though commit C is, at this point, not included in any branch:

```
[user@localhost]$ git cherry-pick 9621dae
[first_branch 5844535] added file C
1 file changed, 1 insertion(+)
create mode 100644 file_C.py
[user@localhost]$ git log --oneline
5844535 added file C
bf817a5 added file A
5b5588e base commit
```

And, again, we note that the SHA1 of commit C changed because its parent changed. Voila, now you have two branches where the first contains commits A, C and the second contains commit B.

Interactively Rebasing

An alternative approach to *Rewriting History* is to use the interactive rebase feature. This will open an editor where you can modify the most recent commits. Again, this will naturally modify the hash of all changed commits and all of their children.

Now we start by making an identical branch to the first branch:

```
[user@localhost]$ git log --oneline
9621dae added file C
7873447 added file B
bf817a5 added file A
5b5588e base commit
[user@localhost]$ git checkout -b second_branch
Switched to a new branch 'second_branch'
[user@localhost]$ git rebase -i HEAD~3
```

This will open an editor with the last 3 (corresponding to HEAD~3) commits and instructions for how to modify them:

```

pick bf817a5 added file A
pick 7873447 added file B
pick 9621dae added file C

# Rebase 5b5588e..9621dae onto 5b5588e
#
# Commands:
# p, pick = use commit
# r, reword = use commit, but edit the commit message
# e, edit = use commit, but stop for amending
# s, squash = use commit, but meld into previous commit
# f, fixup = like "squash", but discard this commit's log message
# x, exec = run command (the rest of the line) using shell
#
# These lines can be re-ordered; they are executed from top to bottom.
#
# If you remove a line here THAT COMMIT WILL BE LOST.
#
# However, if you remove everything, the rebase will be aborted.
#
# Note that empty commits are commented out

```

To only use commit B, we delete the first and third line. Then save and quit your editor, and your branch now consists only of the B commit.

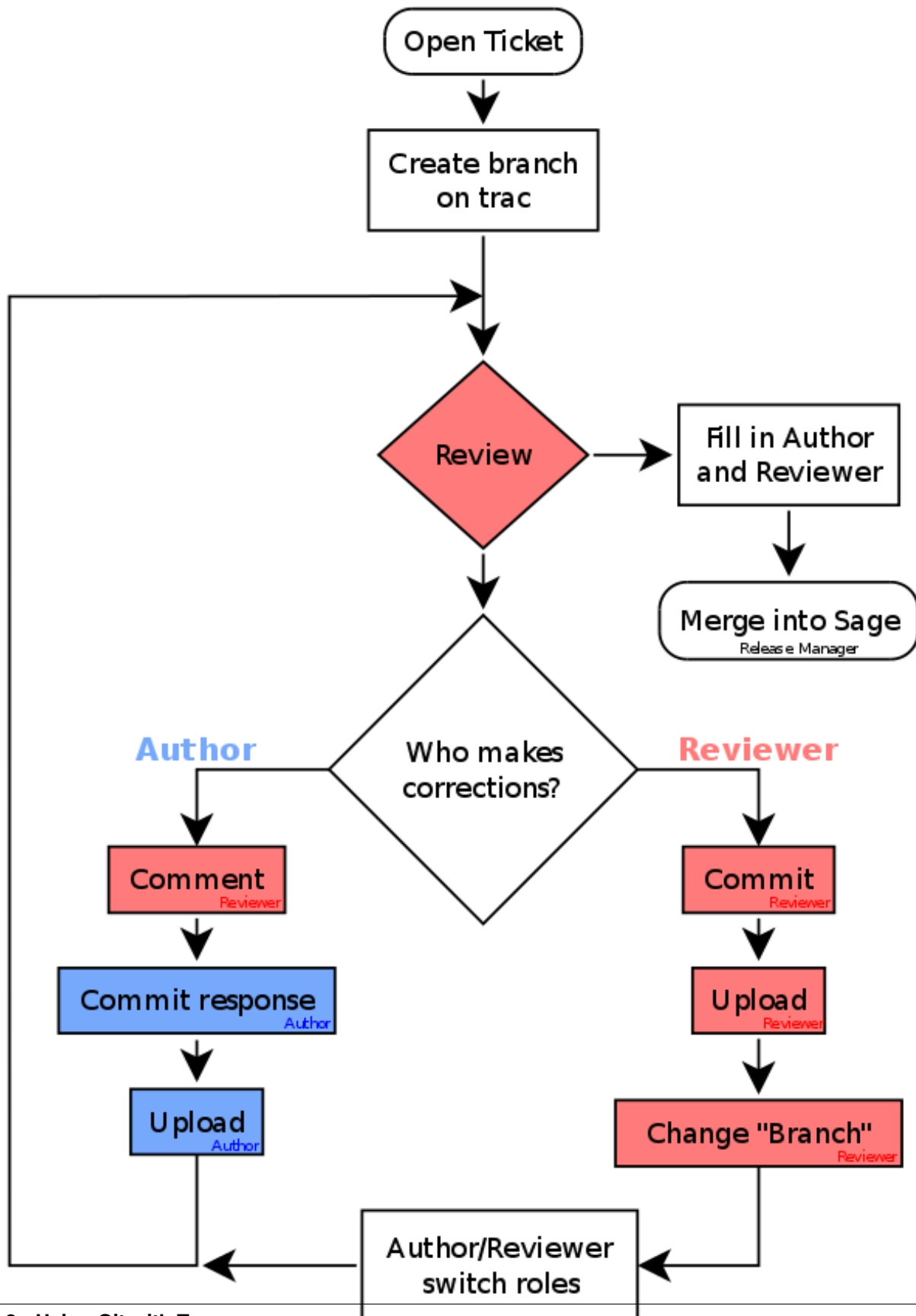
You still have to delete the B commit from the first branch, so you would go back (`git checkout first_branch`) and then run the same `git rebase -i` command and delete the B commit.

1.2.5 Distributed Development

Git is a tool to exchange commits (organized into branches) with other developers. As a distributed revision control system, it does not have the notion of a central server. The Sage trac server is just one of many possible remote repositories from your point of view. This lets you use and experiment with different ways to interact with other developers. In this chapter, we describe some common ways to develop for Sage.

For simplicity, let us assume two developers (Alice and Bob) are collaborating on a ticket. The first step of opening the ticket is always the same, and could be performed by either Alice or Bob or a third person.

Simple Workflow



1. Alice creates a *new local branch* and *commits* changes to the Sage sources.
2. Alice *uploads her branch* to the trac server. This fills in the “Branch:” field with her remote branch name `u/alice/description`.
3. Bob *downloads Alice's branch*, looks through the source, and leaves a comment on the ticket about a mistake in Alice's code.
4. Alice fixes the bug on top of her current branch, and uploads the updated branch.
5. Bob *retrieves Alice's updates* and reviews the changes.
6. Once Bob is satisfied, he sets the ticket to positive review. The “Author:” field is set to Alice's full name, and the “Reviewer:” field is set to Bob's full name.

Alternatively, Bob might want to make some changes himself. Then, instead, we would have

3. Bob *downloads Alice's branch*, makes changes, and *commits* them to his local branch.
4. Bob *uploads his branch* to the trac server. This fills in the “Branch:” field with his remote branch name `u/bob/description`.
5. Alice *downloads Bob's branch* and reviews his changes.
6. Once Alice is satisfied, she sets the ticket to positive review. If both contributions are of comparable size, then the “Author:” and “Reviewer:” fields are set to both Alice's and Bob's full name.

Public Repository

In addition to the user branches (`u/<user>/<description>` on the Sage trac server with `<user>` replaced by your trac user name) that only you can write to, you can also create a public branch that everybody with a trac account can write to. These start with `public/` plus some description. To avoid branch name collisions it is a good idea to include your trac user name in the branch name, so it is recommended that you use `public/<user>/<description>` as the branch name. Now all ticket authors push to the same remote branch.

1. Alice creates a *new local branch* and *commits* some changes to the Sage library.
2. Alice *uploads her branch* as a public branch to the trac server. This fills in the “Branch:” field with her remote branch name `public/alice/description`.
3. Bob *downloads Alice's branch* and makes changes to his local copy.
4. Bob *commits* changes to his local branch of the Sage sources.
5. Bob uploads his changes to the joint remote repository:

```
[bob@localhost sage]$ git push trac local_branch:public/alice/description
```

6. Alice *retrieves Bob's updates*, makes more changes, commits, and pushes them to trac.
7. Charly reviews the final version, and then sets the ticket to positive review. The “Author:” field is set to Alice's and Bob's full name, and the “Reviewer:” field is set to Charly's full name.

GitHub

Yet another possible workflow is to use GitHub (or any other third-party git repository) to collaboratively edit your new branch, and only push the result to trac once you and your ticket co-authors are satisfied.

Fork

The first step is to create your own fork of the Sage repository; simply click “Fork” on the [Sage GitHub repository](#). Then add it as one of the remotes to your local Sage repository. In the following, we will use the label “github” for this remote repository, though you are of course free to use a different one:

```
$ git remote add github git@github.com:github_user_name/sage.git
$ git remote -v
github      git@github.com:github_user_name/sage.git (fetch)
github      git@github.com:github_user_name/sage.git (push)
trac        git@trac.sagemath.org:sage.git (fetch)
trac        git@trac.sagemath.org:sage.git (push)
$ git fetch github
remote: Counting objects: 107, done.
remote: Compressing objects: 100% (63/63), done.
remote: Total 74 (delta 41), reused 40 (delta 10)
Unpacking objects: 100% (74/74), done.
From github.com:github_user_name/sage
* [new branch]      master    -> github/master
```

Develop

You now use the github repository to develop your ticket branch; First create a new branch:

```
$ git checkout -b my_branch --track github/master
Branch my_branch set up to track remote branch master from github.
Switched to a new branch 'my_branch'
$ git push github my_branch
Total 0 (delta 0), reused 0 (delta 0)
To git@github.com:github_user_name/sage.git
* [new branch]      my_branch -> my_branch
```

Because of the `--track` option, the `git pull` command will default to downloading your coauthor's changes from your github branch. Alternatively, you can create a new branch on your fork's GitHub webpage.

At this point you can use the GitHub workflow that you prefer. In particular, your choices are

- Give your coauthors write permissions to your github fork. Every author edits/commits to their own local copy and they jointly push to your github branch.
- Have every coauthor create their own fork and send you (the lead author) pull requests to your GitHub fork.
- Use the GitHub web page editing & committing feature, that way you can make changes without ever using your local machine.

Push to Trac

When you are satisfied with your branch, you push it to the Sage trac server:

```
$ git push trac HEAD:u/user/description
```

and then fill in the “Branch” field in the trac ticket description as explained in *Pushing Your Changes to a Ticket*.

1.2.6 Optional: Using the Git-Trac Command

Git is a separate project from trac, and the two do not know how to talk to each other. To simplify the development, we have a special `git trac` subcommand for the git suite. Note that this really is only to simplify interaction with our trac issue management, you can perform every development task with just git and a web browser.

Installing the Git-Trac Command

```
[user@localhost]$ git clone https://github.com/sagemath/git-trac-command.git Cloning into 'git-trac-command'... [...] Checking connectivity... done. [user@localhost]$ source git-trac-command/enable.sh Prepending the git-trac command to your search PATH
```

This creates a directory `git-trac-command`.

Sourcing the `enable.sh` script in there is just a quick and dirty way to enable it temporarily. For a more permanent installation on your system later, make sure to put the `git-trac` command in your `PATH`. Assuming that `~/bin` is already in your `PATH`, you can do this by symlinking:

```
[user@localhost]$ echo $PATH
/home/user/bin:/usr/local/bin:/usr/bin:/bin:/usr/local/sbin:/usr/sbin
[user@localhost]$ cd git-trac-command
[user@localhost git-trac-command]$ ln -s `pwd`/git-trac ~/bin/
```

See the `git-trac README` for more details. At this point you leave `git-trac-command` subdirectory, and only go there whenever you need to update the `git-trac` command.

Git and Trac Configuration

Note:

- `trac` uses username/password for authentication.
 - Our `git repository server` uses SSH public key authentication for write access.
-

You need to set up both authentication mechanisms to be able to upload your changes with “git trac”. For read-only access neither authentication mechanism is needed. To set up `git trac`, first go to the Sage directory and tell `git trac` about your trac account:

```
[user@localhost sage]$ git trac config --user USERNAME --pass 'PASSWORD'
Trac xmlrpc URL:
  https://trac.sagemath.org/xmlrpc (anonymous)
  https://trac.sagemath.org/login/xmlrpc (authenticated)
  realm sage.math.washington.edu
Username: USERNAME
```

(continues on next page)

(continued from previous page)

```
Password: PASSWORD
```

```
Retrieving SSH keys...
```

```
1024 ab:1b:7c:c9:9b:48:fe:dd:59:56:1e:9d:a4:a6:51:9d  My SSH Key
```

where you have to replace USERNAME with your trac user name and PASSWORD with your trac password. If you don't have a trac account, use `git trac config` without any arguments. The single quotes in 'PASSWORD' escape special characters that you might have in your password. The password is stored in plain-text in `.git/config`, so make sure that it is not readable by other users on your system. For example, by running `chmod 0600 .git/config` if your home directory is not already private.

Instead of a username and password you may also configure authentication via a generated token by passing `--token=<token>` instead of `--pass:`

```
[user@localhost sage]$ git trac config --user=<username> --token=<token>
```

This is required if you authenticate to Trac with your GitHub account, as you do not have a Trac password. Logged in users can find their token under [the token tab in preferences on the trac site](#).

Note: The username to be entered here is NOT the GitHub username, but rather the trac username which is `gh-<GitHub-username>` as given on the top right corner of the trac server.

If both a token and a username/password are configured, the token-based authentication takes precedence.

If you do not want to store your trac username/password/token on disk you can temporarily override it with the environment variables `TRAC_USERNAME`, `TRAC_PASSWORD`, and `TRAC_TOKEN` respectively. These take precedence over any other configuration.

If there is no SSH key listed then you haven't uploaded your SSH public key to the trac server. You should do that now following the instructions to [Linking your Public Key to your Trac Account](#), if you want to upload any changes. You may have to add your private key to your authentication agent:

```
[user@localhost sage]$ ssh-add
```

Note: The `git trac config` command will automatically add a trac remote git repository to your list of remotes if necessary.

If you followed the above instructions then you will have two remote repositories set up:

```
[user@localhost sage]$ git remote -v
origin      https://github.com/sagemath/sage.git (fetch)
origin      https://github.com/sagemath/sage.git (push)
trac        git@trac.sagemath.org:sage.git (fetch)
trac        git@trac.sagemath.org:sage.git (push)
```

The `git@...` part of the push url means that write access is secured with SSH keys, which you must have set up as in [Linking your Public Key to your Trac Account](#). Read-only access happens through the fetch url and does not require SSH.

Trac Tickets and Git Branches

Now let's start adding code to Sage!

Create a Ticket

Suppose you have written an algorithm for calculating the last twin prime, and want to add it to Sage. You would first open a ticket for that:

```
[user@localhost sage]$ git trac create 'Last Twin Prime'
Remote branch: u/user/last_twin_prime
Newly-created ticket number: 12345
Ticket URL: https://trac.sagemath.org/12345
Local branch: t/12345/last_twin_prime
```

This will create a new trac ticket titled “Last Twin Prime” with a *remote branch* `u/user/last_twin_prime` attached to it. The remote branch name is automatically derived from the ticket title; If you don't like this then you can use the `-b` switch to specify it explicitly. See `git trac create -h` for details. This new branch is automatically checked out for you with the *local branch* name `t/12345/last_twin_prime`.

Note: Only some trac fields are filled in automatically. See *The Ticket Fields* for what trac fields are available and how we use them.

Check out an Existing Ticket

Alternatively, you can use the [web interface to the Sage trac development server](#) to open a new ticket. Just log in and click on “Create Ticket”.

Or maybe somebody else already opened a ticket. Then, to get a suitable local branch to make your edits, you would just run:

```
[user@localhost sage]$ git trac checkout 12345
Loading ticket #12345...
Checking out Trac #13744 remote branch u/user/last_twin_prime -> local branch t/12345/
↪ last_twin_prime...
```

The `git trac checkout` command downloads an existing branch (as specified in the “Branch:” field on the trac ticket) or creates a new one if there is none yet. Just like the create command, you can specify the remote branch name explicitly using the `-b` switch if you want.

Note on Branch Names

The “Branch:” field of a trac ticket (see *The Ticket Fields*) indicates the git branch containing its code. Our git server implements the following access restrictions for **remote branch names**:

- You can read/write/create a branch named `u/your_username/whatever_you_like`. Everybody else can read.
- Everybody can read/write/create a branch named `public/whatever_you_like`.

Depending on your style of collaboration, you can use one or the other. The `git trac` subcommands defaults to the former.

As a convention, the `git trac` subcommand uses **local branch names** of the form `t/12345/description`, where the number is the trac ticket number. The script uses this number to figure out the ticket from the local branch name. You can rename the local branches if you want, but if they don't contain the ticket number then you will have to specify the ticket number manually when you are uploading your changes.

Making Changes

Once you have checked out a ticket, edit the appropriate files and commit your changes to the branch as described in *Editing the Source Code* and *Commits (Snapshots)*.

Uploading Changes to Trac

Automatic Push

At some point, you may wish to share your changes with the rest of us: maybe it is ready for review, or maybe you are collaborating with someone and want to share your changes “up until now”. This is simply done by:

```
[user@localhost sage]$ git trac push
Pushing to Trac #12345...
Guessed remote branch: u/user/last_twin_prime

To git@trac.sagemath.org:sage.git
* [new branch]      HEAD -> u/user/last_twin_prime

Changing the trac "Branch:" field...
```

This uploads your changes to a remote branch on the [Sage git server](#). The `git trac` command uses the following logic to find out the remote branch name:

- By default, the remote branch name will be whatever is already on the trac ticket.
- If there is no remote branch yet, the branch will be called `u/user/description` (`u/user/last_twin_prime` in the example).
- You can use the `--branch` option to specify the remote branch name explicitly, but it needs to follow the naming convention from *Note on Branch Names* for you to have write permission.

Specifying the Ticket Number

You can upload any local branch to an existing ticket, whether or not you created the local branch with `git trac`. This works exactly like in the case where you started with a ticket, except that you have to specify the ticket number (since there is no way to tell which ticket you have in mind). That is:

```
[user@localhost sage]$ git trac push TICKETNUM
```

where you have to replace `TICKETNUM` with the number of the trac ticket.

Finishing It Up

It is common to go through a few iterations of commits before you upload, and you will probably also have pushed your changes a few times before your changes are ready for review.

Once you are happy with the changes you uploaded, they must be reviewed by somebody else before they can be included in the next version of Sage. To mark your ticket as ready for review, you should set it to `needs_review` on the trac server. Also, add yourself as the (or one of the) author(s) for that ticket by inserting the following as the first line:

```
Authors: Your Real Name
```

Downloading Changes from Trac

If somebody else worked on a ticket, or if you just switched computers, you'll want to get the latest version of the branch from a ticket into your local branch. This is done with:

```
[user@localhost sage]$ git trac pull
```

Technically, this does a *merge* (just like the standard `git pull`) command. See [Merging and Rebasing](#) for more background information.

Merging

As soon as you are working on a bigger project that spans multiple tickets you will want to base your work on branches that have not been merged into Sage yet. This is natural in collaborative development, and in fact you are very much encouraged to split your work into logically different parts. Ideally, each part that is useful on its own and can be reviewed independently should be a different ticket instead of a huge patch bomb.

For this purpose, you can incorporate branches from other tickets (or just other local branches) into your current branch. This is called merging, and all it does is include commits from other branches into your current branch. In particular, this is done when a new Sage release is made: the finished tickets are merged with the Sage master and the result is the next Sage version. Git is smart enough to not merge commits twice. In particular, it is possible to merge two branches, one of which had already merged the other branch. The syntax for merging is easy:

```
[user@localhost sage]$ git merge other_branch
```

This creates a new “merge” commit, joining your current branch and `other_branch`.

Warning: You should avoid merging branches both ways. Once A merged B and B merged A, there is no way to distinguish commits that were originally made in A or B. Effectively, merging both ways combines the branches and makes individual review impossible.

In practice, you should only merge when one of the following holds:

- Either two tickets conflict, then you have to merge one into the other in order to resolve the merge conflict.
- Or you definitely need a feature that has been developed as part of another branch.

A special case of merging is merging in the `develop` branch. This brings your local branch up to date with the newest Sage version. The above warning against unnecessary merges still applies, though. Try to do all of your development with the Sage version that you originally started with. The only reason for merging in the `develop` branch is if you need a new feature or if your branch conflicts. See [Update Branch to Latest SageMath Version \(and Minimizing Recompile Time\)](#) for details.

Collaboration and conflict resolution

Exchanging Branches

It is very easy to collaborate by just going through the above steps any number of times. For example, Alice starts a ticket and adds some initial code:

```
[alice@laptop sage]$ git trac create "A and B Ticket"
... EDIT EDIT ...
[alice@laptop sage]$ git add .
[alice@laptop sage]$ git commit
[alice@laptop sage]$ git trac push
```

The trac ticket now has “Branch:” set to u/alice/a_and_b_ticket. Bob downloads the branch and works some more on it:

```
[bob@home sage]$ git trac checkout TICKET_NUMBER
... EDIT EDIT ...
[bob@home sage]$ git add .
[bob@home sage]$ git commit
[bob@home sage]$ git trac push
```

The trac ticket now has “Branch:” set to u/bob/a_and_b_ticket, since Bob cannot write to u/alice/.... Now the two authors just pull/push in their collaboration:

```
[alice@laptop sage]$ git trac pull
... EDIT EDIT ...
[alice@laptop sage]$ git add .
[alice@laptop sage]$ git commit
[alice@laptop sage]$ git trac push

[bob@home sage]$ git trac pull
... EDIT EDIT ...
[bob@home sage]$ git add .
[bob@home sage]$ git commit
[bob@home sage]$ git trac push
```

Alice and Bob need not alternate, they can also add further commits on top of their own remote branch. As long as their changes do not conflict (edit the same lines simultaneously), this is fine.

Conflict Resolution

Merge conflicts happen if there are overlapping edits, and they are an unavoidable consequence of distributed development. Fortunately, resolving them is common and easy with git. As a hypothetical example, consider the following code snippet:

```
def fibonacci(i):
    """
    Return the i-th Fibonacci number
    """
    return fibonacci(i-1) * fibonacci(i-2)
```

This is clearly wrong; Two developers, namely Alice and Bob, decide to fix it. First, in a cabin in the woods far away from any internet connection, Alice corrects the seed values:

```
def fibonacci(i):
    """
    Return the `i`-th Fibonacci number
    """
    if i > 1:
        return fibonacci(i-1) * fibonacci(i-2)
    return [0, 1][i]
```

and turns those changes into a new commit:

```
[alice@laptop sage]$ git add fibonacci.py
[alice@laptop sage]$ git commit -m 'return correct seed values'
```

However, not having an internet connection, she cannot immediately send her changes to the trac server. Meanwhile, Bob changes the multiplication to an addition since that is the correct recursion formula:

```
def fibonacci(i):
    """
    Return the `i`-th Fibonacci number
    """
    return fibonacci(i-1) + fibonacci(i-2)
```

and immediately uploads his change:

```
[bob@home sage]$ git add fibonacci.py
[bob@home sage]$ git commit -m 'corrected recursion formula, must be + instead of *'
[bob@home sage]$ git trac push
```

Eventually, Alice returns to civilization. In her mailbox, she finds a trac notification email that Bob has uploaded further changes to their joint project. Hence, she starts out by getting his changes into her own local branch:

```
[alice@laptop sage]$ git trac pull
...
CONFLICT (content): Merge conflict in fibonacci.py
Automatic merge failed; fix conflicts and then commit the result.
```

The file now looks like this:

```
def fibonacci(i):
    """
    Return the `i`-th Fibonacci number
    """
<<<<<<< HEAD
    if i > 1:
        return fibonacci(i-1) * fibonacci(i-2)
    return [0, 1][i]
=====
    return fibonacci(i-1) + fibonacci(i-2)
>>>>>>> 41675dfaedbfb89dcff0a47e520be4aa2b6c5d1b
```

The conflict is shown between the conflict markers <<<<<<< and >>>>>>>. The first half (up to the ===== marker) is Alice's current version, the second half is Bob's version. The 40-digit hex number after the second conflict marker is the SHA1 hash of the most recent common parent of both.

It is now Alice's job to resolve the conflict by reconciling their changes, for example by editing the file. Her result is:

```
def fibonacci(i):
    """
    Return the `i`-th Fibonacci number
    """
    if i > 1:
        return fibonacci(i-1) + fibonacci(i-2)
    return [0, 1][i]
```

And then upload both her original change *and* her merge commit to trac:

```
[alice@laptop sage]$ git add fibonacci.py
[alice@laptop sage]$ git commit -m "merged Bob's changes with mine"
```

The resulting commit graph now has a loop:

```
[alice@laptop sage]$ git log --graph --oneline
* 6316447 merged Bob's changes with mine
|\
| * 41675df corrected recursion formula, must be + instead of *
* | 14ae1d3 return correct seed values
|/
* 14afe53 initial commit
```

If Bob decides to do further work on the ticket then he will have to pull Alice's changes. However, this time there is no conflict on his end: git downloads both Alice's conflicting commit and her resolution.

Reviewing

For an explanation of what should be checked by the reviewer, see *The reviewer's check list*.

If you go to the [web interface to the Sage trac development server](#) then you can click on the “Branch:” field and see the code that is added by combining all commits of the ticket. This is what needs to be reviewed.

The `git trac` command gives you two commands that might be handy (replace 12345 with the actual ticket number) if you do not want to use the web interface:

- `git trac print 12345` displays the trac ticket directly in your terminal.
- `git trac review 12345` downloads the branch from the ticket and shows you what is being added, analogous to clicking on the “Branch:” field.

To review tickets with minimal recompiling, start by building the “develop” branch, that is, the latest beta. Just checking out an older ticket would most likely reset the Sage tree to an older version, so you would have to compile older versions of packages to make it work. Instead, you can create an anonymous (“detached HEAD”) merge of the ticket and the develop branch using

```
$ git trac try 12345
```

This will only touch files that are really modified by the ticket. In particular, if only Python files are changed by the ticket (which is true for most tickets) then you just have to run `sage -b` to rebuild the Sage library. If files other than Python have been changed, you must run `make`. When you are finished reviewing, just check out a named branch, for example

```
$ git checkout develop
```

If you want to edit the ticket branch (that is, add additional commits) you cannot use `git trac try`. You must *Check out an Existing Ticket* to get the actual ticket branch as a starting point.

WRITING CODE FOR SAGE

2.1 Setting up your workspace

2.1.1 Configuring text editors and IDEs for use with Sage

In Meta-ticket [trac ticket #30500](#) we are collecting instructions how to configure various text editors and IDEs for use with Sage.

2.1.2 Gitpod

[Gitpod](#) is a free service that will let you build and run Sage from an online development environment based on VS Code. Without needing to install anything on your computer, Gitpod creates a virtual fully-functional workspace with all the dependencies and tools pre-installed.

To get started, [go to Gitpod](#) and log in using your GitHub or GitLab account. Wait while Gitpod creates a workspace. The first time, it may take some time to build Sage.

You can now run and edit Sage's code. Contributing your changes follows the normal [Git workflow](#). For this to work, you first have to authorize Gitpod with Trac:

1. In the running Gitpod workspace, generate a new SSH key pair by `ssh-keygen -f tempkey`.
2. Save the private key as a secure environment variable in Gitpod using `gp env PRIVATE_SSH_KEY="$(cat tempkey)"`, or by using the [Gitpod UI](#).
3. Register the public key with Trac following the instructions in [Linking your Public Key to your Trac Account](#).
4. Close this Gitpod workspace.

After following this procedure, every new Gitpod workspace will have a working `trac` remote to which you can push your changes.

You can also [use your VS Code Desktop](#) to keep your local IDE configuration while still benefiting from Gitpod's high-spec servers and automated prebuilds.

2.2 General Conventions

There are many ways to contribute to Sage including sharing scripts and Sage worksheets that implement new functionality using Sage, improving to the Sage library, or to working on the many underlying libraries distributed with Sage¹. This guide focuses on editing the Sage library itself.

Sage is not just about gathering together functionality. It is about providing a clear, systematic and consistent way to access a large number of algorithms, in a coherent framework that makes sense mathematically. In the design of Sage, the semantics of objects, the definitions, etc., are informed by how the corresponding objects are used in everyday mathematics.

To meet the goal of making Sage easy to read, maintain, and improve, all Python/Cython code that is included with Sage should adhere to the style conventions discussed in this chapter.

2.2.1 Python Code Style

Follow the standard Python formatting rules when writing code for Sage, as explained at the following URLs:

- [PEP 0008](#)
- [PEP 0257](#)

In particular,

- Use 4 spaces for indentation levels. Do not use tabs as they can result in indentation confusion. Most editors have a feature that will insert 4 spaces when the tab key is hit. Also, many editors will automatically search/replace leading tabs with 4 spaces.
- Whitespace before and after assignment and binary operator of the lowest priority in the expression:

```
i = i + 1
c = (a+b) * (a-b)
```

- No whitespace before or after the = sign if it is used for keyword arguments:

```
def complex(real, imag=0.0):
    return magic(r=real, i=imag)
```

- No whitespace immediately inside parenthesis, brackets, and braces:

```
spam(ham[1], {eggs: 2})
[i^2 for i in range(3)]
```

- Use all lowercase function names with words separated by underscores. For example, you are encouraged to write Python functions using the naming convention:

```
def set_some_value():
    return 1
```

Note, however, that some functions do have uppercase letters where it makes sense. For instance, the function for lattice reduction by the LLL algorithm is called `Matrix_integer_dense.LLL`.

- Use CamelCase for class names:

¹ See <https://www.sagemath.org/links-components.html> for a full list of packages shipped with every copy of Sage

```
class SomeValue():
    def __init__(self, x):
        self._x = 1
```

and factory functions that mimic object constructors, for example `PolynomialRing` or:

```
def SomeIdentityValue(x):
    return SomeValue(1)
```

2.2.2 Files and Directory Structure

Roughly, the Sage directory tree is layout like this. Note that we use `SAGE_ROOT` in the following as a shortcut for the (arbitrary) name of the directory containing the Sage sources:

```
SAGE_ROOT/
  sage          # the Sage launcher
  Makefile      # top level Makefile
  build/        # Sage's build system
    pkgs/       # install, patch, and metadata from spkgs
  src/
    setup.py
    ...
    sage/       # Sage library
      ext_data/ # extra Sage resources (formerly src/ext)
    bin/        # the scripts in local/bin that are tracked
  upstream/    # tarballs of upstream sources
  local/       # installed binaries
```

Python Sage library code goes into `src/sage/` and uses the following conventions. Directory names may be plural (e.g. `rings`) and file names are almost always singular (e.g. `polynomial_ring.py`). Note that the file `polynomial_ring.py` might still contain definitions of several different types of polynomial rings.

Note: You are encouraged to include miscellaneous notes, emails, design discussions, etc., in your package. Make these plain text files (with extension `.txt`) in a subdirectory called `notes`.

If you want to create a new directory (*package*) in the Sage library `SAGE_ROOT/src/sage` (say, `measure_theory`), that directory will usually contain an empty file `__init__.py`, which marks the directory as an ordinary package (see *Ordinary packages vs. implicit namespace packages*), and also a file `all.py`, listing imports from this package that are user-facing and important enough to be in the global namespace of Sage at startup. The file `all.py` might look like this:

```
from .borel_measure import BorelMeasure
from .banach_tarski import BanachTarskiParadox
```

but it is generally better to use the `lazy_import` framework:

```
from sage.misc.lazy_import import lazy_import
lazy_import('sage.measure_theory.borel_measure', 'BorelMeasure')
lazy_import('sage.measure_theory.banach_tarski', 'BanachTarskiParadox')
```

Then in the file `SAGE_ROOT/src/sage/all.py`, add a line

```
from sage.measure_theory.all import *
```

Adding new top-level packages below `sage` should be done sparingly. It is often better to create subpackages of existing packages.

Non-Python Sage source code and supporting files can be included in one of the following places:

- In the directory of the Python code that uses that file. When the Sage library is installed, the file will be installed in the same location as the Python code. For example, `SAGE_ROOT/src/sage/interfaces/maxima.py` needs to use the file `SAGE_ROOT/src/sage/interfaces/maxima.lisp` at runtime, so it refers to it as

```
os.path.join(os.path.dirname(__file__), 'sage-maxima.lisp')
```

- In an appropriate subdirectory of `SAGE_ROOT/src/sage/ext_data/`. (At runtime, it is then available in the directory indicated by `SAGE_EXTCODE`). For example, if `file` is placed in `SAGE_ROOT/src/sage/ext_data/directory/` it can be accessed with

```
from sage.env import SAGE_EXTCODE
file = os.path.join(SAGE_EXTCODE, 'directory', 'file')
```

In both cases, the files must be listed (explicitly or via wildcards) in the section `options.package_data` of the file `SAGE_ROOT/pkgs/sagemath-standard/setup.cfg.m4` (or the corresponding file of another distribution).

2.2.3 Learn by copy/paste

For all of the conventions discussed here, you can find many examples in the Sage library. Browsing through the code is helpful, but so is searching: the functions `search_src`, `search_def`, and `search_doc` are worth knowing about. Briefly, from the “sage:” prompt, `search_src(string)` searches Sage library code for the string `string`. The command `search_def(string)` does a similar search, but restricted to function definitions, while `search_doc(string)` searches the Sage documentation. See their docstrings for more information and more options.

2.2.4 Headings of Sage Library Code Files

The top of each Sage code file should follow this format:

```
r"""
<Short one-line summary that ends with no period>

<Paragraph description>

EXAMPLES::

<Lots and lots of examples>

AUTHORS:

- YOUR NAME (2005-01-03): initial version

- person (date in ISO year-month-day format): short desc

"""
```

(continues on next page)

(continued from previous page)

```
# *****
#      Copyright (C) 2013 YOUR NAME <your email>
#
# This program is free software: you can redistribute it and/or modify
# it under the terms of the GNU General Public License as published by
# the Free Software Foundation, either version 2 of the License, or
# (at your option) any later version.
#      https://www.gnu.org/licenses/
# *****
```

As an example, see `SAGE_ROOT/src/sage/rings/integer.pyx`, which contains the implementation for `Z`. The names of the people who made major contributions to the file appear in the `AUTHORS` section. You can add your name to the list if you belong to the people, but refrain from being verbose in the description. The `AUTHORS` section shows very rough overview of the history, especially if a lot of people have been working on that source file. The authoritative log for who wrote what is always the git repository (see the output of `git blame`).

All code included with Sage must be licensed under the GPLv2+ or a compatible, that is, less restrictive license (e.g. the BSD license).

2.2.5 Documentation Strings

The docstring of a function: content

Every function must have a docstring that includes the following information. You can use the existing functions of Sage as templates.

- A **one-sentence description** of the function.

It must be followed by a blank line and end in a period. It describes the function or method's effect as a command ("Do this", "Return that"), not as a description like "Returns the pathname ...".

For methods of a class, it is recommended to refer to the `self` argument in a descriptive way, unless this leads to a confusion. For example, if `self` is an integer, then `this integer` or `the integer` is more descriptive, and it is preferable to write

```
Return whether this integer is prime.
```

- A **longer description**.

This is optional if the one-sentence description does not need more explanations.

Start with assumptions of the object, if there are any. For example,

```
The poset is expected to be ranked.
```

if the function raises an exception when called on a non-ranked poset.

Define your terms

```
The lexicographic product of `G` and `H` is the graph with vertex set ...
```

and mention possible aliases

```
The tensor product is also known as the categorical product and ...
```

- An **INPUT** and an **OUTPUT** block describing the input/output of the function.

The INPUT block describes all arguments that the function accepts.

1. The type names should be descriptive, but do not have to represent the exact Sage/Python types. For example, use “integer” for anything that behaves like an integer, rather than `int`.
2. Mention the default values of the input arguments when applicable.

INPUT:

```
- ``n`` -- integer
- ``p`` -- prime integer (default: `2`); coprime with ``n``
```

The OUTPUT block describes the expected output. This is required if the one-sentence description of the function needs more explanation.

OUTPUT: the plaintext decrypted from the ciphertext ``C``

It is often the case that the output consists of several items.

OUTPUT: a tuple of

- the reduced echelon form ``H`` of the matrix ``A``
- the transformation matrix ``U`` such that $UA = H$

You are recommended to be verbose enough for complicated outputs.

OUTPUT:

The decomposition of the free module on which this matrix ``A`` acts from the right (i.e., the action is `x` goes to `xA`), along with whether this matrix acts irreducibly on each factor. The factors are guaranteed to be sorted in the same way as the corresponding factors of the characteristic polynomial.

- An **EXAMPLES** block for examples. This is not optional.

These examples are used for documentation, but they are also tested before each release just like TESTS block.

They should have good coverage of the functionality in question.

- A **SEEALSO** block (highly recommended) with links to related parts of Sage. This helps users find the features that interest them and discover the new ones.

.. **SEEALSO**::

```
:ref:`chapter-sage_manuals_links`,
:meth:`sage.somewhere.other_useful_method`,
:mod:`sage.some.related.module`.
```

See [Hyperlinks](#) for details on how to setup links in Sage.

- An **ALGORITHM** block (optional).

It indicates what algorithm and/or what software is used, e.g. **ALGORITHM:** Uses Pari. Here's a longer example with a bibliographical reference:

ALGORITHM:

The following algorithm is adapted from page 89 of [Nat2000].

Let p be an odd (positive) prime and let g be a generator modulo p . Then g^k is a generator modulo p if and only if $\gcd(k, p-1) = 1$. Since p is an odd prime and positive, then $p-1$ is even so that any even integer between 1 and $p-1$, inclusive, is not relatively prime to $p-1$. We have now narrowed our search to all odd integers k between 1 and $p-1$, inclusive.

So now start with a generator g modulo an odd (positive) prime p . For any odd integer k between 1 and $p-1$, inclusive, g^k is a generator modulo p if and only if $\gcd(k, p-1) = 1$.

The bibliographical reference should go in Sage's master bibliography file, `SAGE_ROOT/src/doc/en/reference/references/index.rst`:

```
.. [Nat2000] \M. B. Nathanson. Elementary Methods in Number Theory.
   Springer, 2000.
```

- A **NOTE** block for tips/tricks (optional).

```
.. NOTE::
```

You should note that this sentence is indented at least 4 spaces. Never use the tab character.

- A **WARNING** block for critical information about your code (optional).

For example known situations for which the code breaks, or anything that the user should be aware of.

```
.. WARNING::
```

Whenever you edit the Sage documentation, make sure that the edited version still builds. That is, you need to ensure that you can still build the HTML and PDF versions of the updated documentation. If the edited documentation fails to build, it is very likely that you would be requested to change your patch.

- A **TODO** block for future improvements (optional).

It can contain disabled doctests to demonstrate the desired feature. Here's an example of a TODO block:

```
.. TODO::
```

Add to `have_fresh_beers` an interface with the faster algorithm "Buy a Better Fridge" (BaBF)::

```
    sage: have_fresh_beers('Bière de l'Yvette', algorithm="BaBF") # not
↪implemented
    Enjoy !
```

- A **PLOT** block to illustrate with pictures the output of a function.

Generate with Sage code an object `g` with a `.plot` method, then call `sphinx_plot(g)`:

```
.. PLOT::  
  
    g = graphs.PetersenGraph()  
    sphinx_plot(g)
```

- A **REFERENCES** block to list related books or papers (optional).

Almost all bibliographic information should be put in the master bibliography file, see below. Citations will then link to the master bibliography where the reader can find the bibliographic details (see below for citation syntax). REFERENCE blocks in individual docstrings are therefore usually not necessary.

Nevertheless, a REFERENCE block can be useful if there are relevant sources which are not explicitly mentioned in the docstring or if the docstring is particularly long. In that case, add the bibliographic information to the master bibliography file, if not already present, and add a reference block to your docstring as follows:

```
REFERENCES:  
  
For more information, see [Str1969]_, or one of the following references:  
  
- [Sto2000]_  
  
- [Voe2003]_
```

Note the trailing underscores which makes the citations into hyperlinks. See below for more about the master bibliography file. For more about citations, see the [Sphinx/reST markup for citations](#). For links to trac tickets or wikipedia, see [Hyperlinks](#).

- A **TESTS** block (highly recommended).

Formatted just like EXAMPLES, containing tests that are not relevant to users. In particular, these blocks are not shown when users ask for help via `foo?`: they are stripped by the function `sage.misc.sagedoc.skip_TESTS_block()`.

Special and corner cases, like number zero, one-element group etc. should usually go to this block. This is also right place for most tests of input validation; for example if the function accepts `direction='up'` and `direction='down'`, you can use this block to check that `direction='junk'` raises an exception.

For the purposes of removal, A “TESTS” block is a block starting with “TESTS:” (or the same with two colons), on a line on its own, and ending either with a line indented less than “TESTS”, or with a line with the same level of indentation – not more – matching one of the following:

- a Sphinx directive of the form “`.. foo:`”, optionally followed by other text.
- text of the form “UPPERCASE:”, optionally followed by other text.
- lines which look like a reST header: one line containing anything, followed by a line consisting only of whitespace, followed by a string of hyphens, equal signs, or other characters which are valid markers for reST headers: `- = ` : ' " ~ _ ^ * + # < >`. However, lines only containing double colons `::` do not end “TESTS” blocks.

Sometimes (but rarely) one has private or protected methods that don’t need a proper EXAMPLES doctest. In these cases, one can either write traditional doctest using the TESTS block or use `pytest` to test the method. In the latter case, one has to add `TESTS: pytest` to the docstring, so that the method is explicitly marked as tested.

Note about Sphinx directives vs. other blocks

The main Sphinx directives that are used in Sage are:

```
.. MATH::, .. NOTE::, .. PLOT::, .. RUBRIC::, .. SEEALSO::, .. TODO::, .. TOPIC:: and ..
WARNING::.
```

They must be written exactly as above, so for example `WARNING::` or `.. WARNING ::` will not work.

Some other directives are also available, but less frequently used, namely:

```
.. MODULEAUTHOR::, .. automethod::, .. autofunction::, .. image::, .. figure::.
```

Other blocks shall not be used as directives; for example `.. ALGORITHM::` will not be shown at all.

Sage documentation style

All Sage documentation is written in reStructuredText (reST) and is processed by Sphinx. See <https://www.sphinx-doc.org/rest.html> for an introduction. Sage imposes these styles:

- Lines should be shorter than 80 characters. If in doubt, read [PEP8: Maximum Line Length](#).
- All reST and Sphinx directives (like `.. WARNING::`, `.. NOTE::`, `.. MATH::`, etc.) are written in uppercase.
- Code fragments are quoted with double backticks. This includes function arguments and the Python literals like ```True```, ```False``` and ```None```. For example:

```
If ``check`` is ``True``, then ...
```

Sage's master BIBLIOGRAPHY file

All bibliographical references should be stored in the master bibliography file, `SAGE_ROOT/src/doc/en/reference/references/index.rst`, in the format

```
.. [Gau1801] \C. F. Gauss, *Disquisitiones Arithmeticae*, 1801.

.. [RSA1978] \R. Rivest, A. Shamir, L. Adleman,
    "A Method for Obtaining Digital Signatures and
    Public-Key Cryptosystems".
    Communications of the ACM 21 (February 1978),
    120-126. :doi:`10.1145/359340.359342`.
```

The part in brackets is the citation key: given these examples, you could then use `[Gau1801]` in a docstring to provide a link to the first reference. Note the trailing underscore which makes the citation a hyperlink.

When possible, the key should have this form: for a single author, use the first three letters of the family name followed by the year; for multiple authors, use the first letter of each of the family names followed by the year. Note that the year should be four digits, not just the last two – Sage already has references from both 1910 and 2010, for example.

When abbreviating the first name of an author in a bibliography listing, be sure to put a backslash in front of it. This ensures that the letter (C. in the example above) will not be interpreted as a list enumerator.

For more about citations, see the [Sphinx/reST markup for citations](#).

Template

Use the following template when documenting functions. Note the indentation:

```
def point(self, x=1, y=2):
    r"""
    Return the point  $(x^5, y)$ .

    INPUT:

    - ``x`` -- integer (default: `1`); the description of the
      argument ``x`` goes here. If it contains multiple lines, all
      the lines after the first need to begin at the same indentation
      as the backtick.

    - ``y`` -- integer (default: `2`); the description of the
      argument ``y``

    OUTPUT: the point as a tuple

    EXAMPLES:

    This example illustrates ... ::

        sage: A = ModuliSpace()
        sage: A.point(2,3)
        xxx

    We now ... ::

        sage: B = A.point(5,6)
        sage: xxx

    It is an error to ... ::

        sage: C = A.point('x',7)
        Traceback (most recent call last):
        ...
        TypeError: unable to convert 'r' to an integer

    .. NOTE::

        This function uses the algorithm of [BCDT2001]_ to determine
        whether an elliptic curve  $E$  over  $Q$  is modular.

    ...

    .. SEEALSO::

        :func:`line`

    TESTS::
```

(continues on next page)

(continued from previous page)

```

    sage: A.point(42, 0) # Check for corner case y=0
    XXX
    """
    <body of the function>

```

The master bibliography file would contain

```

.. [BCDT2001] Breuil, Conrad, Diamond, Taylor,
    "Modularity ...."

```

You are strongly encouraged to:

- Use LaTeX typesetting (see *LaTeX Typesetting*).
- Liberally describe what the examples do.

Note: There must be a blank line after the example code and before the explanatory text for the next example (indentation is not enough).

- Illustrate the exceptions raised by the function with examples (as given above: “It is an error to [...]”, ...)
- Include many examples.

They are helpful for the users, and are crucial for the quality and adaptability of Sage. Without such examples, small changes to one part of Sage that break something else might not go seen until much later when someone uses the system, which is unacceptable.

Fine points on styles

A Sage developer, in writing code and docstrings, should follow the styles suggested in this manual, except special cases with good reasons. However, there are some details where we as a community did not reach to an agreement on the official style. These are

- one space:

```
This is the first sentence. This is the second sentence.
```

vs two spaces:

```
This is the first sentence. This is the second sentence.
```

between sentences.

- tight list:

```
- first item
- second item
- third item
```

vs spaced list:

```
- first item
- second item
```

(continues on next page)

(continued from previous page)

```
- third item
```

There are different opinions on each of these, and in reality, we find instances in each style in our codebase. Then what should we do? Do we decide on one style by voting? There are different opinions even on what to do!

We can at least do this to prevent any dispute about these style conflicts:

- Acknowledge different authors may have different preferences on these.
- Respect the style choice of the author who first wrote the code or the docstrings.

Private functions

Functions whose names start with an underscore are considered private. They do not appear in the reference manual, and their docstring should not contain any information that is crucial for Sage users. You can make their docstrings be part of the documentation of another method. For example:

```
class Foo(SageObject):

    def f(self):
        """
        <usual docstring>

        .. automethod:: _f
        """
        return self._f()

    def _f(self):
        """
        This would be hidden without the ``.. automethod::``
        """
```

Private functions should contain an EXAMPLES (or TESTS) block.

A special case is the constructor `__init__`: due to its special status the `__init__` docstring is used as the class docstring if there is not one already. That is, you can do the following:

```
sage: class Foo(SageObject):
.....:     # no class docstring
.....:     def __init__(self):
.....:         """Construct a Foo."""
sage: foo = Foo()
sage: from sage.misc.sageinspect import sage_getdoc
sage: sage_getdoc(foo)           # class docstring
'Construct a Foo.\n'
sage: sage_getdoc(foo.__init__)  # constructor docstring
'Construct a Foo.\n'
```

LaTeX Typesetting

In Sage's documentation LaTeX code is allowed and is marked with **backticks**:

``x^2 + y^2 = 1`` yields $x^2 + y^2 = 1$.

Backslashes: For LaTeX commands containing backslashes, either use double backslashes or begin the docstring with a `r"""` instead of `"""`. Both of the following are valid:

```
def cos(x):
    """
    Return \\cos(x).
    """

def sin(x):
    r"""
    Return \\sin(x).
    """
```

MATH block: This is similar to the LaTeX syntax `\[<math expression>\]` (or `$$<math expression>$$`). For instance:

```
.. MATH::

\sum_{i=1}^{\infty} (a_1 a_2 \cdots a_i)^{1/i}
\leq
e \sum_{i=1}^{\infty} a_i
```

$$\sum_{i=1}^{\infty} (a_1 a_2 \cdots a_i)^{1/i} \leq e \sum_{i=1}^{\infty} a_i$$

The **aligned** environment works as it does in LaTeX:

```
.. MATH::

\begin{aligned}
f(x) &= x^2 - 1 \\
g(x) &= x^x - f(x - 2)
\end{aligned}
```

$$f(x) = x^2 - 1$$

$$g(x) = x^x - f(x - 2)$$

When building the PDF documentation, everything is translated to LaTeX and each MATH block is automatically wrapped in a math environment – in particular, it is turned into `\begin{gather} block \end{gather}`. So if you want to use a LaTeX environment (like `align`) which in ordinary LaTeX would not be wrapped like this, you must add a **:nowrap:** flag to the MATH mode. See also [Sphinx's documentation for math blocks](#). :

```
.. MATH::
:nowrap:

\begin{align}
1+\dots+n &= n(n+1)/2 \\
&= O(n^2)
\end{align}
```

$$1 + \dots + n = n(n+1)/2 \tag{2.1}$$

$$= O(n^2) \tag{2.2}$$

$$\tag{2.3}$$

Readability balance: in the interactive console, LaTeX formulas contained in the documentation are represented by their LaTeX code (with backslashes stripped). In this situation `\frac{a}{b}` is less readable than `a/b` or `a b^{-1}` (some users may not even know LaTeX code). Make it pleasant for everybody as much as you can manage.

Commons rings ($\mathbb{Z}, \mathbb{N}, \dots$): The Sage LaTeX style is to typeset standard rings and fields using the locally-defined macro `\Bold` (e.g. `\Bold{Z}` gives \mathbb{Z}).

Shortcuts are available which preserve readability, e.g. `\ZZ` (\mathbb{Z}), `\RR` (\mathbb{R}), `\CC` (\mathbb{C}), and `\QQ` (\mathbb{Q}). They appear as LaTeX-formatted `\Bold{Z}` in the html manual, and as \mathbb{Z} in the interactive help. Other examples: `\GF{q}` (\mathbb{F}_q) and `\Zmod{p}` ($\mathbb{Z}/p\mathbb{Z}$).

See the file `SAGE_ROOT/src/sage/misc/latex_macros.py` for a full list and for details about how to add more macros.

Writing Testable Examples

The examples from Sage's documentation have a double purpose:

- They provide **illustrations** of the code's usage to the users
- They are **tests** that are checked before each release, helping us avoid new bugs.

All new doctests added to Sage should **pass all tests** (see *Running Sage's doctests*), i.e. running `sage -t your_file.py` should not give any error messages. Below are instructions about how doctests should be written.

What doctests should test:

- **Interesting examples** of what the function can do. This will be the most helpful to a lost user. It is also the occasion to check famous theorems (just in case):

```
sage: is_prime(6) # 6 is not prime
False
sage: 2 * 3 # and here is a proof
6
```

- All **meaningful combinations** of input arguments. For example a function may accept an `algorithm="B"` argument, and doctests should involve both `algorithm="A"` and `algorithm="B"`.
- **Corner cases:** the code should be able to handle a 0 input, or an empty set, or a null matrix, or a null function, ... All corner cases should be checked, as they are the most likely to be broken, now or in the future. This probably belongs to the TESTS block (see *The docstring of a function: content*).
- **Systematic tests** of all small-sized inputs, or tests of **random** instances if possible.

Note: Note that **TestSuites** are an automatic way to generate some of these tests in specific situations. See `SAGE_ROOT/src/sage/misc/sage_unittest.py`.

The syntax:

- **Environment:** doctests should work if you copy/paste them in Sage's interactive console. For example, the function `AA()` in the file `SAGE_ROOT/src/sage/algebras/steenrod/steenrod_algebra.py` includes an EXAMPLES block containing the following:

```
sage: from sage.algebras.steenrod.steenrod_algebra import AA as A
sage: A()
mod 2 Steenrod algebra, milnor basis
```

Sage does not know about the function `AA()` by default, so it needs to be imported before it is tested. Hence the first line in the example.

- **Preparsing:** As in Sage's console, `4/3` returns `4/3` and not `1.3333333333333333` as in Python 3.8. Testing occurs with full Sage preparsing of input within the standard Sage shell environment, as described in *Sage Preparsing*.
- **Writing files:** If a test outputs to a file, the file should be a temporary file. Use `tmp_filename()` to get a temporary filename, or `tmp_dir()` to get a temporary directory. An example from `SAGE_ROOT/src/sage/plot/graphics.py`:

```
sage: plot(x^2 - 5, (x, 0, 5), ymin=0).save(tmp_filename(ext='.png'))
```

- **Multiline doctests:** You may write tests that span multiple lines, using the line continuation marker `....`:

```
sage: for n in xrange(1,10):
.....:     if n.is_prime():
.....:         print(n)
2
3
5
7
```

- **Python3 print:** Python3 syntax for `print` must be used in Sage code and doctests. If you use an old-style `print` in doctests, it will raise a `SyntaxError`:

```
sage: print "not like that"
Traceback (most recent call last):
...
SyntaxError: ...
sage: print("but like this")
but like this
```

- **Split long lines:** You may want to split long lines of code with a backslash. Note: this syntax is non-standard and may be removed in the future:

```
sage: n = 123456789123456789123456789\
.....:     123456789123456789123456789
sage: n.is_prime()
False
```

- **Doctests flags:** flags are available to change the behaviour of doctests: see *Special Markup to Influence Doctests*.

Special Markup to Influence Doctests

Overly complicated output in the example code can be shortened by an ellipsis marker ...:

```
sage: [ZZ(n).ordinal_str() for n in range(25)]
['0th',
 '1st',
 '2nd',
 '3rd',
 '4th',
 '5th',
 ...
 '21st',
 '22nd',
 '23rd',
 '24th']
sage: ZZ('sage')
Traceback (most recent call last):
...
TypeError: unable to convert 'sage' to an integer
```

On the proper usage of the ellipsis marker, see [Python's documentation](#).

There are a number of magic comments that you can put into the example code that change how the output is verified by the Sage doctest framework. Here is a comprehensive list:

- **random:** The line will be executed, but its output will not be checked with the output in the documentation string:

```
sage: c = CombinatorialObject([1,2,3])
sage: hash(c) # random
1335416675971793195
sage: hash(c) # random
This doctest passes too, as the output is not checked
```

Doctests are expected to pass with any state of the pseudorandom number generators (PRNGs). When possible, avoid the problem, e.g.: rather than checking the value of the hash in a doctest, one could illustrate successfully using it as a key in a dict.

One can also avoid the random-tag by checking basic properties:

```
sage: QQ.random_element().parent() is QQ
True
sage: QQ.random_element() in QQ
True
sage: a = QQ.random_element()
sage: b = QQ._random_nonzero_element()
sage: c = QQ._random_nonzero_element()
sage: (a/c) / (b/c) == a/b
True
```

Distribution can be checked with loops:

```
sage: found = {i: False for i in range(-2, 3)}
sage: while not all(found.values()):
.....:     found[ZZ.random_element(-2, 3)] = True
```


This is mathematically correct, as it is guaranteed to terminate. However, there is a nonzero probability of a timeout.

- **long time:** The line is only tested if the `--long` option is given, e.g. `sage -t --long f.py`.

Use it for doctests that take more than a second to run. No example should take more than about 30 seconds:

```
sage: E = EllipticCurve([0, 0, 1, -1, 0])
sage: E.regulator()           # long time (1 second)
0.0511114082399688
```

- **tol** or **tolerance:** The numerical values returned by the line are only verified to the given tolerance. It is useful when the output is subject to numerical noise due to system-dependent (floating point arithmetic, math libraries, ...) or non-deterministic algorithms.
 - This may be prefixed by `abs[olute]` or `rel[ative]` to specify whether to measure **absolute** or **relative** error (see the [Wikipedia article Approximation_error](#)).
 - If none of `abs/rel` is specified, the error is considered to be absolute when the expected value is **zero**, and is relative for **nonzero** values.

```
sage: n(pi) # abs tol 1e-9
3.14159265358979
sage: n(pi) # rel tol 2
6
sage: n(pi) # abs tol 1.41593
2
sage: K.<zeta8> = CyclotomicField(8)
sage: N(zeta8) # absolute tolerance 1e-10
0.7071067812 + 0.7071067812*I
```

Multiple numerical values: the representation of complex numbers, matrices, or polynomials usually involves several numerical values. If a doctest with tolerance contains several numbers, each of them is checked individually:

```
sage: print("The sum of 1 and 1 equals 5") # abs tol 1
The sum of 2 and 2 equals 4
sage: e^(i*pi/4).n() # rel tol 1e-1
0.7 + 0.7*I
sage: ((x+1.001)^4).expand() # rel tol 2
x^4 + 4*x^3 + 6*x^2 + 4*x + 1
sage: M = matrix.identity(3) + random_matrix(RR,3,3)/10^3
sage: M^2 # abs tol 1e-2
[1 0 0]
[0 1 0]
[0 0 1]
```

The values that the doctesting framework involves in the error computations are defined by the regular expression `float_regex` in `sage.doctest.parsing`.

- **not implemented** or **not tested:** The line is never tested.

Use it for very long doctests that are only meant as documentation. It can also be used for todo notes of what will eventually be implemented:

```
sage: factor(x*y - x*z) # todo: not implemented
```

It is also immediately clear to the user that the indicated example does not currently work.

Note: Skip all doctests of a file/directory

- **file:** If one of the first 10 lines of a file starts with any of `r""" nodotest` (or `""" nodotest` or `# nodotest` or `% nodotest` or `.. nodotest`, or any of these with different spacing), then that file will be skipped.
- **directory:** If a directory contains a file `nodotest.py`, then that whole directory will be skipped.

Neither of this applies to files or directories which are explicitly given as command line arguments: those are always tested.

- **optional:** A line flagged with `optional - keyword` is not tested unless the `--optional=keyword` flag is passed to `sage -t` (see [Run Optional Doctests](#)). The main applications are:

- **optional packages:** When a line requires an optional package to be installed (e.g. the `sloane_database` package):

```
sage: SloaneEncyclopedia[60843]      # optional - sloane_database
```

Note: If one of the first 10 lines of a file starts with any of `r""" sage.doctest: optional - keyword` (or `""" sage.doctest: optional - keyword` or `# sage.doctest: optional - keyword` or `% sage.doctest: optional - keyword` or `.. sage.doctest: optional - keyword`, or any of these with different spacing), then that file will be skipped unless the `--optional=keyword` flag is passed to `sage -t`.

This does not apply to files which are explicitly given as command line arguments: those are always tested.

If you add such a line to a file, you are strongly encouraged to add a note to the module-level documentation, saying that the doctests in this file will be skipped unless the appropriate conditions are met.

- **internet:** For lines that require an internet connection:

```
sage: oeis(60843)                    # optional - internet
A060843: Busy Beaver problem: a(n) = maximal number of steps that an
n-state Turing machine can make on an initially blank tape before
eventually halting.
```

- **bug:** For lines that describe bugs. Alternatively, use `# known bug` instead: it is an alias for `optional bug`.

```
The following should yield 4.  See :trac:`2`.  ::

sage: 2+2 # optional - bug
5
sage: 2+2 # known bug
5
```

Note:

- Any words after `# optional` are interpreted as a list of package (spkg) names or other feature tags, separated by spaces.
- Any punctuation other than underscores (`_`) and periods (`.`), that is, commas, hyphens, semicolons, ..., after the first word ends the list of packages. Hyphens or colons between the word `optional` and the first

package name are allowed. Therefore, you should not write `optional: needs package CHomP` but simply `optional: CHomP`.

- Optional tags are case-insensitive, so you could also write `optional: chOMP`.

- **indirect doctest:** in the docstring of a function `A(...)`, a line calling `A` and in which the name `A` does not appear should have this flag. This prevents `sage --coverage <file>` from reporting the docstring as “not testing what it should test”.

Use it when testing special functions like `__repr__`, `__add__`, etc. Use it also when you test the function by calling `B` which internally calls `A`:

This is the docstring of an `__add__` method. The following example tests it, but `__add__` is not written anywhere::

```
sage: 1+1 # indirect doctest
2
```

- **32-bit or 64-bit:** for tests that behave differently on 32-bit or 64-bit machines. Note that this particular flag is to be applied on the **output** lines, not the input lines:

```
sage: hash(2^31 + 2^13)
8193                # 32-bit
2147491840          # 64-bit
```

Using `search_src` from the Sage prompt (or `grep`), one can easily find the aforementioned keywords. In the case of `todo: not implemented`, one can use the results of such a search to direct further development on Sage.

2.2.6 Running Automated Doctests

This section describes Sage’s automated testing of test files of the following types: `.py`, `.pyx`, `.sage`, `.rst`. Briefly, use `sage -t <file>` to test that the examples in `<file>` behave exactly as claimed. See the following subsections for more details. See also *Documentation Strings* for a discussion on how to include examples in documentation strings and what conventions to follow. The chapter *Running Sage’s doctests* contains a tutorial on doctesting modules in the Sage library.

Testing .py, .pyx and .sage Files

Run `sage -t <filename.py>` to test all code examples in `filename.py`. Similar remarks apply to `.sage` and `.pyx` files:

```
$ sage -t [--verbose] [--optional] [files and directories ... ]
```

The Sage doctesting framework is based on the standard Python doctest module, but with many additional features (such as parallel testing, timeouts, optional tests). The Sage doctester recognizes `sage:` prompts as well as `>>>` prompts. It also preprocesses the doctests, just like in interactive Sage sessions.

Your file passes the tests if the code in it will run when entered at the `sage:` prompt with no extra imports. Thus users are guaranteed to be able to exactly copy code out of the examples you write for the documentation and have them work.

For more information, see *Running Sage’s doctests*.

Testing reST Documentation

Run `sage -t <filename.rst>` to test the examples in verbatim environments in reST documentation.

Of course in reST files, one often inserts explanatory texts between different verbatim environments. To link together verbatim environments, use the `.. link` comment. For example:

```
EXAMPLES::

    sage: a = 1

Next we add 1 to ``a``.

.. link::

    sage: 1 + a
    2
```

If you want to link all the verbatim environments together, you can put `.. linkall` anywhere in the file, on a line by itself. (For clarity, it might be best to put it near the top of the file.) Then `sage -t` will act as if there were a `.. link` before each verbatim environment. The file `SAGE_ROOT/src/doc/en/tutorial/interfaces.rst` contains a `.. linkall` directive, for example.

You can also put `.. skip` right before a verbatim environment to have that example skipped when testing the file. This goes in the same place as the `.. link` in the previous example.

See the files in `SAGE_ROOT/src/doc/en/tutorial/` for many examples of how to include automated testing in reST documentation for Sage.

2.2.7 General Coding Style Regarding Whitespace

Use spaces instead of tabs for indentation. The only exception is for makefiles, in which tabs have a syntactic meaning different from spaces.

Do not add trailing whitespace.

Sage provides editor configuration for Emacs, using the file `.dir-locals.el`, to use spaces instead of tabs. Regarding trailing whitespace, see <https://www.emacswiki.org/emacs/DeletingWhitespace> for various solutions.

If you use another editor, we recommend to configure it so you do not add tabs to files. See *Configuring text editors and IDEs for use with Sage*.

2.2.8 Global Options

Global options for classes can be defined in Sage using `GlobalOptions`.

2.2.9 Miscellaneous minor things

Some decisions are arbitrary, but common conventions make life easier.

- Non-ASCII names in identifiers:
 - Translate *ä* and *ö* to *ae* and *oe*, like `moebius_function` for Möbius function.
 - Translate *á* to *a*, like `lovasz_number` for Lovász number.
- Common function keyword arguments:

This is a list of some keyword arguments that many functions and methods take. For consistency, you should use the keywords from the list below with the meaning as explained here. Do not use a different keyword with the same meaning (for example, do not use `method`; use `algorithm` instead).

- `algorithm`, a string or `None`: choose between various implementation or algorithm. Use `None` as a default that selects a sensible default, which could depend on installed optional packages.
- `certificate`, a Boolean with `False` as default: whether the function should return some kind of certificate together with the result. With `certificate=True` the return value should be a pair (r, c) where r is the result that would be given with `certificate=False` and c is the certificate or `None` if there is no meaningful certificate.
- `proof`, a Boolean with `True` as default: if `True`, require a mathematically proven computation. If `False`, a probabilistic algorithm or an algorithm relying to non-proved hypothesis like RH can be used.
- `check`, a Boolean: do some additional checks to verify the input parameters. This should not otherwise influence the functioning of the code: if code works with `check=True`, it should also work with `check=False`.
- `coerce`, a Boolean: convert the input parameters to a suitable parent. This is typically used in constructors. You can call a method with `coerce=False` to skip some checks if the parent is known to be correct.
- `inplace`, a Boolean: whether to modify the object in-place or to return a copy.

2.3 The reviewer's check list

All code that goes into Sage is peer-reviewed. Two reasons for this are:

- Because a developer cannot think of everything at once;
- Because a fresh pair of eyes may spot a mathematical error, a corner-case in the code, insufficient documentation, a missing consistency check, etc.

Anybody (e.g. you) can do this job for somebody else's ticket. This document lists things that the reviewer must check before deciding that a ticket is ready for inclusion into Sage.

- Do you know what the **trac server** is? If not, [click here](#).
- Do you have a **trac account**? If not, [click here](#).

You can now begin the review by reading the diff code.

Read the diff: the diff (i.e. the ticket's content) can be obtained by clicking on the (green) branch's name that appears on the trac ticket. If that name appears in red (see *The Ticket Fields*) you can say so in a comment and set the ticket to `needs_work` (see *The Status of a Ticket*).

Build the code: while you read the code, you can *rebuild Sage with the new code*. If you do not know how to **download the code**, [click here](#) (with git trac) or [here](#) (git only).

The following should generally be checked while reading and testing the code:

- **The purpose:** Does the code address the ticket's stated aim? Can it introduce any new problems? Does testing the new or fixed functionality with a variety of input, not just the examples in the documentation, give expected and robust output (and no unexpected errors or crashes)?
- **User documentation:** Is the use of the new code clear to a user? Are all mathematical notions involved standard, or is there explanation (or a link to one) provided? Can he/she find the new code easily if he/she needs it?
- **Code documentation:** Is the code sufficiently commented so that a developer does not have to wonder what exactly it does?
- **Conventions:** Does the code respect *Sage's conventions*? *Python's convention*? *Cython's convention*?
- **Doctest coverage:** Do all functions contain doctests? Use `sage -coverage <files>` to check it. Are all aspects of the new/modified methods and classes tested (see *Writing Testable Examples*)?
- **Bugfixes:** If the ticket contains a bugfix, does it add a doctest illustrating that the bug has been fixed? This new doctest should contain the ticket number, for example `See :trac: 12345``.
- **Speedup:** Can the ticket make any existing code slower? if the ticket claims to speed up some computation, does the ticket contain code examples to illustrate the claim? The ticket should explain how the speedup is achieved.
- **Build the manuals:** Does the reference manual build without errors (check both html and pdf)? See *The Sage Manuals* to learn how to build the manuals.
- **Look at the manuals:** Does the reference manual look okay? The changes may have typos that allow the documentation to build without apparent errors but that may cause badly formatted output or broken hyperlinks.
- **Run the tests:** Do all doctests pass without errors? Unrelated components of Sage may be affected by the change. Check all tests in the whole library, including "long" doctests (this can be done with `make ptestlong`) and any optional doctests related to the functionality. See *Running Sage's doctests* for more information.

You are now ready to change the ticket's status (see *The Status of a Ticket*):

- **positive review:** If the answers to the questions above and other reasonable questions are "yes", you can set the ticket to `positive_review`. Add your full name to the "reviewer" field (see *The Ticket Fields*).
- **needs_work:** If something is not as it should, write a list of all points that need to be addressed in a comment and change the ticket's status to `needs_work`.
- **needs_info:** If something is not clear to you and prevents you from going further with the review, ask your question and set the ticket's status to `needs_info`.
- If you **do not know what to do**, for instance if you don't feel experienced enough to take a final decision, explain what you already did in a comment and ask if someone else could take a look.

Reviewer's commit: if you can fix the issues yourself, you may make a commit in your own name and mark the commit as a reviewer's patch. To learn how [click here](#) (git trac) or [here](#) (git only). This contribution must also be reviewed, for example by the author of the original patch.

For more advice on reviewing, see [\[WSblog\]](#).

Note: "The perfect is the enemy of the good"

The point of the review is to ensure that the Sage code guidelines are followed and that the implementation is mathematically correct. Please refrain from additional feature requests or open-ended discussion about alternative implementations. If you want the patch written differently, your suggestion should be a clear and actionable request.

REFERENCES:

2.4 Running Sage's tests

2.4.1 Running Sage's doctests

Doctesting a function ensures that the function performs as claimed by its documentation. Testing can be performed using one thread or multiple threads. After compiling a source version of Sage, doctesting can be run on the whole Sage library, on all modules under a given directory, or on a specified module only. For the purposes of this chapter, suppose we have compiled Sage 6.0 from source and the top level Sage directory is:

```
[jdemeyer@sage sage-6.0]$ pwd
/scratch/jdemeyer/build/sage-6.0
```

See the section *Running Automated Doctests* for information on Sage's automated testing process. The general syntax for doctesting is as follows. To doctest a module in the library of a version of Sage, use this syntax:

```
/path/to/sage-x.y.z/sage -t [--long] /path/to/sage-x.y.z/path/to/module.py[x]
```

where `--long` is an optional argument (see *Optional Arguments* for more options). The version of `sage` used must match the version of Sage containing the module we want to doctest. A Sage module can be either a Python script (with the file extension `".py"`) or it can be a Cython script, in which case it has the file extension `".pyx"`.

Testing a Module

Say we want to run all tests in the sudoku module `sage/games/sudoku.py`. In a terminal window, first we `cd` to the top level Sage directory of our local Sage installation. Now we can start doctesting as demonstrated in the following terminal session:

```
[jdemeyer@sage sage-6.0]$ ./sage -t src/sage/games/sudoku.py
Running doctests with ID 2012-07-03-03-36-49-d82849c6.
Doctesting 1 file.
sage -t src/sage/games/sudoku.py
    [103 tests, 3.6 s]
-----
All tests passed!
-----
Total time for all tests: 4.8 seconds
    cpu time: 3.6 seconds
    cumulative wall time: 3.6 seconds
```

The numbers output by the test show that testing the sudoku module takes about four seconds, while testing all specified modules took the same amount of time; the total time required includes some startup time for the code that runs the tests. In this case, we only tested one module so it is not surprising that the total testing time is approximately the same as the time required to test only that one module. Notice that the syntax is:

```
[jdemeyer@sage sage-6.0]$ ./sage -t src/sage/games/sudoku.py
Running doctests with ID 2012-07-03-03-39-02-da6accbb.
Doctesting 1 file.
sage -t src/sage/games/sudoku.py
    [103 tests, 3.6 s]
-----
All tests passed!
-----
```

(continues on next page)

(continued from previous page)

```
Total time for all tests: 4.9 seconds
  cpu time: 3.6 seconds
  cumulative wall time: 3.6 seconds
```

but not:

```
[jdemeyer@sage sage-6.0]$ ./sage -t sage/games/sudoku.py
Running doctests with ID 2012-07-03-03-40-53-6cc4f29f.
No files matching sage/games/sudoku.py
No files to doctest
```

We can also first `cd` to the directory containing the module `sudoku.py` and doctest that module as follows:

```
[jdemeyer@sage sage-6.0]$ cd src/sage/games/
[jdemeyer@sage games]$ ls
__init__.py  hexad.py      sudoku.py      sudoku_backtrack.pyx
all.py       quantumino.py sudoku_backtrack.c
[jdemeyer@sage games]$ ../../../../sage -t sudoku.py
Running doctests with ID 2012-07-03-03-41-39-95ebd2ff.
Doctesting 1 file.
sage -t sudoku.py
  [103 tests, 3.6 s]

-----
All tests passed!
-----
Total time for all tests: 5.2 seconds
  cpu time: 3.6 seconds
  cumulative wall time: 3.6 seconds
```

In all of the above terminal sessions, we used a local installation of Sage to test its own modules. Even if we have a system-wide Sage installation, using that version to doctest the modules of a local installation is a recipe for confusion.

You can also run the Sage doctester as follows:

```
[jdemeyer@sage sage-6.0]$ ./sage -tox -e doctest -- src/sage/games/sudoku.py
```

See *Additional development and testing tools* for more information about `tox`.

Troubleshooting

To doctest modules of a Sage installation, from a terminal window we first `cd` to the top level directory of that Sage installation, otherwise known as the `SAGE_ROOT` of that installation. When we run tests, we use that particular Sage installation via the syntax `./sage`; notice the “dot-forward-slash” at the front of `sage`. This is a precaution against confusion that can arise when our system has multiple Sage installations. For example, the following syntax is acceptable because we explicitly specify the Sage installation in the current `SAGE_ROOT`:

```
[jdemeyer@sage sage-6.0]$ ./sage -t src/sage/games/sudoku.py
Running doctests with ID 2012-07-03-03-43-24-a3449f54.
Doctesting 1 file.
sage -t src/sage/games/sudoku.py
  [103 tests, 3.6 s]

-----
All tests passed!
```

(continues on next page)

(continued from previous page)

```

-----
Total time for all tests: 4.9 seconds
  cpu time: 3.6 seconds
  cumulative wall time: 3.6 seconds
[jdemeyer@sage sage-6.0]$ ./sage -t "src/sage/games/sudoku.py"
Running doctests with ID 2012-07-03-03-43-54-ac8ca007.
Doctesting 1 file.
sage -t src/sage/games/sudoku.py
  [103 tests, 3.6 s]
-----

All tests passed!
-----

Total time for all tests: 4.9 seconds
  cpu time: 3.6 seconds
  cumulative wall time: 3.6 seconds

```

The following syntax is not recommended as we are using a system-wide Sage installation (if it exists):

```

[jdemeyer@sage sage-6.0]$ sage -t src/sage/games/sudoku.py
sage -t "src/sage/games/sudoku.py"
*****
File "/home/jdemeyer/sage/sage-6.0/src/sage/games/sudoku.py", line 515:
    sage: next(h.solve(algorithm='backtrack'))
Exception raised:
Traceback (most recent call last):
  File "/usr/local/sage/local/bin/ncadoctest.py", line 1231, in run_one_test
    self.run_one_example(test, example, filename, compileflags)
  File "/usr/local/sage/local/bin/sagedoctest.py", line 38, in run_one_example
    OrigDocTestRunner.run_one_example(self, test, example, filename, compileflags)
  File "/usr/local/sage/local/bin/ncadoctest.py", line 1172, in run_one_example
    compileflags, 1) in test.globs
  File "<doctest __main__.example_13[4]>", line 1, in <module>
    next(h.solve(algorithm='backtrack'))###line 515:
sage: next(h.solve(algorithm='backtrack'))
  File "/home/jdemeyer/.sage/tmp/sudoku.py", line 607, in solve
    for soln in gen:
  File "/home/jdemeyer/.sage/tmp/sudoku.py", line 719, in backtrack
    from sudoku_backtrack import backtrack_all
ImportError: No module named sudoku_backtrack
*****
[...more errors...]
2 items had failures:
  4 of 15 in __main__.example_13
  2 of  8 in __main__.example_14
***Test Failed*** 6 failures.
For whitespace errors, see the file /home/jdemeyer/.sage//tmp/.doctest_sudoku.py
  [21.1 s]

```

The following tests failed:

(continues on next page)

(continued from previous page)

```
sage -t "src/sage/games/sudoku.py"
Total time for all tests: 21.3 seconds
```

In this case, we received an error because the system-wide Sage installation is a different (older) version than the one we are using for Sage development. Make sure you always test the files with the correct version of Sage.

Parallel Testing Many Modules

So far we have used a single thread to doctest a module in the Sage library. There are hundreds, even thousands of modules in the Sage library. Testing them all using one thread would take a few hours. Depending on our hardware, this could take up to six hours or more. On a multi-core system, parallel doctesting can significantly reduce the testing time. Unless we also want to use our computer while doctesting in parallel, we can choose to devote all the cores of our system for parallel testing.

Let us doctest all modules in a directory, first using a single thread and then using four threads. For this example, suppose we want to test all the modules under `sage/crypto/`. We can use a syntax similar to that shown above to achieve this:

```
[jdemeyer@sage sage-6.0]$ ./sage -t src/sage/crypto
Running doctests with ID 2012-07-03-03-45-40-7f837dcf.
Doctesting 24 files.
sage -t src/sage/crypto/__init__.py
    [0 tests, 0.0 s]
sage -t src/sage/crypto/all.py
    [0 tests, 0.0 s]
sage -t src/sage/crypto/boolean_function.pyx
    [252 tests, 4.4 s]
sage -t src/sage/crypto/cipher.py
    [10 tests, 0.0 s]
sage -t src/sage/crypto/classical.py
    [718 tests, 11.3 s]
sage -t src/sage/crypto/classical_cipher.py
    [130 tests, 0.5 s]
sage -t src/sage/crypto/cryptosystem.py
    [82 tests, 0.1 s]
sage -t src/sage/crypto/lattice.py
    [1 tests, 0.0 s]
sage -t src/sage/crypto/lfsr.py
    [31 tests, 0.1 s]
sage -t src/sage/crypto/stream.py
    [17 tests, 0.1 s]
sage -t src/sage/crypto/stream_cipher.py
    [114 tests, 0.2 s]
sage -t src/sage/crypto/util.py
    [122 tests, 0.2 s]
sage -t src/sage/crypto/block_cipher/__init__.py
    [0 tests, 0.0 s]
sage -t src/sage/crypto/block_cipher/all.py
    [0 tests, 0.0 s]
sage -t src/sage/crypto/block_cipher/miniaes.py
    [430 tests, 1.3 s]
sage -t src/sage/crypto/block_cipher/sdes.py
```

(continues on next page)

(continued from previous page)

```

[290 tests, 0.9 s]
sage -t src/sage/crypto/mq/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/mq/mpolynomialssystem.py
[320 tests, 9.1 s]
sage -t src/sage/crypto/mq/mpolynomialssystemgenerator.py
[42 tests, 0.1 s]
sage -t src/sage/crypto/sbox.pyx
[124 tests, 0.8 s]
sage -t src/sage/crypto/mq/sr.py
[435 tests, 5.5 s]
sage -t src/sage/crypto/public_key/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/public_key/all.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/public_key/blum_goldwasser.py
[135 tests, 0.2 s]
-----
All tests passed!
-----
Total time for all tests: 38.1 seconds
    cpu time: 29.8 seconds
    cumulative wall time: 35.1 seconds

```

Now we do the same thing, but this time we also use the optional argument `--long`:

```

[jdemeyer@sage sage-6.0]$ ./sage -t --long src/sage/crypto/
Running doctests with ID 2012-07-03-03-48-11-c16721e6.
Doctesting 24 files.
sage -t --long src/sage/crypto/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/all.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/boolean_function.pyx
[252 tests, 4.2 s]
sage -t --long src/sage/crypto/cipher.py
[10 tests, 0.0 s]
sage -t --long src/sage/crypto/classical.py
[718 tests, 10.3 s]
sage -t --long src/sage/crypto/classical_cipher.py
[130 tests, 0.5 s]
sage -t --long src/sage/crypto/cryptosystem.py
[82 tests, 0.1 s]
sage -t --long src/sage/crypto/lattice.py
[1 tests, 0.0 s]
sage -t --long src/sage/crypto/lfsr.py
[31 tests, 0.1 s]
sage -t --long src/sage/crypto/stream.py
[17 tests, 0.1 s]
sage -t --long src/sage/crypto/stream_cipher.py
[114 tests, 0.2 s]
sage -t --long src/sage/crypto/util.py

```

(continues on next page)

(continued from previous page)

```

[122 tests, 0.2 s]
sage -t --long src/sage/crypto/block_cipher/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/block_cipher/all.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/block_cipher/miniaes.py
[430 tests, 1.1 s]
sage -t --long src/sage/crypto/block_cipher/sdes.py
[290 tests, 0.7 s]
sage -t --long src/sage/crypto/mq/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/mq/mpolynomialssystem.py
[320 tests, 7.5 s]
sage -t --long src/sage/crypto/mq/mpolynomialssystemgenerator.py
[42 tests, 0.1 s]
sage -t --long src/sage/crypto/sbox.pyx
[124 tests, 0.7 s]
sage -t --long src/sage/crypto/mq/sr.py
[437 tests, 82.4 s]
sage -t --long src/sage/crypto/public_key/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/public_key/all.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/public_key/blum_goldwasser.py
[135 tests, 0.2 s]
-----
All tests passed!
-----
Total time for all tests: 111.8 seconds
  cpu time: 106.1 seconds
  cumulative wall time: 108.5 seconds

```

Notice the time difference between the first set of tests and the second set, which uses the optional argument `--long`. Many tests in the Sage library are flagged with `# long` time because these are known to take a long time to run through. Without using the optional `--long` argument, the module `sage/crypto/mq/sr.py` took about five seconds. With this optional argument, it required 82 seconds to run through all tests in that module. Here is a snippet of a function in the module `sage/crypto/mq/sr.py` with a doctest that has been flagged as taking a long time:

```

def test_consistency(max_n=2, **kwargs):
    r"""
    Test all combinations of ``r``, ``c``, ``e`` and ``n`` in ``(1,
    2)`` for consistency of random encryptions and their polynomial
    systems.  $\mathbb{GF}\{2\}$  and  $\mathbb{GF}\{2^e\}$  systems are tested. This test takes
    a while.

    INPUT:

    - ``max_n`` -- maximal number of rounds to consider (default: 2)
    - ``kwargs`` -- are passed to the SR constructor

    TESTS:

```

(continues on next page)

(continued from previous page)

The following test called with ``max_n`` = 2 requires a LOT of RAM (much more than 2GB). Since this might cause the doctest to fail on machines with "only" 2GB of RAM, we test ``max_n`` = 1, which has a more reasonable memory usage. ::

```
sage: from sage.crypto.mq.sr import test_consistency
sage: test_consistency(1) # long time (80s on sage.math, 2011)
True
"""
```

Now we doctest the same directory in parallel using 4 threads:

```
[jdemeyer@sage sage-6.0]$ ./sage -tp 4 src/sage/crypto/
Running doctests with ID 2012-07-07-00-11-55-9b17765e.
Sorting sources by runtime so that slower doctests are run first....
Doctesting 24 files using 4 threads.
sage -t src/sage/crypto/boolean_function.pyx
[252 tests, 3.8 s]
sage -t src/sage/crypto/block_cipher/miniaes.py
[429 tests, 1.1 s]
sage -t src/sage/crypto/mq/sr.py
[432 tests, 5.7 s]
sage -t src/sage/crypto/sbox.pyx
[123 tests, 0.8 s]
sage -t src/sage/crypto/block_cipher/sdes.py
[289 tests, 0.6 s]
sage -t src/sage/crypto/classical_cipher.py
[123 tests, 0.4 s]
sage -t src/sage/crypto/stream_cipher.py
[113 tests, 0.1 s]
sage -t src/sage/crypto/public_key/blum_goldwasser.py
[134 tests, 0.1 s]
sage -t src/sage/crypto/lfsr.py
[30 tests, 0.1 s]
sage -t src/sage/crypto/util.py
[121 tests, 0.1 s]
sage -t src/sage/crypto/cryptosystem.py
[79 tests, 0.0 s]
sage -t src/sage/crypto/stream.py
[12 tests, 0.0 s]
sage -t src/sage/crypto/mq/mpolynomialssystemgenerator.py
[40 tests, 0.0 s]
sage -t src/sage/crypto/cipher.py
[3 tests, 0.0 s]
sage -t src/sage/crypto/lattice.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/block_cipher/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/all.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/public_key/__init__.py
[0 tests, 0.0 s]
```

(continues on next page)

(continued from previous page)

```

sage -t src/sage/crypto/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/public_key/all.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/mq/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/block_cipher/all.py
[0 tests, 0.0 s]
sage -t src/sage/crypto/mq/mpolynomialssystem.py
[318 tests, 8.4 s]
sage -t src/sage/crypto/classical.py
[717 tests, 10.4 s]
-----
All tests passed!
-----
Total time for all tests: 12.9 seconds
    cpu time: 30.5 seconds
    cumulative wall time: 31.7 seconds
[jdemeyer@sage sage-6.0]$ ./sage -tp 4 --long src/sage/crypto/
Running doctests with ID 2012-07-07-00-13-04-d71f3cd4.
Sorting sources by runtime so that slower doctests are run first....
Doctesting 24 files using 4 threads.
sage -t --long src/sage/crypto/boolean_function.pyx
[252 tests, 3.7 s]
sage -t --long src/sage/crypto/block_cipher/miniaes.py
[429 tests, 1.0 s]
sage -t --long src/sage/crypto/sbox.pyx
[123 tests, 0.8 s]
sage -t --long src/sage/crypto/block_cipher/sdes.py
[289 tests, 0.6 s]
sage -t --long src/sage/crypto/classical_cipher.py
[123 tests, 0.4 s]
sage -t --long src/sage/crypto/util.py
[121 tests, 0.1 s]
sage -t --long src/sage/crypto/stream_cipher.py
[113 tests, 0.1 s]
sage -t --long src/sage/crypto/public_key/blum_goldwasser.py
[134 tests, 0.1 s]
sage -t --long src/sage/crypto/lfsr.py
[30 tests, 0.0 s]
sage -t --long src/sage/crypto/cryptosystem.py
[79 tests, 0.0 s]
sage -t --long src/sage/crypto/stream.py
[12 tests, 0.0 s]
sage -t --long src/sage/crypto/mq/mpolynomialssystemgenerator.py
[40 tests, 0.0 s]
sage -t --long src/sage/crypto/cipher.py
[3 tests, 0.0 s]
sage -t --long src/sage/crypto/lattice.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/block_cipher/all.py
[0 tests, 0.0 s]

```

(continues on next page)

(continued from previous page)

```
sage -t --long src/sage/crypto/public_key/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/mq/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/all.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/block_cipher/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/__init__.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/public_key/all.py
[0 tests, 0.0 s]
sage -t --long src/sage/crypto/mq/mpolynomialssystem.py
[318 tests, 9.0 s]
sage -t --long src/sage/crypto/classical.py
[717 tests, 10.5 s]
sage -t --long src/sage/crypto/mq/sr.py
[434 tests, 88.0 s]
```

```
-----
All tests passed!
-----
```

```
Total time for all tests: 90.4 seconds
  cpu time: 113.4 seconds
  cumulative wall time: 114.5 seconds
```

As the number of threads increases, the total testing time decreases.

Parallel Testing the Whole Sage Library

The main Sage library resides in the directory `SAGE_ROOT/src/`. We can use the syntax described above to doctest the main library using multiple threads. When doing release management or patching the main Sage library, a release manager would parallel test the library using 10 threads with the following command:

```
[jdemeyer@sage sage-6.0]$ ./sage -tp 10 --long src/
```

Another way is run `make ptestlong`, which builds Sage (if necessary), builds the Sage documentation (if necessary), and then runs parallel doctests. This determines the number of threads by reading the environment variable `MAKE`: if it is set to `make -j12`, then use 12 threads. If `MAKE` is not set, then by default it uses the number of CPU cores (as determined by the Python function `multiprocessing.cpu_count()`) with a minimum of 2 and a maximum of 8.

In any case, this will test the Sage library with multiple threads:

```
[jdemeyer@sage sage-6.0]$ make ptestlong
```

Any of the following commands would also doctest the Sage library or one of its clones:

```
make test
make check
make testlong
make ptest
make ptestlong
```

The differences are:

- `make test` and `make check` — These two commands run the same set of tests. First the Sage standard documentation is tested, i.e. the documentation that resides in

- `SAGE_ROOT/src/doc/common`
- `SAGE_ROOT/src/doc/en`
- `SAGE_ROOT/src/doc/fr`

Finally, the commands doctest the Sage library. For more details on these command, see the file `SAGE_ROOT/Makefile`.

- `make testlong` — This command doctests the standard documentation:

- `SAGE_ROOT/src/doc/common`
- `SAGE_ROOT/src/doc/en`
- `SAGE_ROOT/src/doc/fr`

and then the Sage library. Doctesting is run with the optional argument `--long`. See the file `SAGE_ROOT/Makefile` for further details.

- `make ptest` — Similar to the commands `make test` and `make check`. However, doctesting is run with the number of threads as described above for `make ptestlong`.
- `make ptestlong` — Similar to the command `make ptest`, but using the optional argument `--long` for doctesting.

The underlying command for running these tests is `sage -t --all`. For example, `make ptestlong` executes the command `sage -t -p --all --long --logfile=logs/ptestlong.log`. So if you want to add extra flags when you run these tests, for example `--verbose`, you can execute `sage -t -p --all --long --verbose --logfile=path/to/logfile`. Some of the extra testing options are discussed here; run `sage -t -h` for a complete list.

Beyond the Sage Library

Doctesting also works fine for files not in the Sage library. For example, suppose we have a Python script called `my_python_script.py`:

```
[mvngu@sage build]$ cat my_python_script.py
from sage.all_cmdline import * # import sage library

def square(n):
    """
    Return the square of n.

    EXAMPLES::

        sage: square(2)
        4
    """
    return n**2
```

Then we can doctest it just as with Sage library files:

```
[mvngu@sage sage-6.0]$ ./sage -t my_python_script.py
Running doctests with ID 2012-07-07-00-17-56-d056f7c0.
Doctesting 1 file.
```

(continues on next page)

(continued from previous page)

```
sage -t my_python_script.py
[1 test, 0.0 s]

-----

All tests passed!

-----

Total time for all tests: 2.2 seconds
  cpu time: 0.0 seconds
  cumulative wall time: 0.0 seconds
```

Doctesting can also be performed on Sage scripts. Say we have a Sage script called `my_sage_script.sage` with the following content:

```
[mvngu@sage sage-6.0]$ cat my_sage_script.sage
def cube(n):
    r"""
    Return the cube of n.

    EXAMPLES::

        sage: cube(2)
        8
    """
    return n**3
```

Then we can doctest it just as for Python files:

```
[mvngu@sage build]$ sage-6.0/sage -t my_sage_script.sage
Running doctests with ID 2012-07-07-00-20-06-82ee728c.
Doctesting 1 file.
sage -t my_sage_script.sage
[1 test, 0.0 s]

-----

All tests passed!

-----

Total time for all tests: 2.5 seconds
  cpu time: 0.0 seconds
  cumulative wall time: 0.0 seconds
```

Alternatively, we can preprocess it to convert it to a Python script, and then doctest that:

```
[mvngu@sage build]$ sage-6.0/sage --preparse my_sage_script.sage
[mvngu@sage build]$ cat my_sage_script.sage.py
# This file was *autogenerated* from the file my_sage_script.sage.
from sage.all_cmdline import * # import sage library
_sage_const_3 = Integer(3)
def cube(n):
    r"""
    Return the cube of n.

    EXAMPLES::

        sage: cube(2)
        8
```

(continues on next page)

(continued from previous page)

```

"""
    return n**_sage_const_3
[mvngu@sage build]$ sage-6.0/sage -t my_sage_script.sage.py
Running doctests with ID 2012-07-07-00-26-46-2bb00911.
Doctesting 1 file.
sage -t my_sage_script.sage.py
    [2 tests, 0.0 s]
-----
All tests passed!
-----
Total time for all tests: 2.3 seconds
    cpu time: 0.0 seconds
    cumulative wall time: 0.0 seconds

```

Doctesting from Within Sage

You can run doctests from within Sage, which can be useful since you don't have to wait for Sage to start. Use the `run_doctests` function in the global namespace, passing it either a string or a module:

```

sage: run_doctests(sage.combinat.affine_permutation)
Running doctests with ID 2018-02-07-13-23-13-89fe17b1.
Git branch: develop
Using --optional=sagemath_doc_html,sage
Doctesting 1 file.
sage -t /opt/sage/sage_stable/src/sage/combinat/affine_permutation.py
    [338 tests, 4.32 s]
-----
All tests passed!
-----
Total time for all tests: 4.4 seconds
    cpu time: 3.6 seconds
    cumulative wall time: 4.3 seconds

```

Optional Arguments

Run Long Doctests

Ideally, doctests should not take any noticeable amount of time. If you really need longer-running doctests (anything beyond about one second) then you should mark them as:

```
sage: my_long_test() # long time
```

Even then, long doctests should ideally complete in 5 seconds or less. We know that you (the author) want to show off the capabilities of your code, but this is not the place to do so. Long-running tests will sooner or later hurt our ability to run the testsuite. Really, doctests should be as fast as possible while providing coverage for the code.

Use the `--long` flag to run doctests that have been marked with the comment `# long time`. These tests are normally skipped in order to reduce the time spent running tests:

```
[roed@sage sage-6.0]$ sage -t src/sage/rings/tests.py
Running doctests with ID 2012-06-21-16-00-13-40835825.
Doctesting 1 file.
sage -t tests.py
[18 tests, 1.1 s]

-----

All tests passed!

-----

Total time for all tests: 2.9 seconds
  cpu time: 0.9 seconds
  cumulative wall time: 1.1 seconds
```

In order to run the long tests as well, do the following:

```
[roed@sage sage-6.0]$ sage -t --long src/sage/rings/tests.py
Running doctests with ID 2012-06-21-16-02-05-d13a9a24.
Doctesting 1 file.
sage -t tests.py
[20 tests, 34.7 s]

-----

All tests passed!

-----

Total time for all tests: 46.5 seconds
  cpu time: 25.2 seconds
  cumulative wall time: 34.7 seconds
```

To find tests that take longer than the allowed time use the `--warn-long` flag. Without any options it will cause tests to print a warning if they take longer than 1.0 second. Note that this is a warning, not an error:

```
[roed@sage sage-6.0]$ sage -t --warn-long src/sage/rings/factorint.pyx
Running doctests with ID 2012-07-14-03-27-03-2c952ac1.
Doctesting 1 file.
sage -t --warn-long src/sage/rings/factorint.pyx
*****
File "src/sage/rings/factorint.pyx", line 125, in sage.rings.factorint.base_exponent
Failed example:
    base_exponent(-4)
Test ran for 4.09 s
*****
File "src/sage/rings/factorint.pyx", line 153, in sage.rings.factorint.factor_
↪aurifeuillian
Failed example:
    fa(2^6+1)
Test ran for 2.22 s
*****
File "src/sage/rings/factorint.pyx", line 155, in sage.rings.factorint.factor_
↪aurifeuillian
Failed example:
    fa(2^58+1)
Test ran for 2.22 s
*****
File "src/sage/rings/factorint.pyx", line 163, in sage.rings.factorint.factor_
↪aurifeuillian
```

(continues on next page)

(continued from previous page)

```

Failed example:
  fa(2^4+1)
Test ran for 2.25 s
*****
-----
All tests passed!
-----
Total time for all tests: 16.1 seconds
  cpu time: 9.7 seconds
  cumulative wall time: 10.9 seconds

```

You can also pass in an explicit amount of time:

```

[roed@sage sage-6.0]$ sage -t --long --warn-long 2.0 src/sage/rings/tests.py
Running doctests with ID 2012-07-14-03-30-13-c9164c9d.
Doctesting 1 file.
sage -t --long --warn-long 2.0 tests.py
*****
File "tests.py", line 240, in sage.rings.tests.test_random_elements
Failed example:
  sage.rings.tests.test_random_elements(trials=1000) # long time (5 seconds)
Test ran for 13.36 s
*****
File "tests.py", line 283, in sage.rings.tests.test_random_arith
Failed example:
  sage.rings.tests.test_random_arith(trials=1000) # long time (5 seconds?)
Test ran for 12.42 s
*****
-----
All tests passed!
-----
Total time for all tests: 27.6 seconds
  cpu time: 24.8 seconds
  cumulative wall time: 26.3 seconds

```

Finally, you can disable any warnings about long tests with `--warn-long 0`.

Doctests start from a random seed:

```

[kliem@sage sage-9.2]$ sage -t src/sage/doctest/tests/random_seed.rst
Running doctests with ID 2020-06-23-23-22-59-49f37a55.
...
Doctesting 1 file.
sage -t --warn-long 89.5 --random-seed=112986622569797306072457879734474628454 src/sage/
↪ doctest/tests/random_seed.rst
*****
File "src/sage/doctest/tests/random_seed.rst", line 3, in sage.doctest.tests.random_seed
Failed example:
  randint(5, 10)
Expected:
  9
Got:
  8

```

(continues on next page)

(continued from previous page)

```

*****
1 item had failures:
  1 of 2 in sage.doctest.tests.random_seed
  [1 test, 1 failure, 0.00 s]
-----
sage -t --warn-long 89.5 --random-seed=112986622569797306072457879734474628454 src/sage/
↳doctest/tests/random_seed.rst # 1 doctest failed
-----
Total time for all tests: 0.0 seconds
  cpu time: 0.0 seconds
  cumulative wall time: 0.0 seconds

```

This seed can be set explicitly to reproduce possible failures:

```

[kliem@sage sage-9.2]$ sage -t --warn-long 89.5 --random-
↳seed=112986622569797306072457879734474628454 src/sage/doctest/tests/random_seed.rst
Running doctests with ID 2020-06-23-23-24-28-14a52269.
...
Doctesting 1 file.
sage -t --warn-long 89.5 --random-seed=112986622569797306072457879734474628454 src/sage/
↳doctest/tests/random_seed.rst
*****
File "src/sage/doctest/tests/random_seed.rst", line 3, in sage.doctest.tests.random_seed
Failed example:
  randint(5, 10)
Expected:
  9
Got:
  8
*****
1 item had failures:
  1 of 2 in sage.doctest.tests.random_seed
  [1 test, 1 failure, 0.00 s]
-----
sage -t --warn-long 89.5 --random-seed=112986622569797306072457879734474628454 src/sage/
↳doctest/tests/random_seed.rst # 1 doctest failed
-----
Total time for all tests: 0.0 seconds
  cpu time: 0.0 seconds
  cumulative wall time: 0.0 seconds

```

It can also be set explicitly using the environment variable SAGE_DOCTEST_RANDOM_SEED.

Run Optional Doctests

You can run tests that require optional packages by using the `--optional` flag. Obviously, you need to have installed the necessary optional packages in order for these tests to succeed. See <http://www.sagemath.org/packages/optional/> in order to download optional packages.

By default, Sage only runs doctests that are not marked with the `optional` tag. This is equivalent to running

```
[roed@sage sage-6.0]$ sage -t --optional=sagemath_doc_html,sage src/sage/rings/real_mpfr.  
↪pyx  
Running doctests with ID 2012-06-21-16-18-30-a368a200.  
Doctesting 1 file.  
sage -t src/sage/rings/real_mpfr.pyx  
[819 tests, 7.0 s]  
  
-----  
All tests passed!  
-----  
  
Total time for all tests: 8.4 seconds  
cpu time: 4.1 seconds  
cumulative wall time: 7.0 seconds
```

If you want to also run tests that require magma, you can do the following:

```
[roed@sage sage-6.0]$ sage -t --optional=sagemath_doc_html,sage,magma src/sage/rings/  
↪real_mpfr.pyx  
Running doctests with ID 2012-06-21-16-18-30-a00a7319  
Doctesting 1 file.  
sage -t src/sage/rings/real_mpfr.pyx  
[823 tests, 8.4 s]  
  
-----  
All tests passed!  
-----  
  
Total time for all tests: 9.6 seconds  
cpu time: 4.0 seconds  
cumulative wall time: 8.4 seconds
```

In order to just run the tests that are marked as requiring magma, omit `sage` and `sagemath_doc_html`:

```
[roed@sage sage-6.0]$ sage -t --optional=magma src/sage/rings/real_mpfr.pyx  
Running doctests with ID 2012-06-21-16-18-33-a2bc1fdf  
Doctesting 1 file.  
sage -t src/sage/rings/real_mpfr.pyx  
[4 tests, 2.0 s]  
  
-----  
All tests passed!  
-----  
  
Total time for all tests: 3.2 seconds  
cpu time: 0.1 seconds  
cumulative wall time: 2.0 seconds
```

If you want Sage to detect external software or other capabilities (such as magma, latex, internet) automatically and run all of the relevant tests, then add `external`:

```
$ sage -t --optional=external src/sage/rings/real_mpfr.pyx
Running doctests with ID 2016-03-16-14-10-21-af2ebb67.
Using --optional=external
External software to be detected: cplex,gurobi,internet,latex,macaulay2,magma,maple,
↪mathematica,matlab,octave,scilab
Doctesting 1 file.
sage -t --warn-long 28.0 src/sage/rings/real_mpfr.pyx
[5 tests, 0.04 s]
-----
All tests passed!
-----
Total time for all tests: 0.5 seconds
  cpu time: 0.0 seconds
  cumulative wall time: 0.0 seconds
External software detected for doctesting: magma
```

To run all tests, regardless of whether they are marked optional, pass all as the optional tag:

```
[roed@sage sage-6.0]$ sage -t --optional=all src/sage/rings/real_mpfr.pyx
Running doctests with ID 2012-06-21-16-31-18-8c097f55
Doctesting 1 file.
sage -t src/sage/rings/real_mpfr.pyx
[865 tests, 11.2 s]
-----
All tests passed!
-----
Total time for all tests: 12.8 seconds
  cpu time: 4.7 seconds
  cumulative wall time: 11.2 seconds
```

Running Doctests in Parallel

If you're testing many files, you can get big speedups by using more than one thread. To run doctests in parallel use the `--nthreads` flag (`-p` is a shortened version). Pass in the number of threads you would like to use (by default Sage just uses 1):

```
[roed@sage sage-6.0]$ sage -tp 2 src/sage/doctest/
Running doctests with ID 2012-06-22-19-09-25-a3afdb8c.
Sorting sources by runtime so that slower doctests are run first....
Doctesting 8 files using 2 threads.
sage -t src/sage/doctest/control.py
[114 tests, 4.6 s]
sage -t src/sage/doctest/util.py
[114 tests, 0.6 s]
sage -t src/sage/doctest/parsing.py
[187 tests, 0.5 s]
sage -t src/sage/doctest/sources.py
[128 tests, 0.1 s]
sage -t src/sage/doctest/reporting.py
[53 tests, 0.1 s]
sage -t src/sage/doctest/all.py
[0 tests, 0.0 s]
```

(continues on next page)

(continued from previous page)

```
sage -t src/sage/doctest/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/doctest/forker.py
[322 tests, 15.5 s]

-----
All tests passed!
-----

Total time for all tests: 17.0 seconds
    cpu time: 4.2 seconds
    cumulative wall time: 21.5 seconds
```

Doctesting All of Sage

To doctest the whole Sage library use the `--all` flag (`-a` for short). In addition to testing the code in Sage's Python and Cython files, this command will run the tests defined in Sage's documentation as well as testing the Sage notebook:

```
[roed@sage sage-6.0]$ sage -t -a
Running doctests with ID 2012-06-22-19-10-27-e26fce6d.
Doctesting entire Sage library.
Sorting sources by runtime so that slower doctests are run first....
Doctesting 2020 files.
sage -t /Users/roed/sage/sage-5.3/src/sage/plot/plot.py
[304 tests, 69.0 s]
...
```

Debugging Tools

Sometimes doctests fail (that's why we run them after all). There are various flags to help when something goes wrong. If a doctest produces a Python error, then normally tests continue after reporting that an error occurred. If you use the flag `--debug` (`-d` for short) then you will drop into an interactive Python debugger whenever a Python exception occurs. As an example, I modified `sage.schemes.elliptic_curves.constructor` to produce an error:

```
[roed@sage sage-6.0]$ sage -t --debug src/sage/schemes/elliptic_curves/constructor.py
Running doctests with ID 2012-06-23-12-09-04-b6352629.
Doctesting 1 file.
*****
File "sage.schemes.elliptic_curves.constructor", line 4, in sage.schemes.elliptic_curves.
↳ constructor
Failed example:
    EllipticCurve([0,0])
Exception raised:
  Traceback (most recent call last):
    File "/Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/doctest/
↳ forker.py", line 573, in _run
      self.execute(example, compiled, test.globs)
    File "/Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/doctest/
↳ forker.py", line 835, in execute
      exec compiled in globs
    File "<doctest sage.schemes.elliptic_curves.constructor[0]>", line 1, in <module>
```

(continues on next page)

(continued from previous page)

```

    EllipticCurve([Integer(0),Integer(0)])
File "/Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/schemes/
↳ elliptic_curves/constructor.py", line 346, in EllipticCurve
    return ell_rational_field.EllipticCurve_rational_field(x, y)
File "/Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/schemes/
↳ elliptic_curves/ell_rational_field.py", line 216, in __init__
    EllipticCurve_number_field.__init__(self, Q, ainvs)
File "/Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/schemes/
↳ elliptic_curves/ell_number_field.py", line 159, in __init__
    EllipticCurve_field.__init__(self, [field(x) for x in ainvs])
File "/Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/schemes/
↳ elliptic_curves/ell_generic.py", line 156, in __init__
    "Invariants %s define a singular curve."%ainvs
ArithmeticError: Invariants [0, 0, 0, 0, 0] define a singular curve.
> /Users/roed/sage/sage-5.3/local/lib/python2.7/site-packages/sage/schemes/elliptic_
↳ curves/ell_generic.py(156)__init__()
-> "Invariants %s define a singular curve."%ainvs
(Pdb) l
151             if len(ainvs) == 2:
152                 ainvs = [K(0),K(0),K(0)] + ainvs
153             self.__ainvs = tuple(ainvs)
154             if self.discriminant() == 0:
155                 raise ArithmeticError(
156 ->                 "Invariants %s define a singular curve."%ainvs)
157             PP = projective_space.ProjectiveSpace(2, K, names='xyz');
158             x, y, z = PP.coordinate_ring().gens()
159             a1, a2, a3, a4, a6 = ainvs
160             f = y**2*z + (a1*x + a3*z)*y*z \
161                 - (x**3 + a2*x**2*z + a4*x*z**2 + a6*z**3)
(Pdb) p ainvs
[0, 0, 0, 0, 0]
(Pdb) quit
*****
1 items had failures:
  1 of 1 in sage.schemes.elliptic_curves.constructor
***Test Failed*** 1 failures.
sage -t src/sage/schemes/elliptic_curves/constructor.py
[64 tests, 89.2 s]

-----
sage -t src/sage/schemes/elliptic_curves/constructor.py # 1 doctest failed
-----

Total time for all tests: 90.4 seconds
  cpu time: 4.5 seconds
  cumulative wall time: 89.2 seconds

```

Sometimes an error might be so severe that it causes Sage to segfault or hang. In such a situation you have a number of options. The doctest framework will print out the output so far, so that at least you know what test caused the problem (if you want this output to appear in real time use the `--verbose` flag). To have doctests run under the control of gdb, use the `--gdb` flag:

```

[roed@sage sage-6.0]$ sage -t --gdb src/sage/schemes/elliptic_curves/constructor.py
exec gdb --eval-commands="run" --args /home/roed/sage-9.7/local/var/lib/sage/venv-
↳ python3.9/bin/python3 sage-runtests --serial --timeout=0 --stats_path=/home/roed/sage/
↳ timings2.json --optional=pip,sage,sage_spkg src/sage/schemes/elliptic_curves/
↳ constructor.py
(continues on next page)

```

2.4. Running Sage's tests

(continued from previous page)

```
GNU gdb 6.8-debian
Copyright (C) 2008 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.  Type "show copying"
and "show warranty" for details.
This GDB was configured as "x86_64-linux-gnu"...
[Thread debugging using libthread_db enabled]
[New Thread 0x7f10f85566e0 (LWP 6534)]
Running doctests with ID 2012-07-07-00-43-36-b1b735e7.
Doctesting 1 file.
sage -t src/sage/schemes/elliptic_curves/constructor.py
    [67 tests, 5.8 s]

-----
All tests passed!
-----
Total time for all tests: 15.7 seconds
    cpu time: 4.4 seconds
    cumulative wall time: 5.8 seconds

Program exited normally.
(gdb) quit
```

Sage also includes valgrind, and you can run doctests under various valgrind tools to track down memory issues: the relevant flags are `--valgrind` (or `--memcheck`), `--massif`, `--cachegrind` and `--omega`. See <http://wiki.sagemath.org/ValgrindingSage> for more details.

Once you're done fixing whatever problems were revealed by the doctests, you can rerun just those files that failed their most recent test by using the `--failed` flag (`-f` for short):

```
[roed@sage sage-6.0]$ sage -t -fa
Running doctests with ID 2012-07-07-00-45-35-d8b5a408.
Doctesting entire Sage library.
Only doctesting files that failed last test.
No files to doctest
```

Miscellaneous Options

There are various other options that change the behavior of Sage's doctesting code.

Show only first failure

The first failure in a file often causes a cascade of others, as `NameErrors` arise from variables that weren't defined and tests fail because old values of variables are used. To only see the first failure in each doctest block use the `--initial` flag (`-i` for short).

Show skipped optional tests

To print a summary at the end of each file with the number of optional tests skipped, use the `--show-skipped` flag:

```
[roed@sage sage-6.0]$ sage -t --show-skipped src/sage/rings/finite_rings/integer_mod.pyx
Running doctests with ID 2013-03-14-15-32-05-8136f5e3.
Doctesting 1 file.
sage -t sage/rings/finite_rings/integer_mod.pyx
  2 axiom tests not run
  1 cunningham test not run
  2 fricas tests not run
  1 long test not run
  3 magma tests not run
[440 tests, 4.0 s]
-----
All tests passed!
-----
Total time for all tests: 4.3 seconds
  cpu time: 2.4 seconds
  cumulative wall time: 4.0 seconds
```

Running tests with iterations

Sometimes tests fail intermittently. There are two options that allow you to run tests repeatedly in an attempt to search for Heisenbugs. The flag `--global-iterations` takes an integer and runs the whole set of tests that many times serially:

```
[roed@sage sage-6.0]$ sage -t --global-iterations 2 src/sage/sandpiles
Running doctests with ID 2012-07-07-00-59-28-e7048ad9.
Doctesting 3 files (2 global iterations).
sage -t src/sage/sandpiles/__init__.py
  [0 tests, 0.0 s]
sage -t src/sage/sandpiles/all.py
  [0 tests, 0.0 s]
sage -t src/sage/sandpiles/sandpile.py
  [711 tests, 14.7 s]
-----
All tests passed!
-----
Total time for all tests: 17.6 seconds
  cpu time: 13.2 seconds
  cumulative wall time: 14.7 seconds
sage -t src/sage/sandpiles/__init__.py
  [0 tests, 0.0 s]
sage -t src/sage/sandpiles/all.py
  [0 tests, 0.0 s]
sage -t src/sage/sandpiles/sandpile.py
  [711 tests, 13.8 s]
-----
All tests passed!
-----
Total time for all tests: 14.3 seconds
```

(continues on next page)

(continued from previous page)

```
cpu time: 26.4 seconds
cumulative wall time: 28.5 seconds
```

You can also iterate in a different order: the `--file-iterations` flag runs the tests in each file *N* times before proceeding:

```
[roed@sage sage-6.0]$ sage -t --file-iterations 2 src/sage/sandpiles
Running doctests with ID 2012-07-07-01-01-43-8f954206.
Doctesting 3 files (2 file iterations).
sage -t src/sage/sandpiles/__init__.py
[0 tests, 0.0 s]
sage -t src/sage/sandpiles/all.py
[0 tests, 0.0 s]
sage -t src/sage/sandpiles/sandpile.py
[1422 tests, 13.3 s]
-----
All tests passed!
-----
Total time for all tests: 29.6 seconds
  cpu time: 12.7 seconds
  cumulative wall time: 13.3 seconds
```

Note that the reported results are the average time for all tests in that file to finish. If a failure in a file occurs, then the failure is reported and testing proceeds with the next file.

Using a different timeout

On a slow machine the default timeout of 5 minutes may not be enough for the slowest files. Use the `--timeout` flag (`-T` for short) to set it to something else:

```
[roed@sage sage-6.0]$ sage -tp 2 --all --timeout 1
Running doctests with ID 2012-07-07-01-09-37-deblab83.
Doctesting entire Sage library.
Sorting sources by runtime so that slower doctests are run first....
Doctesting 2067 files using 2 threads.
sage -t src/sage/schemes/elliptic_curves/ell_rational_field.py
  Timed out!
...

```

Using absolute paths

By default filenames are printed using relative paths. To use absolute paths instead pass in the `--abspath` flag:

```
[roed@sage sage-6.0]$ sage -t --abspath src/sage/doctest/control.py
Running doctests with ID 2012-07-07-01-13-03-a023e212.
Doctesting 1 file.
sage -t /home/roed/sage-6.0/src/sage/doctest/control.py
[133 tests, 4.7 s]
-----
All tests passed!
```

(continues on next page)

(continued from previous page)

```
-----
Total time for all tests: 7.1 seconds
  cpu time: 0.2 seconds
  cumulative wall time: 4.7 seconds
```

Testing changed files

If you are working on some files in the Sage library it can be convenient to test only the files that have changed. To do so use the `--new` flag, which tests files that have been modified or added since the last commit:

```
[roed@sage sage-6.0]$ sage -t --new
Running doctests with ID 2012-07-07-01-15-52-645620ee.
Doctesting files changed since last git commit.
Doctesting 1 file.
sage -t src/sage/doctest/control.py
  [133 tests, 3.7 s]
-----
All tests passed!
-----
Total time for all tests: 3.8 seconds
  cpu time: 0.1 seconds
  cumulative wall time: 3.7 seconds
```

Running tests in a random order

By default, tests are run in the order in which they appear in the file. To run tests in a random order (which can reveal subtle bugs), use the `--randorder` flag and pass in a random seed:

```
[roed@sage sage-6.0]$ sage -t --new --randorder 127
Running doctests with ID 2012-07-07-01-19-06-97c8484e.
Doctesting files changed since last git commit.
Doctesting 1 file.
sage -t src/sage/doctest/control.py
  [133 tests, 3.6 s]
-----
All tests passed!
-----
Total time for all tests: 3.7 seconds
  cpu time: 0.2 seconds
  cumulative wall time: 3.6 seconds
```

Note that even with this option, the tests within a given doctest block are still run in order.

Testing external files

When testing a file which is not part of a package (which is not in a directory containing an `__init__.py` file), the testing code loads the globals from that file into the namespace before running tests. To disable this behaviour (and require imports to be explicitly specified), use the `--force-lib` option.

Auxiliary files

To specify a logfile (rather than use the default which is created for `sage -t --all`), use the `--logfile` flag:

```
[roed@sage sage-6.0]$ sage -t --logfile test1.log src/sage/doctest/control.py
Running doctests with ID 2012-07-07-01-25-49-e7c0e52d.
Doctesting 1 file.
sage -t src/sage/doctest/control.py
    [133 tests, 4.3 s]

-----
All tests passed!
-----
Total time for all tests: 6.7 seconds
    cpu time: 0.1 seconds
    cumulative wall time: 4.3 seconds
[roed@sage sage-6.0]$ cat test1.log
Running doctests with ID 2012-07-07-01-25-49-e7c0e52d.
Doctesting 1 file.
sage -t src/sage/doctest/control.py
    [133 tests, 4.3 s]

-----
All tests passed!
-----
Total time for all tests: 6.7 seconds
    cpu time: 0.1 seconds
    cumulative wall time: 4.3 seconds
```

To give a json file storing the timings for each file, use the `--stats_path` flag. These statistics are used in sorting files so that slower tests are run first (and thus multiple processes are utilized most efficiently):

```
[roed@sage sage-6.0]$ sage -tp 2 --stats-path ~/.sage/timings2.json --all
Running doctests with ID 2012-07-07-01-28-34-2df4251d.
Doctesting entire Sage library.
Sorting sources by runtime so that slower doctests are run first....
Doctesting 2067 files using 2 threads.
...
```

2.5 Testing on multiple platforms

2.5.1 Testing on multiple platforms

Sage is intended to build and run on a variety of platforms, including all major Linux distributions, as well as MacOS, and Windows (with Cygwin and WSL).

There is considerable variation among these platforms. To ensure that Sage continues to build correctly on users' machines, it is crucial to test changes to Sage, in particular when external packages are added or upgraded, on a wide spectrum of platforms.

Sage patchbots

The [Sage patchbots](#) will automatically test your Trac ticket by attempting an incremental build of Sage and running doctests.

Sage buildbots

The [Sage Release buildbot](#) builds entire tarballs (e.g., all the development releases) on a variety of machines.

Developers' and users' tests on sage-release

Sage developers and users are encouraged to contribute to testing releases that are announced on [Sage Release](#) on their machines and to report test results (success and failures) by responding to the announcements.

Testing Sage on a different platform using Docker

[Docker](#) is a popular virtualization software, running Linux operating system images ("Docker images") in containers on a shared Linux kernel. These containers can be run using a Docker client on your Linux, Mac, or Windows box, as well as on various cloud services.

To get started, you need to install a [Docker client](#). The clients are available for Linux, Mac, and Windows. The clients for the latter are known as "Docker Desktop".

Make sure that your Docker client is configured to provide enough RAM to the containers (8 GB are a good choice). In Docker Desktop this setting is in Preferences -> Resources -> Advanced.

All examples in this section were obtained using Docker Desktop for Mac; but the [command-line user interface](#) for the other platforms is identical.

All major Linux distributions provide ready-to-use Docker images, which are published via [Docker Hub](#). For example, to run the current stable (LTS) version of Ubuntu interactively, you can use the shell command:

```
[mkoepp@sage sage]$ docker run -it ubuntu:latest
root@9f3398da43c2:/#
```

Here `ubuntu` is referred to as the "image (name)" and `latest` as the "tag". Other releases of Ubuntu are available under different tags, such as `xenial` or `devel`.

The above command drops you in a root shell on the container:

```
root@9f3398da43c2:/# uname -a
Linux 9f3398da43c2 4.19.76-linuxkit #1 SMP Thu Oct 17 19:31:58 UTC 2019 x86_64 x86_64_
↳x86_64 GNU/Linux
root@9f3398da43c2:/# df -h
Filesystem      Size  Used Avail Use% Mounted on
overlay          181G  116G   56G  68% /
tmpfs            64M    0    64M   0% /dev
tmpfs            2.7G    0   2.7G   0% /sys/fs/cgroup
shm             64M    0    64M   0% /dev/shm
/dev/sda1        181G  116G   56G  68% /etc/hosts
tmpfs            2.7G    0   2.7G   0% /proc/acpi
tmpfs            2.7G    0   2.7G   0% /sys/firmware
```

Exiting the shell terminates the container:

```
root@9f3398da43c2:/# ^D
[mkoeppesage sage]$
```

Let us work with a distclean Sage source tree. If you are using git, a good way to get one (without losing a precious installation in SAGE_LOCAL) is by creating a new worktree:

```
[mkoeppesage sage] git worktree add worktree-ubuntu-latest
[mkoeppesage sage] cd worktree-ubuntu-latest
[mkoeppesage worktree-ubuntu-latest] ls
COPYING.txt ... Makefile ... configure.ac ... src tox.ini
```

This is not bootstrapped (configure is missing), so let's bootstrap it:

```
[mkoeppesage worktree-ubuntu-latest] make configure
...
```

We can start a container again with same image, ubuntu:latest, but this time let's mount the current directory into it:

```
[mkoeppesage worktree-ubuntu-latest]$ docker run -it --mount type=bind,source=$(pwd),
↳target=/sage ubuntu:latest
root@39d693b2a75d:/# mount | grep sage
osxfs on /sage type fuse.osxfs (rw,nosuid,nodev,relatime,user_id=0,group_id=0,allow_
↳other,max_read=1048576)
root@39d693b2a75d:/# cd sage
root@39d693b2a75d:/sage# ls
COPYING.txt ... Makefile ... config configure configure.ac ... src tox.ini
```

Typical Docker images provide minimal installations of packages only:

```
root@39d693b2a75d:/sage# command -v python
root@39d693b2a75d:/sage# command -v gcc
root@39d693b2a75d:/sage#
```

As you can see above, the image ubuntu:latest has neither a Python nor a GCC installed, which are among the build prerequisites of Sage. We need to install them using the distribution's package manager first.

Sage facilitates testing various distributions on Docker as follows.

Discovering the system's package system

```
root@39d693b2a75d:/sage# build/bin/sage-guess-package-system
debian
```

Let's install gcc, hoping that the Ubuntu package providing it is simply named gcc. If we forgot what the package manager on Debian-derived distributions is called, we can ask Sage for a reminder:

```
root@39d693b2a75d:/sage# build/bin/sage-print-system-package-command debian install gcc
apt-get install gcc
```

We remember that we need to fetch the current package lists from the server first:

```
root@39d693b2a75d:/sage# apt-get update
root@39d693b2a75d:/sage# apt-get install gcc
```

Using Sage's database of distribution prerequisites

The source code of the Sage distribution contains a database of package names in various distributions' package managers. For example, the file `build/pkgs/_prereq/distros/debian.txt` contains the following

```
# This file, build/pkgs/_prereq/distros/debian.txt, contains names
# of Debian/Ubuntu packages needed for installation of Sage from source.
#
# In addition, the files build/pkgs/SPKG/distros/debian.txt contain the names
# of packages that provide the equivalent of SPKG.
#
# Everything on a line after a # character is ignored.
binutils
make
m4
perl
# python3-minimal is not enough on debian buster, ubuntu bionic - it does not have urllib
python3    # system python for bootstrapping the build
tar
bc
gcc
# On debian buster, need C++ even to survive 'configure'. Otherwise:
# checking how to run the C++ preprocessor... /lib/cpp
# configure: error: in `/sage':
# configure: error: C++ preprocessor "/lib/cpp" fails sanity check
g++
# Needed if we download some packages from a https upstream URL
ca-certificates
```

From this information, we know that we can use the following command on our container to install the necessary build prerequisites:

```
root@39d693b2a75d:/sage# apt-get install binutils make m4 perl python3 tar bc gcc g++ ca-
↳certificates
Reading package lists... Done
Building dependency tree
```

(continues on next page)

(continued from previous page)

```

Reading state information... Done
tar is already the newest version (1.29b-2ubuntu0.1).
The following additional packages will be installed:
...
Done.

```

(The Sage [Installation Guide](#) also provides such command lines for some distributions; these are automatically generated from the database of package names.)

Now we can start the build:

```

root@39d693b2a75d:/sage# ./configure
checking for a BSD-compatible install... /usr/bin/install -c
checking for root user... yes
configure: error: You cannot build Sage as root, switch to an unprivileged user. (If
↳building in a container, use --enable-build-as-root.)

```

Let's just follow this helpful hint:

```

root@39d693b2a75d:/sage# ./configure --enable-build-as-root
checking for a BSD-compatible install... /usr/bin/install -c
...

```

Using Sage's database of equivalent distribution packages

At the end of the `./configure` run, Sage issued a message like the following:

```

configure: notice: the following SPKGs did not find equivalent system packages: arb
↳boost_cropped bzip2 ... zeromq zlib
checking for the package system in use... debian
configure: hint: installing the following system packages is recommended and may avoid
↳building some of the above SPKGs from source:
configure: $ sudo apt-get install libflint-arb-dev ... libzmq3-dev libz-dev
configure: After installation, re-run configure using:
configure: $ ./config.status --recheck && ./config.status

```

This information comes from Sage's database of equivalent distribution packages. For example:

```

root@39d693b2a75d:/sage# ls build/pkgs/arb/distros/
arch.txt      conda.txt      debian.txt      gentoo.txt
root@39d693b2a75d:/sage# cat build/pkgs/arb/distros/debian.txt
libflint-arb-dev

```

Note that these package equivalencies are based on a current stable or testing version of the distribution; the packages are not guaranteed to exist in every release or derivative distribution.

The Sage distribution is intended to build correctly no matter what superset of the set of packages forming the minimal build prerequisites is installed on the system. If it does not, this is a bug of the Sage distribution and should be reported and fixed on a ticket. Crucial part of a bug report is the configuration of the system, in particular a list of installed packages and their versions.

Let us install a subset of these packages:

```
root@39d693b2a75d:/sage# apt-get install libbz2-dev bzip2 libz-dev
Reading package lists... Done
...
Setting up zlib1g-dev:amd64 (1:1.2.11.dfsg-0ubuntu2) ...
root@39d693b2a75d:/sage#
```

Committing a container to disk

After terminating the container, we can create a new image corresponding to its current state:

```
root@39d693b2a75d:/sage# ^D
[mkoeppe@sage worktree-ubuntu-latest]$ docker ps -a | head -n3
CONTAINER ID        IMAGE               COMMAND             CREATED
↳ STATUS
39d693b2a75d        ubuntu:latest      "/bin/bash"        8 minutes ago
↳ Exited (0) 6 seconds ago
9f3398da43c2        ubuntu:latest      "/bin/bash"        8 minutes ago
↳ Exited (0) 8 minutes ago
[mkoeppe@sage worktree-ubuntu-latest]$ docker commit 39d693b2a75d ubuntu-latest-minimal-
↳ 17
sha256:4151c5ca4476660f6181cdb13923da8fe44082222b984c377fb4fd6cc05415c1
```

Here, 39d693b2a75d was the container id (which appeared in the shell prompts and in the output of `docker ps`), and `ubuntu-latest-minimal-17` is an arbitrary symbolic name for the new image. The output of the command is the id of the new image. We can use either the symbolic name or the id to refer to the new image.

We can run the image and get a new container with the same state as the one that we terminated. Again we want to mount our worktree into it; otherwise, because we did not make a copy, the new container will have no access to the worktree:

```
[mkoeppe@sage worktree-ubuntu-latest]$ docker run -it \
  --mount type=bind,source=$(pwd),target=/sage ubuntu-latest-minimal-17
root@73987568712c:/# cd sage
root@73987568712c:/sage# command -v gcc
/usr/bin/gcc
root@73987568712c:/sage# command -v bunzip2
/usr/bin/bunzip2
root@73987568712c:/sage# ^D
[mkoeppe@sage worktree-ubuntu-latest]$
```

The image `ubuntu-latest-minimal-17` can be run in as many containers as we want and can also be shared with other users or developers so that they can run it in a container on their machine. (See the Docker documentation on how to [share images on Docker Hub](#) or to [save images to a tar archive](#).)

This facilitates collaboration on fixing portability bugs of the Sage distribution. After reproducing a portability bug on a container, several developers can work on fixing the bug using containers running on their respective machines.

Generating Dockerfiles

Sage also provides a script for generating a Dockerfile, which is a recipe for automatically building a new image:

```
[mkoeppe@sage sage]$ build/bin/write-dockerfile.sh debian ":standard: :optional:" > Dockerfile
```

(The second argument is passed to `sage -package list` to find packages for the listed package types.)

The Dockerfile instructs the command `docker build` to build a new Docker image. Let us take a quick look at the generated file; this is slightly simplified:

```
[mkoeppe@sage sage]$ cat Dockerfile
# Automatically generated by SAGE_ROOT/build/bin/write-dockerfile.sh
# the :comments: separate the generated file into sections
# to simplify writing scripts that customize this file
...
```

First, it instructs `docker build` to start from an existing base image...:

```
...
ARG BASE_IMAGE=ubuntu:latest
FROM ${BASE_IMAGE}
...
```

Then, to install system packages...:

```
...
RUN apt-get update && DEBIAN_FRONTEND=noninteractive apt-get install -qqq --no-install-
recommends --yes binutils make m4 perl python3 ... libzmq3-dev libz-dev && apt-get
clean
```

Then, to bootstrap and configure...:

```
RUN mkdir -p /sage
WORKDIR /sage
ADD Makefile VERSION.txt README.md bootstrap configure.ac sage ./
ADD src/doc/bootstrap src/doc/bootstrap
ADD m4 ./m4
ADD build ./build
RUN ./bootstrap
ADD src/bin src/bin
ARG EXTRA_CONFIGURE_ARGS=""
RUN ./configure --enable-build-as-root ${EXTRA_CONFIGURE_ARGS} || (cat config.log; exit
1)
```

Finally, to build and test...:

```
ARG NUMPROC=8
ENV MAKE="make -j${NUMPROC}"
ARG USE_MAKEFLAGS="-k"
RUN make ${USE_MAKEFLAGS} base-toolchain
ARG TARGETS_PRE="all-sage-local"
RUN make ${USE_MAKEFLAGS} ${TARGETS_PRE}
ADD src src
```

(continues on next page)

(continued from previous page)

```
ARG TARGETS="build ptest"
RUN make ${USE_MAKEFLAGS} ${TARGETS}
```

You can customize the image build process by passing build arguments to the command `docker build`. For example:

```
[mkoeppe@sage sage]$ docker build . -f Dockerfile \
--build-arg BASE_IMAGE=ubuntu:latest \
--build-arg NUMPROC=4 \
--build-arg EXTRA_CONFIGURE_ARGS="--with-python=/usr/bin/python3.42"
```

These arguments (and their default values) are defined using `ARG` commands in the `Dockerfile`.

The above command will build Sage from scratch and will therefore take quite long. Let us instead just do a partial build, consisting of one small package, by setting the arguments `TARGETS_PRE` and `TARGETS`. We use a silent build (make `V=0`):

```
[mkoeppe@sage sage]$ docker build . -f Dockerfile \
--build-arg TARGETS_PRE=ratpoints \
--build-arg TARGETS=ratpoints \
--build-arg USE_MAKEFLAGS="V=0"
Sending build context to Docker daemon   285MB
Step 1/28 : ARG BASE_IMAGE=ubuntu:latest
...
Step 2/28 : FROM ${BASE_IMAGE}
---> 549b9b86cb8d
...
Step 25/28 : RUN make SAGE_SPKG="sage-spkg -y -o" ${USE_MAKEFLAGS} ${TARGETS_PRE}
...
make[1]: Entering directory '/sage/build/make'
sage-logger -p 'sage-spkg -y -o ratpoints-2.1.3.p5' '/sage/logs/pkgs/ratpoints-2.1.3.p5.
↪log'
[ratpoints-2.1.3.p5] installing. Log file: /sage/logs/pkgs/ratpoints-2.1.3.p5.log
[ratpoints-2.1.3.p5] successfully installed.
make[1]: Leaving directory '/sage/build/make'

real   0m18.886s
user   0m1.779s
sys    0m0.314s
Sage build/upgrade complete!
...
---> 2d06689d39fa
Successfully built 2d06689d39fa
```

We can now start a container using the image id shown in the last step:

```
[mkoeppe@sage sage]$ docker run -it 2d06689d39fa bash
root@fab59e09a641:/sage# ls -l logs/pkgs/
total 236
-rw-r--r-- 1 root root 231169 Mar 26 22:07 config.log
-rw-r--r-- 1 root root   6025 Mar 26 22:27 ratpoints-2.1.3.p5.log
root@fab59e09a641:/sage# ls -l local/lib/*rat*
-rw-r--r-- 1 root root 177256 Mar 26 22:27 local/lib/libratpoints.a
```

You can customize the image build process further by editing the `Dockerfile`. For example, by default, the generated

Dockerfile configures, builds, and tests Sage. By deleting or commenting out the commands for the latter, you can adjust the Dockerfile to stop after the configure phase, for example.

Dockerfile is the default filename for Dockerfiles. You can change it to any other name, but it is recommended to use Dockerfile as a prefix, such as Dockerfile-debian-standard. It should be placed within the tree rooted at the current directory (.); if you want to put it elsewhere, you need to learn about details of “Docker build contexts”.

Note that in contrast to the workflow described in the above sections, the Dockerfile **copies** a snapshot of your Sage worktree into the build container, using ADD commands, instead of mounting the directory into it. This copying is subject to the exclusions in the .gitignore file (via a symbolic link from .dockerignore). Therefore, only the sources are copied, but not your configuration (such as the file config.status), nor the \$SAGE_LOCAL tree, nor any other build artefacts.

Because of this, you can build a Docker image using the generated Dockerfile from your main Sage development tree. It does not have to be distclean to start, and the build will not write into it at all. Hence, you can continue editing and compiling your Sage development tree even while Docker builds are running.

Debugging a portability bug using Docker

Let us do another partial build. We choose a package that we suspect might not work on all platforms, surf, which was marked as “experimental” in 2017:

```
[mkoeppe@sage sage]$ docker build . -f Dockerfile \
--build-arg BASE_IMAGE=ubuntu:latest \
--build-arg NUMPROC=4 \
--build-arg TARGETS_PRE=surf \
--build-arg TARGETS=surf
Sending build context to Docker daemon   285MB
Step 1/28 : ARG BASE_IMAGE=ubuntu:latest
Step 2/28 : FROM ${BASE_IMAGE}
----> 549b9b86cb8d
...
Step 24/28 : ARG TARGETS_PRE="all-sage-local"
----> Running in 17d0ddb5ad7b
Removing intermediate container 17d0ddb5ad7b
----> 7b51411520c3
Step 25/28 : RUN make SAGE_SPKG="sage-spkg -y -o" ${USE_MAKEFLAGS} ${TARGETS_PRE}
----> Running in 61833bea6a6d
make -j4 build/make/Makefile --stop
...
[surf-1.0.6-gcc6] Attempting to download package surf-1.0.6-gcc6.tar.gz from mirrors
...
[surf-1.0.6-gcc6] http://mirrors.mit.edu/sage/spkg/upstream/surf/surf-1.0.6-gcc6.tar.gz
...
[surf-1.0.6-gcc6] Setting up build directory for surf-1.0.6-gcc6
...
[surf-1.0.6-gcc6] /usr/bin/ld: cannot find -lfl
[surf-1.0.6-gcc6] collect2: error: ld returned 1 exit status
[surf-1.0.6-gcc6] Makefile:504: recipe for target 'surf' failed
[surf-1.0.6-gcc6] make[3]: *** [surf] Error 1
...
[surf-1.0.6-gcc6] Error installing package surf-1.0.6-gcc6
...
Makefile:2088: recipe for target '/sage/local/var/lib/sage/installed/surf-1.0.6-gcc6'
↪ failed
```

(continues on next page)

(continued from previous page)

```

make[1]: *** [/sage/local/var/lib/sage/installed/surf-1.0.6-gcc6] Error 1
make[1]: Target 'surf' not remade because of errors.
make[1]: Leaving directory '/sage/build/make'
...
Error building Sage.

The following package(s) may have failed to build (not necessarily
during this run of 'make surf'):

* package:          surf-1.0.6-gcc6
  last build time:  Mar 26 22:07
  log file:         /sage/logs/pkgs/surf-1.0.6-gcc6.log
  build directory:  /sage/local/var/tmp/sage/build/surf-1.0.6-gcc6
...
Makefile:31: recipe for target 'surf' failed
make: *** [surf] Error 1
The command '/bin/sh -c make SAGE_SPKG="sage-spkg -y -o" ${USE_MAKEFLAGS} ${TARGETS_PRE}
↳ ' returned a non-zero code: 2

```

Note that no image id is shown at the end; the build failed, and no image is created. However, the container in which the last step of the build was attempted exists:

```

[mkoeppe@sage sage]$ docker ps -a | head -n3
CONTAINER ID        IMAGE                                     COMMAND                  CREATED
↳ STATUS
61833bea6a6d        7b51411520c3                          "/bin/sh -c 'make SA..." 9 minutes ago
↳ Exited (2) 1 minute ago
73987568712c        ubuntu-latest-minimal-17              "/bin/bash"              24 hours ago
↳ Exited (0) 23 hours ago

```

We can copy the build directory from the container for inspection:

```

[mkoeppe@sage sage]$ docker cp 61833bea6a6d:/sage/local/var/tmp/sage/build ubuntu-build
[mkoeppe@sage sage]$ ls ubuntu-build/surf*/src
AUTHORS      TODO          curve          misc
COPYING      acinclude.m4  debug          missing
ChangeLog    aclocal.m4    dither         mkinstalldirs
INSTALL      background.pic docs           mt
Makefile     config.guess  draw           src
Makefile.am  config.log    drawfunc       surf.1
Makefile.global config.status examples        surf.xpm
Makefile.in  config.sub    gtkgui         yaccsrc
NEWS         configure     image-formats
README       configure.in  install-sh

```

Alternatively, we can use `docker commit` as explained earlier to create an image from the container:

```

[mkoeppe@sage sage]$ docker commit 61833bea6a6d
sha256:003fbd511016fe305bd8494bb1747f0fbf4cb2c788b4e755e9099d9f2014a60d
[mkoeppe@sage sage]$ docker run -it 003fbd511 bash
root@2d9ac65f4572:/sage# (cd /sage/local/var/tmp/sage/build/surf* && /sage/sage --
↳ buildsh)

```

(continues on next page)

(continued from previous page)

```

Starting subshell with Sage environment variables set. Don't forget
to exit when you are done.
...
Note: SAGE_ROOT=/sage
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ ls /usr/lib/libfl*
/usr/lib/libflint-2.5.2.so /usr/lib/libflint-2.5.2.so.13.5.2 /usr/lib/libflint.a /usr/
↳ lib/libflint.so
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ apt-get update && apt-get install apt-
↳ file
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ apt-file update
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ apt-file search "/usr/lib/libfl.a"
flex-old: /usr/lib/libfl.a
freebsd-buildutils: /usr/lib/libfl.a
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ apt-get install flex-old
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ ./spkg-install
checking for a BSD-compatible install... /usr/bin/install -c
checking whether build environment is sane... yes
...
  /usr/bin/install -c surf /sage/local/bin/surf
  /usr/bin/install -c -m 644 ./surf.1 /sage/local/share/man/man1/surf.1
...
make[1]: Leaving directory '/sage/local/var/tmp/sage/build/surf-1.0.6-gcc6/src'
(sage-buildsh) root@2d9ac65f4572:surf-1.0.6-gcc6$ exit
root@2d9ac65f4572:/sage# exit
[mkoepp@sage sage]$

```

A standard case of bitrot.

Automatic Docker-based build testing using tox

`tox` is a Python package that is widely used for automating tests of Python projects.

Install `tox` for use with your system Python, for example using:

```
[mkoepp@sage sage]$ pip install --user tox
```

A tox “environment” is identified by a symbolic name composed of several `Tox` “factors”, which are defined in the file `$$SAGE_ROOT/tox.ini`.

The **technology** factor describes how the environment is run:

- `docker` builds a Docker image as described above.
- `local` runs testing on the host OS instead. We explain this technology in a later section.

The next two factors determine the host system configuration: The **system factor** describes a base operating system image.

- Examples are `ubuntu-focal`, `debian-buster`, `archlinux-latest`, `fedora-30`, `slackware-14.2`, `centos-7-i386`, and `ubuntu-bionic-arm64`.
- See `$$SAGE_ROOT/tox.ini` for a complete list, and to which images on Docker hub they correspond.

The **packages factor** describes a list of system packages to be installed on the system before building Sage:

- **minimal** installs the system packages known to Sage to provide minimal prerequisites for bootstrapping and building the Sage distribution. This corresponds to the packages `_bootstrap` and `_prereq`.
- **standard** additionally installs all known system packages that are equivalent to standard packages of the Sage distribution, for which the mechanism `spkg-configure.m4` is implemented. This corresponds to the packages listed by:

```
[mkoeppesage sage]$ sage --package list --has-file=spkg-configure.m4 :standard:
```

- **maximal** does the same for all standard and optional packages. This corresponds to the packages listed by:

```
[mkoeppesage sage]$ sage --package list :standard: :optional:
```

The factors are connected by a hyphen to name a system configuration, such as `debian-buster-standard` and `centos-7-i386-minimal`.

Finally, the **configuration** factor (which is allowed to be empty) controls how the `configure` script is run.

The factors are connected by a hyphen to name a tox environment. (The order of the factors does not matter; however, for consistency and because the ordered name is used for caching purposes, we recommend to use the factors in the listed order.)

To run an environment:

```
[mkoeppesage sage]$ tox -e docker-slackware-14.2-minimal
[mkoeppesage sage]$ tox -e docker-ubuntu-bionic-standard
```

Arbitrary extra arguments to `docker build` can be supplied through the environment variable `EXTRA_DOCKER_BUILD_ARGS`. For example, for a non-silent build (make `V=1`), use:

```
[mkoeppesage sage]$ EXTRA_DOCKER_BUILD_ARGS="--build-arg USE_MAKEFLAGS=\"V=1\" \" \" \
tox -e docker-ubuntu-bionic-standard
```

By default, tox uses `TARGETS_PRE=all-sage-local` and `TARGETS=build`, leading to a complete build of Sage without the documentation. If you pass positional arguments to tox (separated from tox options by `--`), then both `TARGETS_PRE` and `TARGETS` are set to these arguments. In this way, you can build some specific packages instead of all of Sage, for example:

```
[mkoeppesage sage]$ tox -e docker-centos-8-standard -- ratpoints
```

If the build succeeds, this will create a new image named `sage-docker-centos-8-standard-with-targets:9.1.beta9-431-gca4b5b2f33-dirty`, where

- the image name is derived from the tox environment name and the suffix `with-targets` expresses that the make targets given in `TARGETS` have been built;
- the tag name describes the git revision of the source tree as per `git describe --dirty`.

You can ask for tox to create named intermediate images as well. For example, to create the images corresponding to the state of the OS after installing all system packages (`with-system-packages`) and the one just after running the `configure` script (`configured`):

```
[mkoeppesage sage]$ DOCKER_TARGETS="with-system-packages configured with-targets" \
tox -e docker-centos-8-standard -- ratpoints
...
Sending build context to Docker daemon ...
Step 1/109 : ARG BASE_IMAGE=fedora:latest
Step 2/109 : FROM ${BASE_IMAGE} as with-system-packages
```

(continues on next page)

(continued from previous page)

```
...
Step 109/109 : RUN yum install -y zlib-devel || echo "(ignoring error)"
...
Successfully built 4bb14c3d5646
Successfully tagged sage-docker-centos-8-standard-with-system-packages:9.1.beta9-435-
↳g861ba33bbc-dirty
Sending build context to Docker daemon ...
...
Successfully tagged sage-docker-centos-8-standard-configured:9.1.beta9-435-g861ba33bbc-
↳dirty
...
Sending build context to Docker daemon ...
...
Successfully tagged sage-docker-centos-8-standard-with-targets:9.1.beta9-435-g861ba33bbc-
↳dirty
```

Let's verify that the images are available:

```
(base) egret:~/s/sage/sage-rebasing/worktree-algebraic-2018-spring (mkoeppe *$%>)$
↳docker images | head
REPOSITORY                                TAG
↳  IMAGE ID
sage-docker-centos-8-standard-with-targets  9.1.beta9-435-g861ba33bbc-
↳dirty  7ecfa86fceab
sage-docker-centos-8-standard-configured    9.1.beta9-435-g861ba33bbc-
↳dirty  4314929e2b4c
sage-docker-centos-8-standard-with-system-packages  9.1.beta9-435-g861ba33bbc-
↳dirty  4bb14c3d5646
...
```

Automatic build testing on the host OS using tox -e local-direct

The `local` technology runs testing on the host OS instead.

In contrast to the `docker` technology, it does not make a copy of the source tree. It is most straightforward to run it from a separate, distclean git worktree.

Let us try a first variant of the `local` technology, the tox environment called `local-direct`. Because all builds with tox begin by bootstrapping the source tree, you will need autotools and other prerequisites installed in your system. See `build/pkgs/_bootstrap/distros/*.txt` for a list of system packages that provide these prerequisites.

We start by creating a fresh (distclean) git worktree:

```
[mkoeppe@sage sage] git worktree add worktree-local
[mkoeppe@sage sage] cd worktree-local
[mkoeppe@sage worktree-local] ls
COPYING.txt ... Makefile ... configure.ac ... src tox.ini
```

Again we build only a small package. Build targets can be passed as positional arguments (separated from tox options by `--`):

```
[mkoeppe@sage worktree-local] tox -e local-direct -- ratpoints
local-direct create: /Users/mkoeppe/.../worktree-local/.tox/local-direct
```

(continues on next page)

(continued from previous page)

```

local-direct run-test-pre: PYTHONHASHSEED='2211987514'
...
src/doc/bootstrap:48: installing src/doc/en/installation/debian.txt...
bootstrap:69: installing 'config/config.rpath'
configure.ac:328: installing 'config/compile'
configure.ac:113: installing 'config/config.guess'
...
checking for a BSD-compatible install... /usr/bin/install -c
checking whether build environment is sane... yes
...
sage-logger -p 'sage-spkg -y -o ratpoints-2.1.3.p5' '../worktree-local/logs/pkgs/
↳ratpoints-2.1.3.p5.log'
[ratpoints-2.1.3.p5] installing. Log file: ../worktree-local/logs/pkgs/ratpoints-2.1.3.
↳p5.log
[ratpoints-2.1.3.p5] successfully installed.
...
local-direct: commands succeeded
congratulations :)

```

Let's investigate what happened here:

```

[mkoeppe@sage worktree-local]$ ls -la
total 2576
drwxr-xr-x  35 mkoeppe  staff    1120 Mar 26 22:20 .
drwxr-xr-x  63 mkoeppe  staff    2016 Mar 27 09:35 ..
...
lrwxr-xr-x   1 mkoeppe  staff      10 Mar 26 20:34 .dockerignore -> .gitignore
-rw-r--r--   1 mkoeppe  staff      74 Mar 26 20:34 .git
...
-rw-r--r--   1 mkoeppe  staff    1212 Mar 26 20:41 .gitignore
...
drwxr-xr-x   7 mkoeppe  staff     224 Mar 26 22:11 .tox
...
-rw-r--r--   1 mkoeppe  staff   7542 Mar 26 20:41 Makefile
...
lrwxr-xr-x   1 mkoeppe  staff     114 Mar 26 20:45 config.log -> .tox/local-direct/log/
↳config.log
-rwxr-xr-x   1 mkoeppe  staff   90411 Mar 26 20:46 config.status
-rwxr-xr-x   1 mkoeppe  staff  887180 Mar 26 20:45 configure
-rw-r--r--   1 mkoeppe  staff   17070 Mar 26 20:41 configure.ac
...
lrwxr-xr-x   1 mkoeppe  staff     103 Mar 26 20:45 logs -> .tox/local-direct/log
drwxr-xr-x  24 mkoeppe  staff     768 Mar 26 20:45 m4
lrwxr-xr-x   1 mkoeppe  staff     105 Mar 26 20:45 prefix -> .tox/local-direct/local
-rwxr-xr-x   1 mkoeppe  staff   4868 Mar 26 20:34 sage
drwxr-xr-x  16 mkoeppe  staff     512 Mar 26 20:46 src
-rw-r--r--   1 mkoeppe  staff  13478 Mar 26 20:41 tox.ini
drwxr-xr-x   4 mkoeppe  staff     128 Mar 26 20:46 upstream

```

There is no local subdirectory. This is part of a strategy to keep the source tree clean to the extent possible. In particular:

- tox configured the build to use a separate \$SAGE_LOCAL hierarchy in a directory under the tox environment

directory `.tox/local-direct`. It created a symbolic link `prefix` that points there, for convenience:

```
[mkoeppe@sage worktree-local]$ ls -l prefix/lib/*rat*
-rw-r--r-- 1 mkoeppe staff 165968 Mar 26 20:46 prefix/lib/libratpoints.a
```

- Likewise, it created a separate logs directory, again under the tox environment directory, and a symbolic link.

This makes it possible for advanced users to test several local tox environments (such as `local-direct`) out of one worktree. However, because a build still writes configuration scripts and build artefacts (such as `config.status`) into the worktree, only one local build can run at a time in a given worktree.

The tox environment directory will be reused for the next tox run, which will therefore do an incremental build. To start a fresh build, you can use the `-r` option.

Automatic build testing on the host OS with best-effort isolation using tox -e local

`tox -e local` (without `-direct`) attempts a best-effort isolation from the user's environment as follows:

- All environment variables are set to standard values; with the exception of `MAKE` and `EXTRA_CONFIGURE_ARGS`. In particular, `PATH` is set to just `/usr/bin:/bin:/usr/sbin:/sbin`; it does not include `/usr/local/bin`.

Note, however, that various packages have build scripts that use `/usr/local` or other popular file system locations such as `/opt/sfw/`. Therefore, the isolation is not complete. Using `/usr/local` is considered standard behavior. On the other hand, we consider a package build script that inspects other file system locations to be a bug of the Sage distribution, which should be reported and fixed on a ticket.

Automatic build testing on macOS with a best-effort isolated installation of Homebrew

XCode on macOS does not provide the prerequisites for bootstrapping the Sage distribution. A good way to install them is using the Homebrew package manager.

In fact, Sage provides a tox environment that automatically installs an isolated copy of Homebrew with all prerequisites for bootstrapping:

```
[mkoeppe@sage worktree-local]$ tox -e local-homebrew-macos-minimal -- lrslib
local-homebrew-macos-minimal create: .../worktree-local/.tox/local-homebrew-macos-minimal
local-homebrew-macos-minimal run-test-pre: PYTHONHASHSEED='4246149402'
...
Initialized empty Git repository in .../worktree-local/.tox/local-homebrew-macos-minimal/
↳ homebrew/.git/
...
Tapped 2 commands and 4942 formulae (5,205 files, 310.7MB).
==> Downloading https://ftp.gnu.org/gnu/gettext/gettext-0.20.1.tar.xz
...
==> Pouring autoconf-2.69.catalina.bottle.4.tar.gz
...
==> Pouring pkg-config-0.29.2.catalina.bottle.1.tar.gz
.../worktree-local/.tox/local-homebrew-macos-minimal/homebrew/Cellar/pkg-config/0.29.
↳ 2: 11 files, 623.4KB
==> Caveats
==> gettext
gettext is keg-only, which means it was not symlinked into .../worktree-local/.tox/local-
↳ homebrew-macos-minimal/homebrew,
because macOS provides the BSD gettext library & some software gets confused if both are
↳ in the library path.
```

(continues on next page)

(continued from previous page)

```

If you need to have gettext first in your PATH run:
  echo 'export PATH=".../worktree-local/.tox/local-homebrew-macos-minimal/homebrew/opt/
↳gettext/bin:$PATH"' >> ~/.bash_profile

For compilers to find gettext you may need to set:
  export LDFLAGS="-L.../worktree-local/.tox/local-homebrew-macos-minimal/homebrew/opt/
↳gettext/lib"
  export CPPFLAGS="-I.../worktree-local/.tox/local-homebrew-macos-minimal/homebrew/opt/
↳gettext/include"
...
local-homebrew-macos-minimal run-test: commands[0] | bash -c 'export PATH=.../worktree-
↳local/.tox/local-homebrew-macos-minimal/homebrew/bin:/usr/bin:/bin:/usr/sbin:/sbin && .
↳.homebrew-build-env && ./bootstrap && ./configure --prefix=.../worktree-local/.tox/
↳local-homebrew-macos-minimal/local && make -k V=0 ... lrslib'
...
bootstrap:69: installing 'config/config.rpath'
...
checking for a BSD-compatible install... /usr/bin/install -c
checking whether build environment is sane... yes
...
configure: notice: the following SPKGs did not find equivalent system packages: arb cbc
↳cliquer ... tachyon xz zeromq
checking for the package system in use... homebrew
configure: hint: installing the following system packages is recommended and may avoid
↳building some of the above SPKGs from source:
configure:  $ brew install cmake gcc gsl mpfi ninja openblas gpatch r readline xz zeromq
...
sage-logger -p 'sage-spkg -y -o lrslib-062+autotools-2017-03-03.p1' '.../worktree-local/
↳logs/pkgs/lrslib-062+autotools-2017-03-03.p1.log'
[lrslib-062+autotools-2017-03-03.p1] installing. Log file: .../worktree-local/logs/pkgs/
↳lrslib-062+autotools-2017-03-03.p1.log
[lrslib-062+autotools-2017-03-03.p1] successfully installed.
...
local-homebrew-macos-minimal: commands succeeded
congratulations :)

```

The `tox` environment uses the subdirectory `homebrew` of the environment directory `.tox/local-homebrew-macos-minimal` as the Homebrew prefix. This installation does not interact in any way with a Homebrew installation in `/usr/local` that you may have.

The test script sets the `PATH` to the `bin` directory of the Homebrew prefix, followed by `/usr/bin:/bin:/usr/sbin:/sbin`. It then uses the script `$SAGE_ROOT/.homebrew-build-env` to set environment variables so that Sage's build scripts will find “keg-only” packages such as `gettext`.

The `local-homebrew-macos-minimal` environment does not install Homebrew's `python3` package. It uses XCode's `/usr/bin/python3` as system python. However, because various packages are missing that Sage considers as dependencies, Sage builds its own copy of these packages and of `python3`.

The `local-homebrew-macos-standard` environment additionally installs (in its separate isolated copy of Homebrew) all Homebrew packages known to Sage for which the `spkg-configure.m4` mechanism is implemented; this is similar to the `docker-standard` `tox` environments described earlier. In particular it installs and uses Homebrew's `python3` package.

By using configuration factors, more variants can be tested. The `local-homebrew-macos-standard-python3_xcode`

environment installs the same packages, but uses XCode's `/usr/bin/python3`.

The `local-homebrew-macos-standard-python3_pythonorg` expects an installation of Python 3.10 in `/Library/Frameworks/Python.framework`; this is where the binary packages provided by python.org install themselves.

Automatic build testing with a best-effort isolated installation of Conda

Sage provides environments `local-conda-forge-standard` and `local-conda-forge-minimal` that create isolated installations of Miniconda in the subdirectory `conda` of the environment directory. They do not interact in any way with other installations of Anaconda or Miniconda that you may have on your system.

The environments use the conda-forge channel and use the `python` package and the compilers from this channel.

Options for build testing with the local technology

The environments using the `local` technology can be customized by setting environment variables.

- If `SKIP_SYSTEM_PKG_INSTALL` is set to 1 (or yes), then all steps of installing system packages are skipped in this run. When reusing a previously created tox environment, this option can save time and also give developers more control for experiments with system packages.
- If `SKIP_BOOTSTRAP` is set to 1 (or yes), then the bootstrapping phase is skipped. When reusing a previously created tox environment, this option can save time.
- If `SKIP_CONFIGURE` is set to 1 (or yes), then the `configure` script is not run explicitly. When reusing a previously created tox environment, this option can save time. (The Makefile may still rerun configuration using `config.status --recheck`.)

The `local` technology also defines a special target `bash`: Instead of building anything with `make`, it just starts an interactive shell. For example, in combination with the above options:

```
[mkoepp@sage worktree-local]$ SKIP_SYSTEM_PKG_INSTALL=yes SKIP_BOOTSTRAP=1 SKIP_
↳CONFIGURE=1 tox -e local-homebrew-macos-minimal -- bash
```

Automatic testing on multiple platforms on GitHub Actions

The Sage source tree includes a default configuration for GitHub Actions that runs our portability tests with tox on a multitude of platforms on every pull request and on every push of a tag (but not of a branch) to a repository for which GitHub Actions are enabled.

In particular, it automatically runs on our main repository on every release tag.

This is defined in the files `$$SAGE_ROOT/.github/workflows/tox*.yaml`.

An additional GitHub Actions workflow for testing on Cygwin, not based on tox, is defined in the files `$$SAGE_ROOT/.github/workflows/ci-cygwin*.yaml`.

GitHub Actions runs these build jobs on 2-core machines with 7 GB of RAM memory and 14 GB of SSD disk space, cf. [here](#), and has a time limit of 6h per job. This is just barely enough for a typical `minimal` build followed by `make ptest` to succeed; and plenty of time for a typical `standard` build to succeed.

Build logs become available as “artifacts” when all jobs of the workflow have finished. Each job generates one tarball. “Annotations” highlight certain top-level errors or warnings issued during the build.

The following procedure triggers a run of tests with the default set of system configurations.

- Push your changes to trac.
- Go to the [Actions page on the GitHub mirror](#) and select the workflow you would like to run.
- Click on “Run workflow” above the list of workflow runs and select the branch where the workflow will run.

For more information, see the [GitHub documentation](#).

Alternatively, you can create and push a custom tag in order to trigger a run of tests as follows. Let's assume that `my-github` is the name of the remote corresponding to your GitHub fork of the Sage repository:

```
$ git remote -v | grep /my-github
my-github      https://github.com/mkoeppe/sage.git (fetch)
my-github      https://github.com/mkoeppe/sage.git (push)
```

- Create a (“lightweight”, not “annotated”) tag with an arbitrary name, say `ci` (for “Continuous Integration”):

```
git tag -f ci
```

- Then push the tag to your GitHub repository:

```
git push -f my-github ci
```

(In both commands, the “force” option (`-f`) allows overwriting a previous tag of that name.)

For testing branches against a custom set of system configurations during development, the following procedure seems to work well. It avoids changing the CI configuration on your development branch:

- Create a branch from a recent beta release that contains the default GitHub Actions configuration; name it `TESTER`, say.
- Edit `$SAGE_ROOT/.github/workflows/tox.yml` to include the system config you wish to test.
- Commit and push the branch to your GitHub fork of sage.
- Push your development branch to your GitHub repository and create a pull request against the `TESTER` branch. This will trigger the GitHub Actions workflow.

You will find a workflow status page in the “Actions” tab of your repository.

Here is how to read it. Each of the items in the left pane represents a full build of Sage on a particular system configuration. A test item in the left pane is marked with a green checkmark in the left pane if `make build doc-html` finished without error. (It also runs package testsuites and the Sage doctests but failures in these are not reflected in the left pane; see below.)

The right pane (“Artifacts”) offers archives of the logs for download.

Scrolling down in the right pane shows “Annotations”:

- Red “check failure” annotations appear for each log file that contains a build error. For example, you might see:

```
docker (fedora-28, standard)
artifacts/logs-commit-8ca1c2df8f1fb4c6d54b44b34b4d8320ebecb164-tox-docker-fedora-28-
↳ standard/logs/pkgs/sagetex-3.4.log#L1
==== ERROR IN LOG FILE artifacts/logs-commit-
↳ 8ca1c2df8f1fb4c6d54b44b34b4d8320ebecb164-tox-docker-fedora-28-standard/logs/pkgs/
↳ sagetex-3.4.log ====
```

- Yellow “check warning” annotations. There are 2 types of these:
 - a) Package testsuite or Sage doctest failures, like the following:


```
docker (fedora-30, standard)
artifacts/logs-commit-8ca1c2df8f1fb4c6d54b44b34b4d8320ebebcb164-tox-docker-
↳ fedora-30-standard/logs/ptest.log#L1
==== TESTSUITE FAILURE IN LOG FILE artifacts/logs-commit-
↳ 8ca1c2df8f1fb4c6d54b44b34b4d8320ebebcb164-tox-docker-fedora-30-standard/logs/
↳ ptest.log ====
```

b) Notices from `./configure` about not finding equivalent system packages, like the following:

```
docker (fedora-31, standard)
artifacts/logs-commit-8ca1c2df8f1fb4c6d54b44b34b4d8320ebebcb164-tox-docker-
↳ fedora-31-standard/config.log#L1
configure: notice: the following SPKGs did not find equivalent system packages:↳
↳ arb cbc cddlib cmake eclib ecm fflas_ffpack flint flintqs fplll givaro gp
```

Clicking on the annotations does not take you to a very useful place. To view details, click on one of the items in the pane. This changes the right pane to a log viewer.

The `docker` workflows automatically push images to `ghcr.io`. You find them in the Packages tab of your GitHub repository.

In order to pull them for use on your computer, you need to first generate a Personal Access Token providing the `read:packages` scope as follows. Visit <https://github.com/settings/tokens/new> (this may prompt you for your GitHub password). As “Note”, type “Access `ghcr.io`”; then in “Select scopes”, select the checkbox for `read:packages`. Finally, push the “Generate token” button at the bottom. This will lead to a page showing your token, such as `de1ec7ab1ec0ffee5ca1dedbaff1ed0ddba11`. Copy this token and paste it to the command line:

```
$ echo de1ec7ab1ec0ffee5ca1dedbaff1ed0ddba11 | docker login ghcr.io --username YOUR-
↳ GITHUB-USERNAME
```

where you replace the token by your token, of course, and `YOUR-GITHUB-USERNAME` by your GitHub username.

Now you can pull the image and run it:

```
$ docker pull ghcr.io/YOUR-GITHUB-USERNAME/sage/sage-docker-fedora-31-standard-
↳ configured:f4bd671
$ docker run -it ghcr.io/YOUR-GITHUB-USERNAME/sage/sage-docker-fedora-31-standard-
↳ configured:f4bd671 bash
```

Using our pre-built Docker images published on `ghcr.io`

Our portability CI on GitHub Actions builds [Docker images](#) for all tested Linux platforms (and system package configurations) and makes them available on [GitHub Packages](#) (`ghcr.io`).

This makes it easy for developers to debug problems that showed up in the build logs for a given platform.

The image version corresponding to the latest development release receives the additional Docker tag `dev`, see for example the Docker image for the platform `ubuntu-focal-standard`. Thus, for example, the following command will work:

```
$ docker run -it ghcr.io/sagemath/sage/sage-docker-ubuntu-focal-standard-with-targets-
↳ optional:dev bash
Unable to find image 'ghcr.io/sagemath/sage/sage-docker-ubuntu-focal-standard-with-
↳ targets-optional:dev' locally
dev: Pulling from sagemath/sage/sage-docker-ubuntu-focal-standard-with-targets-optional
```

(continues on next page)

(continued from previous page)

```

d5fd17ec1767: Already exists
67586203f0c7: Pull complete
b63c529f4777: Pull complete
...
159775d1a3d2: Pull complete
Digest: sha256:e6ba5e12f59c6c4668692ef4cfe4ae5f242556482664fb347bf260f32bf8e698
Status: Downloaded newer image for ghcr.io/sagemath/sage/sage-docker-ubuntu-focal-
↳ standard-with-targets-optional:dev
root@8055a7ba0607:/sage# ./sage
+-----+
| SageMath version 9.6, Release Date: 2022-05-15           |
| Using Python 3.8.10. Type "help()" for help.             |
+-----+
sage:

```

Images whose names end with the suffix `-with-targets-optional` are the results of full builds and a run of `make ptest`. They also contain a copy of the source tree and the full logs of the build and test.

Also [smaller images corresponding to earlier build stages](#) are available:

- `-with-system-packages` provides a system installation with system packages installed, no source tree,
- `-configured` contains a partial source tree (`SAGE_ROOT`) and has completed the bootstrapping phase and the run of the `configure` script,
- `-with-targets-pre` contains the full source tree and a full installation of all non-Python packages (`SAGE_LOCAL`),
- `-with-targets` contains the full source tree and a full installation of Sage, including the HTML documentation, but `make ptest` has not been run yet.

Using our pre-built Docker images for development in VS Code

VS Code is very convenient for developing with Docker containers thanks to the [Visual Studio Code Remote - Containers](#) extension.

If the extension is not already installed, then in VS Code, click the “Extension” icon on the left (or press `Ctrl + Shift + X`; on macOS, `Command + Shift + X`) to open a list of extensions. Search for “Remote - Containers” and install it.

The extension needs a `devcontainer.json` configuration file to work. Sage provides sample `devcontainer.json` configuration files `$(SAGE_ROOT)/devcontainer/*/devcontainer.json` for this purpose.

To get started, symlink (or copy) one of the sample files to `$(SAGE_ROOT)/.devcontainer/devcontainer.json`. For example, choose `$(SAGE_ROOT)/devcontainer/portability-ubuntu-jammy-standard/devcontainer.json`, which uses the Docker image based on `ubuntu-jammy-standard`, the most recent development version of Sage (dev tag), and a full installation of the Sage distribution (`with-targets`).

In macOS for example, you can do this using the shell as follows:

```

[mkoeppe@sage sage] $ (cd .devcontainer && ln -s portability-ubuntu-jammy-standard/
↳ devcontainer.json .)

```

Now start VS Code:

```

[mkoeppe@sage sage] $ code .

```

Then VS Code may prompt you whether you would like to open the current directory in the dev container (yes). If it does not, use the command palette (Ctrl + Shift + P), enter the command “Remote-Containers: Reopen Folder in Container”, and hit Enter.

If the above code . command does not work, start VS Code as a regular application, then in the command palette of VS Code, enter “Remote-Containers: Open Folder in Container”, and hit Enter, and choose the directory \$SAGE_ROOT of your local Sage repository.

Once VS Code starts configuring the dev container, by clicking on “show log”, you can see what it does:

- It pulls the prebuilt image from ghcr.io (via \$SAGE_ROOT/.devcontainer/portability-Dockerfile); note that these are multi-gigabyte images, so it may take a while.
- As part of the “onCreateCommand”, it installs additional system packages to support VS Code and for development.
- Then, as part of the “updateContentCommand”, it bootstraps and configures the source tree and starts to build Sage from source, reusing the installation (SAGE_LOCAL, SAGE_VENV) from the prebuilt image.

After VS Code finished configuring the dev container (when the message “Done. Press any key to close the terminal.” appears in the terminal named “Configuring”), your local Sage repository at \$SAGE_ROOT is available in the container at the directory /workspaces/<repository name>. To use Sage in a terminal, [open a new terminal in VS Code](#), type ./sage and hit Enter.

Note: Your Sage at \$SAGE_ROOT was configured and rebuilt inside the dev container. In particular, \$SAGE_ROOT/venv, \$SAGE_ROOT/prefix, and (possibly) \$SAGE_ROOT/logs will be symbolic links that work inside the dev container, but not in your local file system; and also the script \$SAGE_ROOT/sage will not work. Hence after working with the dev container, you will want to remove logs if it is a symbolic link, and rerun the configure script.

You can edit a copy of the configuration file to change to a different platform, another version, or build stage. After editing the configuration file (or changing the symlink), run “Remote-Containers: Rebuild Container” from the command palette. See the [VS Code devcontainer.json reference](#) and the [GitHub introduction to dev containers](#) for more information.

In addition to the \$SAGE_ROOT/.devcontainer/portability-.../devcontainer.json files, Sage also provides several other sample devcontainer.json configuration files in the directory \$SAGE_ROOT/.devcontainer.

Files named \$SAGE_ROOT/.devcontainer/develop-.../devcontainer.json configure containers from a public Docker image that provides SageMath and then updates the installation of SageMath in this container by building from the current source tree.

- [develop-docker-computop/devcontainer.json](#) configures a container with the [Docker image from the 3-manifolds project](#), providing SnapPy, Regina, PHCPack, etc.

If you want to use one of these devcontainer.json files, symlink (or copy) it and start VS Code as explained above. After VS Code finished configuring the dev container, to use Sage in a terminal, [open a new terminal in VS Code](#), type ./sage and hit Enter.

Files named \$SAGE_ROOT/.devcontainer/downstream-.../devcontainer.json configure containers with an installation of downstream packages providing SageMath from a package manager (downstream-archlinux-..., downstream-conda-forge; see also the [_sagemath dummy package](#)), or from a public Docker image that provides SageMath (docker-cocalc, docker-computop). These devcontainer.json configuration files are useful for testing user scripts on these deployments of SageMath. You may also find it useful to copy these configurations into your own projects (they should work without change) or to adapt them to your needs.

- [downstream-archlinux-latest/devcontainer.json](#) configures a container with an installation of [Arch Linux](#) and its SageMath package. (The suffix latest indicates the most recent version of Arch Linux as available on Docker Hub.)

- `downstream-conda-forge-latest/devcontainer.json` configures a container with an installation of conda-forge and its SageMath package.
- `downstream-docker-cocalc/devcontainer.json` configures a container with the CoCalc Docker image.
- `downstream-docker-computop/devcontainer.json` configures a container with the Docker image from the 3-manifolds project, providing SnapPy, Regina, PHCPack, etc.

If you want to use one of these `devcontainer.json` files, symlink (or copy) it and start VS Code as explained above. After VS Code finished configuring the dev container, to use Sage in a terminal, [open a new terminal in VS Code](#), type `sage` and hit Enter. (Do not use `./sage`; this will not work because the source tree is not configured.)

2.6 Additional development and testing tools

2.6.1 Additional development and testing tools

Tox

Tox is a popular package that is used by a large number of Python projects as the standard entry point for testing and linting.

Sage includes tox as a standard package and uses it for three purposes:

- For portability testing of the Sage distribution, as we explain in [Testing on multiple platforms](#). This is configured in the file `SAGE_ROOT/tox.ini`.
- For testing modularized distributions of the Sage library. This is configured in `tox.ini` files in subdirectories of `SAGE_ROOT/pkgs/`, such as `SAGE_ROOT/pkgs/sagemath-standard/tox.ini`. Each distribution's configuration defines tox environments for testing the distribution with different Python versions and different ways how the dependencies are provided. We explain this in [Packaging the Sage Library](#).
- As an entry point for testing and linting of the Sage library, as we describe below. This is configured in the file `SAGE_ROOT/src/tox.ini`.

The tox configuration `SAGE_ROOT/src/tox.ini` can be invoked by using the command `./sage --tox`. (If tox is available in your system installation, you can just type `tox` instead.)

This configuration provides an entry point for various testing/linting methods, known as “tox environments”. We can type `./sage --advanced` to see what is available:

```
$ ./sage --advanced
SageMath version 9.2
...
Testing files:
...
--tox [options] <files|dirs> -- general entry point for testing
                             and linting of the Sage library
  -e <envlist>                -- run specific test environments
                             (default: run all except full pycodestyle)
    doctest                   -- run the Sage doctester
                             (same as "sage -t")
    coverage                   -- give information about doctest coverage of files
                             (same as "sage --coverage[all]")
    startuptime                -- display how long each component of Sage takes to start up
                             (same as "sage --startuptime")
    pycodestyle-minimal        -- check against Sage's minimal style conventions
```

(continues on next page)

(continued from previous page)

```
relint                -- check whether some forbidden patterns appear
                        (includes all patchbot pattern-exclusion plugins)
codespell              -- check for misspelled words in source code
pycodestyle            -- check against the Python style conventions of PEP8
-p auto               -- run test environments in parallel
--help                -- show tox help
```

Doctest

The command `./sage -tox -e doctest` requires that Sage has been built already. `doctest` is a special tox environment that runs the Sage doctester in the normal Sage environment. This is equivalent to using the command `./sage -t`; see [Running Sage's doctests](#).

Coverage

The command `./sage -tox -e coverage` requires that Sage has been built already. `coverage` is a special tox environment that is equivalent to using the command `./sage --coverageall` (if no arguments are provided) or `./sage --coverage` (if arguments are provided).

Startuptime

The command `./sage -tox -e startuptime` requires that Sage has been built already. `startuptime` is a special tox environment that is equivalent to using the command `./sage --startuptime`.

Pycodestyle

[Pycodestyle](#) (formerly known as `pep8`) checks Python code against the style conventions of [PEP 8](#). Tox automatically installs `pycodestyle` in a separate virtual environment on the first use.

Sage defines two configurations for `pycodestyle`. The command `./sage -tox -e pycodestyle-minimal` uses `pycodestyle` in a minimal configuration. As of Sage 9.5, the entire Sage library conforms to this configuration:

```
$ ./sage -tox -e pycodestyle-minimal -- src/sage/
pycodestyle-minimal installed: pycodestyle==2.8.0
pycodestyle-minimal run-test-pre: PYTHONHASHSEED='28778046'
pycodestyle-minimal run-test: commands[0] | pycodestyle --select E401,E70,W605,E711,E712,
↳E721 sage
----- summary -----
pycodestyle-minimal: commands succeeded
congratulations :)
```

When preparing a branch for a Sage ticket, developers should verify that `./sage -tox -e pycodestyle-minimal` passes. When the Sage patchbot runs on the ticket, it will perform similar coding style checks; but running the check locally reduces the turnaround time from hours to seconds.

The second configuration is used with the command `./sage -tox -e pycodestyle` and runs a more thorough check:

```

$ ./sage -tox -e pycodestyle -- src/sage/quadratic_forms/quadratic_form.py
pycodestyle installed: pycodestyle==2.8.0
pycodestyle run-test-pre: PYTHONHASHSEED='2520226550'
pycodestyle run-test: commands[0] | pycodestyle sage/quadratic_forms/quadratic_form.py
sage/quadratic_forms/quadratic_form.py:135:9: E225 missing whitespace around operator
sage/quadratic_forms/quadratic_form.py:163:64: E225 missing whitespace around operator
sage/quadratic_forms/quadratic_form.py:165:52: E225 missing whitespace around operator
sage/quadratic_forms/quadratic_form.py:173:42: E228 missing whitespace around modulo
↳operator
...
sage/quadratic_forms/quadratic_form.py:1620:9: E266 too many leading '#' for block
↳comment
sage/quadratic_forms/quadratic_form.py:1621:9: E266 too many leading '#' for block
↳comment
25      E111 indentation is not a multiple of 4
2       E117 over-indented
129     E127 continuation line over-indented for visual indent
1      E128 continuation line under-indented for visual indent
4      E201 whitespace after '['
4      E202 whitespace before ']'
2      E222 multiple spaces after operator
7      E225 missing whitespace around operator
1      E228 missing whitespace around modulo operator
25     E231 missing whitespace after ','
1      E262 inline comment should start with '#'
3      E265 block comment should start with '#'
62     E266 too many leading '#' for block comment
2      E272 multiple spaces before keyword
2      E301 expected 1 blank line, found 0
17     E303 too many blank lines (2)
ERROR: InvocationError for command .../pycodestyle sage/quadratic_forms/quadratic_form.
↳py (exited with code 1)
----- summary -----
ERROR: pycodestyle: commands failed

```

When preparing a branch for a Sage ticket that adds new code, developers should verify that `./sage -tox -e pycodestyle` does not issue warnings for the added code. This will avoid later cleanup tickets as the Sage codebase is moving toward full PEP 8 compliance.

On the other hand, it is usually not advisable to mix coding-style fixes with productive changes on the same ticket because this would make it harder for reviewers to evaluate the changes.

By passing the options `--count -qq` we can reduce the output to only show the number of style violation warnings. This can be helpful for planning work on coding-style clean-up tickets that focus on one or a few related issues:

```

$ ./sage -tox -e pycodestyle -- --count -qq src/sage
pycodestyle installed: pycodestyle==2.8.0
pycodestyle run-test-pre: PYTHONHASHSEED='3166223974'
pycodestyle run-test: commands[0] | pycodestyle --count -qq sage
557     E111 indentation is not a multiple of 4
1      E112 expected an indented block
194     E114 indentation is not a multiple of 4 (comment)
...
7      E743 ambiguous function definition 'l'

```

(continues on next page)

(continued from previous page)

```

335      W291 trailing whitespace
4       W292 no newline at end of file
229     W293 blank line contains whitespace
459     W391 blank line at end of file
97797
ERROR: InvocationError for command .../pycodestyle --count -qq sage (exited with code 1)
----- summary -----
ERROR:   pycodestyle: commands failed

```

Installation: (for manual use:) `pip install -U pycodestyle --user`

Usage:

- With tox: See above.
- Manual: Run `pycodestyle path/to/the/file.py`.
- VS Code: The minimal version of pycodestyle is activated by default in `SAGE_ROOT/.vscode/settings.json` (the corresponding setting is `"python.linting.pycodestyleEnabled": true`). Note that the `settings.json` file is not ignored by git so be aware to keep it in sync with the trac repo. For further details, see the [official VS Code documentation](#).

Configuration: [pycodestyle] block in `SAGE_ROOT/src/tox.ini`

Documentation: <https://pycodestyle.pycqa.org/en/latest/index.html>

Relint

Relint checks all source files for forbidden text patterns specified by regular expressions.

Our configuration of relint flags some outdated Python constructions, plain TeX commands when equivalent LaTeX commands are available, common mistakes in documentation markup, and modularization anti-patterns.

Configuration: `SAGE_ROOT/src/.relint.yml`

Documentation: <https://pypi.org/project/relint/>

Codespell

Codespell uses a dictionary to check for misspelled words in source code.

Sage defines a configuration for codespell:

```

$ ./sage -tox -e codespell -- src/sage/homology/
codespell installed: codespell==2.1.0
codespell run-test-pre: PYTHONHASHSEED='1285169064'
codespell run-test: commands[0] | codespell '--skip=*.png,*.jpg,*.JPG,*.inv,*.dia,*.pdf,
↳ *.ico,##*,*~*,*.bak,*.orig,*.log,*.sobj,*.tar,*.gz,*.pyc,*.o,*.sws,*.so,*.a,*.DS_Store'
↳ --skip=doc/ca,doc/de,doc/es,doc/hu,doc/ja,doc/ru,doc/fr,doc/it,doc/pt,doc/tr --
↳ skip=src/doc/ca,src/doc/de,src/doc/es,src/doc/hu,src/doc/ja,src/doc/ru,src/doc/fr,src/
↳ doc/it,src/doc/pt,src/doc/tr '--skip=.git,.tox,worktree*,dist,upstream,logs,local,
↳ cythonized,scripts-3,autom4te.cache,tmp,lib.*,*.egg-info' --dictionary=- --dictionary=/
↳ Users/mkoeppe/s/sage/sage-rebasing/src/.codespell-dictionary.txt --ignore-words=/Users/
↳ mkoeppe/s/sage/sage-rebasing/src/.codespell-ignore.txt sage/homology
sage/homology/hochschild_complex.py:271: mone ==> mono, money, none
sage/homology/hochschild_complex.py:277: mone ==> mono, money, none

```

(continues on next page)

(continued from previous page)

```

sage/homology/hochschild_complex.py:280: mone ==> mono, money, none
sage/homology/chain_complex.py:2185: mor ==> more
sage/homology/chain_complex.py:2204: mor ==> more
sage/homology/chain_complex.py:2210: mor ==> more
sage/homology/chain_complex.py:2211: mor ==> more
sage/homology/chain_complex.py:2214: mor ==> more
sage/homology/chain_complex.py:2215: mor ==> more
ERROR: InvocationError for command ../codespell '--skip=*.png,...' --dictionary=- --
↳ dictionary=/Users/mkoeppe/s/sage/sage-rebasing/src/.codespell-dictionary.txt --ignore-
↳ words=/Users/mkoeppe/s/sage/sage-rebasing/src/.codespell-ignore.txt sage/homology.
↳ (exited with code 65)
----- summary -----
ERROR: codespell: commands failed

```

Configuration:

- [testenv:codespell] block in SAGE_ROOT/src/tox.ini
- SAGE_ROOT/src/.codespell-dictionary.txt and SAGE_ROOT/src/.codespell-ignore.txt

Pytest

Pytest is a testing framework. It is included in the Sage distribution as an optional package.

Currently, Sage only makes very limited use of pytest, for testing the package `sage.numerical.backends` and some modules in `sage.manifolds`.

Installation:

- `./sage -i pytest pytest_xdist`.

Usage:

- Tox, Sage doctester: At the end of `./sage -t` (or `./sage --tox -e doctest`), Pytest is automatically invoked.
- Manual: Run `./sage -pytest path/to/the/test_file.py` or `./sage -pytest` to run all tests. The additional argument `-n` can be used to distribute tests across multiple CPUs to speed up test execution. For example, `./sage -pytest -n 4` will run 4 tests in parallel, while `./sage -pytest -n auto` will spawn a number of workers processes equal to the number of available CPUs.
- VS Code: Install the [Python extension](#) and follow the [official VS Code documentation](#).

Configuration: SAGE_ROOT/src/conftest.py

Documentation: <https://docs.pytest.org/en/stable/index.html>

Pyright

Pyright is static type checker.

Installation:

- (for manual use:) `npm install -g pyright`, see [documentation](#) for details.

Usage:

- Tox: Run `./sage -tox -e pyright path/to/the/file.py`
- Manual: Run `pyright path/to/the/file.py`
- VS Code: Install the [Pylance](#) extension.

Configuration: `SAGE_ROOT/pyrightconfig.json`

Documentation: <https://github.com/microsoft/pyright#documentation>

Pyflakes

Pyflakes checks for common coding errors.

LGTM

The website lgtm.com offers a detailed diagnostic about the global code quality and its evolution.

The reports can be found [here](#).

Our choice of configuration is made in `.lgtm.yml`.

2.7 Contributing to Manuals and Tutorials

2.7.1 The Sage Manuals

Sage's manuals are written in [ReST](#) (reStructuredText), and generated with the software [Sphinx](#):

Name	Files
Tutorial	<code>SAGE_ROOT/src/doc/en/tutorial</code>
Developer's guide	<code>SAGE_ROOT/src/doc/en/developer</code>
Constructions	<code>SAGE_ROOT/src/doc/en/constructions</code>
Installation guide	<code>SAGE_ROOT/src/doc/en/installation</code>
Reference manual	<code>SAGE_ROOT/src/doc/en/reference</code> (most of it is generated from the source code)

- Additionally, more specialized manuals can be found under `SAGE_ROOT/src/doc/en`.
- Some documents have been **translated** into other languages. In order to access them, change `en/` into `fr/es/de/...` See [Document Names](#).

Editing the documentation

After modifying some files in the Sage tutorial (`SAGE_ROOT/src/doc/en/tutorial/`), you will want to visualize the result. In order to build a **html** version of this document, type:

```
sage --docbuild tutorial html
```

You can now open `SAGE_ROOT/local/share/doc/sage/html/en/tutorial/index.html` in your web browser.

- Do you want to **add a new file** to the documentation? [Click here](#).
- For more detailed information on the `--docbuild` command, see [Building the Manuals](#).

Run doctests: All files must pass tests. After modifying a document (e.g. `tutorial`), you can run tests with the following command (see [Running Automated Doctests](#)):

```
sage -tp SAGE_ROOT/src/doc/en/tutorial/
```

Reference manual: as this manual is mostly generated from Sage's source code, you will need to build Sage in order to see the changes you made to some function's documentation. Type:

```
sage -b && sage --docbuild reference html
```

Hyperlinks

The documentation can contain links toward modules, classes, or methods, e.g.:

```
:mod:`link to a module <sage.module_name>`
:mod:`sage.module_name` (here the link's text is the module's name)
```

For links toward classes, methods, or function, replace **:mod:** by **:class:**, **:meth:** or **:func:** respectively. See [Sphinx' documentation](#).

Short links: the link `:func:`~sage.mod1.mod2.mod3.func1`` is equivalent to `:func:`func1 <sage.mod1.mod2.mod3.func1>``: the function's name will be used as the link name, instead of its full path.

Local names: links between methods of the same class do not need to be absolute. If you are documenting `method_one`, you can write `:meth:`method_two``.

Global namespace: if an object (e.g. `integral`) is automatically imported by Sage, you can link toward it without specifying its full path:

```
:func:`A link toward the integral function <integral>`
```

Sage-specific roles: Sage defines several specific *roles*:

Trac server	<code>:trac:`17596`</code>	trac ticket #17596
Wikipedia	<code>:wikipedia:`Sage_(mathematics_software)`</code>	Sage_(mathematics_software) article
arXiv	<code>:arxiv:`1202.1506`</code>	arXiv 1202.1506
On-Line Encyclopedia of Integer Sequences	<code>:oeis:`A000081`</code>	OEIS sequence A000081
Digital Object Identifier	<code>:doi:`10.2752/175303708X390473`</code>	doi:10.2752/175303708X390473
MathSciNet	<code>:mathscinet:`MR0100971`</code>	MathSciNet MR0100971

http links: copy/pasting a http link in the documentation works. If you want a specific link name, use ``link name <http://www.example.com>`_`

Anonymous hyperlinks: Using a single underscore creates an *explicit target name* "link name" which needs to be unique in the current page. Using the same target name twice in the same page creates an error while building the documentation saying `WARNING: Duplicate explicit target name:` To avoid this issue, one can change the target names to be all different or another option is to use [anonymous hyperlinks](#) with two underscores, as in see ``this page <http://www.example.com>`__` or ``this page <http://www.example2.com>`__`.

Broken links: Sphinx can report broken links. See *Building the Manuals*.

Adding a New File

If you added a new file to Sage (e.g. `sage/matroids/my_algorithm.py`) and you want its content to appear in the reference manual, you have to add its name to the file `SAGE_ROOT/src/doc/en/reference/matroids/index.rst`. Replace 'matroids' with whatever fits your case.

The combinat/ folder: if your new file belongs to a subdirectory of combinat/ the procedure is different:

- Add your file to the index stored in the `__init__.py` file located in the directory that contains your file.
- Add your file to the index contained in `SAGE_ROOT/src/doc/en/reference/combinat/module_list.rst`.

Building the Manuals

(Do you want to edit the documentation? [Click here](#))

All of the Sage manuals are built using the `sage --docbuild` script. The content of the `sage --docbuild` script is defined in `SAGE_ROOT/src/sage_docbuild/__init__.py`. It is a thin wrapper around the `sphinx-build` script which does all of the real work. It is designed to be a replacement for the default Makefiles generated by the `sphinx-quickstart` script. The general form of the command is:

```
sage --docbuild <document-name> <format>
```

For example:

```
sage --docbuild reference html
```

Two **help** commands which give plenty of documentation for the `sage --docbuild` script:

```
sage --docbuild -h # short help message
sage --docbuild -H # a more comprehensive one
```

Output formats: All output formats supported by Sphinx (e.g. pdf) can be used in Sage. See <http://sphinx.pocoo.org/builders.html>.

Broken links: in order to build the documentation while reporting the broken links that it contains, use the `--warn-links` flag. Note that Sphinx will not rebuild a document that has not been updated, and thus not report its broken links:

```
sage --docbuild --warn-links reference html
```

Document Names

The <document-name> has the form:

```
lang/name
```

where `lang` is a two-letter language code, and `name` is the descriptive name of the document. If the language is not specified, then it defaults to English (`en`). The following two commands do the exact same thing:

```
sage --docbuild tutorial html
sage --docbuild en/tutorial html
```

To specify the French version of the tutorial, you would simply run:

```
sage --docbuild fr/tutorial html
```

Syntax Highlighting Cython Code

If you want to write *Cython* code in a ReST file, precede the code block by `.. CODE-BLOCK:: cython` instead of the usual `::`. Enable syntax-highlighting in a whole file with `.. HIGHLIGHT:: cython`. Example:

```
cdef extern from "descrobject.h":
    ctypedef struct PyMethodDef:
        void *ml_meth
    ctypedef struct PyMethodDescrObject:
        PyMethodDef *d_method
    void* PyCFunction_GET_FUNCTION(object)
    bint PyCFunction_Check(object)
```

2.8 Sage Coding Details

2.8.1 Coding in Python for Sage

This chapter discusses some issues with, and advice for, coding in Sage.

Python Language Standard

Sage library code needs to be compatible with all versions of Python that Sage supports. The information regarding the supported versions can be found in the files `build/pkgs/python3/spkg-configure.m4` and `src/setup.cfg.m4`.

As of Sage 9.7, Python 3.8 is the oldest supported version. Hence, all language and library features that are available in Python 3.8 can be used; but features introduced in Python 3.9 cannot be used. If a feature is deprecated in a newer supported version, it must be ensured that deprecation warnings issued by Python do not lead to failures in doctests.

Some key language and library features have been backported to Python 3.8 using one of two mechanisms:

- `from __future__ import annotations` (see https://docs.python.org/3.7/library/__future__.html) modernizes type annotations according to PEP 563 (Postponed evaluation of annotations, see <https://www.python.org/dev/peps/pep-0563>). All Sage library code that uses type annotations should include this `__future__` import and follow PEP 563.
- The Sage distribution includes the backport packages `importlib_metadata` and `importlib_resources`.

Meta-ticket [trac ticket #29756](#) keeps track of newer Python features and serves as a starting point for discussions on how to make use of them in the Sage library.

Design

If you are planning to develop some new code for Sage, design is important. So think about what your program will do and how that fits into the structure of Sage. In particular, much of Sage is implemented in the object-oriented language Python, and there is a hierarchy of classes that organize code and functionality. For example, if you implement elements of a ring, your class should derive from `sage.structure.element.RingElement`, rather than starting from scratch. Try to figure out how your code should fit in with other Sage code, and design it accordingly.

Special Sage Functions

Functions with leading and trailing double underscores `__XXX__` are all predefined by Python. Functions with leading and trailing single underscores `_XXX_` are defined for Sage. Functions with a single leading underscore are meant to be semi-private, and those with a double leading underscore are considered really private. Users can create functions with leading and trailing underscores.

Just as Python has many standard special methods for objects, Sage also has special methods. They are typically of the form `_XXX_`. In a few cases, the trailing underscore is not included, but this will eventually be changed so that the trailing underscore is always included. This section describes these special methods.

All objects in Sage should derive from the Cython extension class `SageObject`:

```
from sage.structure.sage_object import SageObject

class MyClass(SageObject, ...):
    ...
```

or from some other already existing Sage class:

```
from sage.rings.ring import Algebra

class MyFavoriteAlgebra(Algebra):
    ...
```

You should implement the `_latex_` and `_repr_` method for every object. The other methods depend on the nature of the object.

LaTeX Representation

Every object `x` in Sage should support the command `latex(x)`, so that any Sage object can be easily and accurately displayed via LaTeX. Here is how to make a class (and therefore its instances) support the command `latex`.

1. Define a method `_latex_(self)` that returns a LaTeX representation of your object. It should be something that can be typeset correctly within math mode. Do not include opening and closing `$`'s.
2. Often objects are built up out of other Sage objects, and these components should be typeset using the `latex` function. For example, if `c` is a coefficient of your object, and you want to typeset `c` using LaTeX, use `latex(c)` instead of `c._latex_()`, since `c` might not have a `_latex_` method, and `latex(c)` knows how to deal with this.
3. Do not forget to include a docstring and an example that illustrates LaTeX generation for your object.

4. You can use any macros included in `amsmath`, `amssymb`, or `amsfonts`, or the ones defined in `SAGE_ROOT/doc/commontex/macros.tex`.

An example template for a `_latex_` method follows. Note that the `.. skip` line should not be included in your code; it is here to prevent doctests from running on this fake example.

```
class X:
    ..
    def _latex_(self):
        r"""
        Return the LaTeX representation of X.

        EXAMPLES::

            sage: a = X(1,2)
            sage: latex(a)
            '\frac{1}{2}'
        """
        return '\\frac{%s}{%s}'%(latex(self.numer), latex(self.denom))
```

As shown in the example, `latex(a)` will produce LaTeX code representing the object `a`. Calling `view(a)` will display the typeset version of this.

Print Representation

The standard Python printing method is `__repr__(self)`. In Sage, that is for objects that derive from `SageObject` (which is everything in Sage), instead define `_repr_(self)`. This is preferable because if you only define `_repr_(self)` and not `__repr__(self)`, then users can rename your object to print however they like. Also, some objects should print differently depending on the context.

Here is an example of the `_latex_` and `_repr_` functions for the `Pi` class. It is from the file `SAGE_ROOT/src/sage/symbolic/constants.py`:

```
class Pi(Constant):
    """
    The ratio of a circle's circumference to its diameter.

    EXAMPLES::

        sage: pi
        pi
        sage: float(pi) # rel tol 1e-10
        3.1415926535897931
    """
    ..
    def _repr_(self):
        return "pi"

    def _latex_(self):
        return "\\pi"
```

Matrix or Vector from Object

Provide a `_matrix_` method for an object that can be coerced to a matrix over a ring R . Then the Sage function `matrix` will work for this object.

The following is from `SAGE_ROOT/src/sage/graphs/generic_graph.py`:

```
class GenericGraph(SageObject):
    ...
    def _matrix_(self, R=None):
        if R is None:
            return self.am()
        else:
            return self.am().change_ring(R)

    def adjacency_matrix(self, sparse=None, boundary_first=False):
        ...
```

Similarly, provide a `_vector_` method for an object that can be coerced to a vector over a ring R . Then the Sage function `vector` will work for this object. The following is from the file `SAGE_ROOT/src/sage/modules/free_module_element.pyx`:

```
cdef class FreeModuleElement(element_Vector): # abstract base class
    ...
    def _vector_(self, R):
        return self.change_ring(R)
```

Sage Preparing

To make Python even more usable interactively, there are a number of tweaks to the syntax made when you use Sage from the commandline or via the notebook (but not for Python code in the Sage library). Technically, this is implemented by a `preparse()` function that rewrites the input string. Most notably, the following replacements are made:

- Sage supports a special syntax for generating rings or, more generally, parents with named generators:

```
sage: R.<x,y> = QQ[]
sage: preparse('R.<x,y> = QQ[]')
"R = QQ['x, y']; (x, y,) = R._first_ngens(2)"
```

- Integer and real literals are Sage integers and Sage floating point numbers. For example, in pure Python these would be an attribute error:

```
sage: 16.sqrt()
4
sage: 87.factor()
3 * 29
```

- Raw literals are not preparsed, which can be useful from an efficiency point of view. Just like Python ints are denoted by an `L`, in Sage raw integer and floating literals are followed by an “`r`” (or “`R`”) for raw, meaning not preparsed. For example:

```
sage: a = 393939r
sage: a
```

(continues on next page)

(continued from previous page)

```

393939
sage: type(a)
<... 'int'>
sage: b = 393939
sage: type(b)
<class 'sage.rings.integer.Integer'>
sage: a == b
True

```

- Raw literals can be very useful in certain cases. For instance, Python integers can be more efficient than Sage integers when they are very small. Large Sage integers are much more efficient than Python integers since they are implemented using the GMP C library.

Consult the file `preparser.py` for more details about Sage preparsing, more examples involving raw literals, etc.

When a file `foo.sage` is loaded or attached in a Sage session, a preparsed version of `foo.sage` is created with the name `foo.sage.py`. The beginning of the preparsed file states:

```
This file was *autogenerated* from the file foo.sage.
```

You can explicitly preparse a file with the `--preparse` command-line option: running

```
sage --preparse foo.sage
```

creates the file `foo.sage.py`.

The following files are relevant to preparsing in Sage:

1. `SAGE_ROOT/src/bin/sage`
2. `SAGE_ROOT/src/bin/sage-preparse`
3. `SAGE_ROOT/src/sage/repl/preparse.py`

In particular, the file `preparse.py` contains the Sage preparser code.

The Sage Coercion Model

The primary goal of coercion is to be able to transparently do arithmetic, comparisons, etc. between elements of distinct sets. For example, when one writes $3 + 1/2$, one wants to perform arithmetic on the operands as rational numbers, despite the left term being an integer. This makes sense given the obvious and natural inclusion of the integers into the rational numbers. The goal of the coercion system is to facilitate this (and more complicated arithmetic) without having to explicitly map everything over into the same domain, and at the same time being strict enough to not resolve ambiguity or accept nonsense.

The coercion model for Sage is described in detail, with examples, in the Coercion section of the Sage Reference Manual.

Mutability

Parent structures (e.g. rings, fields, matrix spaces, etc.) should be immutable and globally unique whenever possible. Immutability means, among other things, that properties like generator labels and default coercion precision cannot be changed.

Global uniqueness while not wasting memory is best implemented using the standard Python weakref module, a factory function, and module scope variable.

Certain objects, e.g. matrices, may start out mutable and become immutable later. See the file `SAGE_ROOT/src/sage/structure/mutability.py`.

The `__hash__` Special Method

Here is the definition of `__hash__` from the Python reference manual:

Called by built-in function `hash()` and for operations on members of hashed collections including `set`, `frozenset`, and `dict`. `__hash__()` should return an integer. The only required property is that objects which compare equal have the same hash value; it is advised to mix together the hash values of the components of the object that also play a part in comparison of objects by packing them into a tuple and hashing the tuple.

If a class does not define an `__eq__()` method it should not define a `__hash__()` operation either; if it defines `__eq__()` but not `__hash__()`, its instances will not be usable as items in hashable collections. If a class defines mutable objects and implements an `__eq__()` method, it should not implement `__hash__()`, since the implementation of hashable collections requires that a key's hash value is immutable (if the object's hash value changes, it will be in the wrong hash bucket).

See https://docs.python.org/3/reference/datamodel.html#object.__hash__ for more information on the subject.

Notice the phrase, “The only required property is that objects which compare equal have the same hash value.” This is an assumption made by the Python language, which in Sage we simply cannot make (!), and violating it has consequences. Fortunately, the consequences are pretty clearly defined and reasonably easy to understand, so if you know about them they do not cause you trouble. The following example illustrates them pretty well:

```
sage: v = [Mod(2,7)]
sage: 9 in v
True
sage: v = set([Mod(2,7)])
sage: 9 in v
False
sage: 2 in v
True
sage: w = {Mod(2,7): 'a'}
sage: w[2]
'a'
sage: w[9]
Traceback (most recent call last):
...
KeyError: 9
```

Here is another example:

```
sage: R = RealField(10000)
sage: a = R(1) + R(10)^-100
```

(continues on next page)

(continued from previous page)

```
sage: a == RDF(1) # because the a gets coerced down to RDF
True
```

but `hash(a)` should not equal `hash(1)`.

Unfortunately, in Sage we simply cannot require

```
(#) "a == b ==> hash(a) == hash(b)"
```

because serious mathematics is simply too complicated for this rule. For example, the equalities `z == Mod(z, 2)` and `z == Mod(z, 3)` would force `hash()` to be constant on the integers.

The only way we could “fix” this problem for good would be to abandon using the `==` operator for “Sage equality”, and implement Sage equality as a new method attached to each object. Then we could follow Python rules for `==` and our rules for everything else, and all Sage code would become completely unreadable (and for that matter unwritable). So we just have to live with it.

So what is done in Sage is to attempt to satisfy (#) when it is reasonably easy to do so, but use judgment and not go overboard. For example,

```
sage: hash(Mod(2, 7))
2
```

The output 2 is better than some random hash that also involves the moduli, but it is of course not right from the Python point of view, since `9 == Mod(2, 7)`. The goal is to make a hash function that is fast, but within reason respects any obvious natural inclusions and coercions.

Exceptions

Please avoid catch-all code like this:

```
try:
    some_code()
except: # bad
    more_code()
```

If you do not have any exceptions explicitly listed (as a tuple), your code will catch absolutely anything, including `ctrl-C`, typos in the code, and alarms, and this will lead to confusion. Also, this might catch real errors which should be propagated to the user.

To summarize, only catch specific exceptions as in the following example:

```
try:
    return self.__coordinate_ring
except (AttributeError, OtherExceptions) as msg: # good
    more_code_to_compute_something()
```

Note that the syntax in `except` is to list all the exceptions that are caught as a tuple, followed by an error message.

Integer Return Values

Many functions and methods in Sage return integer values. Those should usually be returned as Sage integers of class `Integer` rather than as Python integers of class `int`, as users may want to explore the resulting integers' number-theoretic properties such as prime factorization. Exceptions should be made when there are good reasons such as performance or compatibility with Python code, for instance in methods such as `__hash__`, `__len__`, and `__int__`.

To return a Python integer `i` as a Sage integer, use:

```
from sage.rings.integer import Integer
return Integer(i)
```

To return a Sage integer `i` as a Python integer, use:

```
return int(i)
```

Importing

We mention two issues with importing: circular imports and importing large third-party modules. See also *Dependencies and distribution packages* for a discussion of imports from the viewpoint of modularization.

First, you must avoid circular imports. For example, suppose that the file `SAGE_ROOT/src/sage/algebras/steenrod_algebra.py` started with a line:

```
from sage.sage.algebras.steenrod_algebra_bases import *
```

and that the file `SAGE_ROOT/src/sage/algebras/steenrod_algebra_bases.py` started with a line:

```
from sage.sage.algebras.steenrod_algebra import SteenrodAlgebra
```

This sets up a loop: loading one of these files requires the other, which then requires the first, etc.

With this set-up, running Sage will produce an error:

```
Exception exceptions.ImportError: 'cannot import name SteenrodAlgebra'
in 'sage.rings.polynomial.polynomial_element.
Polynomial_generic_dense.__normalize' ignored
-----
ImportError                                Traceback (most recent call last)
...
ImportError: cannot import name SteenrodAlgebra
```

Instead, you might replace the `import *` line at the top of the file by more specific imports where they are needed in the code. For example, the `basis` method for the class `SteenrodAlgebra` might look like this (omitting the documentation string):

```
def basis(self, n):
    from steenrod_algebra_bases import steenrod_algebra_basis
    return steenrod_algebra_basis(n, basis=self._basis_name, p=self.prime)
```

Second, do not import at the top level of your module a third-party module that will take a long time to initialize (e.g. `matplotlib`). As above, you might instead import specific components of the module when they are needed, rather than at the top level of your file.

It is important to try to make `from sage.all import *` as fast as possible, since this is what dominates the Sage startup time, and controlling the top-level imports helps to do this. One important mechanism in Sage are lazy imports, which don't actually perform the import but delay it until the object is actually used. See [sage.misc.lazy_import](#) for more details of lazy imports, and [Files and Directory Structure](#) for an example using lazy imports for a new module.

If your module needs to make some precomputed data available at the top level, you can reduce its load time (and thus startup time, unless your module is imported using `sage.misc.lazy_import`) by using the decorator `sage.misc.cachedfunc.cached_function()` instead. For example, replace

```
big_data = initialize_big_data() # bad: runs at module load time
```

by

```
from sage.misc.cachedfunc import cached_function

@cached_function # good: runs on first use
def big_data():
    return initialize_big_data()
```

Deprecation

When making a **backward-incompatible** modification in Sage, the old code should keep working and display a message indicating how it should be updated/written in the future. We call this a *deprecation*.

Note: Deprecated code can only be removed one year after the first stable release in which it appeared.

Each deprecation warning contains the number of the trac ticket that defines it. We use 666 in the examples below. For each entry, consult the function's documentation for more information on its behaviour and optional arguments.

- **Rename a keyword:** by decorating a function/method with `rename_keyword`, any user calling `my_function(my_old_keyword=5)` will see a warning:

```
from sage.misc.decorators import rename_keyword
@rename_keyword(deprecation=666, my_old_keyword='my_new_keyword')
def my_function(my_new_keyword=True):
    return my_new_keyword
```

- **Rename a function/method:** call `deprecated_function_alias()` to obtain a copy of a function that raises a deprecation warning:

```
from sage.misc.superseded import deprecated_function_alias
def my_new_function():
    ...

my_old_function = deprecated_function_alias(666, my_new_function)
```

- **Moving an object to a different module:** if you rename a source file or move some function (or class) to a different file, it should still be possible to import that function from the old module. This can be done using a `lazy_import()` with deprecation. In the old module, you would write:

```
from sage.misc.lazy_import import lazy_import
lazy_import('sage.new.module.name', 'name_of_the_function', deprecation=666)
```

You can also lazily import everything using `*` or a few functions using a tuple:

```
from sage.misc.lazy_import import lazy_import
lazy_import('sage.new.module.name', '*', deprecation=666)
lazy_import('sage.other.module', ('func1', 'func2'), deprecation=666)
```

- **Remove a name from a global namespace:** this is when you want to remove a name from a global namespace (say, `sage.all` or some other `all.py` file) but you want to keep the functionality available with an explicit import. This case is similar as the previous one: use a lazy import with deprecation. One detail: in this case, you don't want the name `lazy_import` to be visible in the global namespace, so we add a leading underscore:

```
from sage.misc.lazy_import import lazy_import as _lazy_import
_lazy_import('sage.some.package', 'some_function', deprecation=666)
```

- **Any other case:** if none of the cases above apply, call `deprecation()` in the function that you want to deprecate. It will display the message of your choice (and interact properly with the doctest framework):

```
from sage.misc.superseded import deprecation
deprecation(666, "Do not use your computer to compute 1+1. Use your brain.")
```

Experimental/Unstable Code

You can mark your newly created code (classes/functions/methods) as experimental/unstable. In this case, no deprecation warning is needed when changing this code, its functionality or its interface.

This should allow you to put your stuff in Sage early, without worrying about making (design) changes later.

When satisfied with the code (when stable for some time, say, one year), you can delete this warning.

As usual, all code has to be fully doctested and go through our reviewing process.

- **Experimental function/method:** use the decorator `experimental`. Here is an example:

```
from sage.misc.superseded import experimental
@experimental(66666)
def experimental_function():
    # do something
```

- **Experimental class:** use the decorator `experimental` for its `__init__`. Here is an example:

```
from sage.misc.superseded import experimental
class experimental_class(SageObject):
    @experimental(66666)
    def __init__(self, some, arguments):
        # do something
```

- **Any other case:** if none of the cases above apply, call `experimental_warning()` in the code where you want to warn. It will display the message of your choice:

```
from sage.misc.superseded import experimental_warning
experimental_warning(66666, 'This code is not foolproof.')
```

Using Optional Packages

If a function requires an optional package, that function should fail gracefully—perhaps using a `try-except` block—when the optional package is not available, and should give a hint about how to install it. For example, typing `sage -optional` gives a list of all optional packages, so it might suggest to the user that they type that. The command `optional_packages()` from within Sage also returns this list.

2.8.2 Coding in Cython

This chapter discusses Cython, which is a compiled language based on Python. The major advantage it has over Python is that code can be much faster (sometimes orders of magnitude) and can directly call C and C++ code. As Cython is essentially a superset of the Python language, one often doesn't make a distinction between Cython and Python code in Sage (e.g. one talks of the “Sage Python Library” and “Python Coding Conventions”).

Python is an interpreted language and has no declared data types for variables. These features make it easy to write and debug, but Python code can sometimes be slow. Cython code can look a lot like Python, but it gets translated into C code (often very efficient C code) and then compiled. Thus it offers a language which is familiar to Python developers, but with the potential for much greater speed. Cython also allows Sage developers to interface with C and C++ much easier than using the Python C API directly.

Cython is a compiled version of Python. It was originally based on Pyrex but has changed based on what Sage's developers needed; Cython has been developed in concert with Sage. However, it is an independent project now, which is used beyond the scope of Sage. As such, it is a young, but developing language, with young, but developing documentation. See its web page, <http://www.cython.org/>, for the most up-to-date information or check out the [Language Basics](#) to get started immediately.

Writing Cython Code in Sage

There are several ways to create and build Cython code in Sage.

1. In the Sage Notebook, begin any cell with `%cython`. When you evaluate that cell,
 1. It is saved to a file.
 2. Cython is run on it with all the standard Sage libraries automatically linked if necessary.
 3. The resulting shared library file (`.so` / `.dll` / `.dylib`) is then loaded into your running instance of Sage.
 4. The functionality defined in that cell is now available for you to use in the notebook. Also, the output cell has a link to the C program that was compiled to create the `.so` file.
 5. A `cpdef` or `def` function, say `testfunction`, defined in a `%cython` cell in a worksheet can be imported and made available in a different `%cython` cell within the same worksheet by importing it as shown below:

```
%cython
from __main__ import testfunction
```

2. Create an `.pyx` file and attach or load it from the command line. This is similar to creating a `%cython` cell in the notebook but works completely from the command line (and not from the notebook).
3. Create a `.pyx` file and add it to the Sage library. Then run `sage -b` to rebuild Sage.

Attaching or Loading .spyx Files

The easiest way to try out Cython without having to learn anything about distutils, etc., is to create a file with the extension `spyx`, which stands for “Sage Pyrex”:

1. Create a file `power2.spyx`.
2. Put the following in it:

```
def is2pow(n):  
    while n != 0 and n%2 == 0:  
        n = n >> 1  
    return n == 1
```

3. Start the Sage command line interpreter and load the `spyx` file (this will fail if you do not have a C compiler installed).

```
sage: load("power2.spyx")  
Compiling power2.spyx...  
sage: is2pow(12)  
False
```

Note that you can change `power2.spyx`, then load it again and it will be recompiled on the fly. You can also attach `power2.spyx` so it is reloaded whenever you make changes:

```
sage: attach("power2.spyx")
```

Cython is used for its speed. Here is a timed test on a 2.6 GHz Opteron:

```
sage: %time [n for n in range(10^5) if is2pow(n)]  
[1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384, 32768, 65536]  
CPU times: user 0.60 s, sys: 0.00 s, total: 0.60 s  
Wall time: 0.60 s
```

Now, the code in the file `power2.spyx` is valid Python, and if we copy this to a file `powerslow.py` and load that, we get the following:

```
sage: load("powerslow.py")  
sage: %time [n for n in range(10^5) if is2pow(n)]  
[1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384, 32768, 65536]  
CPU times: user 1.01 s, sys: 0.04 s, total: 1.05 s  
Wall time: 1.05 s
```

By the way, we could gain even a little more speed with the Cython version with a type declaration, by changing `def is2pow(n):` to `def is2pow(unsigned int n):`.

Interrupt and Signal Handling

When writing Cython code for Sage, special care must be taken to ensure that the code can be interrupted with CTRL-C. Sage uses the `cysignals` package for this, see the [cysignals documentation](#) for more information.

Unpickling Cython Code

Pickling for Python classes and extension classes, such as Cython, is different. This is discussed in the [Python pickling documentation](#). For the unpickling of extension classes you need to write a `__reduce__()` method which typically returns a tuple `(f, args, ...)` such that `f(*args)` returns (a copy of) the original object. As an example, the following code snippet is the `__reduce__()` method from `sage.rings.integer.Integer`:

```
def __reduce__(self):
    """
    This is used when pickling integers.

    EXAMPLES::

        sage: n = 5
        sage: t = n.__reduce__(); t
        (<cyfunction make_integer at ...>, ('5',))
        sage: t[0](*t[1])
        5
        sage: loads(dumps(n)) == n
        True

    """
    # This single line below took me HOURS to figure out.
    # It is the *trick* needed to pickle Cython extension types.
    # The trick is that you must put a pure Python function
    # as the first argument, and that function must return
    # the result of unpickling with the argument in the second
    # tuple as input. All kinds of problems happen
    # if we don't do this.
    return sage.rings.integer.make_integer, (self.str(32),)
```

2.8.3 Using External Libraries and Interfaces

When writing code for Sage, use Python for the basic structure and interface. For speed, efficiency, or convenience, you can implement parts of the code using any of the following languages: *Cython*, C/C++, Fortran 95, GAP, Common Lisp, Singular, and PARI/GP. You can also use all C/C++ libraries included with Sage [[SageComponents](#)]. And if you are okay with your code depending on optional Sage packages, you can use Octave, or even Magma, Mathematica, or Maple.

In this chapter, we discuss interfaces between Sage and *PARI*, *GAP* and *Singular*.

The PARI C Library Interface

Here is a step-by-step guide to adding new PARI functions to Sage. We use the Frobenius form of a matrix as an example. Some heavy lifting for matrices over integers is implemented using the PARI library. To compute the Frobenius form in PARI, the `matfrobenius` function is used.

There are two ways to interact with the PARI library from Sage. The `gp` interface uses the `gp` interpreter. The PARI interface uses direct calls to the PARI C functions—this is the preferred way as it is much faster. Thus this section focuses on using PARI.

We will add a new method to the `gen` class. This is the abstract representation of all PARI library objects. That means that once we add a method to this class, every PARI object, whether it is a number, polynomial or matrix, will have our new method. So you can do `pari(1).matfrobenius()`, but since PARI wants to apply `matfrobenius` to matrices, not numbers, you will receive a `PariError` in this case.

The `gen` class is defined in `SAGE_ROOT/src/sage/libs/cypari2/gen.pyx`, and this is where we add the method `matfrobenius`:

```
def matfrobenius(self, flag=0):
    r"""
    M.matfrobenius(flag=0): Return the Frobenius form of the square
    matrix M. If flag is 1, return only the elementary divisors (a list
    of polynomials). If flag is 2, return a two-components vector [F,B]
    where F is the Frobenius form and B is the basis change so that
    `M=B^{-1} F B`.

    EXAMPLES::

        sage: a = pari('[1,2;3,4]')
        sage: a.matfrobenius()
        [0, 2; 1, 5]
        sage: a.matfrobenius(flag=1)
        [x^2 - 5*x - 2]
        sage: a.matfrobenius(2)
        [[0, 2; 1, 5], [1, -1/3; 0, 1/3]]
    """
    sig_on()
    return self.new_gen(matfrobenius(self.g, flag, 0))
```

Note the use of the `sig_on()` statement.

The `matfrobenius` call is just a call to the PARI C library function `matfrobenius` with the appropriate parameters.

The `self.new_gen(GEN x)` call constructs a new Sage `gen` object from a given PARI `GEN` where the PARI `GEN` is stored as the `.g` attribute. Apart from this, `self.new_gen()` calls a closing `sig_off()` macro and also clears the PARI stack so it is very convenient to use in a `return` statement as illustrated above. So after `self.new_gen()`, all PARI `GEN`'s which are not converted to Sage `gen`'s are gone. There is also `self.new_gen_noclear(GEN x)` which does the same as `self.new_gen(GEN x)` except that it does *not* call `sig_off()` nor clear the PARI stack.

The information about which function to call and how to call it can be retrieved from the PARI user's manual (note: Sage includes the development version of PARI, so check that version of the user's manual). Looking for `matfrobenius` you can find:

The library syntax is `GEN matfrobenius(GEN M, long flag, long v = -1)`, where `v` is a variable number.

In case you are familiar with `gp`, please note that the PARI C function may have a name that is different from the corresponding `gp` function (for example, see `mathnf`), so always check the manual.

We can also add a `frobenius(flag)` method to the `matrix_integer` class where we call the `matfrobenius()` method on the PARI object associated to the matrix after doing some sanity checking. Then we convert output from PARI to Sage objects:

```
def frobenius(self, flag=0, var='x'):
    """
    Return the Frobenius form (rational canonical form) of this matrix.

    INPUT:

    - ``flag`` -- 0 (default), 1 or 2 as follows:

        - ``0`` -- (default) return the Frobenius form of this
          matrix.

        - ``1`` -- return only the elementary divisor
          polynomials, as polynomials in var.

        - ``2`` -- return a two-components vector [F,B] where F
          is the Frobenius form and B is the basis change so that
           $M = B^{-1}FB$ .

    - ``var`` -- a string (default: 'x')

    ALGORITHM: uses PARI's :pari:matfrobenius`

    EXAMPLES::

        sage: A = MatrixSpace(ZZ, 3)(range(9))
        sage: A.frobenius(0)
        [ 0  0  0]
        [ 1  0 18]
        [ 0  1 12]
        sage: A.frobenius(1)
        [x^3 - 12*x^2 - 18*x]
        sage: A.frobenius(1, var='y')
        [y^3 - 12*y^2 - 18*y]
    """
    if not self.is_square():
        raise ArithmeticError("frobenius matrix of non-square matrix not defined.")

    v = self.__pari__().matfrobenius(flag)
    if flag == 0:
        return self.matrix_space()(v.python())
    elif flag == 1:
        r = PolynomialRing(self.base_ring(), names=var)
        retr = []
        for f in v:
            retr.append(eval(str(f).replace("^", "**"), {'x':r.gen()}, r.gens_dict()))
        return retr
    elif flag == 2:
        F = matrix_space.MatrixSpace(QQ, self.nrows()(v[0].python()))
        B = matrix_space.MatrixSpace(QQ, self.nrows()(v[1].python()))
        return F, B
```

GAP

Wrapping a GAP function in Sage is a matter of writing a program in Python that uses the pexpect interface to pipe various commands to GAP and read back the input into Sage. This is sometimes easy, sometimes hard.

For example, suppose we want to make a wrapper for the computation of the Cartan matrix of a simple Lie algebra. The Cartan matrix of G_2 is available in GAP using the commands:

```
gap> L:= SimpleLieAlgebra( "G", 2, Rationals );
<Lie algebra of dimension 14 over Rationals>
gap> R:= RootSystem( L );
<root system of rank 2>
gap> CartanMatrix( R );
```

In Sage, one can access these commands by typing:

```
sage: L = gap.SimpleLieAlgebra("G", 2, 'Rationals'); L
Algebra( Rationals, [ v.1, v.2, v.3, v.4, v.5, v.6, v.7, v.8, v.9, v.10,
  v.11, v.12, v.13, v.14 ] )
sage: R = L.RootSystem(); R
<root system of rank 2>
sage: R.CartanMatrix()
[ [ 2, -1 ], [ -3, 2 ] ]
```

Note the "G" which is evaluated in GAP as the string "G".

The purpose of this section is to use this example to show how one might write a Python/Sage program whose input is, say, ('G', 2) and whose output is the matrix above (but as a Sage Matrix—see the code in the directory SAGE_ROOT/src/sage/matrix/ and the corresponding parts of the Sage reference manual).

First, the input must be converted into strings consisting of legal GAP commands. Then the GAP output, which is also a string, must be parsed and converted if possible to a corresponding Sage/Python object.

```
def cartan_matrix(type, rank):
    """
    Return the Cartan matrix of given Chevalley type and rank.

    INPUT:

    - type -- a Chevalley letter name, as a string, for
      a family type of simple Lie algebras
    - rank -- an integer (legal for that type).

    EXAMPLES::

    sage: cartan_matrix("A",5)
    [ 2 -1  0  0  0]
    [-1  2 -1  0  0]
    [ 0 -1  2 -1  0]
    [ 0  0 -1  2 -1]
    [ 0  0  0 -1  2]
    sage: cartan_matrix("G",2)
    [ 2 -1]
    [-3  2]
    """
```

(continues on next page)

(continued from previous page)

```

L = gap.SimpleLieAlgebra("%s" % type, rank, 'Rationals')
R = L.RootSystem()
sM = R.CartanMatrix()
ans = eval(str(sM))
MS = MatrixSpace(QQ, rank)
return MS(ans)

```

The output `ans` is a Python list. The last two lines convert that list to an instance of the Sage class `Matrix`.

Alternatively, one could replace the first line of the above function with this:

```

L = gap.new('SimpleLieAlgebra("%s", %s, Rationals);'%(type, rank))

```

Defining “easy” and “hard” is subjective, but here is one definition. Wrapping a GAP function is “easy” if there is already a corresponding class in Python or Sage for the output data type of the GAP function you are trying to wrap. For example, wrapping any GUAVA (GAP’s error-correcting codes package) function is “easy” since error-correcting codes are vector spaces over finite fields and GUAVA functions return one of the following data types:

- vectors over finite fields,
- polynomials over finite fields,
- matrices over finite fields,
- permutation groups or their elements,
- integers.

Sage already has classes for each of these.

A “hard” example is left as an exercise! Here are a few ideas.

- Write a wrapper for GAP’s `FreeLieAlgebra` function (or, more generally, all the finitely presented Lie algebra functions in GAP). This would require creating new Python objects.
- Write a wrapper for GAP’s `FreeGroup` function (or, more generally, all the finitely presented groups functions in GAP). This would require writing some new Python objects.
- Write a wrapper for GAP’s character tables. Though this could be done without creating new Python objects, to make the most use of these tables, it probably would be best to have new Python objects for this.

LibGAP

The disadvantage of using other programs through interfaces is that there is a certain unavoidable latency (of the order of 10ms) involved in sending input and receiving the result. If you have to call functions in a tight loop this can be unacceptably slow. Calling into a shared library has much lower latency and furthermore avoids having to convert everything into a string in-between. This is why Sage includes a shared library version of the GAP kernel, available as *libgap* in Sage. The *libgap* analogue of the first example in *GAP* is:

```

sage: SimpleLieAlgebra = libgap.function_factory('SimpleLieAlgebra')
sage: L = SimpleLieAlgebra('G', 2, QQ)
sage: R = L.RootSystem(); R
<root system of rank 2>
sage: R.CartanMatrix()      # output is a GAP matrix
[ [ 2, -1 ], [ -3, 2 ] ]
sage: matrix(R.CartanMatrix()) # convert to Sage matrix

```

(continues on next page)

(continued from previous page)

```
[ 2 -1]
[-3  2]
```

Singular

Using Singular functions from Sage is not much different conceptually from using GAP functions from Sage. As with GAP, this can range from easy to hard, depending on how much of the data structure of the output of the Singular function is already present in Sage.

First, some terminology. For us, a *curve* X over a finite field F is an equation of the form $f(x, y) = 0$, where $f \in F[x, y]$ is a polynomial. It may or may not be singular. A *place of degree d* is a Galois orbit of d points in $X(E)$, where E/F is of degree d . For example, a place of degree 1 is also a place of degree 3, but a place of degree 2 is not since no degree 3 extension of F contains a degree 2 extension. Places of degree 1 are also called F -rational points.

As an example of the Sage/Singular interface, we will explain how to wrap Singular's `NSplaces`, which computes places on a curve over a finite field. (The command `closed_points` also does this in some cases.) This is “easy” since no new Python classes are needed in Sage to carry this out.

Here is an example on how to use this command in Singular:

```
A Computer Algebra System for Polynomial Computations / version 3-0-0
                                0<
      by: G.-M. Greuel, G. Pfister, H. Schoenemann      \   May 2005
FB Mathematik der Universitaet, D-67653 Kaiserslautern  \
> LIB "brnoeth.lib";
[...]
```

```
> ring s=5,(x,y),lp;
> poly f=y^2-x^9-x;
> list X1=Adj_div(f);
Computing affine singular points ...
Computing all points at infinity ...
Computing affine singular places ...
Computing singular places at infinity ...
Computing non-singular places at infinity ...
Adjunction divisor computed successfully

The genus of the curve is 4
> list X2=NSplaces(1,X1);
Computing non-singular affine places of degree 1 ...
> list X3=extcurve(1,X2);

Total number of rational places : 6

> def R=X3[1][5];
> setring R;
> POINTS;
[1]:
  [1]:
    0
  [2]:
    1
  [3]:
```

(continues on next page)

(continued from previous page)

```

0
[2]:
[1]:
-2
[2]:
1
[3]:
1
[3]:
[1]:
-2
[2]:
1
[3]:
1
[4]:
[1]:
-2
[2]:
-1
[3]:
1
[5]:
[1]:
2
[2]:
-2
[3]:
1
[6]:
[1]:
0
[2]:
0
[3]:
1

```

Here is another way of doing this same calculation in the Sage interface to Singular:

```

sage: singular.LIB("brnoeth.lib")
sage: singular.ring(5, '(x,y)', 'lp')
      polynomial ring, over a field, global ordering
      // coefficients: ZZ/5
      // number of vars : 2
      //      block  1 : ordering lp
      //              : names    x y
      //      block  2 : ordering C
sage: f = singular('y^2-x^9-x')
sage: print(singular.eval("list X1=Adj_div(%s);"%f.name()))
Computing affine singular points ...
Computing all points at infinity ...
Computing affine singular places ...

```

(continues on next page)

(continued from previous page)

```

Computing singular places at infinity ...
Computing non-singular places at infinity ...
Adjunction divisor computed successfully

The genus of the curve is 4
sage: print(singular.eval("list X2=NSplaces(1,X1);"))
Computing non-singular affine places of degree 1 ...
sage: print(singular.eval("list X3=extcurve(1,X2);"))

Total number of rational places : 6

sage: singular.eval("def R=X3[1][5];")
''
sage: singular.eval("setring R;")
''
sage: L = singular.eval("POINTS;")

sage: print(L) # random
[1]:
  [1]:
    0
  [2]:
    1
  [3]:
    0
...

```

From looking at the output, notice that our wrapper function will need to parse the string represented by L above, so let us write a separate function to do just that. This requires figuring out how to determine where the coordinates of the points are placed in the string L . Python has some very useful string manipulation commands to do just that.

```

def points_parser(string_points, F):
    """
    This function will parse a string of points
    of  $X$  over a finite field  $F$  returned by Singular's NSplaces
    command into a Python list of points with entries from  $F$ .

    EXAMPLES::

        sage: F = GF(5)
        sage: points_parser(L,F)
        ((0, 1, 0), (3, 4, 1), (0, 0, 1), (2, 3, 1), (3, 1, 1), (2, 2, 1))
    """
    Pts = []
    n = len(L)
    # start block to compute a pt
    L1 = L
    while len(L1) > 32:
        idx = L1.index(" ")
        pt = []
        # start block1 for compute pt
        idx = L1.index(" ")

```

(continues on next page)

(continued from previous page)

```

idx2 = L1[idx:].index("\n")
L2 = L1[idx:idx+idx2]
pt.append(F(eval(L2)))
# end block1 to compute pt
L1 = L1[idx+8:] # repeat block 2 more times
# start block2 for compute pt
idx = L1.index(" ")
idx2 = L1[idx:].index("\n")
L2 = L1[idx:idx+idx2]
pt.append(F(eval(L2)))
# end block2 to compute pt
L1=L1[idx+8:] # repeat block 1 more time
# start block3 for compute pt
idx=L1.index(" ")
if "\n" in L1[idx:]:
    idx2 = L1[idx:].index("\n")
else:
    idx2 = len(L1[idx:])
L2 = L1[idx:idx+idx2]
pt.append(F(eval(L2)))
# end block3 to compute pt
# end block to compute a pt
Pts.append(tuple(pt)) # repeat until no more pts
L1 = L1[idx+8:] # repeat block 2 more times
return tuple(Pts)

```

Now it is an easy matter to put these ingredients together into a Sage function which takes as input a triple (f, F, d) : a polynomial f in $F[x, y]$ defining $X : f(x, y) = 0$ (note that the variables x, y must be used), a finite field F of prime order, and the degree d . The output is the number of places in X of degree $d = 1$ over F . At the moment, there is no “translation” between elements of $GF(p^d)$ in Singular and Sage unless $d = 1$. So, for this reason, we restrict ourselves to points of degree one.

```

def places_on_curve(f, F):
    """
    INPUT:

    - f -- element of F[x,y], defining X: f(x,y)=0
    - F -- a finite field of *prime order*

    OUTPUT:

    integer -- the number of places in X of degree d=1 over F

    EXAMPLES::

    sage: F = GF(5)
    sage: R = PolynomialRing(F, 2, names=["x", "y"])
    sage: x,y = R.gens()
    sage: f = y^2-x^9-x
    sage: places_on_curve(f,F)
    ((0, 1, 0), (3, 4, 1), (0, 0, 1), (2, 3, 1), (3, 1, 1), (2, 2, 1))
    """

```

(continues on next page)

(continued from previous page)

```

d = 1
p = F.characteristic()
singular.eval('LIB "brnoeth.lib";')
singular.eval("ring s="+str(p)+", (x,y), lp;")
singular.eval("poly f="+str(f))
singular.eval("list X1=Adj_div(f);")
singular.eval("list X2=NSplaces("+str(d)+", X1);")
singular.eval("list X3=extcurve("+str(d)+", X2);")
singular.eval("def R=X3[1][5];")
singular.eval("setring R;")
L = singular.eval("POINTS;")
return points_parser(L,F)

```

Note that the ordering returned by this Sage function is exactly the same as the ordering in the Singular variable POINTS.

One more example (in addition to the one in the docstring):

```

sage: F = GF(2)
sage: R = MPolynomialRing(F, 2, names = ["x", "y"])
sage: x, y = R.gens()
sage: f = x^3*y + y^3 + x
sage: places_on_curve(f, F)
((0, 1, 0), (1, 0, 0), (0, 0, 1))

```

Singular: Another Approach

There is also a more Python-like interface to Singular. Using this, the code is much simpler, as illustrated below. First, we demonstrate computing the places on a curve in a particular case:

```

sage: singular.lib('brnoeth.lib')
sage: R = singular.ring(5, '(x,y)', 'lp')
sage: f = singular.new('y^2 - x^9 - x')
sage: X1 = f.Adj_div()
sage: X2 = singular.NSplaces(1, X1)
sage: X3 = singular.extcurve(1, X2)
sage: R = X3[1][5]
sage: singular.set_ring(R)
sage: L = singular.new('POINTS')

```

Note that these elements of L are defined modulo 5 in Singular, and they compare differently than you would expect from their print representation:

```

sage: sorted([(L[i][1], L[i][2], L[i][3]) for i in range(1,7)])
[(0, 0, 1), (0, 1, 0), (2, 2, 1), (2, -2, 1), (-2, 1, 1), (-2, -1, 1)]

```

Next, we implement the general function (for brevity we omit the docstring, which is the same as above). Note that the `point_parser` function is not required:

```

def places_on_curve(f, F):
    p = F.characteristic()
    if F.degree() > 1:
        raise NotImplementedError

```

(continues on next page)

(continued from previous page)

```

singular.lib('brnoeth.lib')
R = singular.ring(5, '(x,y)', 'lp')
f = singular.new('y^2 - x^9 - x')
X1 = f.Adj_div()
X2 = singular.NSplaces(1, X1)
X3 = singular.extcurve(1, X2)
R = X3[1][5]
singular.setring(R)
L = singular.new('POINTS')
return [(int(L[i][1]), int(L[i][2]), int(L[i][3])) \
        for i in range(1,int(L.size())+1)]

```

This code is much shorter, nice, and more readable. However, it depends on certain functions, e.g. `singular.setring` having been implemented in the Sage/Singular interface, whereas the code in the previous section used only the barest minimum of that interface.

Creating a New Pseudo-TTY Interface

You can create Sage pseudo-tty interfaces that allow Sage to work with almost any command line program, and which do not require any modification or extensions to that program. They are also surprisingly fast and flexible (given how they work!), because all I/O is buffered, and because interaction between Sage and the command line program can be non-blocking (asynchronous). A pseudo-tty Sage interface is asynchronous because it derives from the Sage class `Expect`, which handles the communication between Sage and the external process.

For example, here is part of the file `SAGE_ROOT/src/sage/interfaces/octave.py`, which defines an interface between Sage and Octave, an open source program for doing numerical computations, among other things:

```

import os
from expect import Expect, ExpectElement

class Octave(Expect):
    ...

```

The first two lines import the library `os`, which contains operating system routines, and also the class `Expect`, which is the basic class for interfaces. The third line defines the class `Octave`; it derives from `Expect` as well. After this comes a docstring, which we omit here (see the file for details). Next comes:

```

def __init__(self, script_subdirectory="", logfile=None,
              server=None, server_tmpdir=None):
    Expect.__init__(self,
                     name = 'octave',
                     prompt = '>',
                     command = "octave --no-line-editing --silent",
                     server = server,
                     server_tmpdir = server_tmpdir,
                     script_subdirectory = script_subdirectory,
                     restart_on_ctrlc = False,
                     verbose_start = False,
                     logfile = logfile,
                     eval_using_file_cutoff=100)

```

This uses the class `Expect` to set up the Octave interface:

```

def set(self, var, value):
    """
    Set the variable var to the given value.
    """
    cmd = '%s=%s;' % (var,value)
    out = self.eval(cmd)
    if out.find("error") != -1:
        raise TypeError("Error executing code in Octave\nCODE:\n\t%s\nOctave ERROR:\n\t%s"
        ↪ "%(cmd, out))

def get(self, var):
    """
    Get the value of the variable var.
    """
    s = self.eval('%s' % var)
    i = s.find('=')
    return s[i+1:]

def console(self):
    octave_console()

```

These let users type `octave.set('x', 3)`, after which `octave.get('x')` returns `' 3'`. Running `octave.console()` dumps the user into an Octave interactive shell:

```

def solve_linear_system(self, A, b):
    """
    Use octave to compute a solution x to  $A*x = b$ , as a list.

    INPUT:

    - A -- mxn matrix A with entries in QQ or RR
    - b -- m-vector b entries in QQ or RR (resp)

    OUTPUT:

    An list x (if it exists) which solves  $M*x = b$ 

    EXAMPLES::

    sage: M33 = MatrixSpace(QQ,3,3)
    sage: A   = M33([1,2,3,4,5,6,7,8,0])
    sage: V3  = VectorSpace(QQ,3)
    sage: b   = V3([1,2,3])
    sage: octave.solve_linear_system(A,b)    # optional - octave
    [-0.333333, 0.666667, 0]

    AUTHOR: David Joyner and William Stein
    """
    m = A.nrows()
    n = A.ncols()
    if m != len(b):
        raise ValueError("dimensions of A and b must be compatible")
    from sage.matrix.all import MatrixSpace

```

(continues on next page)

(continued from previous page)

```

from sage.rings.all import QQ
MS = MatrixSpace(QQ, m, 1)
b = MS(list(b)) # converted b to a "column vector"
sA = self.sage2octave_matrix_string(A)
sb = self.sage2octave_matrix_string(b)
self.eval("a = " + sA )
self.eval("b = " + sb )
soln = octave.eval("c = a \\ b")
soln = soln.replace("\n\n ", "[")
soln = soln.replace("\n\n", "]")
soln = soln.replace("\n", ",")
sol = soln[3:]
return eval(sol)

```

This code defines the method `solve_linear_system`, which works as documented.

These are only excerpts from `octave.py`; check that file for more definitions and examples. Look at other files in the directory `SAGE_ROOT/src/sage/interfaces/` for examples of interfaces to other software packages.

2.9 Packaging the Sage Library

2.9.1 Packaging the Sage Library

Modules, packages, distribution packages

The Sage library consists of a large number of Python modules, organized into a hierarchical set of packages that fill the namespace `sage`. All source files are located in a subdirectory of the directory `SAGE_ROOT/src/sage/`.

For example,

- the file `SAGE_ROOT/src/sage/coding/code_bounds.py` provides the module `sage.coding.code_bounds`;
- the directory containing this file, `SAGE_ROOT/src/sage/coding/`, thus provides the package `sage.coding`.

There is another notion of “package” in Python, the **distribution package** (also known as a “distribution” or a “pip-installable package”). Currently, the entire Sage library is provided by a single distribution, `sagemath-standard`, which is generated from the directory `SAGE_ROOT/pkgs/sagemath-standard`.

Note that the distribution name is not required to be a Python identifier. In fact, using dashes (-) is preferred to underscores in distribution names; `setuptools` and other parts of Python’s packaging infrastructure normalize underscores to dashes. (Using dots in distribution names, to indicate ownership by organizations, still mentioned in [PEP 423](#), appears to have largely fallen out of favor, and we will not use it in the SageMath project.)

A distribution that provides Python modules in the `sage.*` namespace, say mainly from `sage.PAC.KAGE`, should be named **sagemath-DISTRI-BUTION**. Example:

- The distribution `sagemath-categories` provides a small subset of the modules of the Sage library, mostly from the packages `sage.structure`, `sage.categories`, and `sage.misc`.

Other distributions should not use the prefix **sagemath-** in the distribution name. Example:

- The distribution `sage-sws2rst` provides the Python package `sage_sws2rst`, so it does not fill the `sage.*` namespace and therefore does not use the prefix **sagemath-**.

A distribution that provides functionality that does not need to import anything from the `sage` namespace should not use the `sage` namespace for its own packages/modules. It should be positioned as part of the general Python ecosystem instead of as a Sage-specific distribution. Examples:

- The distribution `pply` provides the Python package `ppl` and is a much extended version of what used to be `sage.libs.ppl`, a part of the Sage library. The package `sage.libs.ppl` had dependencies on `sage.rings` to convert to/from Sage number types. `pply` has no such dependencies and is therefore usable in a wider range of Python projects.
- The distribution `memory-allocator` provides the Python package `memory_allocator`. This used to be `sage.ext.memory_allocator`, a part of the Sage library.

Ordinary packages vs. implicit namespace packages

Each module of the Sage library must be packaged in exactly one distribution package. However, modules in a package may be included in different distribution packages. In this regard, there is an important constraint that an ordinary package (directory with `__init__.py` file) cannot be split into more than one distribution package.

By removing the `__init__.py` file, however, we can make the package an “implicit” (or “native”) “namespace” package, following [PEP 420](#). Implicit namespace packages can be included in more than one distribution package. Hence whenever there are two distribution packages that provide modules with a common prefix of Python packages, that prefix needs to be a implicit namespace package, i.e., there cannot be an `__init__.py` file.

For example,

- `sagemath-tdlib` will provide `sage.graphs.graph_decompositions.tdlib`,
- `sagemath-rw` will provide `sage.graphs.graph_decompositions.rankwidth`,
- `sagemath-graphs` will provide all of the rest of `sage.graphs.graph_decompositions` (and most of `sage.graphs`).

Then, none of

- `sage`,
- `sage.graphs`,
- `sage.graphs.graph_decomposition`

can be an ordinary package (with an `__init__.py` file), but rather each of them has to be an implicit namespace package (no `__init__.py` file).

For an implicit namespace package, `__init__.py` cannot be used any more for initializing the package.

In the Sage 9.6 development cycle, we still use ordinary packages by default, but several packages are converted to implicit namespace packages to support modularization.

Source directories of distribution packages

The development of the Sage library uses a monorepo strategy for all distribution packages that fill the `sage.*` namespace. This means that the source trees of these distributions are included in a single `git` repository, in a subdirectory of `SAGE_ROOT/pkgs`.

All these distribution packages have matching version numbers. From the viewpoint of a single distribution, this means that sometimes there will be a new release of some distribution where the only thing changing is the version number.

The source directory of a distribution package, such as `SAGE_ROOT/pkgs/sagemath-standard`, contains the following files:

- `sage` – a relative symbolic link to the monolithic Sage library source tree `SAGE_ROOT/src/sage/`

- `MANIFEST.in` – controls which files and directories of the monolithic Sage library source tree are included in the distribution
- `pyproject.toml`, `setup.cfg`, and `requirements.txt` – standard Python packaging metadata, declaring the distribution name, dependencies, etc.
- `README.rst` – a description of the distribution
- `LICENSE.txt` – relative symbolic link to the same files in `SAGE_ROOT/src`
- `VERSION.txt` – package version. This file is updated by the release manager by running the `sage-update-version` script.

Sometimes it may be necessary to upload a hotfix for a distribution package to PyPI. These should be marked by adding a suffix `.post1`, `.post2`; see [PEP 440 on post-releases](#). For example, if the current development release is `9.7.beta8`, then such a version could be marked `9.7.beta8.post1`.

Also sometimes when working on tickets it may be necessary to increment the version because a new feature is needed in another distribution package. Such versions should be marked by using the version number of the anticipated next development release and adding a suffix `.dev1`, `.dev2` ... (see [PEP 440 on developmental releases](#)). For example, if the current development release is `9.7.beta8`, use `9.7.beta9.dev1`. If the current development release is the stable release `9.8`, use `9.9.beta0.dev1`.

After the ticket is merged in the next development version, it will be synchronized again with the other package versions.

- `setup.py` – a `setuptools`-based installation script
- `tox.ini` – configuration for testing with `tox`

The technique of using symbolic links pointing into `SAGE_ROOT/src` has allowed the modularization effort to keep the `SAGE_ROOT/src` tree monolithic: Modularization has been happening behind the scenes and will not change where Sage developers find the source files. When adding a new distribution package that uses a symbolic link pointing into `SAGE_ROOT/src`, please update `search.exclude` in `SAGE_ROOT/.vscode/settings.json`.

Some of these files may actually be generated from source files with suffix `.m4` by the `SAGE_ROOT/bootstrap` script via the `m4` macro processor.

For every distribution package, there is also a subdirectory of `SAGE_ROOT/build/pkgs/`, which contains the build infrastructure that is specific to Sage-the-distribution. Note that these subdirectories follows a different naming convention, using underscores instead of dashes, see [Directory Structure](#). Because the distribution packages are included in the source tree, we set them up as “script packages” instead of “normal packages”, see [Package source types](#).

Dependencies and distribution packages

When preparing a portion of the Sage library as a distribution package, dependencies matter.

Build-time dependencies

If the portion of the library contains any Cython modules, these modules are compiled during the wheel-building phase of the distribution package. If the Cython module uses `cimport` to pull in anything from `.pxd` files, these files must be either part of the portion shipped as the distribution being built, or the distribution that provides these files must be installed in the build environment. Also, any C/C++ libraries that the Cython module uses must be accessible from the build environment.

Declaring build-time dependencies: Modern Python packaging provides a mechanism to declare build-time dependencies on other distribution packages via the file `pyproject.toml` (`[build-system] requires`); this has superseded the older `setup_requires` declaration. (There is no mechanism to declare anything regarding the C/C++ libraries.)

While the namespace `sage.*` is organized roughly according to mathematical fields or categories, how we partition the implementation modules into distribution packages has to respect the hard constraints that are imposed by the build-time dependencies.

We can define some meaningful small distributions that just consist of a single or a few Cython modules. For example, **sagemath-tdlib** ([trac ticket #29864](#)) would just package the single Cython module that must be linked with `tdlib`, `sage.graphs.graph_decompositions.tdlib`. Starting with the Sage 9.6 development cycle, as soon as namespace packages are activated, we can start to create these distributions. This is quite a mechanical task.

Reducing build-time dependencies: Sometimes it is possible to replace build-time dependencies of a Cython module on a library by a runtime dependency. In other cases, it may be possible to split a module that simultaneously depends on several libraries into smaller modules, each of which has narrower dependencies.

Module-level runtime dependencies

Any `import` statements at the top level of a Python or Cython module are executed when the module is imported. Hence, the imported modules must be part of the distribution, or provided by another distribution – which then must be declared as a run-time dependency.

Declaring run-time dependencies: These dependencies are declared in `setup.cfg` (generated from `setup.cfg.m4`) as `install_requires`.

Reducing module-level run-time dependencies:

- Avoid importing from `sage.PAC.KAGE.all` modules when `sage.PAC.KAGE` is a namespace package. The main purpose of the `*.all` modules is for populating the global interactive environment that is available to users at the `sage:` prompt. In particular, no Sage library code should import from `sage.rings.all`.
- Replace module-level imports by method-level imports. Note that this comes with a small runtime overhead, which can become noticeable if the method is called in tight inner loops.
- Sage provides the `lazy_import()` mechanism. Lazy imports can be declared at the module level, but the actual importing is only done on demand. It is a runtime error at that time if the imported module is not present. This can be convenient compared to local imports in methods when the same imports are needed in several methods.
- Avoid the “modularization anti-pattern” of importing a class from another module just to run an `isinstance(object, Class)` test, in particular when the module implementing `Class` has heavy dependencies. For example, importing the class `pAdicField` (or the function `is_pAdicField`) requires the libraries `NTL` and `PARI`.

Instead, provide an abstract base class (ABC) in a module that only has light dependencies, make `Class` a subclass of `ABC`, and use `isinstance(object, ABC)`. For example, `sage.rings.abc` provides abstract base classes for many ring (parent) classes, including `sage.rings.abc.pAdicField`. So we can replace:

```
from sage.rings.padics.generic_nodes import pAdicFieldGeneric # heavy dependencies
isinstance(object, pAdicFieldGeneric)
```

and:

```
from sage.rings.padics.generic_nodes import is_pAdicField      # heavy dependencies
is_pAdicField(object)                                         # deprecated
```

by:

```
import sage.rings.abc                                         # no dependencies
isinstance(object, sage.rings.abc.pAdicField)
```

Note that going through the abstract base class only incurs a small performance penalty:

```

sage: object = Qp(5)

sage: from sage.rings.padics.generic_nodes import pAdicFieldGeneric
sage: %timeit isinstance(object, pAdicFieldGeneric)          # fast
↳ # not tested
68.7 ns ± 2.29 ns per loop (...)

sage: import sage.rings.abc
sage: %timeit isinstance(object, sage.rings.abc.pAdicField)  # also fast
↳ # not tested
122 ns ± 1.9 ns per loop (...)

```

- If it is not possible or desired to create an abstract base class for `isinstance` testing (for example, when the class is defined in some external package), other solutions need to be used.

Note that Python caches successful module imports, but repeating an unsuccessful module import incurs a cost every time:

```

sage: from sage.schemes.generic.scheme import Scheme
sage: sZZ = Scheme(ZZ)

sage: def is_Scheme_or_Pluffe(x):
.....:     if isinstance(x, Scheme):
.....:         return True
.....:     try:
.....:         from xxxx_does_not_exist import Pluffe          # slow on every call
.....:     except ImportError:
.....:         return False
.....:     return isinstance(x, Pluffe)

sage: %timeit is_Scheme_or_Pluffe(sZZ)                        # fast
↳ # not tested
111 ns ± 1.15 ns per loop (...)

sage: %timeit is_Scheme_or_Pluffe(ZZ)                         # slow
↳ # not tested
143 μs ± 2.58 μs per loop (...)

```

The `lazy_import()` mechanism can be used to simplify this pattern via the `__instancecheck__()` method and has similar performance characteristics:

```

sage: lazy_import('xxxx_does_not_exist', 'Pluffe')

sage: %timeit isinstance(sZZ, (Scheme, Pluffe))              # fast
↳ # not tested
95.2 ns ± 0.636 ns per loop (...)

sage: %timeit isinstance(ZZ, (Scheme, Pluffe))               # slow
↳ # not tested
158 μs ± 654 ns per loop (...)

```

It is faster to do the import only once, for example when loading the module, and to cache the failure. We can use the following idiom, which makes use of the fact that `isinstance` accepts arbitrarily nested lists and tuples of types:

```

sage: try:
.....:     from xxxx_does_not_exist import Pluffe           # runs once
.....: except ImportError:
.....:     # Set to empty tuple of types for isinstance
.....:     Pluffe = ()

sage: %timeit isinstance(sZZ, (Scheme, Pluffe))              # fast
↪      # not tested
95.9 ns ± 1.52 ns per loop (...)

sage: %timeit isinstance(ZZ, (Scheme, Pluffe))              # fast
↪      # not tested
126 ns ± 1.9 ns per loop (...)

```

Other runtime dependencies

If `import` statements are used within a method, the imported module is loaded the first time that the method is called. Hence the module defining the method can still be imported even if the module needed by the method is not present.

It is then a question whether a run-time dependency should be declared. If the method needing that import provides core functionality, then probably yes. But if it only provides what can be considered “optional functionality”, then probably not, and in this case it will be up to the user to install the distribution enabling this optional functionality.

As an example, let us consider designing a distribution that centers around the package `sage.coding`. First, let’s see if it uses symbolics:

```

(9.5.beta6) $ git grep -E 'sage[.](symbolic|functions|calculus)' src/sage/coding
src/sage/coding/code_bounds.py:         from sage.functions.other import ceil
...
src/sage/coding/grs_code.py:from sage.symbolic.ring import SR
...
src/sage/coding/guruswami_sudan/utils.py:from sage.functions.other import floor

```

Apparently it does not in a very substantial way:

- The imports of the symbolic functions `ceil()` and `floor()` can likely be replaced by the arithmetic functions `integer_floor()` and `integer_ceil()`.
- Looking at the import of `SR` by `sage.coding.grs_code`, it seems that `SR` is used for running some symbolic sum, but the doctests do not show symbolic results, so it is likely that this can be replaced.
- Note though that the above textual search for the module names is merely a heuristic. Looking at the source of “entropy”, through log from `sage.misc.functional`, a runtime dependency on symbolics comes in. In fact, for this reason, two doctests there are already marked as `# optional - sage.symbolic`.

So if packaged as **sagemath-coding**, now a domain expert would have to decide whether these dependencies on symbolics are strong enough to declare a runtime dependency (`install_requires`) on **sagemath-symbolics**. This declaration would mean that any user who installs **sagemath-coding** (`pip install sagemath-coding`) would pull in **sagemath-symbolics**, which has heavy compile-time dependencies (ECL/Maxima/FLINT/Singular/...).

The alternative is to consider the use of symbolics by **sagemath-coding** merely as something that provides some extra features, which will only be working if the user also has installed **sagemath-symbolics**.

Declaring optional run-time dependencies: It is possible to declare such optional dependencies as `extras_require` in `setup.cfg` (generated from `setup.cfg.m4`). This is a very limited mechanism – in particular it does not affect the

build phase of the distribution in any way. It basically only provides a way to give a nickname to a distribution that can be installed as an add-on.

In our example, we could declare an `extras_require` so that users could use `pip install sagemath-coding[symbolics]`.

Doctest-only dependencies

Doctests often use examples constructed using functionality provided by other portions of the Sage library. This kind of integration testing is one of the strengths of Sage; but it also creates extra dependencies.

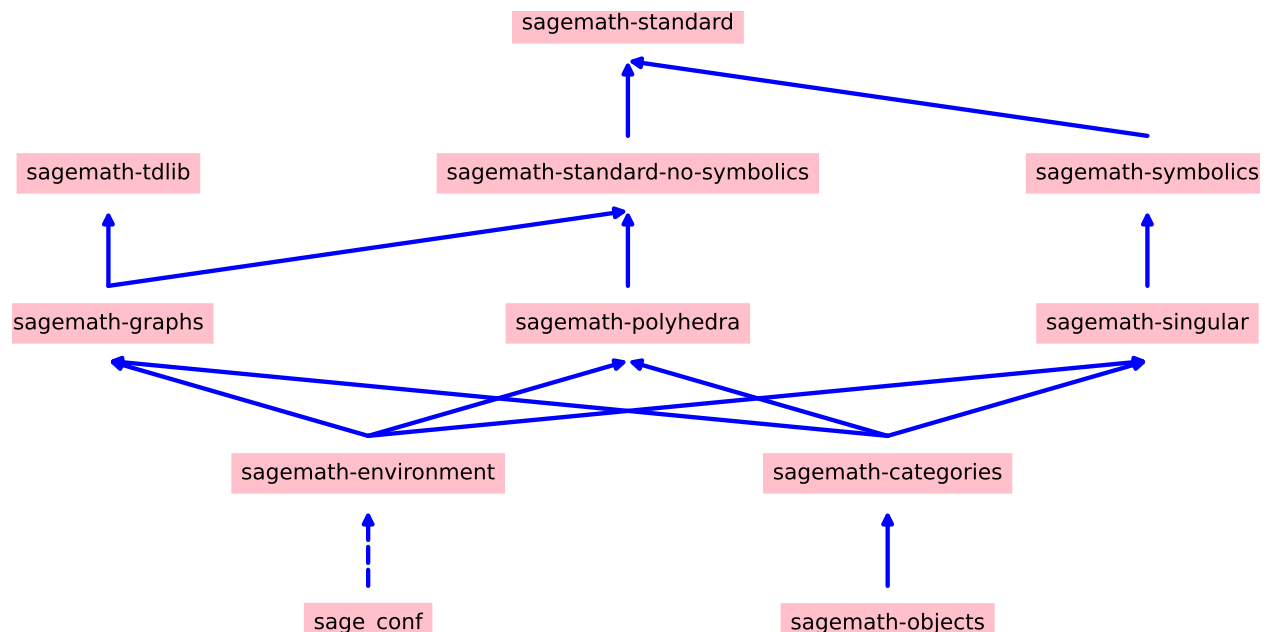
Fortunately, these dependencies are very mild, and we can deal with them using the same mechanism that we use for making doctests conditional on the presence of optional libraries: using `# optional - FEATURE` directives in the doctests. Adding these directives will allow developers to test the distribution separately, without requiring all of Sage to be present.

Declaring doctest-only dependencies: The `extras_require` mechanism mentioned above can also be used for this.

Version constraints of dependencies

The version information for dependencies comes from the files `build/pkgs/*/install-requires.txt` and `build/pkgs/*/package-version.txt`. We use the `m4` macro processor to insert the version information in the generated files `pyproject.toml`, `setup.cfg`, `requirements.txt`.

Hierarchy of distribution packages



Solid arrows indicate `install_requires`, i.e., a declared runtime dependency. Dashed arrows indicate `extras_require`, i.e., a declared optional runtime dependency.

Testing distribution packages

Of course, we need tools for testing modularized distributions of portions of the Sage library.

- Modularized distributions must be testable separately!
- But we want to keep integration testing with other portions of Sage too!

Preparing doctests

Whenever an optional package is needed for a particular test, we use the doctest annotation `# optional`. This mechanism can also be used for making a doctest conditional on the presence of a portion of the Sage library.

The available tags take the form of package or module names such as `sage.combinat`, `sage.graphs`, `sage.plot`, `sage.rings.number_field`, `sage.rings.real_double`, and `sage.symbolic`. They are defined via `Feature` subclasses in the module `sage.features.sagemath`, which also provides the mapping from features to the distributions providing them (actually, to SPKG names). Using this mapping, Sage can issue installation hints to the user.

For example, the package `sage.tensor` is purely algebraic and has no dependency on symbolics. However, there are a small number of doctests that depend on `sage.symbolic.ring.SymbolicRing` for integration testing. Hence, these doctests are marked `# optional - sage.symbolic`.

Testing the distribution in virtual environments with tox

So how to test that this works?

Sure, we could go into the installation directory `SAGE_VENV/lib/python3.9/site-packages/` and do `rm -rf sage/symbolic` and test that things still work. But that's not a good way of testing.

Instead, we use a virtual environment in which we only install the distribution to be tested (and its Python dependencies).

Let's try it out first with the entire Sage library, represented by the distribution **sagemath-standard**. Note that after Sage has been built normally, a set of wheels for all installed Python packages is available in `SAGE_VENV/var/lib/sage/wheels/`:

```
$ ls venv/var/lib/sage/wheels
Babel-2.9.1-py2.py3-none-any.whl
Cython-0.29.24-cp39-cp39-macosx_11_0_x86_64.whl
Jinja2-2.11.2-py2.py3-none-any.whl
...
sage_conf-9.5b6-py3-none-any.whl
...
scipy-1.7.2-cp39-cp39-macosx_11_0_x86_64.whl
setuptools-58.2.0-py3-none-any.whl
...
wheel-0.37.0-py2.py3-none-any.whl
widgetsnbextension-3.5.1-py2.py3-none-any.whl
zipp-3.5.0-py3-none-any.whl
```

Note in particular the wheel for **sage-conf**, which provides configuration variable settings and the connection to the non-Python packages installed in `SAGE_LOCAL`.

We can now set up a separate virtual environment, in which we install these wheels and our distribution to be tested. This is where **tox** comes into play: It is the standard Python tool for creating disposable virtual environments for testing. Every distribution in `SAGE_ROOT/pkgs/` provides a configuration file `tox.ini`.

Following the comments in the file `SAGE_ROOT/pkgs/sagemath-standard/tox.ini`, we can try the following command:

```
$ ./bootstrap && ./sage -sh -c '(cd pkgs/sagemath-standard && SAGE_NUM_THREADS=16 tox -v -v -v -e sagepython-sagewheels-nopypi)'
```

This command does not make any changes to the normal installation of Sage. The virtual environment is created in a subdirectory of `SAGE_ROOT/pkgs/sagemath-standard-no-symbolics/.tox/`. After the command finishes, we can start the separate installation of the Sage library in its virtual environment:

```
$ pkgs/sagemath-standard/.tox/sagepython-sagewheels-nopypi/bin/sage
```

We can also run parts of the testsuite:

```
$ pkgs/sagemath-standard/.tox/sagepython-sagewheels-nopypi/bin/sage -tp 4 src/sage/
↳ graphs/
```

The whole `.tox` directory can be safely deleted at any time.

We can do the same with other distributions, for example the large distribution **sagemath-standard-no-symbolics** (from [trac ticket #32601](#)), which is intended to provide everything that is currently in the standard Sage library, i.e., without depending on optional packages, but without the packages `sage.symbolic`, `sage.functions`, `sage.calculus`, etc.

Again we can run the test with `tox` in a separate virtual environment:

```
$ ./bootstrap && ./sage -sh -c '(cd pkgs/sagemath-standard-no-symbolics && SAGE_NUM_THREADS=16 tox -v -v -v -e sagepython-sagewheels-nopypi)'
```

Some small distributions, for example the ones providing the two lowest levels, **sagemath-objects** and **sagemath-categories** (from [trac ticket #29865](#)), can be installed and tested without relying on the wheels from the Sage build:

```
$ ./bootstrap && ./sage -sh -c '(cd pkgs/sagemath-objects && SAGE_NUM_THREADS=16 tox -v -v -v -e sagepython)'
```

This command finds the declared build-time and run-time dependencies on PyPI, either as source tarballs or as prebuilt wheels, and builds and installs the distribution **sagemath-objects** in a virtual environment in a subdirectory of `pkgs/sagemath-objects/.tox`.

Building these small distributions serves as a valuable regression testsuite. However, a current issue with both of these distributions is that they are not separately testable: The doctests for these modules depend on a lot of other functionality from higher-level parts of the Sage library.

2.10 Packaging Third-Party Code

2.10.1 Packaging Third-Party Code

One of the mottoes of the Sage project is to not reinvent the wheel: If an algorithm is already implemented in a well-tested library then consider incorporating that library into Sage. The current list of available packages are the subdirectories of `SAGE_ROOT/build/pkgs/`. The installation of packages is done through a bash script located in `SAGE_ROOT/build/bin/sage-spkg`. This script is typically invoked by giving the command:

```
[user@localhost]$ sage -i <options> <package name>...
```

options can be:

- `-f`: install a package even if the same version is already installed
- `-s`: do not delete temporary build directory
- `-c`: after installing, run the test suite for the spkg. This should override the settings of `SAGE_CHECK` and `SAGE_CHECK_PACKAGES`.
- `-d`: only download the package

The section *Directory Structure* describes the structure of each individual package in `SAGE_ROOT/build/pkgs`. In section *Building the package* we see how you can install and test a new spkg that you or someone else wrote. Finally, *Inclusion Procedure for New and Updated Packages* explains how to submit a new package for inclusion in the Sage source code.

Package types

Not all packages are built by default, they are divided into standard, optional and experimental ones:

- **standard** packages are built by default. For a few packages, `configure` checks whether they are available from the system, in which case the build of those packages is skipped. Standard packages have stringent quality requirements: they should work on all supported platforms. In order for a new standard package to be accepted, it should have been optional for a while, see *Inclusion Procedure for New and Updated Packages*.
- **optional** packages are subject to the same requirements, they should also work on all supported platforms. If there are *optional doctests* in the Sage library, those tests must pass. Note that optional packages are not tested as much as standard packages, so in practice they might break more often than standard packages.
- for **experimental** packages, the bar is much lower: even if there are some problems, the package can still be accepted.

Package source types

Orthogonal to the division by package types, a package has exactly one of the following source types:

1. A **normal** package:
 - comes from the tarball named in the required file `checksums.ini` and hosted on the Sage mirrors;
 - its version number is defined by the required file `package-version.txt`;
 - Sage installs the package using build and install scripts (see *Build and install scripts of normal packages*);
 - Sage records the version number of the package installed using a file in `$SAGE_LOCAL/var/lib/sage/installed/` and will rerun the installation if `package-version.txt` changes.
2. A **wheel** package:
 - comes from the wheel file named in the required file `checksums.ini` and hosted on the Sage mirrors;
 - per policy, only platform-independent wheels are allowed, i.e., `*-none-any.whl` files;
 - its version number is defined by the required file `package-version.txt`;
 - Sage records the version number of the package installed using a file in `$SAGE_LOCAL/var/lib/sage/installed/` and will rerun the installation if `package-version.txt` changes.
3. A **pip** package:
 - is obtained directly from <https://pypi.org/>;

- the version to be installed is determined using the required file `requirements.txt` – in its simplest form, this file just contains the name of the package (more details at https://pip.pypa.io/en/stable/user_guide/#requirements-files);
- Sage installs the package using the `pip` package manager;
- Sage delegates the recording of installed package version numbers to it;
- by policy, no standard package is allowed to be a `pip` package.

4. A `script` package:

- is not associated with a tarball;
- the file `package-version.txt` is optional;
- installing the package runs the installation script `spkg-install` (see *Build and install scripts of normal packages*);
- Sage records the version number of the package installed using a file in `$SAGE_LOCAL/var/lib/sage/installed/` and will rerun the installation if `package-version.txt` changes.

5. A `dummy` package:

- is only used for recording the names of equivalent system packages;
- there is no `spkg-install` script, and attempts to install the package using Sage will give an error message.

To summarize: the package source type is determined as follows: if there is a file `requirements.txt`, it is a `pip` package. If not, then if there is a `checksums.ini` file, it is `normal` or `wheel`. Otherwise, if it has an `spkg-install` script, it is a `script` package, and if it does not, then it is a `dummy` package.

Directory Structure

Third-party packages in Sage consist of two parts:

1. The tarball as it is distributed by the third party, or as close as possible. Valid reasons for modifying the tarball are deleting unnecessary files to keep the download size manageable, regenerating auto-generated files or changing the directory structure if necessary. In certain cases, you may need to (additionally) change the filename of the tarball. In any case, the actual code must be unmodified: if you need to change the sources, add a *patch* instead. See also *Modified Tarballs* for automating the modifications to the upstream tarball.
2. The build scripts and associated files are in a subdirectory `SAGE_ROOT/build/pkgs/<package>`, where you replace `<package>` with a lower-case version of the upstream project name. If the project name contains characters which are not alphanumeric and are not an underscore, those characters should be removed or replaced by an underscore. For example, the project `FFLAS-FFPACK` is called `fflas_ffpack` in Sage.

As an example, let us consider a hypothetical FoO project. They (upstream) distribute a tarball `FoO-1.3.tar.gz` (that will be automatically placed in `SAGE_ROOT/upstream` during the installation process). To package it in Sage, we create a subdirectory containing as a minimum the following files:

```
SAGE_ROOT/build/pkgs/foo
|-- checksums.ini
|-- dependencies
|-- package-version.txt
|-- spkg-install.in
|-- SPKG.rst
`-- type
```

The following are some additional files which can be added:

```
SAGE_ROOT/build/pkgs/foo
|-- distros
|   |-- platform1.txt
|   `-- platform2.txt
|-- has_nonfree_dependencies
|-- huge
|-- patches
|   |-- bar.patch
|   `-- baz.patch
|-- spkg-check.in
|-- spkg-configure.m4
|-- spkg-src
`-- trees.txt
```

We discuss the individual files in the following sections.

Package type

The file type should contain a single word, which is either `standard`, `optional` or `experimental`. See [Package types](#) for the meaning of these types.

Build and install scripts of normal packages

The `spkg-build.in` and `spkg-install.in` files are templates for bash scripts `spkg-build` and `spkg-install`, which build and/or install the package.

The `*.in` script templates should *not* be prefixed with a shebang line (`#!...`) and should not have the executable bit set in their permissions. These are added automatically when generating the scripts, along with some additional boilerplate, when the package is installed.

The `spkg-build.in` and `spkg-install.in` files in the Sage source tree need only focus on the specific steps for building and installing that package. If no `spkg-build.in` exists, then the `spkg-install.in` is responsible for both steps, though separating them is encouraged where possible.

It is also possible to include similar script templates named `spkg-preinst.in` or `spkg-postinst.in` to run additional steps before or after the package has been installed into `$SAGE_LOCAL`. It is encouraged to put steps which modify already installed files in a separate `spkg-postinst.in` script template rather than combining them with `spkg-install.in`. This is because since [trac ticket #24106](#), `spkg-install` does not necessarily install packages directly to `$SAGE_LOCAL`. However, by the time `spkg-postinst` is run, the installation to `$SAGE_LOCAL` is complete.

In the best case, the upstream project can simply be installed by the usual `configure / make / make install` steps. In that case, the `spkg-build.in` script template would simply consist of:

```
cd src
sdh_configure
sdh_make
```

See [Helper functions](#) for more on the helper functions `sdh_configure`, `sdh_make`, etc.

The `spkg-install.in` script template would consist of:

```
cd src
sdh_make_install
```

Note that the top-level directory inside the tarball is renamed to `src` before calling the `spkg-build` and `spkg-install` scripts, so you can just use `cd src` instead of `cd foo-1.3`.

If there is any meaningful documentation included but not installed by `sdh_make_install` (which calls `make install`), then you can add something like the following to install it:

```
if [ "$SAGE_SPKG_INSTALL_DOCS" = yes ] ; then
    sdh_make doc
    sdh_install doc/ "$SAGE_SHARE"/doc/PACKAGE_NAME
fi
```

At build time `CFLAGS`, `CXXFLAGS`, `FCFLAGS`, and `F77FLAGS` are usually set to `-g -O2 -march=native` (according to debugging options and whether building fat binaries).

Slightly modified versions are available:

```
# No ``-march=native``.
export CFLAGS=$CFLAGS_NON_NATIVE

# ``-O3`` instead of ``-O2``.
export CFLAGS=$CFLAGS_O3

# Use flags as set by the user, possibly empty.
export CFLAGS=$ORIGINAL_CFLAGS
```

Likewise for `CXXFLAGS`, `FCFLAGS`, and `F77FLAGS`.

Note:

Prior to Sage 9.1, the script templates were called `spkg-build`, `spkg-install`, etc., without the extension `.in`.

Prior to Sage 8.1 the shebang line was included, and the scripts were marked executable. However, this is no longer the case as of [trac ticket #23179](#). Now the scripts in the source tree are deliberately written not to be directly executed, and are only made into executable scripts when they are copied to the package's build directory.

Build/install scripts may still be written in Python, but the Python code should go in a separate file (e.g. `spkg-install.py`), and can then be executed from the real `spkg-install.in` like:

```
exec sage-bootstrap-python spkg-install.py
```

or

```
exec python3 spkg-install.py
```

In more detail: `sage-bootstrap-python` runs a version of Python pre-installed on the machine, which is a build prerequisite of Sage. Note that `sage-bootstrap-python` accepts a wide range of Python versions, Python ≥ 2.6 and ≥ 3.4 , see `SAGE_ROOT/build/tox.ini` for details. You should only use `sage-bootstrap-python` for installation tasks that must be able to run before Sage has made `python3` available. It must not be used for running `pip` or `setup.py` for any package.

`python3` runs the version of Python managed by Sage (either its own installation of Python 3 from an SPKG or a `venv` over a system `python3`). You should use this if you are installing a Python package to make sure that the libraries are installed in the right place.

By the way, there is also a script `sage-python`. This should be used at runtime, for example in scripts in `SAGE_LOCAL/bin` which expect Sage's Python to already be built.

Many packages currently do not separate the build and install steps and only provide a `spkg-install.in` file that does both. The separation is useful in particular for root-owned install hierarchies, where something like `sudo` must be used to install files. For this purpose Sage uses an environment variable `$SAGE_SUDO`, the value of which may be provided by the developer at build time, which should to the appropriate system-specific `sudo`-like command (if any). The following rules are then observed:

- If `spkg-build.in` exists, the generated script `spkg-build` is first called, followed by `$SAGE_SUDO spkg-install`.
- Otherwise, only `spkg-install` is called (without `$SAGE_SUDO`). Such packages should prefix all commands in `spkg-install.in` that write into the installation hierarchy with `$SAGE_SUDO`.

Install scripts of script packages

A script package has a single install script named `spkg-install`. It needs to be an executable shell script; it is not subject to the templating described in the previous section.

Sage runs `spkg-install` from the directory `$SAGE_ROOT/build/pkgs/<package>` in the environment obtained by sourcing the files `src/bin/sage-env`, `build/bin/sage-build-env-config`, and `build/bin/sage-build-env`.

Helper functions

In the `spkg-build`, `spkg-install`, and `spkg-check` scripts, the following functions are available. They are defined in the file `$SAGE_ROOT/build/bin/sage-dist-helpers`, if you want to look at the source code. They should be used to make sure that appropriate variables are set and to avoid code duplication. These function names begin with `sdh_`, which stands for “Sage-distribution helper”.

- `sdh_die MESSAGE`: Exit the build script with the error code of the last command if it was non-zero, or with 1 otherwise, and print an error message. This is typically used like:

```
command || sdh_die "Command failed"
```

This function can also (if not given any arguments) read the error message from `stdin`. In particular this is useful in conjunction with a heredoc to write multi-line error messages:

```
command || sdh_die << _EOF_
Command failed.
Reason given.
_EOF_
```

Note: The other helper functions call `sdh_die`, so do not use (for example) `sdh_make || sdh_die`: the part of this after `||` will never be reached.

- `sdh_check_vars [VARIABLE ...]`: Check that one or more variables are defined and non-empty, and exit with an error if any are undefined or empty. Variable names should be given without the ‘\$’ to prevent unwanted expansion.
- `sdh_configure [...]`: Runs `./configure` with arguments `--prefix="$SAGE_LOCAL"`, `--libdir="$SAGE_LOCAL/lib"`, `--disable-static`, `--disable-maintainer-mode`, and `--disable-dependency-tracking`. Additional arguments to `./configure` may be given as arguments.

- **sdh_make [...]:** Runs **\$MAKE** with the default target. Additional arguments to **\$MAKE** may be given as arguments.
- **sdh_make_install [...]:** Runs **\$MAKE install** with **DESTDIR** correctly set to a temporary install directory, for staged installations. Additional arguments to **\$MAKE** may be given as arguments. If **\$SAGE_DESTDIR** is not set then the command is run with **\$SAGE_SUDO**, if set.
- **sdh_setup_bdist_wheel [...]:** Runs **setup.py bdist_wheel** with the given arguments, as well as additional default arguments used for installing packages into Sage.
- **sdh_pip_install [...]:** The equivalent of running **pip install** with the given arguments, as well as additional default arguments used for installing packages into Sage with pip. The last argument must be **.** to indicate installation from the current directory.

sdh_pip_install actually does the installation via **pip wheel**, creating a wheel file in **dist/**, followed by **sdh_store_and_pip_install_wheel** (see below).
- **sdh_pip_editable_install [...]:** The equivalent of running **pip install -e** with the given arguments, as well as additional default arguments used for installing packages into Sage with pip. The last argument must be **.** to indicate installation from the current directory. See [pip documentation](#) for more details concerning editable installs.
- **sdh_pip_uninstall [...]:** Runs **pip uninstall** with the given arguments. If unsuccessful, it displays a warning.
- **sdh_store_and_pip_install_wheel .:** The current directory, indicated by the required argument **.**, must have a subdirectory **dist** containing a unique wheel file (***.whl**).

This command (1) moves this wheel file to the directory **\$SAGE_SPKG_WHEELS** (**\$SAGE_LOCAL/var/lib/sage/wheels**) and then (2) installs the wheel in **\$SAGE_LOCAL**.

Both of these steps, instead of writing directly into **\$SAGE_LOCAL**, use the staging directory **\$SAGE_DESTDIR** if set; otherwise, they use **\$SAGE_SUDO** (if set).
- **sdh_install [-T] SRC [SRC...] DEST:** Copies one or more files or directories given as **SRC** (recursively in the case of directories) into the destination directory **DEST**, while ensuring that **DEST** and all its parent directories exist. **DEST** should be a path under **\$SAGE_LOCAL**, generally. For **DESTDIR** installs, the **\$SAGE_DESTDIR** path is automatically prepended to the destination.

The **-T** option treats **DEST** as a normal file instead (e.g. for copying a file to a different filename). All directory components are still created in this case.

The following is automatically added to each install script, so you should not need to add it yourself.

- **sdh_guard:** Wrapper for **sdh_check_vars** that checks some common variables without which many/most packages won't build correctly (**SAGE_ROOT**, **SAGE_LOCAL**, **SAGE_SHARE**). This is important to prevent installation to unintended locations.

The following are also available, but rarely used.

- **sdh_cmake [...]:** Runs **cmake** in the current directory with the given arguments, as well as additional arguments passed to **cmake** (assuming packages are using the **GNUInstallDirs** module) so that **CMAKE_INSTALL_PREFIX** and **CMAKE_INSTALL_LIBDIR** are set correctly.
- **sdh_preload_lib EXECUTABLE SONAME:** (Linux only – no-op on other platforms.) Check shared libraries loaded by **EXECUTABLE** (may be a program or another library) for a library starting with **SONAME**, and if found appends **SONAME** to the **LD_PRELOAD** environment variable. See [trac ticket #24885](#).

Allowing for the use of system packages

For a number of Sage packages, an already installed system version can be used instead, and Sage's top-level `./configure` script determines when this is possible. To enable this, a package needs to have a script called `spkg-configure.m4`, which can, for example, determine whether the installed software is recent enough (and sometimes not too recent) to be usable by Sage. This script is processed by the [GNU M4 macro processor](#).

Also, if the software for a Sage package is provided by a system package, the `./configure` script can provide that information. To do this, there must be a directory `build/pkgs/PACKAGE/distros` containing files with names like

```
arch.txt
conda.txt
cygwin.txt
debian.txt
homebrew.txt
...
```

corresponding to different packaging systems.

For example, if `./configure` detects that the Homebrew packaging system is in use, and if the current package can be provided by a Homebrew package called “foo”, then the file `build/pkgs/PACKAGE/distros/homebrew.txt` should contain the single line “foo”. If foo is currently uninstalled, then `./configure` will print a message suggesting that the user should run `brew install foo`. See *Using Sage's database of equivalent distribution packages* for more on this.

Important: All new standard packages should, when possible, include a `spkg-configure.m4` script and a populated `distros` directory. There are many examples in `build/pkgs`, including `build/pkgs/python3` and `build/pkgs/suitesparse`, to name a few.

Note that this may not be possible (as of this writing) for some packages, for example packages installed via `pip` for use while running Sage, like `matplotlib` or `scipy`. If a package is installed via `pip` for use in a separate process, like `tox`, then this should be possible.

Self-Tests

The `spkg-check.in` file is an optional, but highly recommended, script template to run self-tests of the package. The format for the `spkg-check` is the same as `spkg-build` and `spkg-install`. It is run after building and installing if the `SAGE_CHECK` environment variable is set, see the Sage installation guide. Ideally, upstream has some sort of tests suite that can be run with the standard `make check` target. In that case, the `spkg-check.in` script template would simply contain:

```
cd src
$MAKE check
```

Python-based packages

Python-based packages should declare `$(PYTHON)` as a dependency, and most Python-based packages will also have `$(PYTHON_TOOLCHAIN)` as an order-only dependency, which will ensure that fundamental packages such as `pip` and `setuptools` are available at the time of building the package.

The best way to install a Python-based package is to use `pip`, in which case the `spkg-install.in` script template might just consist of

```
cd src && sdh_pip_install .
```

Where `sdh_pip_install` is a function provided by `sage-dist-helpers` that points to the correct `pip` for the Python used by Sage, and includes some default flags needed for correct installation into Sage.

If `pip` will not work for a package but a command like `python3 setup.py install` will, you may use `sdh_setup_bdist_wheel`, followed by `sdh_store_and_pip_install_wheel ..`

For `spkg-check.in` script templates, use `python3` rather than just `python`. The paths are set by the Sage build system so that this runs the correct version of Python. For example, the `scipy` `spkg-check.in` file contains the line

```
exec python3 spkg-check.py
```

All normal Python packages and all wheel packages must have a file `install-requires.txt`. If a Python package is available on PyPI, this file must contain the name of the package as it is known to PyPI. Optionally, `install-requires.txt` can encode version constraints (such as lower and upper bounds). The constraints are in the format of the `install_requires` key of `setup.cfg` or `setup.py`.

It is strongly recommended to include comments (starting with `#`) in the file that explain why a particular lower or upper bound is warranted or why we wish to include or reject certain versions.

For example:

```
$ cat build/pkgs/sphinx/package-version.txt
3.1.2.p0
$ cat build/pkgs/sphinx/install-requires.txt
# gentoo uses 3.2.1
sphinx >=3, <3.3
```

The comments may include links to Trac tickets, as in the following example:

```
$ cat build/pkgs/packaging/install-requires.txt
packaging >=18.0
# Trac #30975: packaging 20.5 is known to work but we have to silence
↳ "DeprecationWarning: Creating a LegacyVersion"
```

The currently encoded version constraints are merely a starting point. Developers and downstream packagers are invited to refine the version constraints based on their experience and tests. When a package update is made in order to pick up a critical bug fix from a newer version, then the lower bound should be adjusted. Setting upper bounds to guard against incompatible future changes is a complex topic; see [trac ticket #33520](#).

The SPKG.rst File

The SPKG.rst file should follow this pattern:

```
PACKAGE_NAME: One line description

Description
-----

What does the package do?

License
-----

What is the license? If non-standard, is it GPLv3+ compatible?

Upstream Contact
-----

Provide information for upstream contact.  Usually just an URL.

Dependencies
-----

Only put special dependencies here that are not captured by the
``dependencies`` file. Otherwise omit this section.

Special Update/Build Instructions
-----

If the tarball was modified by hand and not via an ``spkg-src``
script, describe what was changed. Otherwise omit this section.
```

with PACKAGE_NAME replaced by the SPKG name (= the directory name in build/pkgs).

Legacy SPKG.txt files have an additional changelog section, but this information is now kept in the git repository.

Package dependencies

Many packages depend on other packages. Consider for example the eclib package for elliptic curves. This package uses the libraries PARI, NTL and FLINT. So the following is the dependencies file for eclib:

```
pari ntl flint

-----

All lines of this file are ignored except the first.
```

For Python packages, common dependencies include pip, setuptools, and future. If your package depends on any of these, use \$(PYTHON_TOOLCHAIN) instead. For example, here is the dependencies file for configparser:

```
$(PYTHON) | $(PYTHON_TOOLCHAIN)
```

(See below for the meaning of the |.)

If there are no dependencies, you can use

```
# no dependencies

-----
All lines of this file are ignored except the first.
```

There are actually two kinds of dependencies: there are normal dependencies and order-only dependencies, which are weaker. The syntax for the `dependencies` file is

```
normal dependencies | order-only dependencies
```

If there is no `|`, then all dependencies are normal.

- If package A has an **order-only dependency** on B, it simply means that B must be built before A can be built. The version of B does not matter, only the fact that B is installed matters. This should be used if the dependency is purely a build-time dependency (for example, a dependency on `pip` simply because the `spkg-install` file uses `pip`).

Alternatively, you can put the order-only dependencies in a separate file `dependencies_order_only`.

- If A has a **normal dependency** on B, it means additionally that A should be rebuilt every time that B gets updated. This is the most common kind of dependency. A normal dependency is what you need for libraries: if we upgrade NTL, we should rebuild everything which uses NTL.

Some packages are only needed for self-tests of a package (`spkg-check`). These dependencies should be declared in a separate file `dependencies_check`.

Some dependencies are optional in the sense that they are only a dependency if they are configured to be installed. These dependencies should be declared in a separate file `dependencies_optional`.

In order to check that the dependencies of your package are likely correct, the following command should work without errors:

```
[user@localhost]$ make distclean && make base && make PACKAGE_NAME
```

Finally, note that standard packages should only depend on standard packages and optional packages should only depend on standard or optional packages.

Package tags

You can mark a package as “huge” by placing an empty file named `huge` in the package directory. For example, the package `polytopes_db_4d` is a large database whose compressed tarball has a size of 9 GB.

For some other packages, we have placed an empty file named `has_nonfree_dependencies` in the package directory. This is to indicate that Sage with this package installed cannot be redistributed, and also that the package can only be installed after installing some other, non-free package.

We use these tags in our continuous integration scripts to filter out packages that we cannot or should not test automatically.

Where packages are installed

The Sage distribution has the notion of several installation trees.

- `$SAGE_VENV` is the default installation tree for all Python packages, i.e., normal packages with an `install-requires.txt`, wheel packages, and pip packages with a `requirements.txt`.
- `$SAGE_LOCAL` is the default installation tree for all non-Python packages.
- `$SAGE_DOCS` (only set at build time) is an installation tree for the HTML and PDF documentation.

By placing a file `trees.txt` in the package directory, the installation tree can be overridden. For example, `build/pkgs/python3/trees.txt` contains the word `SAGE_VENV`, and `build/pkgs/sagemath_doc_html/trees.txt` contains the word `SAGE_DOCS`.

Patching Sources

Actual changes to the source code must be via patches, which should be placed in the `patches/` directory, and must have the `.patch` extension. GNU patch is distributed with Sage, so you can rely on it being available. Patches must include documentation in their header (before the first diff hunk), and must have only one “prefix” level in the paths (that is, only one path level above the root of the upstream sources being patched). So a typical patch file should look like this:

```
Add autodoc_builtin_argspec config option

Following the title line you can add a multi-line description of
what the patch does, where you got it from if you did not write it
yourself, if they are platform specific, if they should be pushed
upstream, etc...

diff -dru Sphinx-1.2.2/sphinx/ext/autodoc.py.orig Sphinx-1.2.2/sphinx/ext/autodoc.py
--- Sphinx-1.2.2/sphinx/ext/autodoc.py.orig 2014-03-02 20:38:09.000000000 +1300
+++ Sphinx-1.2.2/sphinx/ext/autodoc.py 2014-10-19 23:02:09.000000000 +1300
@@ -1452,6 +1462,7 @@

    app.add_config_value('autoclass_content', 'class', True)
    app.add_config_value('autodoc_member_order', 'alphabetic', True)
+   app.add_config_value('autodoc_builtin_argspec', None, True)
    app.add_config_value('autodoc_default_flags', [], True)
    app.add_config_value('autodoc_docstring_signature', True, True)
    app.add_event('autodoc-process-docstring')
```

Patches directly under the `patches/` directly are applied automatically before running the `spkg-install` script (so long as they have the `.patch` extension). If you need to apply patches conditionally (such as only on a specific platform), you can place those patches in a subdirectory of `patches/` and apply them manually using the `sage-apply-patches` script. For example, considering the layout:

```
SAGE_ROOT/build/pkgs/foo
|-- patches
|   |-- solaris
|   |   |-- solaris.patch
|   |-- bar.patch
|   `-- baz.patch
```

The patches `bar.patch` and `baz.patch` are applied to the unpacked upstream sources in `src/` before running `spkg-install`. To conditionally apply the patch for Solaris the `spkg-install` should contain a section like this:

```
if [ $UNAME == "SunOS" ]; then
    sage-apply-patches -d solaris
fi
```

where the `-d` flag applies all patches in the `solaris/` subdirectory of the main `patches/` directory.

When to patch, when to repackage, when to autoconfiscate

- Use unpatched original upstream tarball when possible.

Sometimes it may seem as if you need to patch a (hand-written) Makefile because it “hard-codes” some paths or compiler flags:

```
--- a/Makefile
+++ b/Makefile
@@ -77,7 +77,7 @@
 # This is a Makefile.
 # Handwritten.

-DESTDIR = /usr/local
+DESTDIR = $(SAGE_ROOT)/local
BINDIR   = $(DESTDIR)/bin
INCDIR   = $(DESTDIR)/include
LIBDIR   = $(DESTDIR)/lib
```

Don't use patching for that. Makefile variables can be overridden from the command-line. Just use the following in `spkg-install`:

```
$(MAKE) DESTDIR="$SAGE_ROOT/local"
```

- Check if Debian or another distribution already provides patches for upstream. Use them, don't reinvent the wheel.
- If the upstream Makefile does not build shared libraries, don't bother trying to patch it. Autoconfiscate the package instead and use the standard facilities of Automake and Libtool. This ensures that the shared library build is portable between Linux and macOS.
- If you have to make changes to `configure.ac` or other source files of the autotools build system (or if you are autoconfiscating the package), then you can't use patching; make a *modified tarball* instead.
- If the patch would be huge, don't use patching. Make a *modified tarball* instead.
- Otherwise, *maintain a set of patches*.

How to maintain a set of patches

We recommend the following workflow for maintaining a set of patches.

- Fork the package and put it on a public git repository.
If upstream has a public version control repository, import it from there. If upstream does not have a public version control repository, import the current sources from the upstream tarball. Let's call the branch `upstream`.
- Create a branch for the changes necessary for Sage, let's call it `sage_package_VERSION`, where `version` is the upstream version number.
- Make the changes and commit them to the branch.
- Generate the patches against the `upstream` branch:

```
rm -Rf SAGE_ROOT/build/pkgs/PACKAGE/patches
mkdir SAGE_ROOT/build/pkgs/PACKAGE/patches
git format-patch -o SAGE_ROOT/build/pkgs/PACKAGE/patches/ upstream
```

- Optionally, create an `spkg-src` file in the Sage package's directory that regenerates the patch directory using the above commands.
- When a new upstream version becomes available, merge (or import) it into `upstream`, then create a new branch and rebase in on top of the updated upstream:

```
git checkout sage_package_OLDVERSION
git checkout -b sage_package_NEWVERSION
git rebase upstream
```

Then regenerate the patches.

Modified Tarballs

The `spkg-src` file is optional and only to document how the upstream tarball was changed. Ideally it is not modified, then there would be no `spkg-src` file present either.

However, if you really must modify the upstream tarball then it is recommended that you write a script, called `spkg-src`, that makes the changes. This not only serves as documentation but also makes it easier to apply the same modifications to future versions.

Package Versioning

The `package-version.txt` file contains just the version. So if upstream is `FoO-1.3.tar.gz` then the package version file would only contain `1.3`.

If the upstream package is taken from some revision other than a stable version or if upstream doesn't have a version number, you should use the date at which the revision is made. For example, the `database_stein_watkins` package with version `20110713` contains the database as of 2011-07-13. Note that the date should refer to the *contents* of the tarball, not to the day it was packaged for Sage. This particular Sage package for `database_stein_watkins` was created in 2014, but the data it contains was last updated in 2011.

If you apply any patches, or if you made changes to the upstream tarball (see [Directory Structure](#) for allowable changes), then you should append a `.p0` to the version to indicate that it's not a vanilla package.

Additionally, whenever you make changes to a package *without* changing the upstream tarball (for example, you add an additional patch or you fix something in the `spkg-install` file), you should also add or increase the patch level.

So the different versions would be 1.3, 1.3.p0, 1.3.p1, ... The change in version number or patch level will trigger re-installation of the package, such that the changes are taken into account.

Checksums and Tarball Names

The `checksums.ini` file contains the filename pattern of the upstream tarball (without the actual version) and its checksums. So if upstream is `$SAGE_ROOT/upstream/FoO-1.3.tar.gz`, create a new file `$SAGE_ROOT/build/pkgs/foo/checksums.ini` containing only:

```
tarball=Foo-VERSION.tar.gz
```

Sage internally replaces the `VERSION` substring with the content of `package-version.txt`. To recompute the checksums, run:

```
[user@localhost]$ sage --package fix-checksum foo
```

which will modify the `checksums.ini` file with the correct checksums.

Upstream URLs

In addition to these fields in `checksums.ini`, the optional field `upstream_url` holds an URL to the upstream package archive.

The Release Manager uses the information in `upstream_url` to download the upstream package archive and to make it available on the Sage mirrors when a new release is prepared. On Trac tickets upgrading a package, the ticket description should no longer contain the upstream URL to avoid duplication of information.

Note that, like the `tarball` field, the `upstream_url` is a template; the substring `VERSION` is substituted with the actual version.

For Python packages available from PyPI, you should use an `upstream_url` from `pypi.io`, which follows the format

```
upstream_url=https://pypi.io/packages/source/m/matplotlib/matplotlib-VERSION.tar.gz
```

A package that has the `upstream_url` information can be updated by simply typing:

```
[user@localhost]$ sage --package update numpy 3.14.59
```

which will automatically download the archive and update the information in `build/pkgs/`.

For Python packages available from PyPI, there is another shortcut:

```
[user@localhost]$ sage --package update-latest matplotlib
Updating matplotlib: 3.3.0 -> 3.3.1
Downloading tarball to ../matplotlib-3.3.1.tar.bz2
[.....]
```

The `upstream_url` information serves yet another purpose. Developers who wish to test a package update from a Trac branch before the archive is available on a Sage mirror can do so by configuring their Sage tree using `./configure --enable-download-from-upstream-url`. Then Sage will fall back to downloading package tarballs from the `upstream_url` after trying all Sage mirrors. (To speed up this process, trim `upstream/mirror_list` to fewer mirrors.) It is then no longer necessary to manually download upstream tarballs.

Utility script to create packages

Assuming that you have downloaded `$SAGE_ROOT/upstream/Fo0-1.3.tar.gz`, you can use:

```
[user@localhost]$ sage --package create foo --version 1.3 --tarball Fo0-VERSION.tar.gz --  
→type experimental
```

to create `$SAGE_ROOT/build/pkgs/foo/package-version.txt`, `checksums.ini`, and `type` in one step.

You can skip the manual downloading of the upstream tarball by using the additional argument `--upstream-url`. This command will also set the `upstream_url` field in `checksums.ini` described above.

For Python packages available from PyPI, you can use:

```
[user@localhost]$ sage -package create scikit_spatial --pypi --type optional
```

This automatically downloads the most recent version from PyPI and also obtains most of the necessary information by querying PyPI. The dependencies file may need editing (watch out for warnings regarding `--no-deps` that Sage issues during installation of the package!). Also you may want to set lower and upper bounds for acceptable package versions in the file `install-requires.txt`.

To create a pip package rather than a normal package, you can use:

```
[user@localhost]$ sage -package create scikit_spatial --pypi --source pip --type optional
```

Building the package

At this stage you have a new tarball that is not yet distributed with Sage (`Fo0-1.3.tar.gz` in the example of section *Directory Structure*). Now you need to manually place it in the `SAGE_ROOT/upstream/` directory and run `sage --fix-pkg-checksums` if you have not done that yet.

Now you can install the package using:

```
[user@localhost]$ sage -i package_name
```

or:

```
[user@localhost]$ sage -f package_name
```

to force a reinstallation. If your package contains a `spkg-check` script (see *Self-Tests*) it can be run with:

```
[user@localhost]$ sage -i -c package_name
```

or:

```
[user@localhost]$ sage -f -c package_name
```

If all went fine, open a ticket, put a link to the original tarball in the ticket and upload a branch with the code under `SAGE_ROOT/build/pkgs`.

Inclusion Procedure for New and Updated Packages

Packages that are not part of Sage will first become optional or experimental (the latter if they will not build on all supported systems). After they have been in optional for some time without problems they can be proposed to be included as standard packages in Sage.

To propose a package for optional/experimental inclusion please open a trac ticket with the respective `Component:` field set to either `packages:experimental` or `packages:optional`. The associated code requirements are described in the following sections.

After the ticket was reviewed and included, optional packages stay in that status for at least a year, after which they can be proposed to be included as standard packages in Sage. For this a trac ticket is opened with the `Component:` field set to `packages:standard`. Then make a proposal in the Google Group `sage-devel`.

Upgrading packages to new upstream versions or with additional patches includes opening a ticket in the respective category too, as described above.

License Information

If you are patching a standard Sage spkg, then you should make sure that the license information for that package is up-to-date, both in its `SPKG.rst` or `SPKG.txt` file and in the file `SAGE_ROOT/COPYING.txt`. For example, if you are producing an spkg which upgrades the vanilla source to a new version, check whether the license changed between versions.

If an upstream tarball of a package cannot be redistributed for license reasons, rename it to include the string `do-not-distribute`. This will keep the release management scripts from uploading it to the Sage mirrors. For an example, see the `scipoptsuite` package, which has an “academic” proprietary license.

Sometimes an upstream tarball contains some distributable parts using a free software license and some non-free parts. In this case, it can be a good solution to make a custom tarball consisting of only the free parts; see [Modified Tarballs](#) and the `giac` package as an example.

Prerequisites for New Standard Packages

For a package to become part of Sage's standard distribution, it must meet the following requirements:

- **License.** For standard packages, the license must be compatible with the GNU General Public License, version 3. The Free Software Foundation maintains a long list of [licenses and comments about them](#).
- **Build Support.** The code must build on all the fully supported platforms (Linux, macOS, Cygwin); see [Testing on multiple platforms](#). It must be installed either from source as a normal package, or as a Python (platform-independent) wheel package, see [Package source types](#).
- **Quality.** The code should be “better” than any other available code (that passes the two above criteria), and the authors need to justify this. The comparison should be made to both Python and other software. Criteria in passing the quality test include:
 - Speed
 - Documentation
 - Usability
 - Absence of memory leaks
 - Maintainable
 - Portability

- Reasonable build time, size, dependencies
- **Previously an optional package.** A new standard package must have spent some time as an optional package. Or have a good reason why this is not possible.
- **Refereeing.** The code must be refereed, as discussed in *The Sage Trac Server*.

INDICES AND TABLES

- `genindex`
- `search`

This work is licensed under a [Creative Commons Attribution-Share Alike 3.0 License](#).

BIBLIOGRAPHY

[WSblog] William Stein, How to Referee Sage Trac Tickets, <http://sagemath.blogspot.com/2010/10/how-to-referee-sage-trac-tickets.html> (Caveat: mercurial was replaced with git)

[SageComponents] See <http://www.sagemath.org/links-components.html> for a list

INDEX

C

CFLAGS, 155

CXXFLAGS, 155

E

environment variable

CFLAGS, 155

CXXFLAGS, 155

F77FLAGS, 155

FCFLAGS, 155

MAKE, 75

SAGE_LOCAL, 109, 110

SAGE_ROOT, 5, 109

SAGE_VENV, 110

F

F77FLAGS, 155

FCFLAGS, 155

M

MAKE, 75

P

Python Enhancement Proposals

PEP 0008, 46

PEP 0257, 46

S

SAGE_LOCAL, 109, 110

SAGE_ROOT, 5, 109

SAGE_VENV, 110