Introduction to GitLab CI/CD pipelines: a complete guide to get you started

2021-12-12 by Marius

This article provides a detailed introduction to the general concepts of GitLab CI/CD pipelines. It discusses the anatomy of the pipeline definition file, how GitLab distributes and runs jobs on runners, and what good practices you can follow. I also explain how the containerization of CI jobs affects their ability to build Docker/OCI images.

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Introduction

As I explained in my previous CI/CD Basics article, CI/CD is the process of fully automating tasks such as building, testing and deploying your software. Instead of running these tasks manually, on a developer laptop, you have them executed on a server all the time.

In this article I provide an introduction to how CI/CD specifically works in *GitLab*. I created this guide because the official GitLab CI/CD manual is huge. The relevant content is scattered on various pages, giving you a hard time when you are completely new to the topic.

Required prerequisite: YAML

In GitLab, you define the pipeline in a YAML file called “.gitlab-ci.yml“. Before you read any of the sections below, you **must** acquire a *solid* basic knowledge of the YAML file format. Otherwise, you will pull your hair over “weird errors”, or worse, there are no errors but the pipeline does not behave the way you want it to.

If any of the following things sound unfamiliar to you, you should definitely brush up your knowledge first, e.g. with an introductory guide such as this one:

- Whitespace / indentation matters and often produces no parser errors (but instead changes the meaning)
- There are several alternative ways of expressing arrays

- There are different approaches to express *multi-line* values
- You know when to quote values, and why quotes are necessary for something like ENV_VAR: "true"

While you are still learning (and assuming that you understand JSON syntax well), it can be helpful to test your knowledge, by converting test files between JSON and YAML, e.g. using [this online converter].

High-level overview

In GitLab, you define your CI/CD pipeline in a YAML file named **.gitlab-ci.yml**, which is located on the *root* level of your project. In this file you declare one or more **jobs**. Each job defines a **script** (=one or more shell commands) to be executed. They could do any kind of task, e.g. running a unit test, compiling your software, etc.

A job is always assigned to a **stage**. You can define which stages you want your pipeline to have, by creating a “stages” key in .gitlab-ci.yml and specifying an array of arbitrarily named strings, e.g. **stages: [lint, build, test, docs, deploy]**. If you don’t specify these stages, GitLab has a few default stages configured (see docs).

The basic idea of stages is to introduce a virtual “barrier”, so that first *all* jobs of a specific stage have to complete successfully, before jobs of the next stage start. All jobs in a particular stage are started *in parallel*, unless you have added artificial constraints (e.g. “needs“, see docs). If *any* job in a stage fails, the next stage (usually) is not executed, and the pipeline ends early.

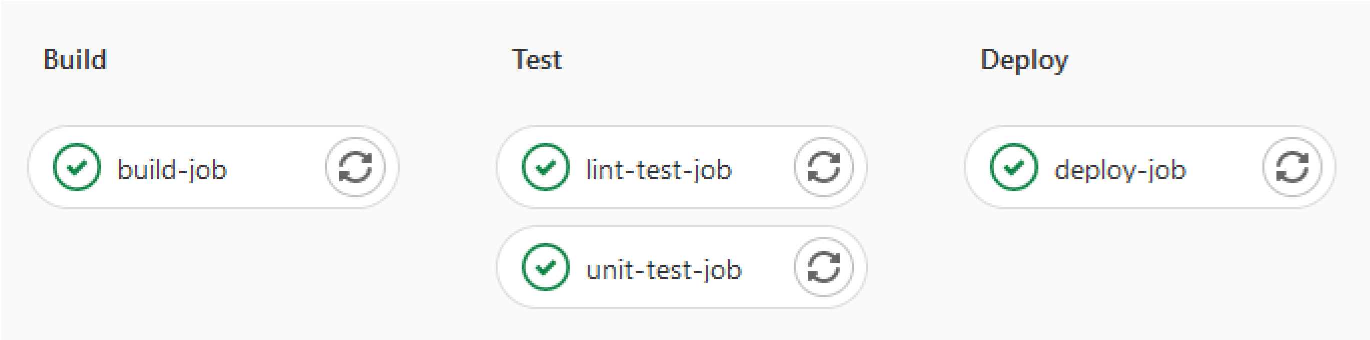
The following is a simple example pipeline:

```
image: alpine:latest  # define the Docker image used for all jobs

stages:
  - build
  - test
  - deploy

build-job:       # This job runs in the build stage, which runs first.
  stage: build
  script:
    - echo "Here you would place calls like 'make' to verify that the
software can be compiled."
```

```
    - echo "The output (binary files) can be shared with the below jobs
(omitted in this example)"

unit-test-job:   # This job runs in the test stage.
  stage: test    # It only starts when the job in the build stage completes
successfully.
  script:
    - echo "Here you place commands that run your unit tests, e.g.
'pytest <path to dir>'."
    - sleep 60

lint-test-job:   # This job also runs in the test stage.
  stage: test    # It can run at the same time as unit-test-job (in
parallel).
```

```yaml
  script:
    - echo "Here you would place commands that lint your code."
    - sleep 10
    - echo "No lint issues found."

deploy-job:      # This job runs in the deploy stage.
  stage: deploy  # It only runs when *both* jobs in the test stage
complete successfully.
  script:
    - echo "Here you would place commands that deploy your
application, e.g. via SSHing to a server."
    - echo "Application successfully deployed."
```
Code language: YAML (yaml)

Visually, illustrating the 3 stages:



How jobs are run

Distributed architecture to run jobs

GitLab uses a distributed architecture that consists of a GitLab **server** (that also renders the web interface) and several (shared) **runners**. The server could be the SaaS offering (gitlab.com), or your company’s self-hosted instance. *A runner* is essentially just a CLI tool (running on some dedicated machine) that registers with the server, and keeps a permanently-opened HTTP connection to the server, waiting for jobs that it should execute. If you use gitlab.com, there are already shared runner instances that you can use, see these docs. For self-hosted GitLab servers, your IT department usually sets up shared runners for you, and documents how to use them.

The GitLab *server* is in charge of detecting **trigger events** that start one or more pipelines (see next subsection). Whenever a new pipeline starts, the GitLab server figures out which of the jobs (defined in your .gitlab-ci.yml file) actually need to run (some might be skipped, some might have to wait for other jobs), and distributes these jobs to available runners in the right order.

Pipeline trigger events

There are many possible *trigger events* that start a pipeline. Most notably:

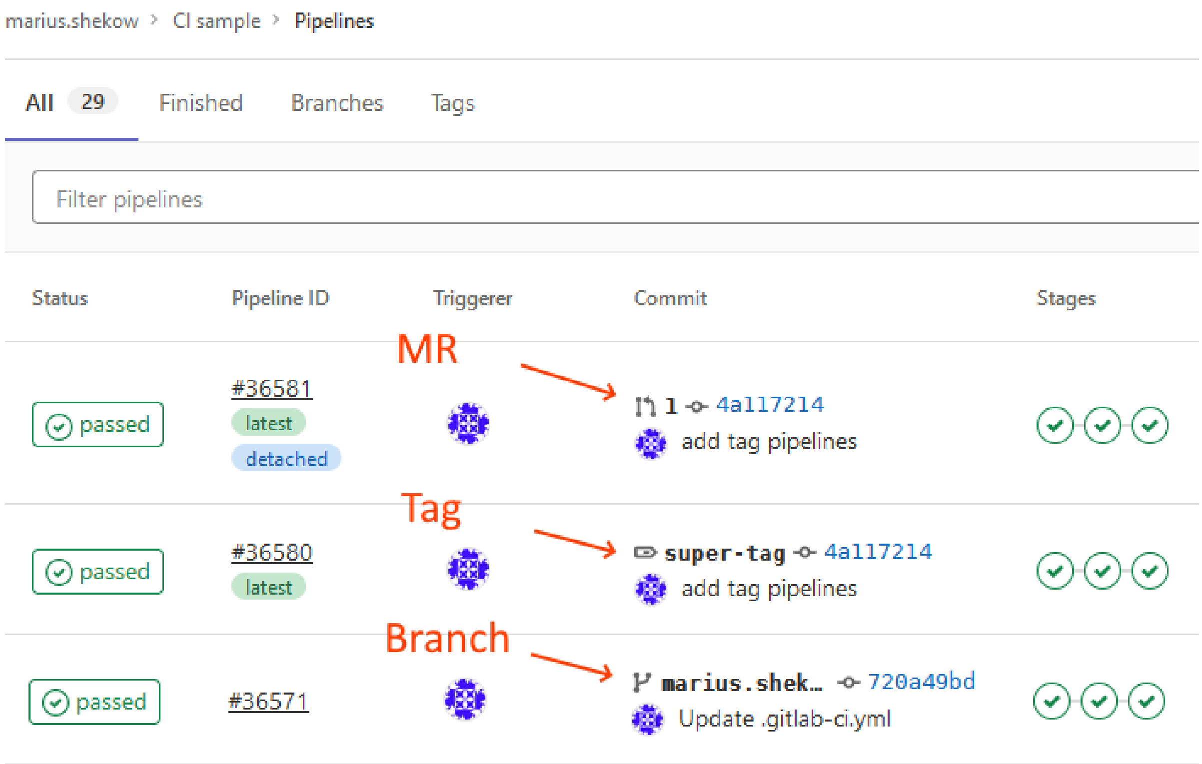
- A developer executed “git push” on their machine, or edits and commits files in the GitLab web IDE
- A regular *schedule* was triggered (defined in GitLab, see menu “CI/CD → Schedules”)
- Someone clicked on the “Retry” button for a *failed* pipeline (see menu “CI/CD → Pipelines”)
- Someone created a pipeline manually, by clicking on “CI/CD → Pipelines” and then on the “Run pipeline” button
- A pipeline was triggered via the GitLab API or web hooks

It is important to be aware which pipeline(s) are created as a consequence of a *push*. A push might cause these pipelines (started and running in parallel):

- A *branch* pipeline, run only for the *newest* commit of a *push* (in case your push contained *multiple* commits).
- An additional *tag* pipeline for all pushed Git tags
    - Note: you need to explicitly push tags with your local Git client, it does *not* happen automatically on “git push“!
- An additional *Merge Request* pipeline in case the commit was for a branch that is associated to an open MR

See docs to learn how you can avoid that a push triggers both a branch and a MR pipeline.

In the GitLab web UI (clicking on “CI/CD → Pipelines”), you can visually identify the pipeline type as follows:



marius.shekow > CI sample > Pipelines
All 29
Finished
Branches
Tags
Filter pipelines
Status
Pipeline ID
Triggerer
Commit
Stages
MR
passed
#36581
latest
detached
1 4a117214
add tag pipelines
Tag
passed
#36580
latest
super-tag 4a117214
add tag pipelines
Branch
passed
#36571
marius.shek… 720a49bd
Update .gitlab-ci.yml

A pipeline is always associated to a specific *commit* (shown in blue in the above image), which is immutable. Consequently, re-running an older, failed *branch pipeline* will run it against that (possibly now-outdated) commit.

A pipeline also always has a “triggerer” (see the *Triggerer* column in the above image), which is a user who owns that pipeline. The triggerer is relevant in case you want to do other things in a job that require permissions, such as cloning another GitLab project located on the same GitLab server. See these docs for more details.

While a pipeline is running, you can inspect the current progress and see a live log view from the runner for each job, by clicking on “CI/CD → Pipelines” in the GitLab web UI.

Runners: (isolated) execution environment

Whenever the GitLab *server* sends a job to a *runner*, the runner will execute this job in some kind of isolated execution environment. This execution environment is determined by an "**executor**", and a runner can be configured with one or more executors. There are many different kinds of executors (see docs), e.g. a "shell executor", "Docker executor" or "Kubernetes executor". The Docker and Kubernetes executors provide a very high isolation level, because they will start each job in a separate Docker *container* (or as container in a Kubernetes *Pod*), using the image that was specified in the .gitlab-ci.yml file for your job (e.g. alpine:latest in the above example). The *shell executor* has a much lower level of isolation, because it runs the commands (from the script section of your jobs) in a shell right on the *host* on which the GitLab runner is running.

It is important to understand that shared runners are set up by admins who choose which executor(s) these runners will use – if you are just a developer, you cannot influence this. However, as explained below (section *Control who runs the job*), you can specify tags, to select which one of the available executors shall be used. If you use gitlab.com, the official docs explain how the shared runners are configured. See e.g. here for *Linux* runners, which uses a Docker-based executor, and thus your jobs will run as Docker containers!

Runners: execution sequence when receiving a job

Whenever a runner receives a job from the GitLab server, it performs these steps:

- Start a new execution environment (e.g. a Docker container, or a shell, or a VM for the [Virtual box executor]), in which it sets pre-defined environment variables (such as $CI_REGISTRY, see [docs] for more) that it received from the GitLab server.
- Clone the Git repo into a new, temporary directory (e.g. "/builds/<runner-ID>/<GitLab-group>/<project-name>/" when running inside a *container*). The runner clones the commit associated to the pipeline instance.
    - If you use git *sub-modules*, and configured the paths correctly, sub-modules are also automatically cloned. See [docs] for more details.
- Download artifacts of previously finished jobs
- Restore caches defined for the job
- Run the before_script, script and after_script sections.

- Upload the logs and job artifacts to the GitLab server.

Anatomy of the .gitlab-ci.yml file

The following subsections explain the most important keywords and structures you would put into the YAML file. You should always have a bookmark of the Keyword reference ready, which explains *all* keywords.

Bird's eye perspective: what is placed on the *root* level

On the *root* level of the .gitlab-ci.yml file, you declare 3 kinds of objects:

- Jobs,
- Hidden jobs,

- Other *global* concepts, such as default, image, services, cache, before_script, after_script, variables, stages, include or workflow.

The example above declared 4 jobs (build-job, unit-test-job, lint-test-job, deploy-job), and the global concepts **image** and **stages**.

Jobs can have arbitrary names (even multiple words separated by spaces), but the job's name must be different to any of the reserved keywords mentioned above. That is, a job may be named "set variables" but not "variables".

Control *what* the job does: via script

Each job needs to do something, which you control via the keywords **script**, **before_script** and **after_script**. Essentially, any of these sections are an array of shell commands. The concrete shell that is used (sh, bash, PowerShell, …) depends on the *execution environment* (see above). If the job is executed by a *Windows* runner, it would be PowerShell, if it is run by a Docker or Kubernetes executor, it depends on what shell is the default shell in the **image** you are using (usually bash or sh).

Make sure to read up on the **script**, **before_script** and **after_script** keywords in the Keyword reference, and also this section of the manual. You will learn how to break long single-line commands into multiple lines, and you will learn about horrible caveats that arise due to the YAML interpretation process. For long and complex scripts, consider extracting them into a separate shell script (with .sh extension) instead of putting them directly into the .gitlab-ci.yml file.

Note: the commands run during **script**, **before_script** and **after_script** will *abort* on the first command that returns an error (and the job will fail). The reason is that the runner will first run “set -eo pipefail” for you, before starting any of your scripts.

Control *who* runs the job: via tags

Whenever an admin sets up a shared runner and its executors, they assign one or more **tags** to the executors. Tags are simple strings, usually using kebab-case naming. To find out which executors are available for your project, open the GitLab UI, click on “Settings ->

CI/CD" and expand the "Runners" section. The tags are highlighted in blue.

You can control to which runner/executor each job is sent, by setting the tags keyword to an array of tag-strings (docs) in the .gitlab-ci.yml file. You can set a different tag for each job, if you want to. If you don't specify any tags, the GitLab server will send the job to *any* available runner, selected at *random*.

Control when jobs are run or skipped: via rules/only/except

You can control when jobs are actually sent to a (shared) runner, or whether they are simply skipped. For instance, you may want to run a job only for certain branches, or only if specific files have changed.

GitLab has two mechanisms for this:

1. only and except ([docs]): this is the older mechanism which is now deprecated, but is kept to avoid breaking changes. It is no longer recommended to use it.
2. rules ([docs]): this is the modern (and more powerful) mechanism. However, it is a bit more complex and has a steeper learning curve, but the official docs explain it sufficiently well. In summary:
   - rules specifies an array of rule-*objects*. Each rule object can have the following (optional) keys: if, changes, exists, allow_failure, variables, when.
   - You will usually specify an “if” keyword, but you can also omit it, which is equivalent to “if: true“

        - If you are using *regular expressions* in the if, you can use https://rubular.com/ to test them.
    - The GitLab server evaluates the rules one after another, considerung only the keys if, changes, exists. If you specified *several* of these, then *all* of them must evaluate to true. The first match counts, there is no “fall-through”. If there was no match, the job won’t be run.
    - In case a match was found, the when keyword controls whether the job should be run, see the docs here for an explanation of the when-values.

You cannot combine these two mechanisms only/except and rules, you must choose one.

Control the job's execution environment: via image

Assuming that your jobs are executed by a (shared) runner that uses the Docker or Kubernetes executor (see above), you can control which Docker image is used while executing the script section, by specifying the image keyword (docs). You can specify the image globally on the root level of the .gitlab-ci.yml file (which is inherited by all jobs), or overwrite it for each job separately.

If you don't specify any image at all, some default image is used, which was chosen by the admin who configured the executor for the shared GitLab runner. Since you don't know (or control) this image, it is highly recommended to always set the image.

Hidden jobs

When you prefix a job name with a dot (e.g. “.some-job-name“), then this job is a **hidden job** (docs). Hidden jobs have two purposes:

1. Temporarily disable a job, without having to comment out the entire job section in the .gitlab-ci.yml file
2. Use job inheritance (see below for details)

Variables

GitLab CI/CD variables (docs) are simply (Shell) environment variables. There are many predefined ones (defined by the GitLab server, sent to the runners along with other job meta-data), but you can also define your own ones.

Defining and using variables

Definition: you can define your own variables in the .gitlab-ci.yml file ([docs]) or on a project/group level using “CI/CD variables” in the GitLab web UI ([docs]). Variables you define globally are *inherited* by all jobs.

Usage: like with any Shell script, the usage of these variables in the script section depends on the shell:

- If you run a Windows-based GitLab runner (with PowerShell), variables are used like this: $env:MY_VARIABLE
- If you run a Linux-based runner: use variables by prepending the dollar sign, e.g. $MY_VARIABLE or ${MY_VARIABLE}. The second form (using curly braces) is only needed if the shell

would otherwise not be able to understand where your environment variable ends

  - Incorrect example: “echo $MY_VARIABLEisgreat” – the shell would try to expand the variable MY_VARIABLEisgreat
  - Correct example: “echo ${MY_VARIABLE}isgreat“

Note: since GitLab 14.4, variables can be *nested*, which can make your definition of variables (that depend on each other) cleaner and shorter. See docs for details.

Predefined variables

There are many predefined variables set by the GitLab server when running your job. See docs for details.

Because the docs don't always show concrete example values, it can be helpful to create your own minimal GitLab project, with a .gitlab-ci.yml file that has a job that prints the values of all defined variables, e.g. like this:

```yaml
print-variables-job:
  stage: build
  script:
    - set
```
Code language: YAML (yaml)

Creating and working with containers in CI/CD

There are several jobs in a CI/CD pipeline that need access to a container engine, such as Docker or containerd. Typical jobs include building, modifying, tagging and pushing (Docker) *images*, or temporarily starting *containers* for testing purposes.

Most commonly, GitLab already launches CI/CD jobs as *Linux containers*. By default, due to the high isolation levels of container engines, containers cannot simply build or start other containers. Consequently, you cannot simply run something like “docker build ...“, or “docker run ...” in the script section of a job, because that script is actually executed inside a container itself.

There are several technical workarounds for this:

- Use a tool such as kaniko, which lets you build, tag and push containers (but cannot *run* them). These tools require little to no privileges or container engines to work.

    - Unfortunately, kaniko has become unmaintained recently. It is riddled with bugs, and therefore risky to use. I might go into details of my kaniko experience in a future article.
    - For pure image-related *maintenance* tasks (e.g. re-tagging and pushing an already-existing image), you can use skopeo, which also does not require any privileges or container engines to work.
- Use **Docker-in-Docker** (official GitLab docs), which lets you do everything that the docker CLI can do (building *and running* images). For this to work, the GitLab executor/runner itself must be configured in privileged mode by the administrator. By adding a services declaration in the .gitlab-ci.yml file, you instruct GitLab to start a completely new, temporary Docker *daemon*(!), which Linux only allows because of the privileged

mode. That new daemon is then used for building Docker images and starting Docker containers.

- Use **Docker socket binding** (official GitLab docs), which gives you the same power as Docker-in-Docker, but technically works differently. *Socket binding* mode always uses the *host*'s Docker daemon. Containers you create from inside your job's container are *sibling* containers of the job container. See the last section of this article for further details about the differences between *Docker-in-Docker* and *Docker socket binding*.

Which workaround you need to use is decided by the administrators who configure the (shared) runners and their executors:

- If you use GitLab.com's SaaS shared Linux runners (whose configuration is documented here), you have to use the **Docker-**

in-Docker workaround. In your .gitlab-ci.yml file, you *must* declare a service: ["docker:dind"] section (see here for an example project, and here to learn what services are and how they work). This service declaration starts a completely new, temporary Docker *daemon*(!), which your CI job can reach via the virtual container network, under the “docker” hostname. Your CI job definition (in the .gitlab-ci.yml file) should use an image: docker:latest (or some fixed version, e.g. docker:*stable* or docker:*20.10*). Not only does this Docker image contain the Docker CLI, but its entrypoint.sh script automatically discovers the temporary “remote” Docker daemon, and sets the DOCKER_HOST environment variable, thereby configuring the Docker CLI to use that daemon. Here is an example of the entrypoint.sh script of the Docker image.

- If your organization / team uses a *self-hosted* GitLab version, you have to talk to your administrators and ask them which approach they use. In case they are using the **Docker socket binding** mode, you simply set the image to docker:latest for your CI job, and do <u>not</u> use the services declaration. The Docker image's entrypoint.sh script will automatically determine that the *host*'s daemon socket is available inside the CI job container, and configure the Docker CLI to use it.

Good practices

The following practices will help you improve working with GitLab CI/CD pipelines.

Use editors / IDEs with syntax support

While writing the .gitlab-ci.yml file, use a text editor or IDE that supports the CI YAML syntax. Editors such as IntelliJ-based IDEs (PyCharm, etc.), or VS Code (via plug-in) provide features such as syntax highlighting and auto-complete, and in some cases even *validation* (which checks for *semantical* correctness – not all editors do this, e.g. IntelliJ-based IDEs check only the *syntactical* correctness!). You can also (semantically) validate the file on the GitLab *server*, see docs. Doing so avoids that you accidentally push commits that break the pipeline definition, simply because the .gitlab-ci.yml file is invalid.

Use job inheritance (via “extends“) for a cleaner, shorter .gitlab-ci.yml file

Beginners often make the mistake of copying&pasting jobs, and then changing only very small bits in the copy. This not only blows up the length of your .gitlab-ci.yml file, but also makes it harder to maintain, because you are violating the DRY principle.

Instead, it is usually better to define an inheritance hierarchy, using *hidden jobs* (see also above), where all commonalities are placed in a hidden job, and the jobs inheriting from it only override the necessary specific bits.

GitLab offers two mechanisms for job inheritance:

1. YAML anchors (docs)
2. extends keyword (docs)

The extends keyword mechanism usually looks a lot cleaner, and is therefore recommended. See the docs for an example.

Reducing the length of the .gitlab-ci.yml file

Once your .gitlab-ci.yml file has become very long and confusing, it makes sense to reduce its length:

- Approach 1: extract long before_script/after_script/script sections into separate shell scripts. For *Linux* shell scripts, make sure that these shell scripts have the executable bit set when

committing them, see my previous article here for background information.
- Approach 2: split the large .gitlab-ci.yml file into several smaller .yml files, using the include (docs) or trigger (docs) mechanism.

Test extensive changes in a separate project

Whenever you need to make extensive changes to your .gitlab-ci.yml file, you might be afraid to break something. You might also fear that you need many commits to get it right, but you don't want to pollute the commit history. There are two approaches to solve this:

1. Create a **fork** of the project, and work only in a new branch of your fork. Once the file is in a good state, you can (optionally)

create another branch in which you have (selectively) squashed bad commits (e.g. using Git's *interactive rebase* functionality). Finally, you create a GitLab merge request that merges the branch of your *fork* into some branch of the *real* project.

    - Since you are working in your own fork, you can even merge the branch in which you are manipulating the .gitlab-ci.yml file into other branches of your fork (e.g. integration, develop, staging, …), to test pipeline feature that are sensitive to the branch. Everything happens inside your fork, so you are not polluting the real project!

2. Create a *new* GitLab project in your private namespace, with a stripped down version of your real project's .gitlab-ci.yml file, which uses dummy commands instead of the real script steps (e.g. replacing “make” with “echo make“). This approach is

suitable if you are experimenting with the GitLab CI syntax, e.g. debugging problems with include, or rules. Thanks to using dummy commands, the pipelines in the stripped-down project will execute much faster compared to the pipelines of the real project, which lets you to iterate on the .gitlab-ci.yml file much faster.

Caveats

Unavailable pipeline features due to license

Some CI/CD pipeline-related features are only available in GitLab *premium* or *ultimate* editions. For instance, the *free* license does not include the Pipelines for Merged Results feature. Keep this in mind when reading the manual, which indicates which features are free.

Look at labels next to the headlines, such as “ALL TIERS” (meaning that it’s free), or “PREMIUM” (only for premium editions).

Running pipelines for older commits

You cannot (retroactively) create and run a pipeline for a specific, older commit for which no pipeline was ever executed. When you create a manual pipeline instance in the GitLab web UI, you can only select the *branch/tag*, and the pipeline will run against the *latest* commit of that branch, or the specified tag.

To run a pipeline against an older commit, you need to (locally) check out that commit, tag it (git tag), push that tag, and then select that tag in the GitLab web UI in the dialog shown once you clicked the “Run pipeline” button.

Conclusion

The keyword reference makes it obvious that GitLab’s CI/CD feature is very powerful. Once you have successfully built and optimized your pipelines, you can always learn about more features (by skimming these docs), which gives you ideas for further improvements of your pipeline.