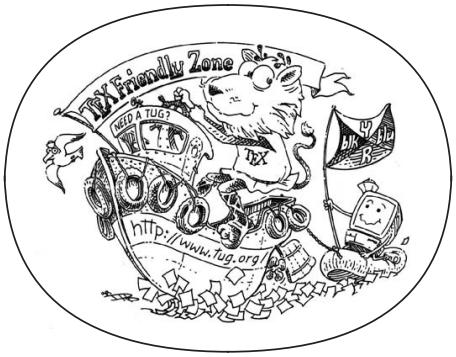
ANDRÉ MIEDE & IVO PLETIKOSIĆ

A CLASSIC THESIS STYLE

[November 21, 2018 at 23:56 – classicthesis v4.6]

A CLASSIC THESIS STYLE

ANDRÉ MIEDE & IVO PLETIKOSIĆ



An Homage to The Elements of Typographic Style

June 2018 – classicthesis v4.6

Politecnico di Milano
V Facoltà di Ingegneria
Corso di laurea in Ingegneria delle Telecomunicazioni
Dipartimento di Elettronica e Informazione

TITOLO DELLA TESI

Relatore: Prof. Nome COGNOME
Correlatore: Ing. Nome COGNOME

Tesi di Laurea di:
Simone Mosciatti Matr. 878758

Anno Accademico 2017-2018

Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.
1939 – 2005

ABSTRACT

Short summary of the contents in English. . . a great guide by Kent Beck how to write good abstracts can be found here:

https://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html

ZUSAMMENFASSUNG

Kurze Zusammenfassung des Inhaltes in deutscher Sprache. . .

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— knuth:1974 [knuth:1974]

ACKNOWLEDGMENTS

Put your acknowledgments here.

Many thanks to everybody who already sent me a postcard!

Regarding the typography and other help, many thanks go to Marco Kuhlmann, Philipp Lehman, Lothar Schlesier, Jim Young, Lorenzo Pantieri and Enrico Gregorio[1], Jörg Sommer, Joachim Köstler, Daniel Gottschlag, Denis Aydin, Paride Legovini, Steffen Prochnow, Nicolas Repp, Hinrich Harms, Roland Winkler, Jörg Weber, Henri Menke, Claus Lahiri, Clemens Niederberger, Stefano Bragaglia, Jörn Hees, Scott Lowe, Dave Howcroft, José M. Alcaide, David Carlisle, Ulrike Fischer, Hugues de Lassus, Csaba Hajdu, Dave Howcroft, and the whole LaTeX-community for support, ideas and some great software.

Regarding LyX: The LyX port was intially done by *Nicholas Mariette* in March 2009 and continued by *Ivo Pletikosić* in 2011. Thank you very much for your work and for the contributions to the original style.

1 Members of GuIT (Gruppo Italiano Utilizzatori di TeX e LaTeX)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LISTINGS

ACRONYMS

1 INTRODUCTION

CERN, European Organization for Nuclear Research, (French: Conseil européen pour la recherche nucléaire) is an European research organization that operates the largest particle physics laboratory in the world.

Its mission is to:

- Provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge
- Perform world-class research in fundamental physics
- Unite people from all over the world to push the frontiers of sciences and technology, for the benefits of all.

It host the instrument of the 4 biggest physic collaboration:

- ALICE
- ATLAS
- CMS
- LHCb

CERN host also a plethora of smaller physical collaborations that benefits from the instruments, know how, network effect and services availables.

Between the services offered to its users the computing service is one of the most interesting. Indeed CERN host and manage one of the biggest computing data center used for public research.

An issues that affect the operations inside the data center is the provisioning of software on the computing servers.

A specialization of the same problem is the provisioning of containers images.

The general problem of software provisioning is been solved by the use of CVMFS, a read only file-system that provides a scalable, reliable and low maintenance software distribution system.

This thesis will explore the problem of creating a suitable read-only file-system structure to provision containers images on computing nodes. We will provide a general read-only file-system structure and we will implement the proposed methodology on top of CVMFS.

This thesis is composed by several parts: The background will provide the necessary information on the CERN computing architecture (WLCG), then we will explore CVMFS and why it is a good fit for the

CERN computing architecture, the last part of the background will cover the integration between CVMFS and containers technologies. The state of the art will explore what alternatives are available for software distribution in general and for distribution of images. We will then define the problem that this thesis is trying to solve and few metrics of interest in our specific case. The methodology part will explain the details of the solution we propose for this specific problem. The implementation chapter will focus on how the proposed methodology is been put in practise. We will evaluate the result of the proposed methodology and implementation on the result part following the metrics that were previously proposed. Finally we will propose future work and enhancement to the implementation

2 BACKGROUND

In this chapter we are going to introduce the concept and technologies that made this work possible. We will start introducing the Worldwide LHC Computing Grid (WLCG) which is the collaboration that provide the computing power necessary to the CERN mission. The dimension of the WLCG and its specific workload required and allowed a specific software distribution system, CernVM-FileSystem which is used to provision the machine on the WLCG.

Then we will introduce the concept of containers a different way to solve the software distribution problem widely adopted in the industry. In particular we will focus on Docker containers and the Docker images format. We will then explore Singularity, in which we are mostly interested in its capability to run containers whose content is all already unpacked in a simple directory. Finally we will explore the Docker `cvmfs/graphdriver`, a Docker plugins that allow to run Docker images whose content is available on a read-only file-system without the need of downloading or access the Docker standard images.

WLCG

The Worldwide LHC Computing Grid is an global collaboration of more than 170 data centers in 42 countries. The mission of the WLCG is to provide the computing resource to store, distribute and analyze the data from the operation of the LHC.

The organization of the WLCG follow a hierarchical model, where each level is called "Tier" The most central Tier is the Tier-0 hosted by CERN in the Geneva Area and in Budapest. There are 13 Tier-1 data center with enough storage and computing capabilities to support the Grid operation around the clock, the Tier-1 are connected to the Tier-0 with at least 10Gb/sec links. Tiers-1 are geographically distributed, 8 of them are in Europe, 3 in the North American and the rest in Asia. Finally the Tier-2 data center do not have strict requirements and are generally operated by research centers and universities.

A schematic representation of the architecture of the WLCG is provide on figure 2.1.

The work on the WLCG is mostly divided in two big classes: analysis of the data from the LHC detectors and Monte Carlo simulations. The WLCG assume and support a batch computing paradigm. Analysis and simulations are split in smaller jobs that are distributed to different computing node that can work in parallel.

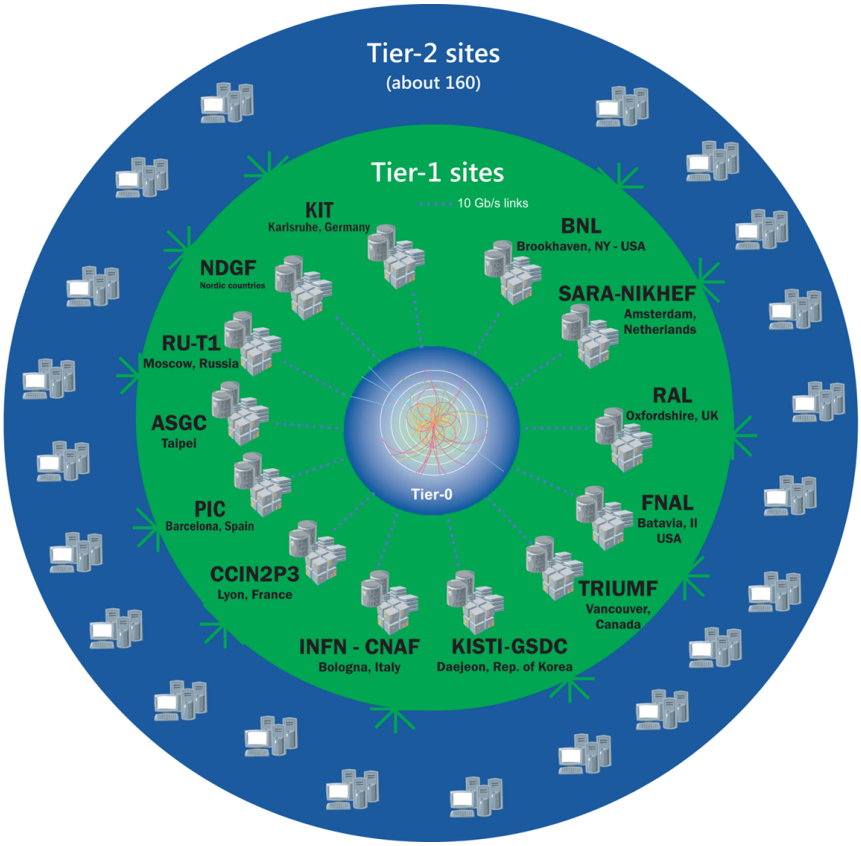


Figure 2.1: Schematic representation of the WLCG

Before to start each job it is necessary to install the software on the server. Unfortunately the amount of software potentially needed in each computing node and the velocity at which the software is updated makes the installation challenging. Moreover simpler installation techniques that relies on packages managers are not applicable since they would put the package managers themselves under too much load.

Several solution have been proposed and used, but eventually it settled for the use of CernVM-FileSystem (CVMFS).

CVMFS

This section will explore CernVM-FileSystem, we will start with an high level overview of CVMFS, then we will explore what happens when a file is requested.

CVMFS High Level Overview

CernVM-FileSystem provides a scalable, reliable and low-maintenance software distribution system. It is implemented as a read-only POSIX file-system in user space exploiting FUSE (File-system in USErspace) and standard web server technologies such as Apache or NGNIX.

CVMFS organize its content in repositories where we can approximate each repository as a CVMFS instance.

CVMFS is engineered to support repository of size on the order of the Terabyte with billions of files.

To save storage space files are addressed by their content (Content Addressable Storage), hence duplicated files will be stored only once.

In order to distribute software to geographically distant data centers and keep a low latency, CVMFS allows to cache content in different machines. This allow to host a cache server in each Tier of the WLCG. The use of caches fits perfectly with the Tiers models of the WLCG presented above. The Tier-0 host the main repository (Stratum-0), and the Tier-1 host the first level of cache (Stratum-1) and so on.

The content of the files are served using the HTTP protocol by a standard web server. The files are lazily downloaded only on the machine that need them and only when necessary.

In order to locate and request files from CVMFS the clients download the catalog a simple SQLite database which describes a subtree of the whole file-system. The catalog contains all the metadata of files and directories, including owner, group, permission, and size. Moreover the catalog contains also the URL where to download the files.

A root catalog is available in a know path, and, if the file-system grows too large, the root catalog links to other sub-catalogs. The use

of sub-catalogs allows to keep each catalog small improving the query time.

CVMFS Details

CVMFS is implemented using the Client-Server architecture. The server is responsible to manage the content of the repository and expose it via HTTP API. The client is installed in the host machine and is responsible to expose the content of the repository to the users. The client is implemented as a FUSE daemon which implements all the system calls necessary for a read-only file-system.

When a CVMFS file-system is mounted, it start by reading a configuration file which describe each repository. The client then download a simple file text file which point to the catalog of the repository. Once the catalog is downloaded the client has all the information necessary to start responding to the system call from the user.

As an example, when the user requires a `stat` system call against a file the client reads from the catalog all the information about the file like, size, permission, mode, etc.. and reply with them.

When the user require to read from a file, then the client first download the file from the server, store it into a local cache and pass through each read operation to the local copy.

This approach allow to download only the file really required, since all the other system calls can be served only by reading from the catalog. However it implies that the reading latency from a file depends on the network latency.

This approach works very well if the reading latency of a file is not a major concern and if reading from the catalog is fast. However, if the catalog grow too big, then the queries become too slow, to overcome this problem the sub-catalogs were introduced.

A sub-catalog is exactly like the normal catalog but while the catalog refers to the whole file-system tree, a sub-catalog refer to a smaller sub tree of the file-system. In order to avoid confusion, we will refer to the root-catalog as the catalog which include the root of the file-system and to sub-catalog to all the other catalogs in the file-system. The root-catalog, of course, embed several sub-catalogs, and each sub-catalog can, recursively, embed another sub-catalog.

When is required to read information about a file the client start by looking into the root catalog and then follows the sub-catalog structure until it does not find the required file.

CONTAINERS

While CERN solved its problems of software distribution with CVMFS the industry opted for a different approach, containers.

Containers are a standard unit of software that packages up code and all its dependencies so that computer applications run quickly and reliable from one computing environment to the others.

The containers are packed up in a specific format, in this work we are only interested in the format used by Docker, called Docker images defined in the OCI standard. A Docker image is an immutable set of tar files, each tar file is called a layer. Before to run the container each layer get mounted one on top of the other to re-create the original environment where to run the application. The content of each image is codified in a `json` file, the manifest, which provide the unique name of the image itself and which refer to each layer that compose the image by their unique identifiers. The unique identifier of both images and layers is the result of the function `hash256` of their content.

Docker images are distributed through Docker registries, simple HTTP servers that given the unique identifiers of a layer provides the layer itself, similarly, given the identifier of an image the registries provides its manifest.

Docker allow to associate a human readable identifier to each image, this name is composed by a namespace, which identify the user or organization that create the image, a name, which identify the image itself and a tag, which identify the version of the image. These names are not immutable and are meant to be used just by humans to reason about the images.

The repository where the image is hosted, its namespace, its name and its tag create a hierarchical structure between the several images that is easy to navigate for humans.

Docker and the cvmfs/graphdriver plugin

Docker is a thin CLI layer on top of a Linux daemon, `dockerd` which is responsible to obtains the Docker images from the registries, mount the layers, manage the runtime of the image and allow communication of a Docker runtime with the host system.

Docker layers can be shared between different images, so the Docker daemon download them once and store them in the local machine for future use. On average only 7% of the content inside a Docker images is used during the runtime of the image. The layers are distributed as a single tar file, hence a naive distribution of layers with CVMFS would not provide any advantage. The whole tar files would need to be downloaded erasing the advantages of using CVMFS.

A solution to this problem was introduced with the `cvmfs/graphdriver` plugin and the concept of "thin-images". In this work we are not interested in the internal of the `cvmfs/graphdriver` plugin, it will be sufficient to know that the Docker daemon can be enhance with the use of plugins and that the plugin allows us to run what are called "thin-images".

"Thin-images" are Docker images that are created starting from a standar ("fat") Docker images. The content of a "thin-image" is only a simple `json` file whose content is the layers needed by the original "fat-image" and where to find them in the host file-system, we call this file the "recipe". "Thin-images" can be executed only if the Docker daemon have enable the `cvmfs/graphdriver` plugin, indeed the plugin is able to read the content of the thin-image, mount the original layers inside the container, and finally execute the application.

If the files necessary to run the "thin-images" are distributed by CVMFS is possible to run docker containers without downloading any unnecessary content.

Moreover the `cvmfs/graphdriver` plugin is able to run standard ("fat") Docker images, hence is possible to enable the plugin and forget about having it.

On figure 2.2 we show how the plugin run a Docker image.

A problem with this approach is that a "thin-image" can be downloaded, store in the local storage and successfully run using the content provide by CVMFS. On a second moment the images can be update, uploaded newly on the registry and the old content in CVMFS is deleted to host the new content of the image. If now the user try to run the same images, it will not download it again from the registry but it will use the image already cached, this thin-image will refer to content not available anymore on CVMFS, hence it will fail to run.

Singularity

Singularity is another container runtime, it provides its own image format but is capable to run standard Docker images as well. Moreover is capable of running containers, also Docker containers, directly from a directory containing the unpacked container file-system itself.

Given the Singularity capability to run Docker containers directly from a directory containing the unpacked Docker image file-system its integration with CVMFS is simpler that the one with Docker itself. Indeed is sufficient to host the directory containing the unpacked file-system of the Docker image in CVMFS.

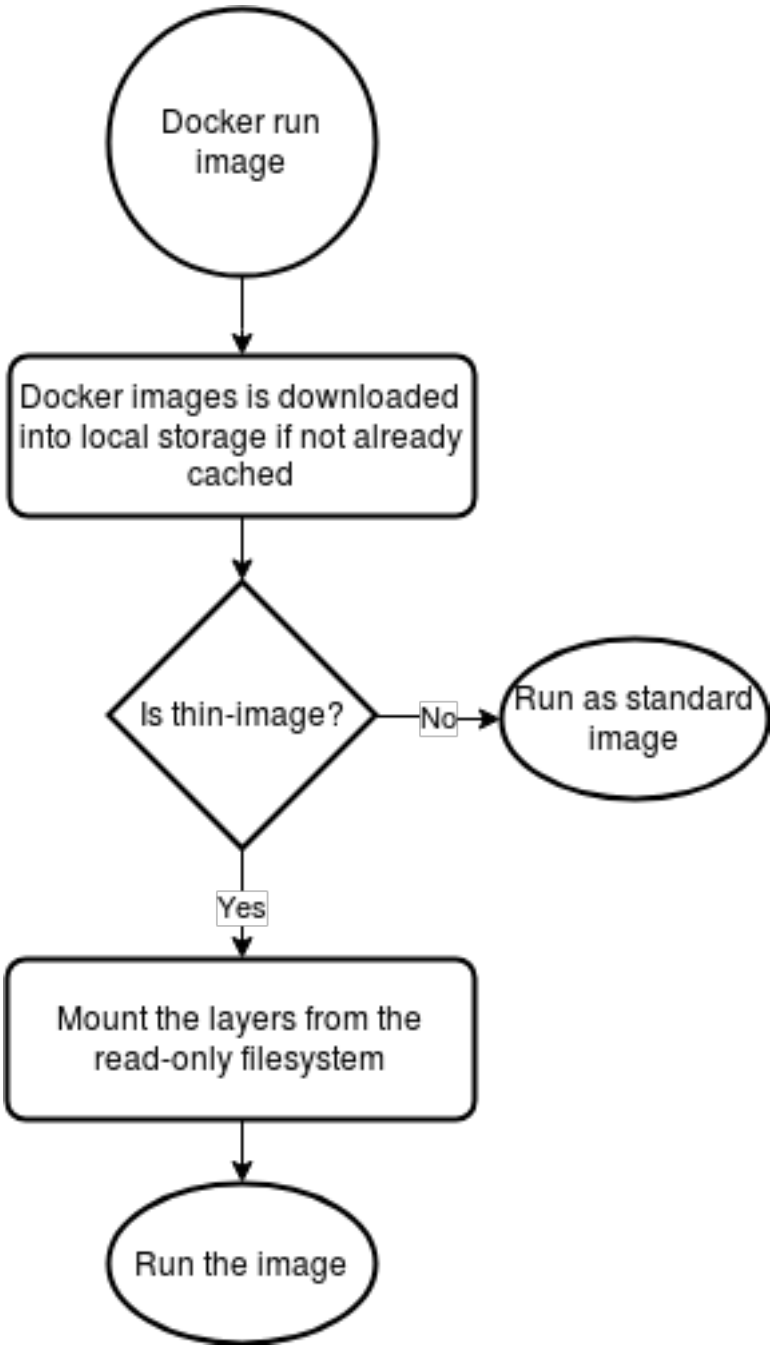


Figure 2.2: Decision proces for running docker thin images

3

STATE OF THE ART

In this chapter we are going to explore what tools and methodologies are already available and know to provision software on a computing cluster. We will explore what is used in the industry as well as what was developed specifically inside the CERN environment We will also focus on how those system works with container technology, in this particular chapter, we will focus just on Docker since Singularity is not widely used in the industry and none of the following tools support it.

ANSIBLE

Ansible is a provisioning system based on the concept of playbooks and inventory.

Playbooks are files that describe the desired final status of a server. It is include software to be installed, configuration files to be created and setted, security policies, status of services and it may also include docker images to be downloaded.

The inventory is a list of the nodes where we wish to reach the final status described in the playbook.

The Ansible approach is declarative, indeed, we describe what we want and where we want it and then we leave it to an internal engine to reach the desired state.

Ansible can also be categorized as a non-intrusive provisioning system, it works using an a remote connection (SSH) to the nodes it is managing without relieing on any software been installed on the node itself.

PUPPET

Puppet is another declarative provisioning system.

Similarly to Ansible, also in Puppet, we describe the desired status of the servers. The big difference with Ansible is that Puppet needs a daemon, called "agent", running on the provisioned servers.

The agent ensure that the desired configuration is keep in spite of manual changes on the machine.

The agent is as well responsible to makes all the necessary changes to the system.

KUBERNETES

Kubernetes (K8S) is a container orchestration system based on docker for computing clusters.

A central master is responsible for managing the cluster. It coordinates all the activities such as scheduling containers or rolling out updates. The worker nodes simply execute the commands from the master.

PACKAGE MANAGERS

Packages managers are the standard way to install software on most linux distribution.

A package is conceptually composed by an archive that contains the actual files to install on the system and by a configuration that describe where to install each file.

Moreover a package describe its dependencies, dependencies that are recursively installed by the package manager.

ALICE SOFTWARE INSTALLATION SYSTEM

In order to ease the load on the network the Alice collaboration opted to distribute packages using the BitTorrent protocol. The installation is still based on standard linux packages, but the use of a peer to peer distribution mechanism avoided to overload the central package manager. However, it still relies on a central authoritative BitTorrent tracker hosted at CERN itself.

DIFFERENCE WITH CVMFS

All the above tools used for installing software relies on installing the software on the machine before that it is actually request, doing so, it normally moves also files that are not strictly necessary for every computation, wasting

CVMFS on the other side avoid to move any software on the machine if it is not necessary. The downloading of a file is defer to when it is necessary (on the OPEN syscall) hence only the file strictly necessary are downloaded.

It results in an increase of latency when starting an application but the bandwidth consumption is keep to the minimun.

4

PROBLEM DEFINITION

In the Background on chapter 2 we addressed how CERN has overcome the challenge of software distributions using CVMFS. Unfortunately this is not enough since run-time dependencies between software components can break application that instead are running perfectly fine in a different environment.

A possible solution to this problem is the use of container technology and we explore how both Singularity and Docker with the `cvmfs/graphdriver` plugin are capable to run Docker images hosted in CVMFS avoiding to download unnecessary from remote host saving bandwidth.

In this work we aim to introduce a read-only file-system structure implementable in CVMFS that will allow us to bridge together the efficient content distribution provide by CVMFS with the encapsulation of runtime dependencies provide by container technologies.

This work will focus on a specific container technology, Docker. Indeed we focus on describe a file-system structure suitable to run Docker images using Singularity and the thin-images Docker graphdriver plugin.

The proposed file-system structure aims to the following goals:

- Minimize the amount of space required
- Minimize the start up time of containers
- Minimize the time necessary to add a new docker image into the file-system
- Minimize the number of files in the CVMFS sub-catalogs
- Minimize the complexity of managing the files-ystem itself
- Provide a great usability for the users.

Some of those goal can be measured to asses if we were successful or not, in particular we are going to:

- Compare the amount of space required by the CVMFS repository versus the amount of space required for each layer.
- Compare the start-up time of containers hosted in CVMFS versus the start-up time of containers not hosted on CVMFS
- Provide the distribution of number of files in each sub-catalog

- Measure the complexity of managing the file-system using as a proxy the cyclomatic complexity of the software that actually create and manage the file-system.

Unfortunately we didn't find usable proxy for measuring the usability of the file-system structure nor it make sense to measure the time necessary to add a new Docker image into the file-system since it depends on too many variable to provide a useful measure.

5 METHODOLOGY

In this chapter we are going to proposed a read-only file-system structure for running Docker images using both Singularity and the docker thin-images plugin. We focus on Singularity because is a widely deployed system in HPC and on docker thin-images because it allow the user to use the Docker infrastructure to run images whose content is distributed with a read only file-system.

The section 5.1 will provide a high level overview of the proposed file-system structure.

The section 5.2 will analyze the file-system structure to host the Docker images to run with Singularity. We will explain how we created a hierarchical structure similar to the one of the docker registries while keeping the repository maintainable and without putting too much pressure in the sub-catalog system.

The section 5.3 will analyze how we store the content used by the thin-images Docker plugin. Structural similarities between Docker images and Docker layers will drive us to adopt a very similar solution to avoid stressing the sub-catalog system. The sharing of layers between different docker images will allow us to avoid repeating work, but it will introduce difficulties during the deletion of the image itself that we will solve using a reference count system.

Finally the section 5.4 will show how we keep track of the images already present in the file-system.

HIGH LEVEL OVERVIEW OF THE PROPOSED FILE SYSTEM

In this section we are providing an high level view of the proposed file-system structure, the details for the Singularity runtime will follow on section 5.2 while the details for the `cvmfs/graphdriver` plugin will follow on section 5.3.

The propose file-system provide two main structure. A non-hidden set of directories that host the unpacked images to run with Singularity and a hidden folder to host the layers used by the `cvmfs/graphdriver` Docker plugin. Along with these structure another hidden directory will contains metadata information about the Docker images already in the repository.

The directories that host the unpacked Docker images have the same hierarchical structure of the Docker structure as mentioned in 2.3, hence the first directory is the name of the registry that host the image, it follow the namespace which refers to the user of the

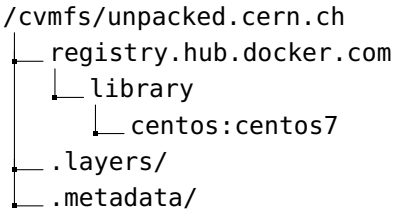


Figure 5.1: High level visualization of the proposed file-system

organization responsible for the image and the last level is the image name along with the tag.

The directory that host the layers of the Docker images can conceptually be a flat structure simply containing the layers each identified by its digest. However a simple flat structure will put too much pressure in the catalog system so we will aggregate layers that share the same digest prefix and create a sub-catalog for each aggregation.

The hidden metadata folder will follow the same hierarchical structure of Docker images that allow to quickly locate the metadata information of an image given just the name of the image itself.

SINGULARITY IMAGES

To run Docker images using Singularity is sufficient to start the singularity executable providing as input the directory where the image is been unpacked. In this section we are going to show how we structure the file-system in a way that allow users to easily discover and run unpacked docker images using Singularity while keeping the file-system easy to maintain.

As mentioned in 2.3 docker images have a hierarchical structure. The first level of the hierarchy is the docker registry where the image is hosted. The most common registries in our case are the official docker hub [1] and the CERN internal registry [2].

The second level in the hierarchical structure is the namespace of the docker image. If the image is one of the official docker images it will be the standard namespace: "library". In all the other cases, the namespace will be the same as the original docker image. For example for the images belonging to the ATLAS collaboration we use the namespace `atlas`.

The last level is the name of the image itself together with the tag of such image, separated by a colon (`:`). We decided to avoid yet another level containing just the tags. Indeed there are relatively few tags for each image and adding another level of indirection would have made it harder to explore the file-system. Moreover, we decided to use the colon because it is the same character used in the docker registries

1 `registry.hub.docker.com`
2 `gitlab-registry.cern.ch`

```
/cvmfs/unpacked.cern.ch
└── registry.hub.docker.com
    ├── library
    │   ├── centos:centos7 -> /cvmfs/unpacked.cern.ch/.flat/75/75835...0c4ab6d
    │   ├── centos:latest -> /cvmfs/unpacked.cern.ch/.flat/75/75835...0c4ab6d
    │   ├── debian:stable -> /cvmfs/unpacked.cern.ch/.flat/a4/a4274...ba594cb
    │   ├── gcc:latest -> /cvmfs/unpacked.cern.ch/.flat/ce/ceccd...a75dd28
    │   ├── openjdk:9 -> /cvmfs/unpacked.cern.ch/.flat/5a/5adaf...5344d70
    │   ├── python:2.7 -> /cvmfs/unpacked.cern.ch/.flat/3c/3c43a...0e7c9d4
    │   └── python:3.4 -> /cvmfs/unpacked.cern.ch/.flat/43/43953...ed73435
    └── efajardo
        └── docker-cms:tensorflow ->
            /cvmfs/unpacked.cern.ch/.flat/2d/2d5b4...97d44fc
```

Figure 5.2: Visualization of the Filesystem structure, the arrows indicate symbolic links

between the images and the tag and it is immediately recognizable by users.

While this structure is user friendly, it makes the maintenance of the repository complex.

The tags used in each image are not immutable, hence, without continuous maintenance, it may happen that the images stored inside the file-system are not up to date making difficult for the user to know what version of the software is being run. However with the described structure, it would be extremely complex to detect if an image is up to date or if it needs further updates.

To work around this issues we exploited the fact that each image is uniquely identified by its digest. Indeed we decided to store the real content of the images in an hidden folder that embed the digest itself while preserving the structure presented above using symbolic links.

We show the directory structure of the file-system on figure 5.2.

The folder that contains the real content of a Singularity images are all below the standard subdirectory `.flat/`. The name `.flat/` was chosen to make it clear that only flatted file systems are stored in there.

Embedding the digest in the name of the folder allows to immediately find the location of an image, which is useful when an image become obsolete and need to be deleted from the file-system.

From a theoretical point of view it would be sufficient to store the whole content of the Singularity images in the folder `.flat/$image_digest`. However, from a practical point of view this would create too much content in a single folder putting too much pressure in the CVMFS sub-catalog system.

To overcome this issue we decided to create a fixed number of "super-directories" where we placed the unpacked folder of the images. To easily locate each unpacked folder in the super-directories we decided

```
/cvmfs/unpacked.cern.ch/.flat
├── 0c
│   └── 0cbf37812bff083eb2325468c10aaf82011527c049d66106c3c74298ed239aaf
├── 2c
│   └── 2cc378c061f7b3e8d9096728eb75722a89f31fb3f3117ed10c66cc2f4b8ab281
├── 5a
│   └── 5adaf00da2a3cf6b611e7c850778fad3dc62c548864706b822b5f3ce65344d70
└── ea
    ├── ea4c82dcd15a33e3e9c4c37050def20476856a08e59526fbe533cc4e98387e39
    └── eadfca9546a132104b8bdb6b76952c6e5d412301704b7bc94e9176bcc5dda0fe
```

Figure 5.3: Visualization of the "super directories" in the ".flat" subdirectory

to call each super-directory as the prefix of the digest of the images it is containing. Since the digest is an hexadecimal string this approach provides us with $16 \times 16 = 256$ fixed super-directories inside the `.flat/` directory, each of which will contain only the content of the images whose digest start with those 2 specific bytes.

On figure 5.3 we can see that "0c", "2c", ..., "ea" are all "super-directories" and each one contains only the file-systems that start with "0c", "2c", ..., "ea" respectively. Note the case of "ea" that contains file-systems of multiple images whose digest start with "ea".

However, to relieve pressure from the catalog system is not sufficient to simply aggregate the images into "super-directories", we also need to create a sub-catalog for each "super-directory." Moreover, since each image can contains itself a lot of files we decide to create a sub-catalog also for each unpacked image.

Another positive side-effect of the use of symbolic links is that symbolic links manipulation is defined as atomic in the POSIX standard.

The use of "super-directories" is necessary for limits in the implementation of CVMFS and they are not necessary on an abstract read-only file-system.

DOCKER THIN IMAGES

While for running docker images using Singularity it is sufficient to have the image unpacked in a simple directory running docker containers using the thin-images plugin requires a more complex set up. As explained in 2.3.1 the recipe of the docker thin-image contains the path of the directories where each layer of the original docker image is hosted, those directories will be mounted by the docker plugin.

All the docker layers are stored under a common subdirectory of the file-system, the `.layers/` directory.

Since the sub-tree of the file-system used by the Docker thin-images is used only by the Docker plugin we don't need to create a human-friendly structure like we did for the Singularity sub-tree.

Like docker images also the docker layers are identified by an unique digest, and similarly to the docker images, store all of them in a single directory will put too much pressure in the CVMFS sub-catalog system, hence we follow the exact same model used for storing the unpacked images also for the layers creating 216 super-directories.

A big advantage of the use of layers over flat images, is that layers can be shared by multiple images.

The sharing of layers allow us to avoid re-doing work that is already been done, in particular if a later is already in the file-system it will not be added again. On the other hand it makes more complex removing an image since it is necessary to remove each layer that compose the image, but some layer may be shared between images.

Removing layers has the important implication that once the layer is removed every thin image that relies on it won't work anymore. However those thin-images could be stored on the client side where we don't have any access. Please refer to the figure **??** on page **??**

To do not disrupt the user workflow while keeping the repository to a manageable size we consider several option:

1. Never remove layers
2. Remove layers as soon as possible
3. Provide a grace period before finally removing the layer

The option to never remove layers is impractical since the size of the file-system will grow unbounded.

Remove layers as soon as possible is not desiderable, even running computation could be broken by this policy and the users have no way to deal with this possibility but retrying the whole computation.

The last option is the most sensible and better suited for our use case, and so it is the one that we implement, this gave users the possibility to:

1. Complete their computation
2. Update the local images in order to always run stable containers

In order to know which layer to delete from the file-system we store a reference that map each layer to the images that use the layer itself.

These references are stored as metadata in a simple `.json` file. We store one of these reference file for each layer in the file-system.

Anytime a new image is added to the file-system we update the several references files, adding for each layer in the image, a reference to the image itself.

When we decide to remove an image, for any layer we check that it is used only by the image we want to remove, if this is the case, we remove the layer, if it is not the case we just remove the reference of the image.

Listing 5.1: Algorithm to add an image reference to the layer metadata

```
Function AddReferenceToImage
        Pass In: LayerReference, ImageReference
        ReferenceFile := FindReferenceFile(LayerReference)
        if ReferenceFile exist
                References := LoadReferenceFromFile RefereceFile
                Add ImageReference to References
                Overwrite References to ReferenceFile
        else
                References = ImageReferences
                Write References to ReferenceFile
        endif
EndFunction
```

Listing 5.2: Algorithm to remove an image from the file-system

```
Function RemoveLayer
        Pass In: LayerReference, ImageReference
        ReferenceFile := FindReferenceFile(LayerReference)
        References := LoadReferenceFromFile RefereceFile
        Remove ImageReference from References
        if size References == 0
                Remove Layer
        else
                Overwrite References to ReferenceFile
        endif
EndFunction
```

```
/cvmfs/unpacked.cern.ch/.layers
├── 21
│   ├── 2100d...d7b7dbf
│   │   ├── .metadata
│   │   │   └── origin.json .........................the reference file
│   │   └── layerfs/ ... This directory contains
│   │                    the file-system of the
│   │                    layer itself and is the
│   │                    one that appears in the
│   │                    recipe of the thin-image
│   └── 217f7...601e9e7
│       ├── .metadata
│       │   └── origin.json
│       └── layerfs/
└── c3
    ├── c300b...4190f83
    │   ├── .metadata
    │   │   └── origin.json
    │   └── layerfs/
    └── c3683...53a1c45
        ├── .metadata
        │   └── origin.json
        └── layerfs/
```

Figure 5.4: Complete visualization of the `.flat` directory

In order to store both the metadata information about the layers (in particular the "reference" file mentioned above) and the actual file-system of the layer an additional directory structure is used. Below the directory called as the digest of the layer there are two more directories:

1. `layerfs/` directory that actually store the content of the layer
2. `.metadata/` directory that stores the references to the image in a simple JSON encoded file, “origin.json”

Of course, the recipe of the thin images is not concerned at all with the content of the `.metadata/` directory. Hence the recipe files points directly to the `layerfs/` directory.

The complete structure for storing docker images is the one showed in 5.4

KEEPING TRACK OF THE WORK ALREADY DONE

To avoid to perform duplicated work is necessary to keep track of which image is already been added to the file-system. The same information may be used by the users to know exactly what images is hosted in the file-system.

```
/cvmfs/unpacked.cern.ch/.metadata
└── registry.hub.docker.com
    ├── library
    │   ├── python:latest
    │   │   └── manifest.json .....................the manifest file
    │   ├── r-base:latest
    │   │   └── manifest.json
    │   └── julia:latest
    │       └── manifest.json
    └── atlas
        └── athena:latest
            └── manifest.json
```

Figure 5.5: Structure of the `.metadata/` directory

In order to know which image is already been converted we need to uniquely identify each image, as already mention, using the combination of image name and tag is not enough, since the tag are mutable. Hence we rely on the digest of the image.

The information about each image is stored into another top-level hidden directory, `.metadata/`.

Inside the `.metadata/` folder we have others directories, one for each hosted image. Inside those directories there is a single file, `manifest.json` that store the manifest of the image itself.

As already mentioned in **??** the manifest contains the digest of the image itself. Comparing the manifest stored in the file-system with the manifest downloaded from the docker registries is possible to understand if the image should be updated or nor.

The structure of the `.metadata/` folder is show in figure 5.5.

CLOSING REMARKS

In this chapter we have introduced a file-system structure suitable to host docker images that can be run using both Singularity and the docker thin-images plugin.

We started by storing the unpacked images used by Singularity in a hierarchical structure that recall the one of the Docker registries to enhance the discoverability of the images itself. This approach however would have make difficult to maintain the repository since we would not know the version of each image unpacked. We overcome this issue storing the real unpacked images in a hidden directory that embed the digest of the image itself and using symbolic links to preserve the hierarchical structure. Too many unpacked images stored under the same directories however would have put too much pressure on the catalog system of CVMFS, hence we adopted the use of super-directories.

On the second part we analyzed how to store the layers used by the docker thin-image plugin. A single layer can be used by multiple images this allowed us to avoid repeating work but at the same time it makes more complex removing an image from the file-system. We decided to keep a reference count to know when is safe to actually delete a layer. The same issue of too many files under the same sub-catalog arose also for storing the layers, we used the same approach used for the unpacked images based on the use of super-directories.

The last section explored how we keep track of exactly which image is already store in the file-system storing the image catalog in a hidden subdirectory.

6 IMPLEMENTATION

In this chapter we are going to explore how the ingestion inside CVMFS is been implemented.

At first we will describe the write interface of CVMFS, then we are going to talk how we decide to ingest Singularity images.

We will move on to describe the challenges in ingesting docker images while transforming them into docker thin-images, hence we will explore the custom modification done to CVMFS in order to accomodate the needs of layer ingestion.

We will then explore how all the bookkeeping of images and layers is manages. Then we are going to understand how the images are removed from the filesystem.

Finally we will show the interface to the administrator.

CVMFS WRITE INTERFACE

CVMFS provides a transactional interface, hence is possible to open a transaction, modify the filesystem and then either publish the modification or abort the transaction. Those actions are carried out respectively by the command 'cvmfs_server transaction', 'cvmfs_server publish' and 'cvmfs_server abort'.

When a transaction is open the modifications of the filesystem can be carried out with standard linux commands or even using a graphical file explorer. Moreover is possible to test locally the new filesystem without actually commit the changes.

Finally is important to keep in mind that only a single transaction can be open at any given time, the system will refuse to open a second transaction.

SINGULARITY INGESTION

The step to ingest a singularity images are pretty straightforward.

Initially the image is downloaded from the remote registry and stored in a temporary area. The download is carried out by Singularity itself, in order to minimize the possibilities of inconsistency or of error. Once the download finish successfully we start the real ingestion phase.

The first step of the ingestion is to open a transaction in CVMFS.

Once we open the transaction we copy the temporary directory into the CVMFS filesystem under the ".flat/" directory.

Then we commit the first transaction.

A second transaction takes care of creating the symbolic link describe above.

This few step are sufficient to make the Singularity images available through CVMFS.

Docker Ingestion

Ingest docker images is much more complex than ingesting the Singularity one.

The first big difference is that during the ingestion is necessary to create also the thin images that then will be distributed through the standard docker registries.

Another difference is the necessities to keep reference to the layers so that is possible to delete layers when they are not necessary anymore.

CVMFS Ingestion of Tarball

In order to make more ergonomic the ingestion of docker images we decide to add a new command to CVMFS, the 'ingest' command.

The 'ingest' command takes as input a tarball and a location. The command expand the tarball into the location materializing all the files.

The command automatically open and commit the transaction, hence is possible to have only a single concurrent ingestion.

Docker Ingestion Algorithm

The first step is to download the manifest of the docker image.

In the manifest is describe which layers compose the image, hence we start to download each layer.

The layers are all stored first in a temporary location, then each one of them is ingested inside the CVMFS file system using the 'ingest' command under the subdirectory ".layers" as described above.

With the information about the layers necessary for an image we can start to create the docker thin image, as soon as the thin-image is created we proceed to upload it to the docker registry.

Then, after all layers have been ingested we write the references necessary to delete the layers in an hidden folder.

Finally, if no error happened during the whole process we store, in another hidden folder, information about the successful conversion and ingestion of the image.

GARBAGE COLLECTION OF IMAGES

We have only described how we add new images to the CVMFS filesystem, however updating an image is quite common, especially if the images are refered by mutable tag such as "latest" which actually represent the latest version of a particular application.

During the update of an image we avoid to immediately delete the files from the CVMFS repository, as mentioned this could cause disruption of service for users.

Instead we keep track of all the images that are not necessary anymore in a specific file, the "remove-schedule.json" file which is stored in the hidden directory ".metadata/" just below the main root of the CVMFS filesystem. The remove-schedule.json files contains a collections of the manifest of all the images we are not interested in anymore.

When is time to actually delete all the old images we scan the "remove-schedule.json" file and we carry out the actual remotion of the images.

The remotion of a singularity image is quite simple, indeed, is sufficient to remove the whole directory.

Removing the layers of the docker images is more complex. At first we need to identify all the layers that we need to check. This is simple since this information is stored in the manifest itself which is stored in the "remove-schedule.json" file.

Then, for each layer we obtain the list of images that need the layer itself. From that list we remove the image we are eliminating from the filesystem. If the list is now empty we proceed to remove also that specific layer from the filesystem.

ADMINISTRATOR INTERFACE

In order to store images in the CVMFS filesystem is necessary to know what image store, in which repository store it and how to call the respective thin-image.

We decide to call the triplet (Input image, CVMFS Repository, Output image) a "wish".

Now, we need a way to express a list of those wishes. We opted for a simple YAML file that store a specialization of a generic "wish list". In the YAML file we specify a list of Input images, only a single CVMFS repository and a single syntactical transformation for the Output images.

The syntactical transformation depends on the input image and is applied to obtain the final name of the output image.

There are several benefits of this approach:

1. The YAML file is a simple text file that is simple to understand and to edit

2. It can be hosted on version control system

Since the wish list can be hosted on a version-control system like Github or Gitlab and since it is a simple file to modificate it allow a Pull-Request based approach to modificate the wish list itself.

Users who wish a new image to be added to the repository can simply make a pull request adding their image to the wish list. The administrator of the system act as a gatekeeper, inspect the image that is been required to be add and decide if add the image or not.

7 RESULTS

In this section we explore the result of this works.

We mentioned 4 metrics that we were considering for this work:

- Minimize the amount of space required
- Minimize the start up time of containers
- Limit the number of files in each CVMFS catalogs
- Minimize the complexity of managing the filesystem itself

All the measurement are going to be done against a CVMFS repository containing images necessary for standard HEP work.

In order to quantify the amount of space required we are simply going to measure the amount of space that the repository uses, we will compare this figure with the amount of data that the repository provides and with a simple summation over the size of the layers stored in the repository.

The startup time of a container is greatly influenced by the cache layer in all cases, either if we serve the content with CVMFS or if the content is already cached in the hosting machine.

We will measure the startup time of all kind of technologies with and without cache a significant number of times, the measurement are made inside the CERN data center where we assume a stable and reliable internet connection.

The amount of files in each CVMFS catalog is a simple measurement, since the amount of catalogs is rather big we will synthetize this measurement.

To measure the complexity of managing the filesystem we are going to measure the cyclomatic complexity of the software that we use to manage it.

SPACE REQUIREMENT

CONTAINER STARTUP TIME

FILE IN THE SUB-CATALOGS

COMPLEXITY

8

FUTURE WORKS

1. New containers technologies
2. Improve ingestion of layers into the filesystem making everything in a single transaction
3. Decrease cyclomatic complexity

DECLARATION

Put your declaration here.

Saarbrücken, June 2018

André Miede & Ivo Pletikosić

COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede and Ivo Pletikosić. The style was inspired by Robert Bringhurst's seminal book on typography "*The Elements of Typographic Style*". `classicthesis` is available for both LaTeX and LyX:

https://bitbucket.org/amiede/classicthesis/

Happy users of `classicthesis` usually send a real postcard to the author, a collection of postcards received so far is featured here:

http://postcards.miede.de/

Thank you very much for your feedback and contribution.