About storage drivers

Estimated reading time: 14 minutes

To use storage drivers effectively, it's important to know how Docker builds and stores images, and how these images are used by containers. You can use this information to make informed choices about the best way to persist data from your applications and avoid performance problems along the way.

Storage drivers allow you to create data in the writable layer of your container. The files won't be persisted after the container is deleted, and both read and write speeds are low.

Learn how to use volumes (https://docs.docker.com/storage/volumes/) to persist data and improve performance.

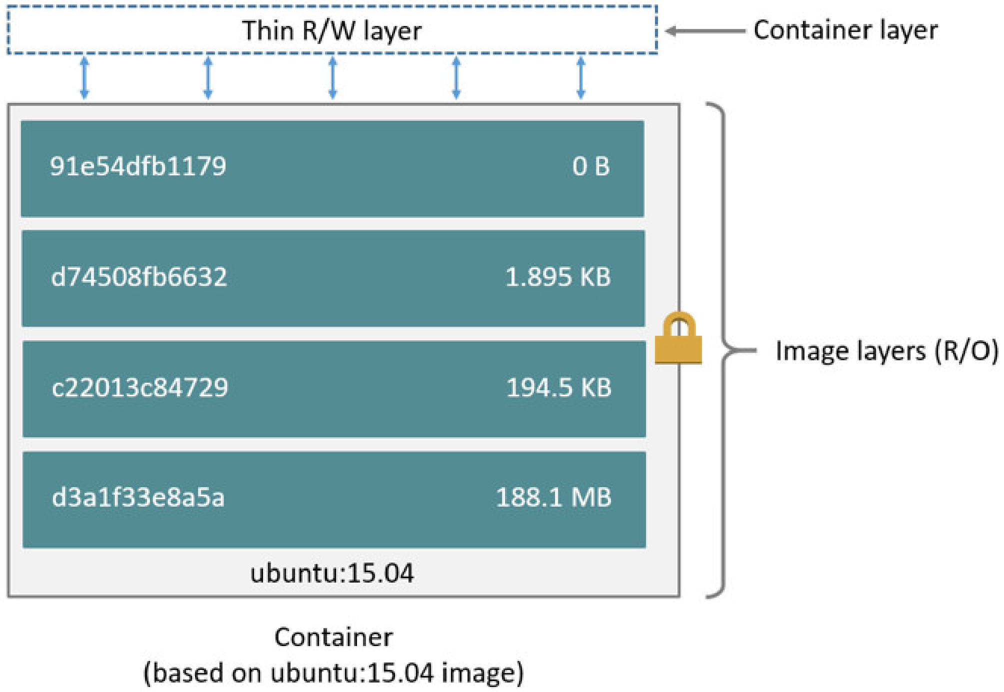
Images and layers

A Docker image is built up from a series of layers. Each layer represents an instruction in the image's Dockerfile. Each layer except the very last one is read-only. Consider the following Dockerfile:

```
FROM ubuntu:15.04
COPY . /app
RUN make /app
CMD python /app/app.py
```

This Dockerfile contains four commands, each of which creates a layer. The `FROM` statement starts out by creating a layer from the `ubuntu:15.04` image. The `COPY` command adds some files from your Docker client's current directory. The `RUN` command builds your application using the `make` command. Finally, the last layer specifies what command to run within the container.

Each layer is only a set of differences from the layer before it. The layers are stacked on top of each other. When you create a new container, you add a new writable layer on top of the underlying layers. This layer is often called the "container layer". All changes made to the running container, such as writing new files, modifying existing files, and deleting files, are written to this thin writable container layer. The diagram below shows a container based on the Ubuntu 15.04 image.

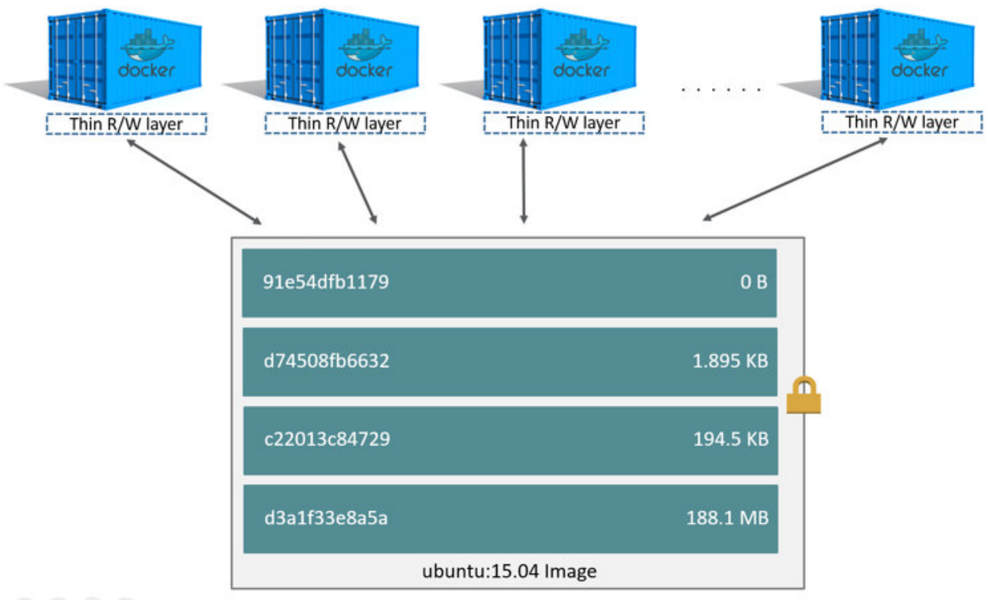


A *storage driver* handles the details about the way these layers interact with each other. Different storage drivers are available, which have advantages and disadvantages in different situations.

Container and layers

The major difference between a container and an image is the top writable layer. All writes to the container that add new or modify existing data are stored in this writable layer. When the container is deleted, the writable layer is also deleted. The underlying image remains unchanged.

Because each container has its own writable container layer, and all changes are stored in this container layer, multiple containers can share access to the same underlying image and yet have their own data state. The diagram below shows multiple containers sharing the same Ubuntu 15.04 image.



> Note: If you need multiple images to have shared access to the exact same data, store this data in a Docker volume and mount it into your containers.

Docker uses storage drivers to manage the contents of the image layers and the writable container layer. Each storage driver handles the implementation differently, but all drivers use stackable image layers and the copy-on-write (CoW) strategy.

Container size on disk

To view the approximate size of a running container, you can use the `docker ps -s` command. Two different columns relate to size.

- `size` : the amount of data (on disk) that is used for the writable layer of each container.
- `virtual size` : the amount of data used for the read-only image data used by the container plus the container's writable layer `size` . Multiple containers may share some or all read-only image data. Two containers started from the same image share 100% of the read-only data, while two containers with different images which have layers in common share those common layers. Therefore, you can't just total the virtual sizes. This over-estimates the total disk usage by a potentially non-trivial amount.

The total disk space used by all of the running containers on disk is some combination of each container's `size` and the `virtual size` values. If multiple containers started from the same exact image, the total size on disk for these containers would be SUM (`size` of containers) plus one image size (`virtual size` - `size`).

This also does not count the following additional ways a container can take up disk space:

- Disk space used for log files if you use the `json-file` logging driver. This can be non-trivial if your container generates a large amount of logging data and log rotation is not configured.
- Volumes and bind mounts used by the container.
- Disk space used for the container's configuration files, which are typically small.
- Memory written to disk (if swapping is enabled).
- Checkpoints, if you're using the experimental checkpoint/restore feature.

The copy-on-write (CoW) strategy

Copy-on-write is a strategy of sharing and copying files for maximum efficiency. If a file or directory exists in a lower layer within the image, and another layer (including the writable layer) needs read access to it, it just uses the existing file. The first time another layer needs to modify the file (when building the image or running the container), the file is copied into that layer and modified. This minimizes I/O and the size of each of the subsequent layers. These advantages are explained in more depth below.

Sharing promotes smaller images

When you use `docker pull` to pull down an image from a repository, or when you create a container from an image that does not yet exist locally, each layer is pulled down separately, and stored in Docker's local storage area, which is usually `/var/lib/docker/` on Linux hosts. You can see these layers being pulled in this example:

```
$ docker pull ubuntu:15.04

15.04: Pulling from library/ubuntu
1ba8ac955b97: Pull complete
f157c4e5ede7: Pull complete
0b7e98f84c4c: Pull complete
a3ed95caeb02: Pull complete
Digest: sha256:5e279a9df07990286cce22e1b0f5b0490629ca6d187698746ae
5e28e604a640e
Status: Downloaded newer image for ubuntu:15.04
```

Each of these layers is stored in its own directory inside the Docker host's local storage area. To examine the layers on the filesystem, list the contents of /var/lib/docker/<storage-driver>/layers/ . This example uses the aufs storage driver:

```
$ ls /var/lib/docker/aufs/layers
1d6674ff835b10f76e354806e16b950f91a191d3b471236609ab13a930275e24
5dbb0cbe0148cf447b9464a358c1587be586058d9a4c9ce079320265e2bb94e7
bef7199f2ed8e86fa4ada1309cfad3089e0542fec8894690529e4c04a7ca2d73
ebf814eccfe98f2704660ca1d844e4348db3b5ccc637eb905d4818fbfb00a06a
```

The directory names do not correspond to the layer IDs (this has been true since Docker 1.10).

Now imagine that you have two different Dockerfiles. You use the first one to create an image called `acme/my-base-image:1.0` .

```
FROM ubuntu:16.10
COPY . /app
```

The second one is based on `acme/my-base-image:1.0` , but has some additional layers:

```
FROM acme/my-base-image:1.0
CMD /app/hello.sh
```

The second image contains all the layers from the first image, plus a new layer with the `CMD` instruction, and a read-write container layer. Docker already has all the layers from the first image, so it does not need to pull them again. The two images share any layers they have in common.

If you build images from the two Dockerfiles, you can use `docker image ls` and `docker history` commands to verify that the cryptographic IDs of the shared layers are the same.

1. Make a new directory `cow-test/` and change into it.
2. Within `cow-test/`, create a new file with the following contents:

   ```
   #!/bin/sh
   echo "Hello world"
   ```

   Save the file, and make it executable:

   ```
   chmod +x hello.sh
   ```

3. Copy the contents of the first Dockerfile above into a new file called `Dockerfile.base`.
4. Copy the contents of the second Dockerfile above into a new file called `Dockerfile`.
5. Within the `cow-test/` directory, build the first image. Don't forget to include the final `.` in the command. That sets the `PATH`, which tells Docker where to look for any files that need to be added to the image.

   ```
   $ docker build -t acme/my-base-image:1.0 -f Dockerfile.base
   .

   Sending build context to Docker daemon  4.096kB
   Step 1/2 : FROM ubuntu:16.10
    ---> 31005225a745
   Step 2/2 : COPY . /app
    ---> Using cache
    ---> bd09118bcef6
   Successfully built bd09118bcef6
   Successfully tagged acme/my-base-image:1.0
   ```

6. Build the second image.

```
$ docker build -t acme/my-final-image:1.0 -f Dockerfile .

Sending build context to Docker daemon  4.096kB
Step 1/2 : FROM acme/my-base-image:1.0
 ---> bd09118bcef6
Step 2/2 : CMD /app/hello.sh
 ---> Running in a07b694759ba
 ---> dbf995fc07ff
Removing intermediate container a07b694759ba
Successfully built dbf995fc07ff
Successfully tagged acme/my-final-image:1.0
```

7. Check out the sizes of the images:

```
$ docker image ls

REPOSITORY                         TAG                      I
MAGE ID            CREATED            SIZE
acme/my-final-image                1.0                      d
bf995fc07ff        58 seconds ago     103MB
acme/my-base-image                 1.0                      b
d09118bcef6        3 minutes ago      103MB
```

8. Check out the layers that comprise each image:

```
$ docker history bd09118bcef6
IMAGE               CREATED             CREATED BY
                            SIZE                COMMENT
bd09118bcef6        4 minutes ago       /bin/sh -c #(nop) CO
PY dir:35a7eb158c1504e...   100B
31005225a745        3 months ago        /bin/sh -c #(nop)  C
MD ["/bin/bash"]            0B
<missing>           3 months ago        /bin/sh -c mkdir -p
/run/systemd && echo '...   7B
<missing>           3 months ago        /bin/sh -c sed -i 's
/^#\s*\(deb.*universe\...   2.78kB
<missing>           3 months ago        /bin/sh -c rm -rf /v
ar/lib/apt/lists/*          0B
<missing>           3 months ago        /bin/sh -c set -xe
 && echo '#!/bin/sh' >...   745B
<missing>           3 months ago        /bin/sh -c #(nop) AD
D file:eef57983bd66e3a...   103MB
```

```
$ docker history dbf995fc07ff

IMAGE               CREATED             CREATED BY
                            SIZE                COMMENT
dbf995fc07ff        3 minutes ago       /bin/sh -c #(nop)  C
MD ["/bin/sh" "-c" "/a...   0B
bd09118bcef6        5 minutes ago       /bin/sh -c #(nop) CO
PY dir:35a7eb158c1504e...   100B
31005225a745        3 months ago        /bin/sh -c #(nop)  C
MD ["/bin/bash"]            0B
<missing>           3 months ago        /bin/sh -c mkdir -p
/run/systemd && echo '...   7B
<missing>           3 months ago        /bin/sh -c sed -i 's
/^#\s*\(deb.*universe\...   2.78kB
<missing>           3 months ago        /bin/sh -c rm -rf /v
ar/lib/apt/lists/*          0B
<missing>           3 months ago        /bin/sh -c set -xe
 && echo '#!/bin/sh' >...   745B
<missing>           3 months ago        /bin/sh -c #(nop) AD
D file:eef57983bd66e3a...   103MB
```

Notice that all the layers are identical except the top layer of the second image. All the other layers are shared between the two images, and are only stored once in `/var/lib/docker/`. The new layer actually doesn't take any room at all, because it is not changing any files, but only running a command.

> Note: The `<missing>` lines in the `docker history` output indicate that those layers were built on another system and are not available locally. This can be ignored.

Copying makes containers efficient

When you start a container, a thin writable container layer is added on top of the other layers. Any changes the container makes to the filesystem are stored here. Any files the container does not change do not get copied to this writable layer. This means that the writable layer is as small as possible.

When an existing file in a container is modified, the storage driver performs a copy-on-write operation. The specifics steps involved depend on the specific storage driver. For the `aufs`, `overlay`, and `overlay2` drivers, the copy-on-write operation follows this rough sequence:

- Search through the image layers for the file to update. The process starts at the newest layer and works down to the base layer one layer at a time. When results are found, they are added to a cache to speed future operations.
- Perform a `copy_up` operation on the first copy of the file that is found, to copy the file to the container's writable layer.
- Any modifications are made to this copy of the file, and the container cannot see the read-only copy of the file that exists in the lower layer.

Btrfs, ZFS, and other drivers handle the copy-on-write differently. You can read more about the methods of these drivers later in their detailed descriptions.

Containers that write a lot of data consume more space than containers that do not. This is because most write operations consume new space in the container's thin writable top layer.

> Note: for write-heavy applications, you should not store the data in the container. Instead, use Docker volumes, which are independent of the running container and are designed to be efficient for I/O. In addition, volumes can be shared among containers and do not increase the size of your container's writable layer.

A `copy_up` operation can incur a noticeable performance overhead. This overhead is different depending on which storage driver is in use. Large files, lots of layers, and deep directory trees can make the impact more noticeable. This is mitigated by the fact that each `copy_up` operation only occurs the first time a given file is modified.

To verify the way that copy-on-write works, the following procedures spins up 5 containers based on the `acme/my-final-image:1.0` image we built earlier and examines how much room they take up.

> Note: This procedure doesn't work on Docker Desktop for Mac or Docker Desktop for Windows.

1. From a terminal on your Docker host, run the following `docker run` commands. The strings at the end are the IDs of each container.

```
$ docker run -dit --name my_container_1 acme/my-final-image:
1.0 bash \
  && docker run -dit --name my_container_2 acme/my-final-ima
ge:1.0 bash \
  && docker run -dit --name my_container_3 acme/my-final-ima
ge:1.0 bash \
  && docker run -dit --name my_container_4 acme/my-final-ima
ge:1.0 bash \
  && docker run -dit --name my_container_5 acme/my-final-ima
ge:1.0 bash

  c36785c423ec7e0422b2af7364a7ba4da6146cbba7981a0951fcc3fa04
30c409
  dcad7101795e4206e637d9358a818e5c32e13b349e62b00bf05cd5a434
3ea513
  1e7264576d78a3134fbaf7829bc24b1d96017cf2bc046b7cd8b08b5775
c33d0c
  38fa94212a419a082e6a6b87a8e2ec4a44dd327d7069b85892a707e3fc
818544
  1a174fc216cccf18ec7d4fe14e008e30130b11ede0f0f94a87982e310c
f2e765
```

2. Run the `docker ps` command to verify the 5 containers are running.

```
CONTAINER ID      IMAGE                     COMMAND     CREA
TED              STATUS              PORTS      NAMES
1a174fc216cc      acme/my-final-image:1.0   "bash"      Abou
t a minute ago   Up About a minute              my_container
_5
38fa94212a41      acme/my-final-image:1.0   "bash"      Abou
t a minute ago   Up About a minute              my_container
_4
1e7264576d78      acme/my-final-image:1.0   "bash"      Abou
t a minute ago   Up About a minute              my_container
_3
dcad7101795e      acme/my-final-image:1.0   "bash"      Abou
t a minute ago   Up About a minute              my_container
_2
c36785c423ec      acme/my-final-image:1.0   "bash"      Abou
t a minute ago   Up About a minute              my_container
_1
```

3. List the contents of the local storage area.

```
$ sudo ls /var/lib/docker/containers

1a174fc216cccf18ec7d4fe14e008e30130b11ede0f0f94a87982e310cf2
e765
1e7264576d78a3134fbaf7829bc24b1d96017cf2bc046b7cd8b08b5775c3
3d0c
38fa94212a419a082e6a6b87a8e2ec4a44dd327d7069b85892a707e3fc81
8544
c36785c423ec7e0422b2af7364a7ba4da6146cbba7981a0951fcc3fa0430
c409
dcad7101795e4206e637d9358a818e5c32e13b349e62b00bf05cd5a4343e
a513
```

4. Now check out their sizes:

```
$ sudo du -sh /var/lib/docker/containers/*

32K  /var/lib/docker/containers/1a174fc216cccf18ec7d4fe14e00
8e30130b11ede0f0f94a87982e310cf2e765
32K  /var/lib/docker/containers/1e7264576d78a3134fbaf7829bc2
4b1d96017cf2bc046b7cd8b08b5775c33d0c
32K  /var/lib/docker/containers/38fa94212a419a082e6a6b87a8e2
ec4a44dd327d7069b85892a707e3fc818544
32K  /var/lib/docker/containers/c36785c423ec7e0422b2af7364a7
ba4da6146cbba7981a0951fcc3fa0430c409
32K  /var/lib/docker/containers/dcad7101795e4206e637d9358a81
8e5c32e13b349e62b00bf05cd5a4343ea513
```

Each of these containers only takes up 32k of space on the filesystem.

Not only does copy-on-write save space, but it also reduces start-up time. When you start a container (or multiple containers from the same image), Docker only needs to create the thin writable container layer.

If Docker had to make an entire copy of the underlying image stack each time it started a new container, container start times and disk space used would be significantly increased. This would be similar to the way that virtual machines work, with one or more virtual disks per virtual machine.

Related information

- Volumes (https://docs.docker.com/storage/volumes/)
- Select a storage driver (https://docs.docker.com/storage/storagedriver/select-storage-driver/)

container (https://docs.docker.com/glossary/?term=container), storage (https://docs.docker.com/glossary/?term=storage), driver (https://docs.docker.com/glossary/?term=driver), AUFS (https://docs.docker.com/glossary/?term=AUFS), btfs (https://docs.docker.com/glossary/?term=btfs), devicemapper (https://docs.docker.com/glossary/?term=devicemapper), zvfs (https://docs.docker.com/glossary/?term=zvfs)