Containers

Software Architecture

Brae Webb

March 10, 2025

Question

What is a *container*?

Question

What is a *container*?

Answer

A way of *packaging software* and its dependencies such that the software can be run in numerous environments.

Okay...

How hard could that be?

Packaging software

```python
#!/usr/bin/env python3

import numpy as np
import re

my_arr = np.array([5, 2, 9, 7, 3])
max_element = np.max(my_arr)

duplicated_max = re.sub(".*", f"{max_element}", "X")
print(sum(int(x) for x in duplicated_max))
```

```
> ./program.py
18
```

demo

Transferring this software to client.

```
> ./program.py
/usr/bin/env: 'python3': No such file or directory
```

```
> ./program.py
/usr/bin/env: 'python3': No such file or directory
```

No Python interpreter installed, have to install Python and all it's dependencies.

```
> ./program.py
File "./program.py", line 9
    duplicated_max = re.sub(".*", f"{max_element}", "X")
                                            ^
SyntaxError: invalid syntax
```

```
> ./program.py
File "./program.py", line 9
    duplicated_max = re.sub(".*", f"{max_element}", "X")
                                                  ^
SyntaxError: invalid syntax
```

f-strings aren’t supported in Python 3.5! Have to upgrade to Python 3.6.

```
> ./program.py
Traceback (most recent call last):
  File "./program.py", line 3, in <module>
    import numpy as np
ModuleNotFoundError: No module named 'numpy'
```

```
> ./program.py
Traceback (most recent call last):
  File "./program.py", line 3, in <module>
    import numpy as np
ModuleNotFoundError: No module named 'numpy'
```

A Python dependency used by our code isn't installed. Have to install numpy (hopefully the right version...).

```
> ./program.py
9
```

```
> ./program.py
9
```

???

Question

Not so easy... what do we need?

A wall

A big wall around our environment so that we *know what software* we are actually depending upon.

A package

A way to box up all your software and dependencies so that it can be *transferred* and *run* in a different environment.

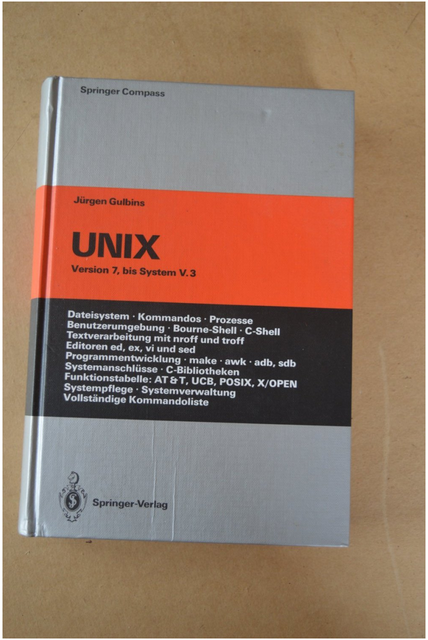
§ *A History of Containers* [1]

[1] This is a very Linux focused history — container technology also exists in the Windows world.

1979

Unix Version 7

Introducing... *chroot*



demo

Exploring *chroot*

Exploring *chroot*

```
> mkdir ./jail
> cd jail
> chroot . /bin/ls
chroot: failed to run command '/bin/ls': No such file or directory
> mkdir bin
> cp /bin/ls bin
> chroot . /bin/ls
chroot: failed to run command '/bin/ls': No such file or directory
```

Exploring *chroot*

```
> ldd /bin/ls
    libselinux.so.1 => /lib/x86_64-linux-gnu/libselinux.so.1 (0
        x00007f0097135000)
    libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f0096f0d000)
    libpcre2-8.so.0 => /lib/x86_64-linux-gnu/libpcre2-8.so.0 (0
        x00007f0096e76000)
    /lib64/ld-linux-x86-64.so.2 (0x00007f0097189000)
> cp --parents /lib/x86_64-linux-gnu/libselinux.so.1 /lib/x86_64-linux
    -gnu/libc.so.6 /lib/x86_64-linux-gnu/libpcre2-8.so.0 /lib64/ld-
    linux-x86-64.so.2 .
> ls
bin lib lib64
> ls lib/x86_64-linux-gnu/
libc.so.6 libpcre2-8.so.0 libselinux.so.1
```

Exploring *chroot*

```
> chroot . /bin/ls
bin lib lib64
> chroot . /bin/ls /
bin lib lib64
> chroot . /bin/ls ..
bin lib lib64
> chroot . /bin/ls /bin
ls
```

Chroot Limitations

- *Only filesystem isolation*
  - processes, network, etc. still accessible
- Not very *user friendly*
- Not very *portable*
- *Jailbreak* is possible

1992

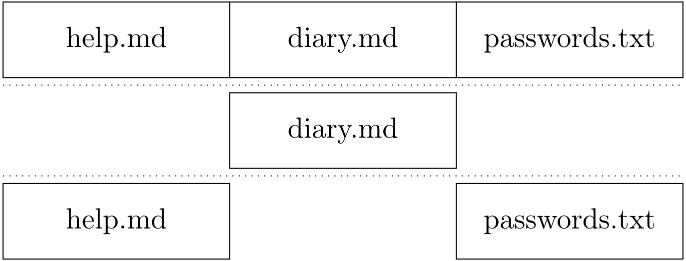
Plan 9

Introducing...
layered filesystem

Layered filesystem

- Projection on *read*
- Copy on *write*

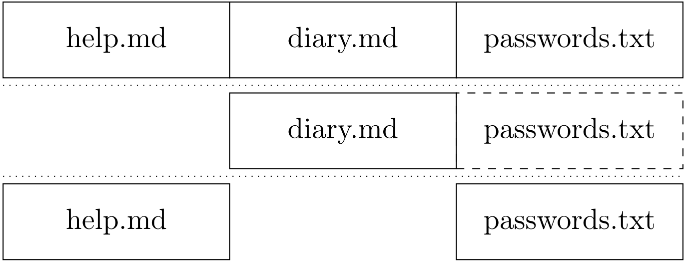
Projection on *read*




```
> ls
passwords.txt help.md diary.md
```

Copy on *write*

```
> echo "1234" >> passwords.txt
```



demo

Exploring a *layered filesystem*

Exploring a *layered filesystem*

```
> mkdir lower upper worker merged
> echo "password1234" >> lower/passwords.txt
> touch lower/help.md upper/diary.md
> mount -t overlay -o lowerdir=lower,upperdir=upper,workdir=worker
    none merged
```

Exploring a *layered filesystem*

```
> ls merged
diary.md help.md passwords.txt
> ls upper
diary.md
> ls lower
> cat lower/passwords.txt
password1234
> echo "1234" >> merged/passwords.txt
> cat merged/passwords.txt
password1234
1234
> ls upper
diary.md passwords.txt
> cat lower/passwords.txt
password1234
```

2002

Linux kernel 2.4.19

Introducing...

namespaces

Linux Namespaces

2002 *Mount* namespace

2006 *Unix Time-Sharing* namespace

2006 *Inter-process Communication* namespace

2008 *Process ID* namespace

2009 *Network* namespace

2013 *User* namespace

2016 *Control group* namespace

2008

LinuX Containers (LXC)

2013

PyCon 2013

Introducing...
Docker

Docker was the magic that made Linux containers usable for mere mortals.

– *Nigel Poulton*

§ The Language of Containers

Definition 0. Container

A *running process* created from a container image. Typically isolated from the host system.

Definition 0. Container Image

A set of files that can be used to *create a container*.

Container Image

```
> docker run -it ubuntu /bin/bash
root@f2b0b0c0b0b0:/# ls
bin dev home lib64 mnt proc run srv
root@f2b0b0c0b0b0:/# exit
```

```
> docker run -it ubuntu /bin/ls
bin dev home lib64 mnt proc run srv
```

Definition 0. Container Engine

A tool to *create* and *manage* containers. Often also manages container images.

Container Engines

- Docker
- rkt
- LXC
- runC
- Containerd
- CRI-O
- Podman

Creating a container image

To create a container image, we need to *create a collection of image layers*.

Fortunately, this is no longer a manual process...

To create a container image, we need to *create a collection of image layers*.

Fortunately, this is no longer a manual process...

Instead we use a *build file*, or image blueprints.

Definition 0. Build File

File containing the *instructions* for *creating a container image*.

Build File

```
» cat Dockerfile

FROM ubuntu
RUN apt-get update
RUN apt-get install -y cowsay
CMD ["/usr/games/cowsay", "Hello World"]
```

Build File

```
» cat Dockerfile
FROM ubuntu
RUN apt-get update
RUN apt-get install -y cowsay
CMD ["/usr/games/cowsay", "Hello World"]
```

```
> docker build -t cowsay .
```

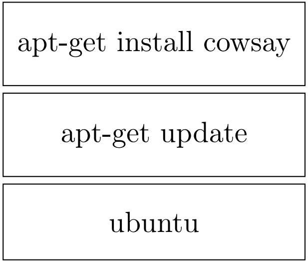
Build File

```
» cat Dockerfile

FROM ubuntu
RUN apt-get update
RUN apt-get install -y cowsay
CMD ["/usr/games/cowsay", "Hello World"]
```

```
> docker build -t cowsay .
```

```
> docker run cowsay
```

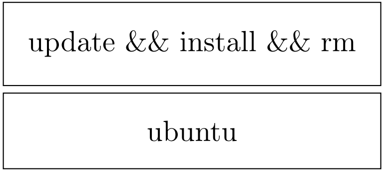
```
» cat Dockerfile

FROM ubuntu
RUN apt-get update
RUN apt-get install -y cowsay
CMD ["/usr/games/cowsay", "Hello World"]
```



```
» cat Dockerfile

FROM ubuntu
RUN apt-get update
RUN apt-get install -y cowsay
RUN rm -rf /var/lib/apt/lists/*
CMD ["/usr/games/cowsay", "Hello World"]
```

rm -rf /var/...
apt-get install cowsay
apt-get update
ubuntu

```
» cat Dockerfile

FROM ubuntu
RUN apt-get update && \
    apt-get install -y cowsay && \
    rm -rf /var/lib/apt/lists/*
CMD ["/usr/games/cowsay", "Hello World"]
```



Question

Where did *ubuntu* come from?

Question

Where did *ubuntu* come from?

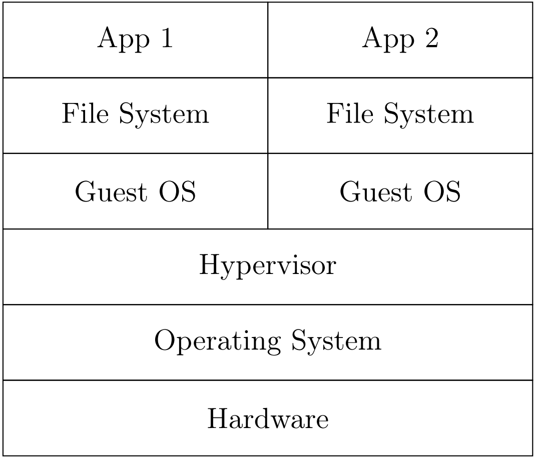
Answer

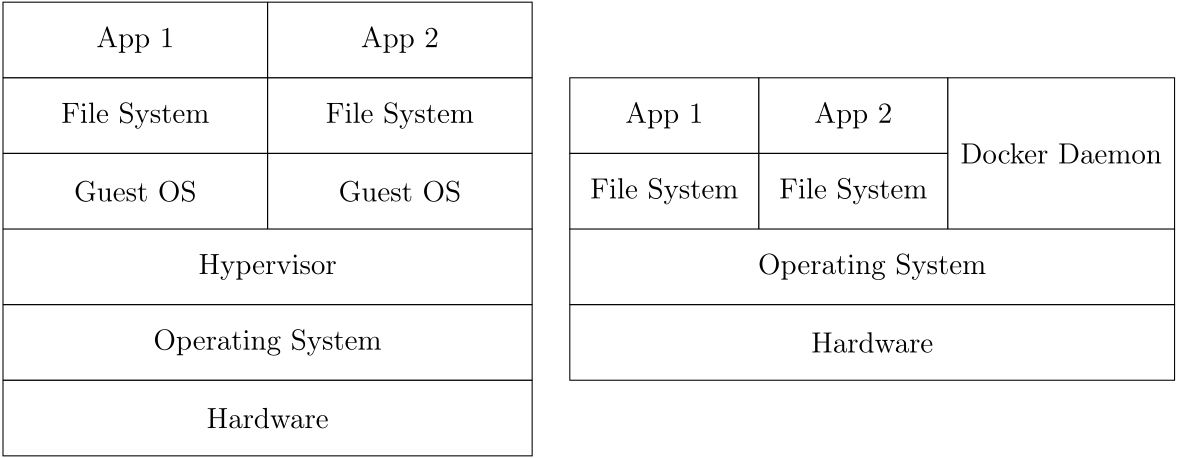
Our final definition — a *container registry*.

Definition 0. Container Registry

A file sharing platform that *hosts container images*. Container images are *pulled* (downloaded) from registries.

§ *Virtual Machines*


App 1
App 2
File System
File System
Guest OS
Guest OS
Hypervisor
Operating System
Hardware


App 1
App 2
File System
File System
Guest OS
Guest OS
Hypervisor
Operating System
Hardware
App 1
App 2
Docker Daemon
File System
File System
Operating System
Hardware

Isolation

Virtual machines are used for *machine isolation*.

Containers are used for *process isolation*.

Size Comparison

I want *10* flask servers running on Ubuntu 22.

$$\begin{aligned} \text{Ubuntu 22} &\simeq 3.8GB \\ \text{Python 3.6} &\simeq 232MB \\ \text{Flask} &\simeq 11.1MB \\ \text{My App} &\simeq 12K \end{aligned}$$

Virtual Machine

$$\begin{aligned} \text{Image Size} &= 3.8GB + 232MB \\ &\quad + 11.1MB + 12K \\ &= 4.04GB \\ \text{Total Space} &= 4.04GB * 10 \\ &= 40.4GB \end{aligned}$$

Container

$$\begin{aligned} \text{Image Size} &= 12K \\ \text{Layer Size} &= 3.8GB + 232MB + 11.1MB \\ &= 4.04GB \\ \text{Total Space} &= (12K * 10) + 4.04GB \\ &\simeq 4.04GB \end{aligned}$$

Question

When would I want a *virtual machine*?

Question

When would I want a *virtual machine*?

Answer

- Running a *different operating system*.
- *Unique hardware requirements* such as emulating old computer hardware.
- Where *security* is crucial virtual machines can offer greater isolation.

Question

When would I want a *container*?

Question

When would I want a *container*?

Answer

- Running a *single application*.
- *Lightweight* and *fast* to startup.
- Running *many containers* on the same system.

Combined Use Cases

Often virtual machines and containers are *combined*.

e.g. If you deploy containers on Google Kubernetes Engine, the containers run inside of virtual machines on Google's hardware.

§ *Use Cases*

Dependency Management

Containers provide a reliable, if brute force, way to *manage dependencies*.

Wrap the whole machine state up and ship it.

Continuous Integration

Containers allow developers to locally *replicate the same test environment* as the CI system.

Continuous Delivery

Containers allow teams to package, deploy, and manage applications more efficiently.

Containers can be used to *deploy* on cloud platforms or on-premise servers with *minimal manual configuration*.

Scaling

Containers allow applications to be *scaled up or down quickly and efficiently*.

Microservices

Containers make it easy to deploy and manage *individual services independently*.

Serverless

Containers are the basis for *serverless computing*.

§ *Docker*

```
$ docker build [context]
```

Summary

Run each instruction in the *blueprint (Dockerfile)* to *build* each layer resulting in the top-level layer (*image*).

Key parameters

- -f The Dockerfile to use (default: [context]/Dockerfile)
- -t The tag (name) of the image to build

```
$ docker run [image]
```

Summary

Run a *container* from the specified *image*.

Key parameters

- -d Run the container in the background
- -p Publish a container's port to the host
- -v Mount a volume
- -e Set environment variables
- -i Keep STDIN open even if not attached
- -t Allocate a pseudo-TTY

```
$ docker exec [container]
```

Summary

Run a command in a *running container*.

Key parameters

- **-d** Run the command in the background
- **-e** Set environment variables
- **-i** Keep STDIN open even if not attached
- **-t** Allocate a pseudo-TTY

```
$ docker ps
```

Summary

List running containers.

Key parameters

- -a Show all containers (default shows just running)
- -f Filter output based on conditions provided

```
$ docker stop [container]
```

Summary

Stop a running container.

Key parameters

-t Seconds to wait for stop before killing it

```
$ docker rm [container]
```

Summary

Remove a container.

Key parameters

- **-f** Force the removal of a running container (uses SIGKILL)
- **-v** Remove the volumes associated with the container

```
$ docker images
```

Summary

List images.

Key parameters

- -a Show all images (default hides intermediate images)
- -f Filter output based on conditions provided

```
$ docker rmi [image]
```

Summary

Remove an image.

Key parameters

-f Force removal of the image

```
$ docker pull [image]
```

Summary

Pull an image or a repository from a registry.

```
$ docker push [image]
```

Summary

Push an image or a repository to a registry.

§ *Examples*

Structurizr

```
> git clone git@github.com:CSSE6400/software-architecture.git
> cd software-architecture/slides/microkernel/c4_model
> docker run -it --rm -p 8080:8080 -v $(pwd):/usr/local/structurizr
    structurizr/lite
```

Open in browser: `http://localhost:8080`

GitLab

```
> mkdir gitlab
> export GITLAB_HOME=$(pwd)/gitlab
> docker run -it --rm -d -p 223:80 --shm-size 256m -v ${GITLAB_HOME}/
    config:/etc/gitlab -v ${GITLAB_HOME}/logs:/var/logs/gitlab -v ${
    GITLAB_HOME}/data:/var/opt/gitlab gitlab/gitlab-ee:latest
> cat ./gitlab/config/initial_password
```

Open in browser: `http://localhost:223`

Doom

```
> docker run -it --rm -p 224:6901 -e VNC_PW=password kasmweb/doom
    :1.12.0
```

Open in browser: `http://localhost:224`
Username: kasm_user
Password: password

§ Docker Compose

Exercise

We want to create *multiple* containers that *work together*.

Exercise

We want to create *multiple* containers that *work together*.

But we don't want to remember all the *commands to start and manage* the containers and get them to talk to each other…

When faced with tedium

Script it!

» cat start.sh

```
docker build -t frontend ./frontend
docker build -t backend ./backend

docker run -p 3000:3000 -v ./frontend:/app -e ... -d frontend
docker run -p 8081:8081 -v ./backend:/app -e ... -d backend
docker run -p 80:80 -v ./nginx.conf:/etc/nginx/nginx.conf -d nginx
```

This turns out to be very common...

This turns out to be very common…

Introducing… *Docker Compose*

```
» cat start.sh

docker build
    -t frontend
    ./frontend

docker run
    -p 3000:3000
    -v ./frontend:/app
    -e ...
    -d
    frontend
```

```
» cat docker-compose.yml

version: '3'
services:
  frontend:
    build:  ./frontend
    ports:
      - "3000:3000"
    volumes:
      - ./frontend:/app
    environment:
      - ...
  backend:
    build: ./backend
    ports:
      - "8081:8081"
    volumes:
```

```
$ docker-compose up
```

Summary

Create and run containers.

Key parameters

- **-d** Detached mode: Run containers in the background, print new container names.
- **–build** Rebuild containers if necessary.

```
$ docker-compose down
```

Summary

Stop and remove containers, networks, images, and volumes.

Key parameters

- **-v** Remove named volumes declared in the ‘volumes’ section of the Compose file and anonymous volumes attached to containers.
- **-t** Specify a shutdown timeout in seconds.

```
$ docker-compose ps
```

Summary

List containers.

```
$ docker-compose logs
```

Summary

View output from containers.

Key parameters

- -f Follow log output.

```
$ docker-compose exec [service]
```

Summary

Run a command in a running container.

Key parameters

- **-d** Detached mode: Run command in the background.
- **-T** Disable pseudo-tty allocation. By default 'docker-compose exec' allocates a TTY.
- **-e** Set environment variables.

```
$ docker-compose build
```

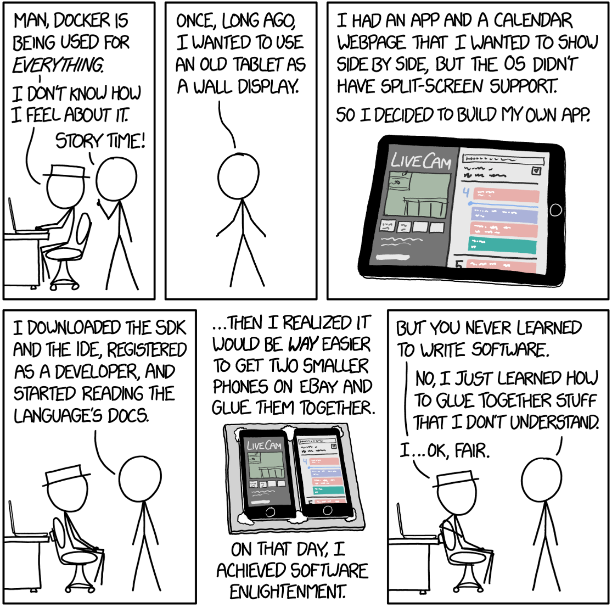
Summary

Build or rebuild services.

Key parameters

- –no-cache Do not use cache when building the image.
- –pull Always attempt to pull a newer version of the image.

In the practical this week...



https://xkcd.com/1988/