

Containers

Software Architecture

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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

```
1 #!/usr/bin/env python3\n\n3 import numpy as np\n4 import re\n\n6 my_arr = np.array([5, 2, 9, 7, 3])\n7 max_element = np.max(my_arr)\n\n9 duplicated_max = re.sub(".*", f"{max_element}", "X")\n10 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
```

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 it can be *transferred* and *run* in a different environment.

§ A History of Containers ¹

¹This 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...

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...

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

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

Build File

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

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

Build File

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

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

```
> docker run cowsay
```

< Hello World >

\ ^__^
 \ (oo)\-----
 (_)\)\/\/
 ||----w |
 || ||

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

apt-get install cowsay

apt-get update

ubuntu

```
» cat Dockerfile

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

```
rm -rf /var/...
```

```
apt-get install cowsay
```

```
apt-get update
```

```
ubuntu
```

```
» cat Dockerfile

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

update && install && rm

ubuntu

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.

\S *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 24.

Ubuntu 24 $\simeq 5.9GB$

Python 3.13.2 $\simeq 649MB$

Flask $\simeq 12MB$

My App $\simeq 12K$

Virtual Machine

$$\begin{aligned}\text{Image Size} &= 5.9GB + 649MB \\ &\quad + 12MB + 12K \\ &= 6.56GB\end{aligned}$$

$$\begin{aligned}\text{Total Space} &= 6.56GB * 10 \\ &= 65.6GB\end{aligned}$$

Container

$$\begin{aligned}\text{Image Size} &= 12K \\ \text{Layer Size} &= 5.9GB + 649MB + 12MB \\ &= 6.56GB\end{aligned}$$

$$\begin{aligned}\text{Total Space} &= (12K * 10) + 6.56GB \\ &\simeq 6.56GB\end{aligned}$$

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

1 docker build -t frontend ./frontend
2 docker build -t backend ./backend

4 docker run -p 3000:3000 -v ./frontend:/app -e ... -d frontend
5 docker run -p 8081:8081 -v ./backend:/app -e ... -d backend
6 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
```

```
1 docker build  
2     -t frontend  
3     ./frontend
```

```
5 docker run  
6     -p 3000:3000  
7     -v ./frontend:/app  
8     -e ...  
9     -d  
10    frontend
```

```
» cat docker-compose.yml
```

```
services:
```

```
    frontend:
```

```
        build: ./frontend
```

```
        ports:
```

```
            - "3000:3000"
```

```
        volumes:
```

```
            - ./frontend:/app
```

```
        environment:
```

```
            - ...
```

```
    backend:
```

```
        build: ./backend
```

```
        ports:
```

```
            - "8081:8081"
```

```
        volumes:
```

```
            - ./backend:/app
```

```
$ 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...



MAN, DOCKER IS
BEING USED FOR
EVERYTHING.
I DON'T KNOW HOW
I FEEL ABOUT IT.
STORY TIME!



ONCE, LONG AGO,
I WANTED TO USE
AN OLD TABLET AS
A WALL DISPLAY.



I HAD AN APP AND A CALENDAR
WEBPAGE THAT I WANTED TO SHOW
SIDE BY SIDE, BUT THE OS DIDN'T
HAVE SPLIT-SCREEN SUPPORT.
SO I DECIDED TO BUILD MY OWN APP.



I DOWNLOADED THE SDK
AND THE IDE, REGISTERED
AS A DEVELOPER, AND
STARTED READING THE
LANGUAGE'S DOCS.



...THEN I REALIZED IT
WOULD BE WAY EASIER
TO GET TWO SMALLER
PHONES ON EBAY AND
GLUE THEM TOGETHER.



ON THAT DAY, I
ACHIEVED SOFTWARE
ENLIGHTENMENT.

BUT YOU NEVER LEARNED
TO WRITE SOFTWARE.

NO, I JUST LEARNED HOW
TO GLUE TOGETHER STUFF
THAT I DON'T UNDERSTAND.

I...OK, FAIR.

