TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Macroarea di Ingegneria
Dipartimento di Ingegneria Civile e Ingegneria Informatica

Container-based virtualization: Docker

Corso di Sistemi Distribuiti e Cloud Computing
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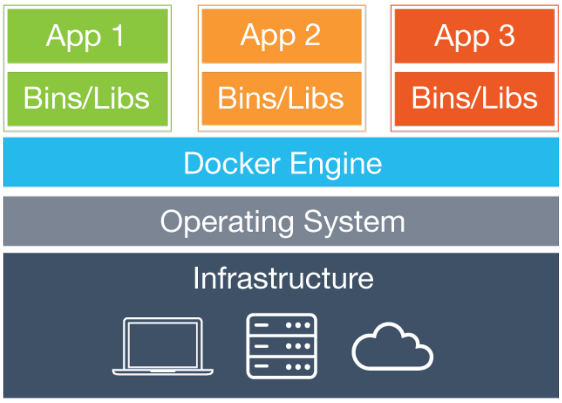
Valeria Cardellini

Laurea Magistrale in Ingegneria Informatica

Case study: Docker

- Lightweight, open and secure container-based virtualization
  - Containers include the application and all of its dependencies, but share the OS kernel with other containers
  - Containers run as an isolated process in userspace on the host OS
  - Containers are also not tied to any specific infrastructure

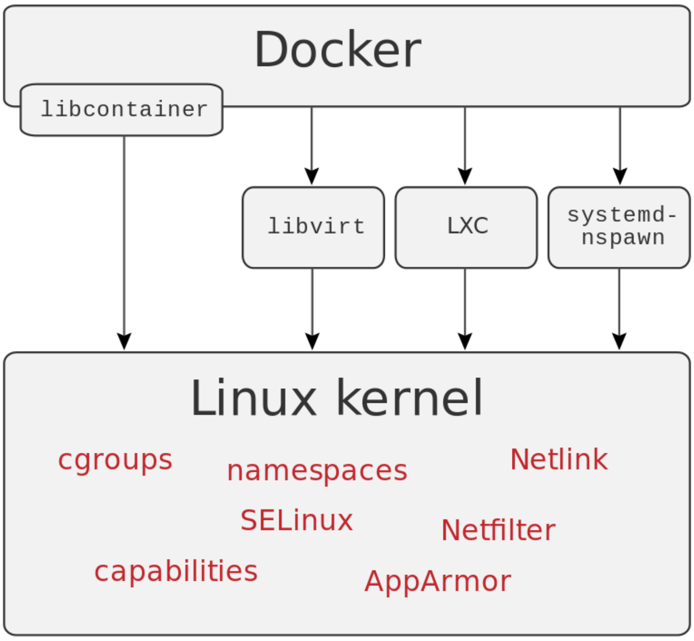


Docker internals

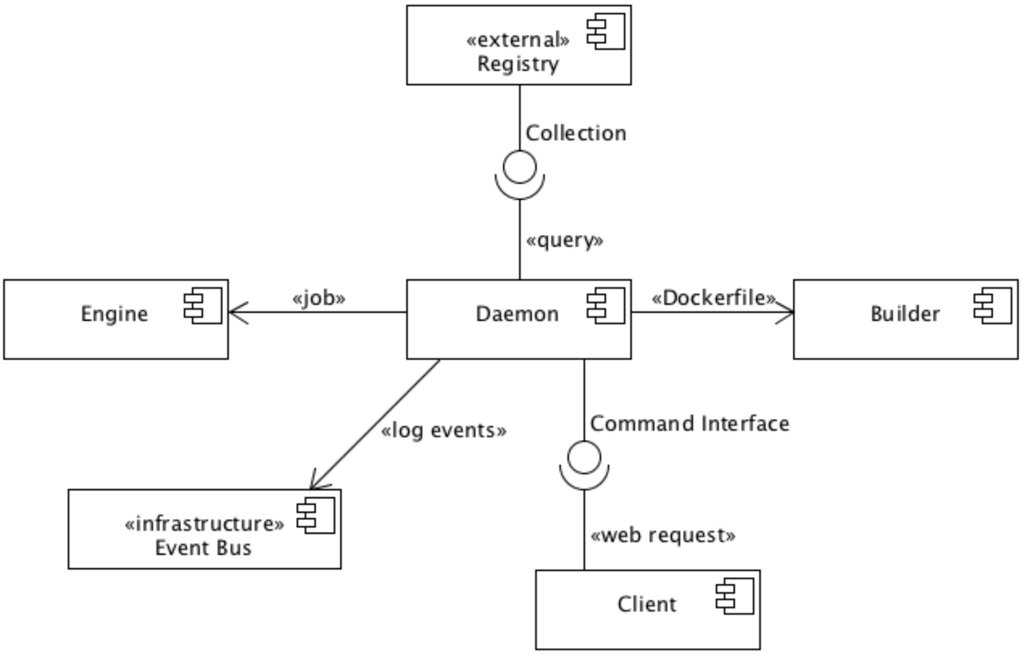
- Written in Go language
- With respect to other OS-level virtualization solutions, Docker is a higher-level platform that exploits Linux kernel mechanisms such as cgroups and namespaces
  - First versions were based on Linux Containers (LXC)
  - Then based on its own *libcontainer* runtime that uses Linux kernel namespaces and cgroups directly
- Features
  - Portable deployment across machines
  - Versioning, i.e., git-like capabilities
  - Component reuse
  - Shared libraries, see Docker Hub

Docker internals

- *libcontainer* (now included in *opencontainers/runc*): cross-system abstraction layer aimed to support a wide range of isolation technologies

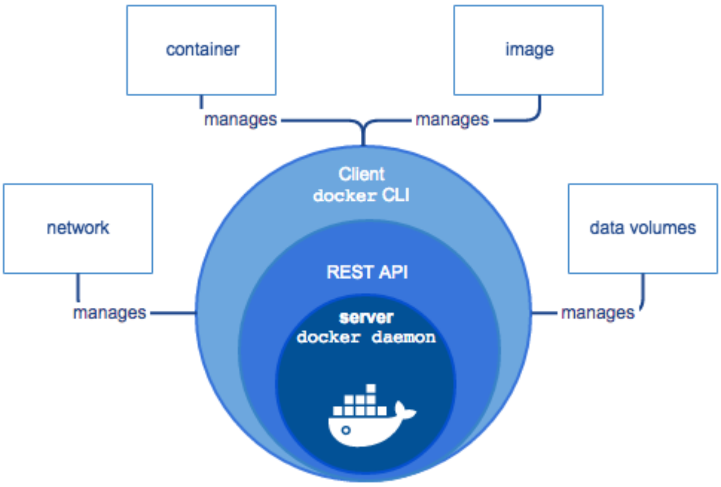


Component diagram of Docker



Docker engine

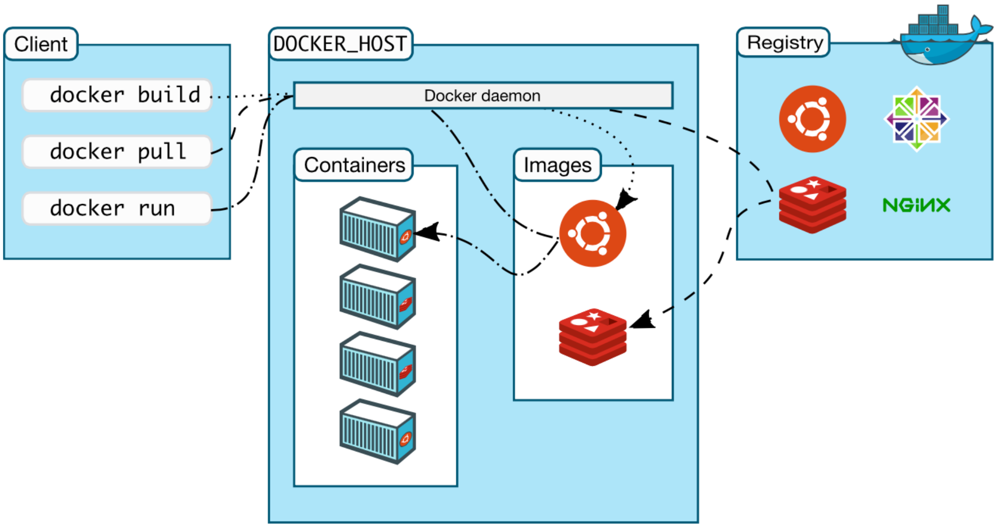
- *Docker Engine:* client-server application composed by:
  - Server, called Docker daemon
  - REST API which specifies interfaces that programs can use to control and interact with the daemon
  - Command line interface (CLI) client



See https://docs.docker.com/engine/docker-overview/

Docker architecture

- Docker uses a client-server architecture
  - The Docker *client* talks to the Docker *daemon*, which builds, runs, and distributes Docker containers
  - Client and daemon communicate via sockets or REST API



Docker image

- Read-only template used to create a Docker container
- ***Build*** component of Docker
  - Enables apps distribution with their runtime environment
    - Incorporates all the dependencies and configuration necessary to apps to run, eliminating the need to install packages and troubleshoot
  - Target machine must be Docker-enabled
- Docker can build images automatically by reading instructions from a **Dockerfile**
  - A text file with simple, well-defined syntax
- Images can be pulled and pushed towards a public/private registry
- Image name: [registry/][user/]name[:tag]
  - Default for tag is latest

Docker image: Dockerfile

- Image created from Dockerfile and context
  - Dockerfile: instructions to assemble the image
  - Context: set of files (e.g., application, libraries)
  - Often, an image is based on a parent image (e.g., alpine)
- Dockerfile syntax

```
# Comment
INSTRUCTION arguments
```

- Instructions in Dockerfile run in order
- Some instructions

`FROM`: to specify parent image (mandatory)

`RUN`: to execute any command in a new layer on top of current image and commit results

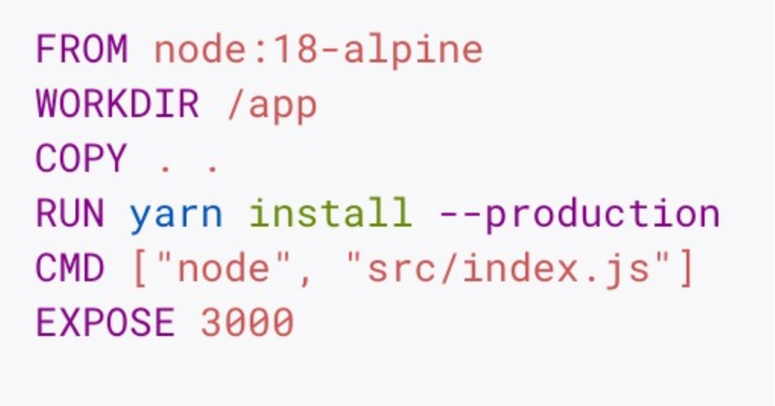
`ENV`: to set environment variables

`EXPOSE`: container listens on specified network ports at runtime

`CMD`: to provide defaults for executing container

Docker image: Dockerfile

- Example: Dockerfile to build the image of a container that will run a simple todo list manager written in Node.js



```
FROM node:18-alpine
WORKDIR /app
COPY . .
RUN yarn install --production
CMD ["node", "src/index.js"]
EXPOSE 3000
```

See https://docs.docker.com/get-started/02_our_app/

Docker image: build

- Build image from Dockerfile

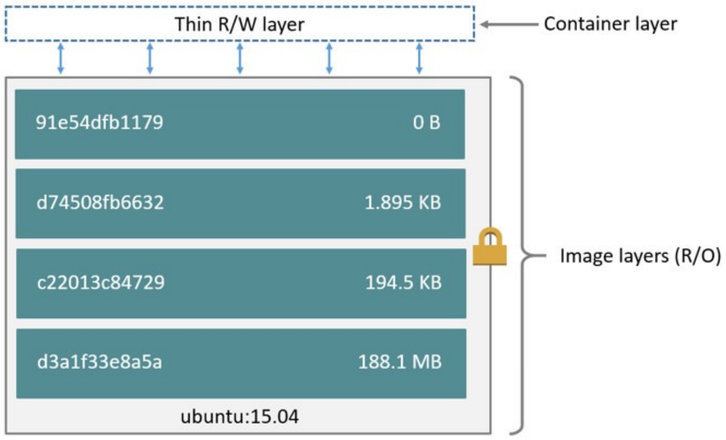
```
$ docker build [OPTIONS] PATH | URL | -
```

  - E.g., to build the image for Node.js app (see previous slide)

```
$ docker build -t getting-started .
```

Docker image: layers

- Each image consists of a *series of layers*
- Docker uses *union file systems* to combine these layers into a single unified view
  - Layers are stacked on top of each other to form a base for a container's root file system
  - Based on *copy-on-write* (CoW) strategy

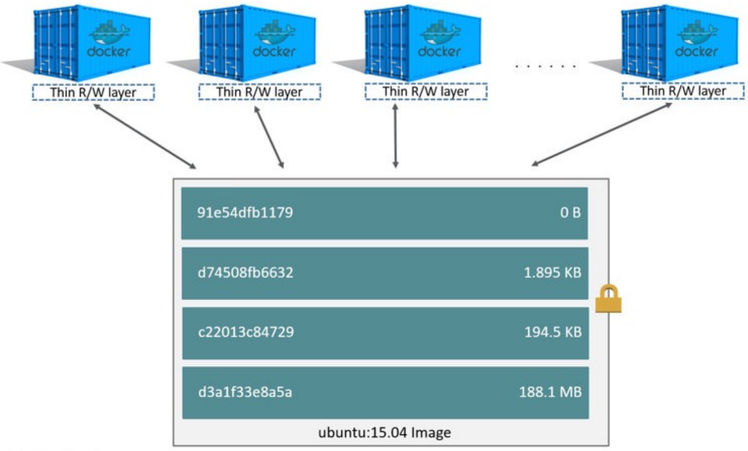


Container
(based on ubuntu:15.04 image)

Docker image: layers

- Layering pros
  - Enable layer sharing and reuse, installing common layers only once and saving bandwidth and storage space
  - Manage dependencies and separate concerns
  - Facilitate software specializations

  See https://docs.docker.com/storage/storagedriver/



Docker image: layers and Dockerfile

- Each layer represents an instruction in Dockerfile
  - Except `CMD` instruction, which specifies what command to run within the container: it only modifies image's metadata, without producing an image layer
- Each layer except the very last one is read-only
- Writable layer on top (aka *container layer*) is added when container is created
  - Changes made to running container (e.g., writing a file) are written to writable layer
  - Does not persist after container is deleted
  - Suitable for storing *ephemeral data* generated at runtime
- To inspect an image, including image layers

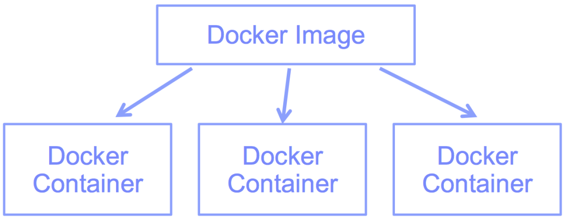
```
$ docker inspect imageid
```

Docker image: storage

- Containers are usually stateless (easier to scale, restart from failure, migrate)
  - Very little data written to container's writable layer
  - Data usually written on **Docker volumes**
  - Nevertheless: some workloads require to write data to container's writable layer
- Storage driver controls how *images* and *containers* are stored and managed on Docker host
- Multiple choices for storage driver
  - Including AuFS and Overlay2 (at file level), Device Mapper, btrfs and zfs (at block level)
  - Storage driver's choice can affect performance of containerized apps: optimized for space efficiency, but write speeds can be lower than native file system performance
  - See https://dockr.ly/2FstUe6

Docker container and registry

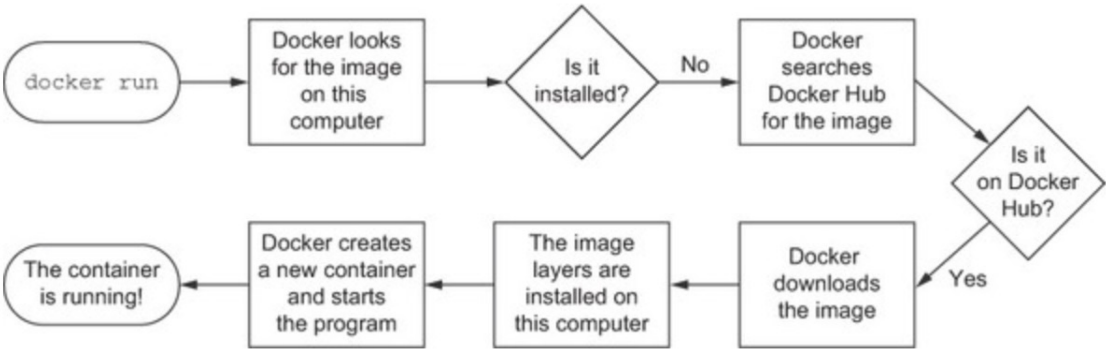
- Docker **container**: runnable instance of Docker image
  - ***Run*** component of Docker
  - Run, start, stop, move, or delete a container using Docker API or CLI commands
  - Docker containers are stateless: when a container is deleted, any data written not stored in a *data volume* is deleted



- Docker **registry**: stateless server-side application that stores and lets you distribute Docker images
  - ***Distribute*** component of Docker
  - Open library of images
  - Docker-hosted registries: Docker Hub, Docker Store (open source and enterprise verified images)

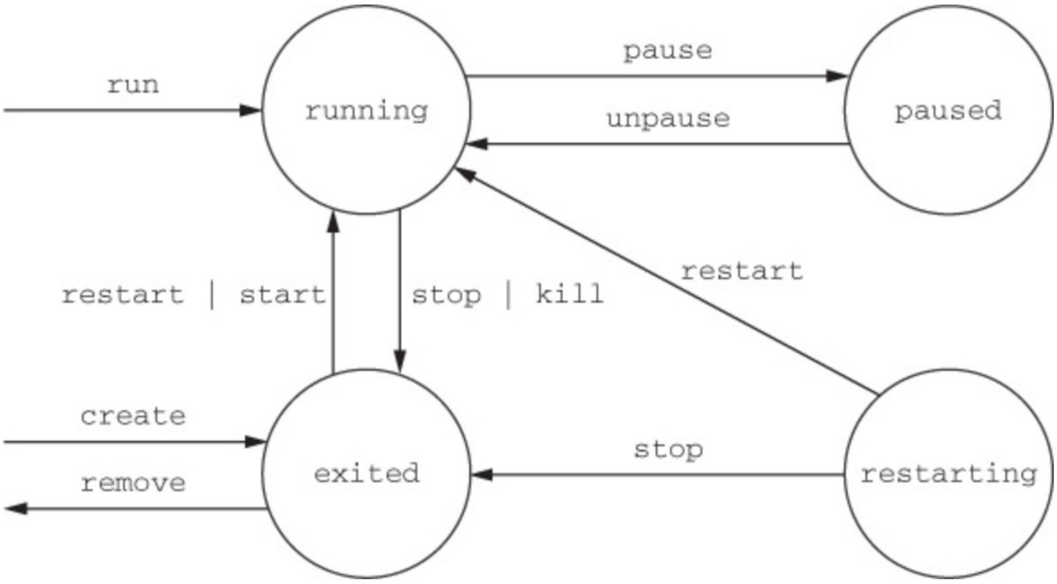
Docker: run command

- When you run a container whose image is not yet installed but is available on Docker Hub


docker run
Docker looks for the image on this computer
Is it installed?
No
Docker searches Docker Hub for the image
Is it on Docker Hub?
Yes
Docker downloads the image
The image layers are installed on this computer
Docker creates a new container and starts the program
The container is running!

Courtesy of "Docker in Action" by J. Nickoloff

State transitions of Docker containers



Courtesy of "Docker in Action" by J. Nickoloff

Commands: Docker info

- Obtain system-wide info on Docker installation

  ```
  $ docker info
  ```

  including:
  - How many images, containers and their status
  - Storage driver
  - Operating system, architecture, total memory
  - Docker registry

Commands: image handling

- List images on host (i.e., local repository)

  `$ docker images` alternatively, `$ docker image ls`
- List every image, including intermediate image layers:

  ```
  $ docker image ls -a
  ```
- Options to list images by name and tag, to list image digests (sha256), to filter images, to format the output
  - E.g., to list untagged images (`<none>`) that have no relationship to any tagged images (no longer used but consume disk space)

  ```
  $ docker images --filter "dangling=true"
  ```
- Remove an image

  ```
  $ docker rmi imageid
  ```

Can also use `imagename` instead of `imageid`

Command: run

```
$ docker run [OPTIONS] IMAGE [COMMAND] [ARGS]
```

- Most common options

`--name`	assign a name to the container
`-d`	detached mode (in background)
`-i`	interactive (keep STDIN open even if not attached)
`-t`	allocate a pseudo-tty
`--expose`	expose a range of ports inside the container
`-p`	publish a container's port or a range of ports to the host
`-v`	bind and mount a volume
`-e`	set environment variables
`--link`	add link to other containers

Commands: containers management

- List containers
  - Only running containers: `$ docker ps`
    - Alternatively, `$ docker container ls`
  - All containers (including stopped or killed containers):

    `$ docker ps -a`
- Manage container lifecycle
  - **Stop** running container

    `$ docker stop containerid`
  - **Start** stopped container

    `$ docker start containerid`
  - **Kill** running container

    `$ docker kill containerid`
  - **Remove** container (need to stop it before attempting removal)

    `$ docker rm containerid`

Can also use `containername` instead of `containerid`

Commands: containers management

- Stop and remove a running container

```
$ docker ps
$ docker stop containerid
$ docker ps -a
$ docker rm containerid
```

- Stop all containers

```
$ for i in $(docker ps -q); do docker stop $i; done
```

Commands: containers management

- Inspect a container
  - Most detailed view of the environment in which a container was launched

```
$ docker inspect containerid
```

- Copy files from and to container

```
$ docker cp containerid:path localpath
$ docker cp localpath containerid:path
```

Docker volumes

- Preferred mechanism for persisting data generated by and used by Docker containers
  - New directory is created within Docker's storage directory on host machine, and Docker manages that directory's contents
  - Directory does not need to exist on host, it is created on demand if it does not yet exist

- To mount a volume, use `-v` or `--mount` flag
- More commands:
  - Create volume: `$ docker volume create my-vol`
  - List volumes: `$ docker volume ls`
  - Inspect volume: `$ docker volume inspect my-vol`
  - Remove volume: `$ docker volume rm my-vol`

Docker volumes

- Example: start nginx container with volume

```
$ docker run -d \
--name devtest \
-v myvol2:/app \
nginx:latest
```

Docker volumes

- Pros
  - Completely managed by Docker
  - Easy to back up or migrate
  - Managed using Docker CLI commands or Docker API
  - Work on both Linux and Windows containers
  - Can be shared among multiple containers
  - Content can be encrypted
  - Content can be pre-populated
  - Better choice than persisting data in a container's writable layer: a volume does not increase the size of the containers using it, and its contents exist outside the container lifecycle

Hands-on Docker

- Download and install Docker
  - Available on multiple platforms

  https://docs.docker.com/get-docker/
  https://docs.docker.com/get-started/

- Test Docker version

```
$ docker --version
```

- Test Docker installation by running hello-world Docker image

```
$ docker run hello-world
```

Hands-on Docker

- Run "Hello World" container with a command

```
$ docker run alpine /bin/echo 'Hello world'
```

  - alpine: lightweight Linux distro with reduced image size

- Use commands to:
  - List containers and container images
  - Remove containers and container images

Hands-on Docker

- Run nginx Web server inside a container
  - Bind container to specific port

```
$ docker run -dp 80:80 --name web nginx
```

Option `-p`: publish container port (80) to host port (80)

Option `-d`: detached mode

1. Send HTTP request through Web browser
   - First retrieve hostname of host machine (e.g., localhost)
2. Send HTTP request through interactive container using a bridge network

```
$ docker network create my_net
$ docker run -dp 80:80 --name web --net=my_net nginx
$ docker run -i -t --net=my_net --name web_test busybox
/ # wget -O - http://web:80/
/ # exit
```

Hands-on Docker

- Running Apache web server with minimal index page
  1. Define container image with Dockerfile
     - Define image starting from Ubuntu, install and configure Apache
     - Incoming port set to 80 using EXPOSE instruction

```
FROM ubuntu:18.04

# Install dependencies
RUN apt-get update -y
RUN apt-get -y install apache2
# Install apache and write hello world message
RUN echo 'Hello World!' > /var/www/html/index.html
# Configure apache
RUN echo '. /etc/apache2/envvars' > /root/run_apache.sh
RUN echo 'mkdir -p /var/run/apache2' >> /root/run_apache.sh
RUN echo 'mkdir -p /var/lock/apache2' >> /root/run_apache.sh
RUN echo '/usr/sbin/apache2 -D FOREGROUND' >> /root/run_apache.sh
RUN chmod 755 /root/run_apache.sh

EXPOSE 80
CMD /root/run_apache.sh
```

Hands-on Docker

2. Build container image from Dockerfile

```
$ docker build -t hello-apache .
```

3. Run container and bind

```
$ docker run -dp 80:80 hello-apache
```

- To reduce Docker image size let’s improve the Dockerfile: avoid adding unnecessary layers
- E.g., update and install multiple packages in a single RUN instruction
  - Use \ to type out the command in multiple lines

Hands-on Docker

```
FROM ubuntu:18.04

# Install dependencies
RUN apt-get update –y && \
 apt-get -y install apache2

# Install apache and write hello world message
RUN echo 'Hello World!' > /var/www/html/index.html

# Configure apache
RUN echo '. /etc/apache2/envvars' > /root/run_apache.sh && \
 echo 'mkdir -p /var/run/apache2' >> /root/run_apache.sh && \
 echo 'mkdir -p /var/lock/apache2' >> /root/run_apache.sh && \
 echo '/usr/sbin/apache2 -D FOREGROUND' >> /root/run_apache.sh && \
 chmod 755 /root/run_apache.sh

EXPOSE 80

CMD /root/run_apache.sh
```

Configuring container memory and CPU

- By default, a container has no resource constraints
  - Can use as much resource as host's kernel scheduler allows

- Docker provides ways to control how much memory or CPU a container can use by setting runtime configuration flags of `docker run` command
  https://docs.docker.com/config/containers/resource_constraints/
  - Docker engine implements configuration changes by modifying settings of container's `cgroup`

Configuring container memory

- Avoid running out of memory (OOM)
  - Individual containers can be killed (Docker daemon has lower OOM priority, containers default one)
- Docker can enforce hard or soft memory limits
  - Hard limits: container cannot use more than a given amount of user or system memory; `--memory` flag
  - Soft limits: container can use as much memory as it needs unless certain conditions are met, such as when kernel detects contention or low memory on host machine
  - Example: limit container to use at most 500 MB of memory (hard limit) and specify also a soft limit

```
$ docker run –it --memory-reservation="300m" \
  --memory="500m" ubuntu /bin/bash
```

Configuring container CPU

- Various constraints to limit container usage of host machine's CPU cycles
- Some options

  `--cpus=<value>`: limit how many CPU resources a container can use (hard limit)

  `--cpu-quota=<value>`: set CPU Completely Fair Scheduler (CFS) quota on container

  `--cpuset-cpus`: limit specific CPUs or cores a container can use

  `--cpu-shares`: set to value >/< 1024 to increase/reduce container's weight, and give it access to greater/less proportion of CPU cycles (soft limit)

  - Example: limit container to use at most 50% of CPU every second

```
$ docker run -it --cpus=".5" ubuntu /bin/bash
```

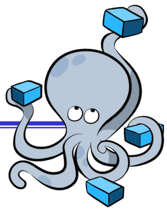
Alternatively,

```
$ docker run -it --cpu-period=100000 \
--cpu-quota=50000 ubuntu /bin/bash
```

Multi-container Docker applications

- How to run multi-container Docker apps?
- **Docker Compose**
  - Deployment only on single host
- Docker Swarm
  - Native orchestration tool for Docker
  - Deployment on multiple hosts
- Kubernetes
  - Deployment on multiple hosts
  - See next lesson

Docker Compose



- To coordinate execution of multiple containers running on a single host https://docs.docker.com/compose/
  - Bundled within Docker Desktop https://docs.docker.com/compose/install/
- Allows to easily express the containers to be instantiated at once, and their relationships
- Runs the composition on a single Docker engine
  - To deploy containers on multiple nodes use either Docker Swarm or Kubernetes

Docker Compose

- Specify how to compose containers in an easy-to-read YAML file named `docker-compose.yml`

- To start Docker composition (background `-d`):

```
$ docker compose up -d
```

- By default, Docker Compose looks for `docker-compose.yml` in current working directory
  - Can specify different file using `-f` flag

```
$ docker compose -f composefile up -d
```

- To stop Docker composition:

```
$ docker compose down
```

Docker Compose file

- Different versions of Docker Compose file format

https://docs.docker.com/compose/compose-file/

Latest: Docker Compose 1.27 implements format defined by Compose Specification

```
version: '3'

services:
    storm-nimbus:
        image: storm
        container_name: nimbus
        command: storm nimbus
        depends_on:
            - zookeeper
        links:
            - zookeeper
        ports:
            - "6627:6627"

    zookeeper:
        image: zookeeper
        container_name: zookeeper
        ports:
            - "2181:2181"

    worker1:
        image: storm
        command: storm supervisor
        depends_on:
            - storm-nimbus
            - zookeeper
        links:
            - storm-nimbus
            - zookeeper
```

Docker Compose: example

- Simple Python web app running on Docker Compose
  - 2 containers: Python web app and Redis
  - Use Flask framework and maintain hit counter in Redis
  - Redis: open-source, networked, in-memory, key-value data store
  - See https://docs.docker.com/compose/gettingstarted/
- Steps:
  1. Write Python app
  2. Define Python container image with Dockerfile
  3. Define services in Compose file →
     - Two services: web (image defined by Dockerfile) and redis (image pulled from Docker Hub)

```
version: "3.9"
services:
  web:
        build: .
        ports: - 8000:5000"
  redis:
        image: "redis:alpine"
```

Docker Compose: example

- Steps (cont'd):
  4. Build and run app with Compose
     `$ docker compose up -d`
  5. Send HTTP requests using curl or browser (counter is increased)
  6. Stop Compose, bringing everything down
     `$ docker compose down`

- Examples of Compose files
  https://github.com/docker/awesome-compose

Docker Compose: some features

- Add volume for `web` app to keep its code, so that code can be modified on the fly without rebuilding the image

- Specify restart policy for containers in Compose file
  - Options: `on-failure[:max-retries]`, `always`, `unless-stopped`

- Start multiple replicas of same container using either option `--scale` or `scale` subsection in Compose file
  - e.g., `docker compose --scale web=2 up -d`
  - Use also port ranges in Compose file
  - Alternatively, use `deploy` subsection in Compose file https://docs.docker.com/compose/compose-file/deploy/

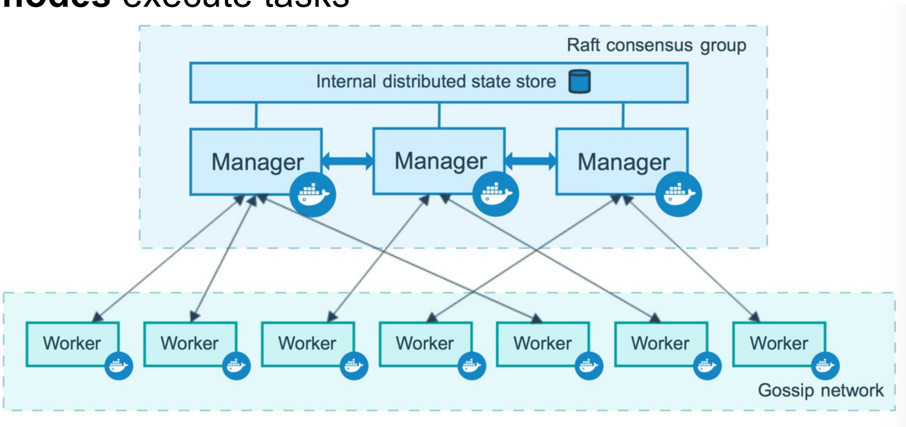
- Examples of Compose files https://github.com/docker/awesome-compose

Docker Swarm

- Docker includes swarm mode for natively managing a cluster of Docker Engines, called *swarm* https://docs.docker.com/engine/swarm/
- Tasks: containers running in a service
- Main features of swarm mode:
  - **Scaling:** number of tasks for each service
    - But auto-scaling is not supported
  - **State reconciliation:** Swarm monitors cluster state and reconciles any differences w.r.t. desired state (e.g., replace containers after host failure)
  - **Multi-host networking:** to specify an overlay network among services
  - **Load balancing:** allows to expose the ports for services to an external load balancer; internally, the swarm lets you specify how to distribute containers among nodes

Docker Swarm: architecture

- A *swarm* consists of multiple Docker engines which run in swarm mode
- Node: instance of Docker engine
  - **Manager node(s):** handles cluster management, including scheduling tasks to worker nodes
    - Multiple managers to improve fault tolerance
    - Raft as consensus algorithm to manage global cluster state
  - **Worker nodes** execute tasks



Docker Swarm: Swarm cluster

- Create a swarm: manager node

```
$ docker swarm init --advertise-addr <MANAGER-IP>
Swarm initialized: current node (<nodeid>) is now a manager.
To add a worker to this swarm, run the following command:

   docker swarm join --token <token> <manager-ip>:port
```

- Create a swarm: add worker node(s)

```
$ docker swarm join --token <token> <manager-ip>:port
```

- Inspect swarm status

```
$ docker info
```

```
$ docker node ls

ID             HOSTNAME      STATUS        AVAILABILITY    MANAGER STATUS
<nodeid> *     manager1      Ready         Active          Leader
<nodeid>       worker1       Ready         Active
```

Docker Swarm: Swarm cluster

- Leave the swarm
  - If the node is a manager node, warning about maintaining the quorum (to override warning, `--force` flag)

```
$ docker swarm leave
```

- After a node leaves the swarm, you can run
  `docker node rm`
  on a manager node to remove the node from the node list

```
$ docker node rm <node-id>
```

Docker Swarm: manage services

- Deploy a service to the swarm (from manager node)

```
$ docker service create -d --replicas 1 \
    --name helloworld alpine ping docker.com
```

  - Deploy service `helloworld`, with 1 running instance; arguments `alpine ping docker.com` define service as an Alpine Linux container that executes `ping docker.c`

- List running services

```
$ docker service ls
```

```
ID           NAME          MODE        REPLICAS  IMAGE          PORTS
<serviceid>  helloworld    replicated  1/1       alpine:latest
```

Docker Swarm: manage services

- Inspect service

```
$ docker service inspect --pretty <SERVICE-ID>
$ docker service ps <SERVICE-ID>
```

```
ID          NAME         IMAGE         NODE      DESIRED ST CURRENT ST  ERROR  PORTS
<cont.id1> helloworld.1 alpine:latest manager1  Running    Running …
<cont.id2> helloworld.2 alpine:latest worker1   Running    Running …
```

- Inspect container

```
$ docker ps <cont.id1>
```

```
# Manager node
CONTAINER ID  IMAGE          COMMAND            CREATED    STATUS    ... NAMES
<cont.id1>    alpine:latest  "ping docker.com"  2 min ago  Up 2 min helloworld.1.iuk1sj…

# Worker node
CONTAINER ID  IMAGE          COMMAND            CREATED    STATUS    ... NAMES
<cont.id2>    alpine:latest  "ping docker.com"  2 min ago  Up 2 min helloworld.2.skfos4…
```

Docker Swarm: manage services

- Scale number of containers in the service

```
$ docker service scale <SERVICE-ID>=<NUMBER-OF-TASKS>
```

  - Swarm manager will enact the updates
- Apply *rolling updates* (i.e., update without downtime) to a service

```
$ docker service update --limit-cpu 2 redis
$ docker service update --replicas 2 helloworld
```

- Roll back an update to the previous version of a service

```
$ docker service rollback [OPTIONS] <SERVICE-ID>
```

- Remove a service

```
$ docker service rm <SERVICE-ID>
```