Containers and Orchestration: a Security Perspective

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Cloud applications

- Traditional applications and **monolithic**
  - Everything is tightly coupled
  - On full servers, managed from OS to deployment
    - This is a constraint on the user
- In the cloud, you don't manage real servers
  - You share servers, thanks to virtualization
  - You get new resources ("servers") on-the-fly
- We can drive this model further!

Cloud native applications

- **No OS** management by the user
- **Component-level** application scalability

Introducing: containers

- Cloud users do not want to run OSes
  - They want to run their **applications**
- How to share cloud resources closer to the applications?
  - Virtualization layer just between the OS and the application
- Virtualize the OS for multiple applications at the same time!
  - In other words, containers are OS-level virtualization
- An OS executes a **container runtime** that uses a **container engine** to run **containers**
  - Docker, LXC, OpenVZ…

Actors of OS-level virtualization

1. Container runtime
2. Container engine
3. Container

Containers runtimes

- **High-level management** of containers, artifacts and runtime configuration
  - Business-oriented container lifecycle
  - Build, download container images
  - Configure networking, volumes, security, etc.
- A **container image** packages an application and its runtime
  - Business core, dependencies, pre-configuration
- Ecosystem of reusable images stored in **registries** (DockerHub, GitLab registries, local registry…)
  - Images are built immutable for portability, reusability and composability
- Examples: Docker (containerd), Podman, Apptainer…

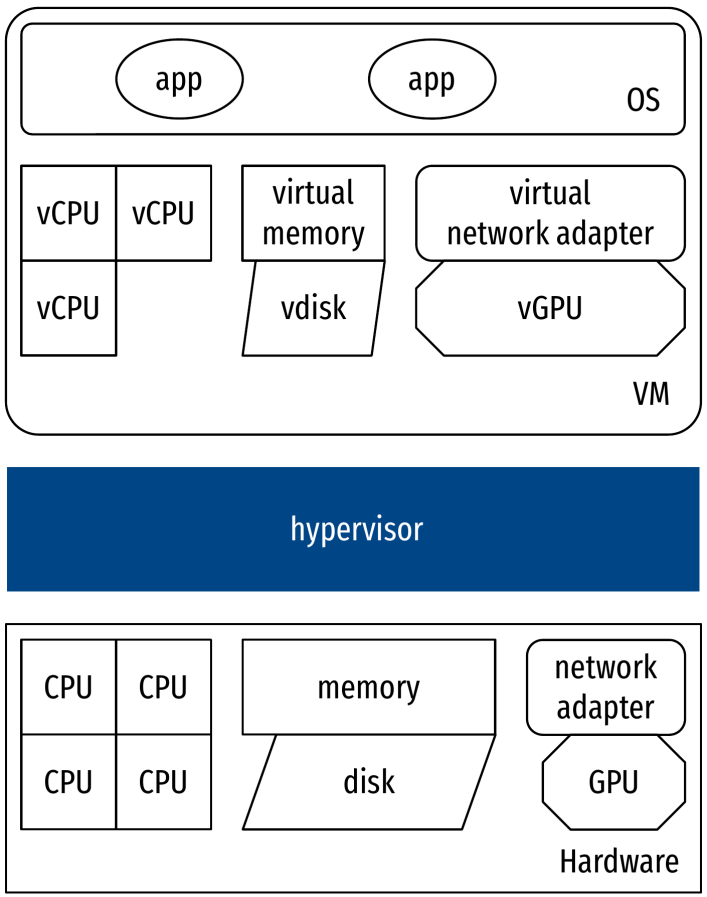
Container engines

- **Low-level management** of containers
  - Create, start, stop, destroy…
  - Prepare images for usage
  - Last-mile setup of networking, mounts, security…
- Different engines for different usages or orientations: generic, security-oriented, scientific…
- Examples: runc, Kata Container, gVisor, wasmtime…

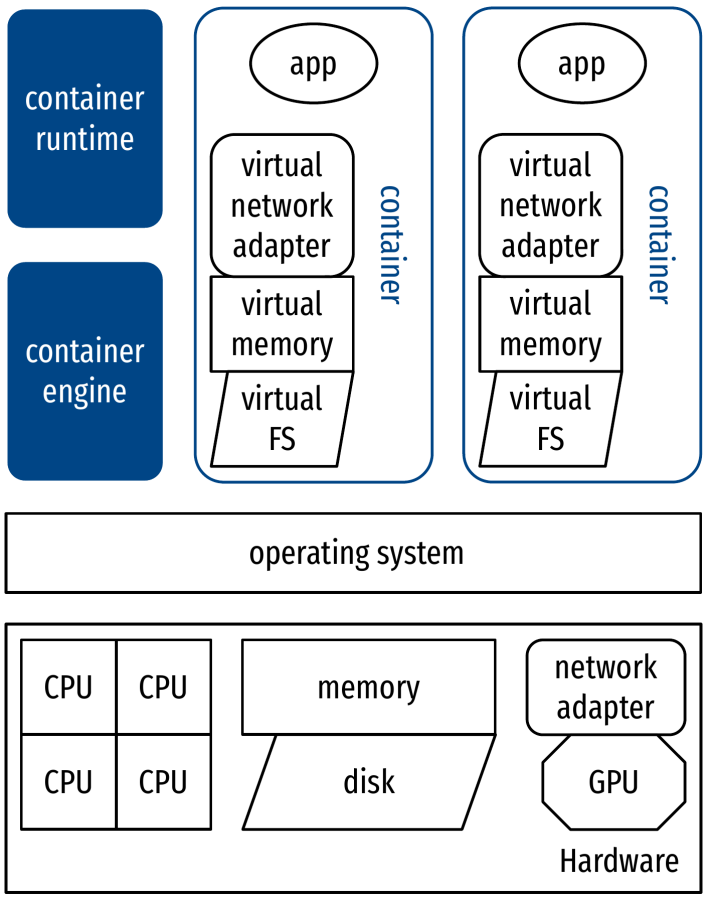
Containers

- **Container:** isolated and limited virtual copy of the host OS
  - Deploys the image to “fill in” the virtual copy
- **Isolation:** users, devices, processes…
  - Virtual filesystem: built from container image
- **Limits:** CPU, memory, I/O…
  - Also monitoring

Comparison with hardware virtualization: stack



Stack for hardware virtualization.



Stack for OS-level virtualization.

Comparison with hardware virtualization: features

Comparison of features between hardware and OS-level virtualization techniques.

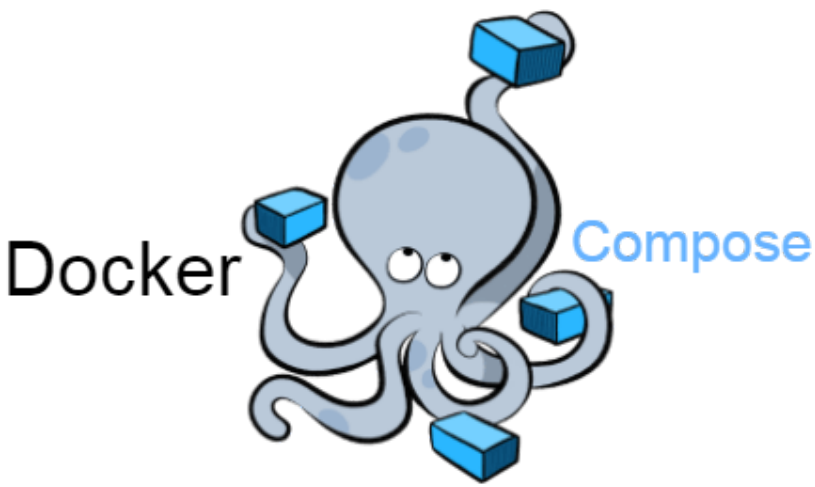
	Operating system-level virtualization	Hardware virtualization
Security	-	+
Usability	++	-
Performance	0	0
Startup time	+	- -
Image size	+	- -
Memory overhead	+	- -

- Containers are better overall for **cloud-native applications**
  - Applications are architectured to be deployed on the cloud
- Security concerns
  - Kernel shared between containers
- **VMs still have use cases:** persistent, interactive environments, robustness, first-level resource provisioning...

Demo: Docker

- Creation and usage of a Docker container
  - Run an interactive image
  - Pull and run a daemon service
  - List images, monitor containers
- Docker is rather “low-level” for applications: compose multiple components (containers) in a single application with Docker Compose

Docker logo.



Docker Compose logo.

Building containers: two ways

1. Interactively
    1. From a base distribution image
    - Linux distributions: Ubuntu, Alpine…
    - Runtime distributions (based on Linux distributions): Python…
    2. Use the package manager to add software
    3. `docker commit` tags the current state of the container as an image
    - Efficient for testing and experimenting
2. Writing a **Dockerfile**
    - DSL to describe how to install and configure the bundled applications
    - Proper method: clean, reusable, reproducible, auditable…

Building containers with a Dockerfile

```
# Starting from a base image.
FROM alpine

# Execute commands to build and configure the image.
RUN apk add --no-cache perl

# Add local files.
COPY cowsay /usr/local/bin/cowsay
COPY docker.cow /usr/local/share/cows/default.cow

# Set the default executable.
ENTRYPOINT ["/usr/local/bin/cowsay"]
```

Sample Dockerfile for docker/cowsay.

- Build the image with `docker build --tag namespace/name:tag`
- Can start from an empty image: `FROM scratch`
  - Rarely used, only by base images of distributions, where the image is built from an archive
- May also include users, volumes, network ports…

Security of containers

1. Isolation
2. Threat models and vectors
3. Good practices

Isolation

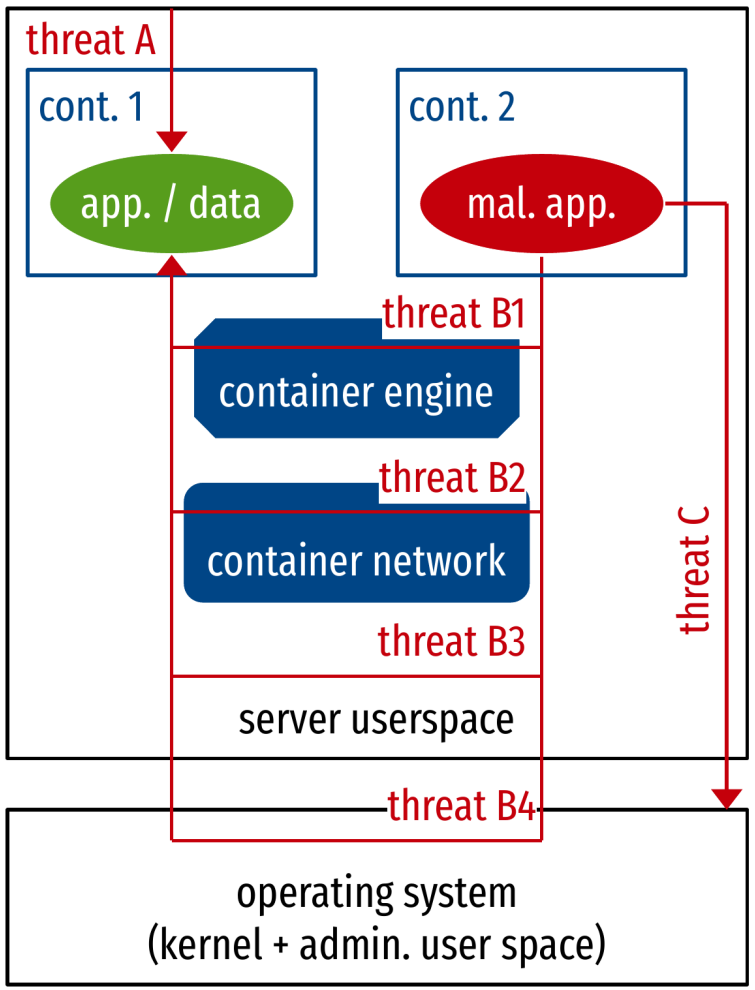
- Fundamental issue for cloud providers: execute untrusted code
- When using containers: **tenants and provider share the kernel**
  - No mitigation when the kernel is compromised
  - Incompatibility of kernel-level security policies
    - Because security measures are mostly not namespaces (AppArmor, etc.)
  - Vast attack surface and trusted code base
    - Virtual Machines (VMs) are better in this regard (hypervisor interface vs. whole host kernel)
- **Isolation** of untrusted code
  - To protect containers from each other
  - To protect the system from containers

Threat models: goals and targets

- Attack goals:
  - **Disrupt services**: bad neighbor, denial of service
  - **Subvert services**: steal identity, steal resources
  - **Steal data**
- Targets are cloud-oriented: applications are **regular services**
  - Mostly web servers or applications accessed by HTTP requests
  - But sometimes containers include system services
    - SSH, cron jobs, logs…
    - More privileged requirements => more care!

Threat models: overview

1. direct attack from outside, on the containerized application
2. indirect attack from a container, on another containerized application
3. attack from a container, on the host system



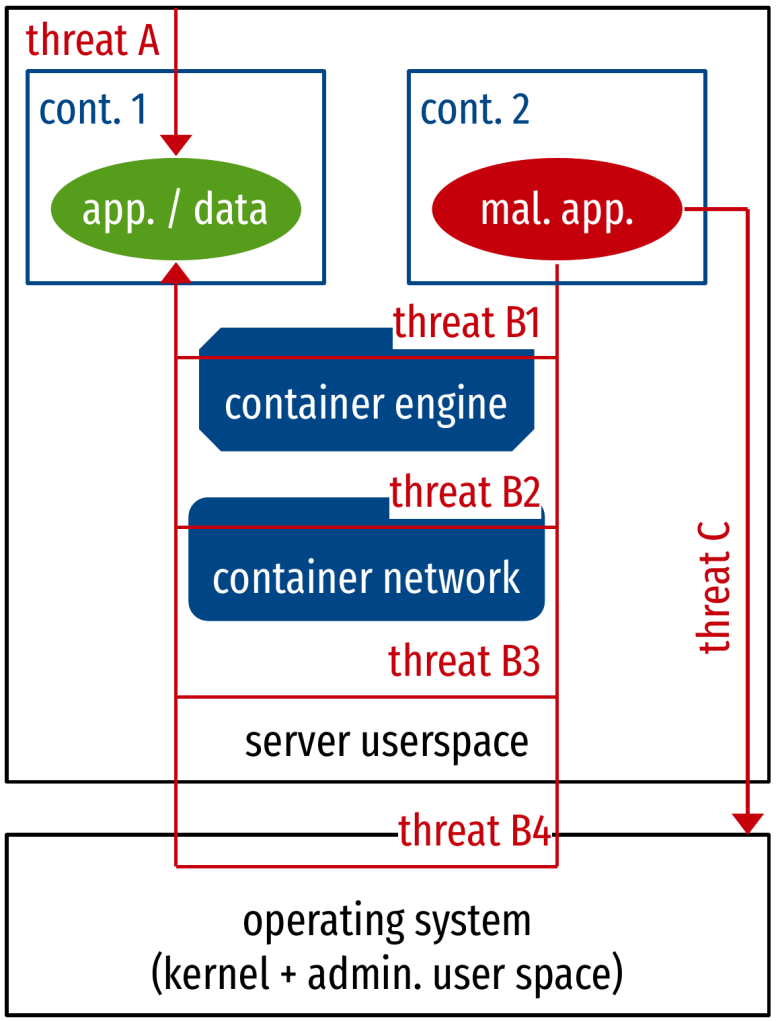
Threat models of containerization.

Threat model (A): direct attack from outside

- Containers are not security magic for Internet-facing applications!
  - A vulnerable web server remains vulnerable
- But containers help against vulnerabilities:
  - **Breach containment**
    - Importance of the micro-service model
  - **Safe configuration** is easier to achieve
    - More secure defaults
    - Fewer configuration items to tweak thank to virtualized environment
  - **Simpler audit**
    - Limited set of dependencies and software pieces
  - Fast, easy **distribution of security updates**
    - Container distribution model: generic images pulled from a centralized place
- Regarding the distribution model: it can also be a threat vector (attacks on the distribution channel)
  - Do not pull unaudited images or updates: may be freshly **vulnerable or compromised**
    - Malicious updates or owner, typosquatting…
  - Use a private repository of audited images

Threat model (B): indirect attack between containers

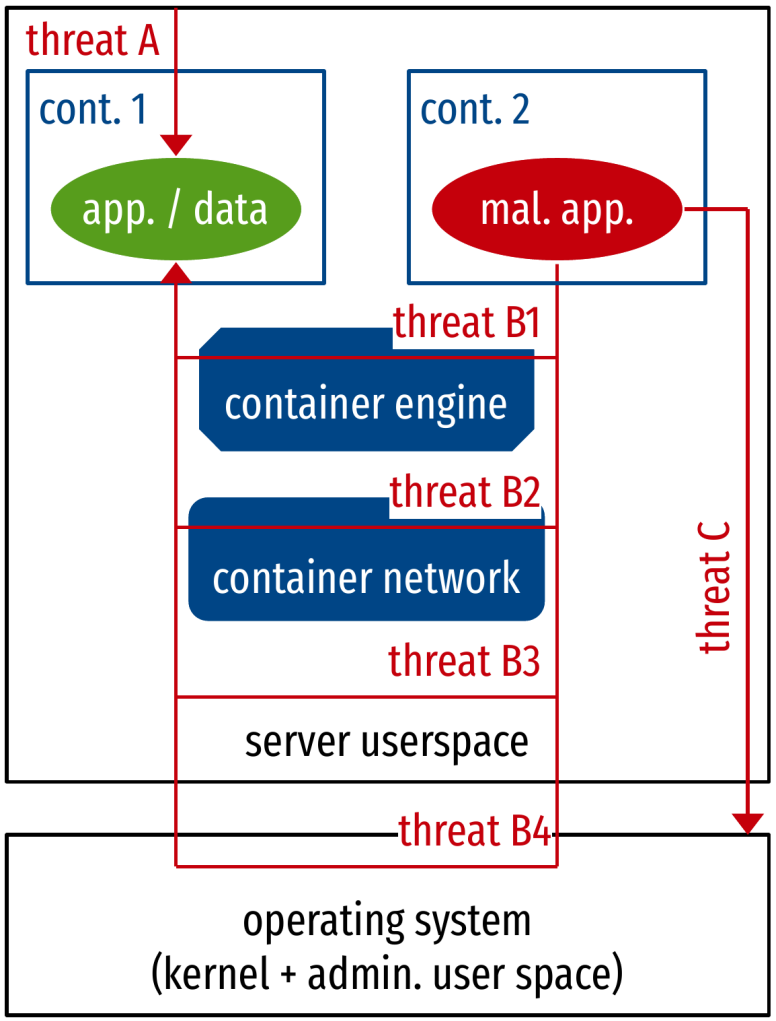
- Containers run **arbitrary code** by definition
- B1: **Escape to another container**
  - Bug in namespaces implementation
  - Leaks in the filesystem
- B2 : **Abuse of the container network**
  - Packet forging
  - Layer 2 attacks
- B3 : **Escalation to root**
  - Vulnerable SUID binaries
  - Vulnerable container engine implementation
- B4 : **Execute arbitrary kernel code**
  - Exploitable system calls
- Not always container-specific



Threat models of containerization.

Threat model (C): attack on the host system

- Containers run **arbitrary code** by definition
- **Escape containment**
  - Namespace bug
  - Filesystem leak
- **Escalate to root**
  - Vulnerable SUID binaries
  - Vulnerable container engine implementation
- **Execute arbitrary kernel code**
  - Exploitable system calls
- Not always container-specific



Threat models of containerization.

Good practices: as a user

- **Audit public images**
  - Fix versions, but monitor for security updates
- Use the micro-services architectures
  - For intrusion detection and containment
  - Every micro-service can be augmented with its own monitor
- Mount volumes read-only when possible
  - Container images are already immutable thanks to the overlay FS
- Drop capabilities
  - Many are dropped by default, but more can usually be dropped

Good practices: as an image developer

- Use and build **immutable container images**
  - I.e., images that can be deployed identically everywhere, only configured to fit the environment
  - Example: do not build images that download binaries when starting
- **Do not run as root** in the container (non root images)
  - User namespaces allow that, but this is not an excuse
  - Do not rely on SUID binaries in general

Good practices: as a system administrator

- **Harden the kernel**
  - Enable MAC: Linux Security Modules (AppArmor, SELinux, etc.), seccomp…
    - Not really containerization-aware but still very well usable
  - Use a hardened kernel (GRSEC…)
  - Update the kernel to vetted versions
    - It is a critical part, because it is shared with all containers (huge trusted codebase between tenants)
- **Configure container networking tightly**
  - Do not use host mode
  - Think about shared network namespaces, open ports, common virtual networks…
    - In practice: managed by docker-compose, Kubernetes, etc.
- Why not go one step beyond: use virtual machines!
  - An application in a Docker container in a virtual machine *(in a container ?)*
  - Kata Containers, gVisor…
  - Or just split physical servers by tenants using VMs

Internal of a container engine

1. Isolation
2. Limit
3. Operation control
4. Virtual filesystem

Isolation: namespaces

- Provide an **isolated view** of the OS
- 8 dimensions:

1. `mnt`: mount points
   - Hierarchy of sub-filesystems
2. `pid`: hierarchy of processes
   - The first process in the container gets PID 1
3. `net`: networking facilities
   - Interfaces, ports, protocol stack…
4. `ipc`: interprocess communication
   - SysV IPC mechanisms: semaphores, message queues, shared memory segments
5. `time`: date and time
6. `user`: users, groups and privileges
   - The engine establishes a mapping between host UIDs (GIDs) and in-container UIDs (GIDs)
     - root is defined as UID 0, which is available inside the container: escape the container as root, and you are root on the host!
7. `uts`: hostname and domain name
   - For UNIX TimeSharing, from an era of remote computers and client terminals
8. `cgroup`: control groups (*see next*)

Limit: control groups (cgroups)

- **Constrain resource usage**
  - Also prioritization, accounting, control
- 8 “dimensions” (controllers):
  - `cpu`: CPU time
  - `cpuset`: task placement on memory and CPU nodes
  - `memory`: memory usage
  - `io`: block I/O
  - `pid`: number of PIDs (i.e., of processes)
  - `device`: access to device files
    - *special: only through BPF*
  - `perf_event`: performance monitoring
  - `net`: network packets priority and classes for QoS
- Other specialized controllers: `rdma`, `hugetlb`, `misc`

Operation control: capabilities and MAC

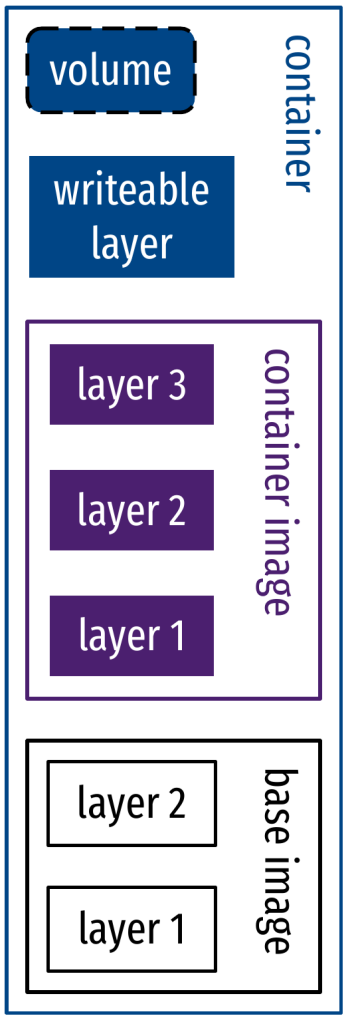
- **Capabilities:** selectively drop root privileges
- **Mandatory Access Control** (MAC): system-level operational policies with Linux Security Modules
  - SELinux, AppArmor, seccomp…
- More than 40 capabilities (`CAP_XXX`):
  1. `SYS_NICE`: change process niceness
  2. `SYS_ADMIN`: system admin (mount…)
  3. `SYS_CHROOT`: change root path of process
  4. `SYS_MODULE`: (un)load kernel modules
  5. `SETGID/UID`: change process GIDs/UIDs
  6. `KILL`: send signals
  7. `NET_ADMIN`: network admin
  8. `NET_RAW`: use RAW sockets
  9. `CHOWN`: change owner

Virtual filesystem

- Isolated filesystem:
  - `mnt` namespace to isolate hierarchy
  - `chroot` to isolate the process to a subtree
- Two parts to the filesystem visible to the container:
  1. Container image: basis for virtual filesystem
     - Bundle of files and filesystem operations in layers
  2. Volumes: external data storage
     - Mounted into the virtual filesystem of the running container

Virtual filesystem: layers and volumes

- An image is made of **layers**
  - Like git commits, to represent modifications on the filesystem
  - Reusable by other images, with caching
  - Visible with `docker image history $IMAGE_NAME`
- Layers of an image, built from a Dockerfile, are **read-only**
  - The engine adds a writeable layer on top during container execution
  - Use **copy-on-write** to modify files from lower layers
- Managed by a **union filesystem**: driver of a layered virtual filesystem (Overlayfs)



Container image layers and volumes.

Virtual filesystem: OverlayFS and copy-on-write

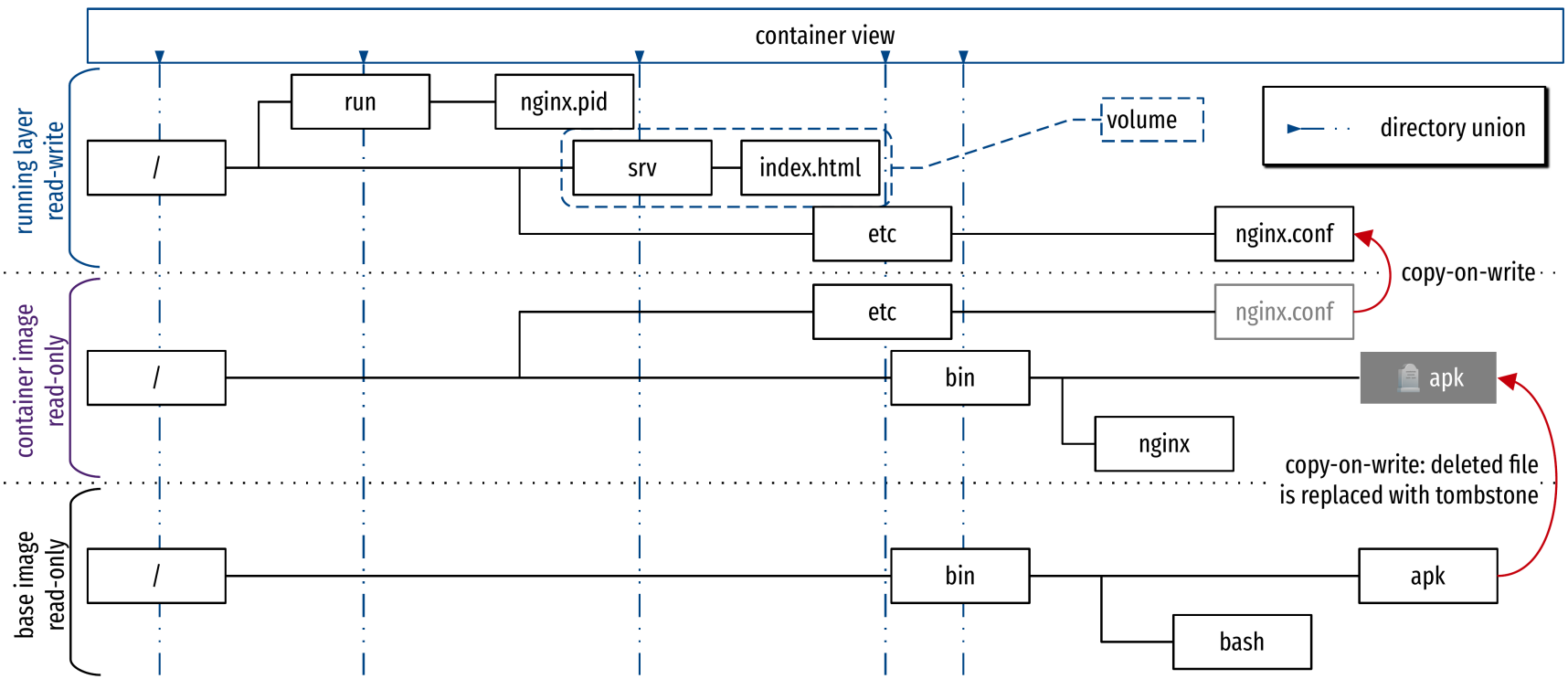
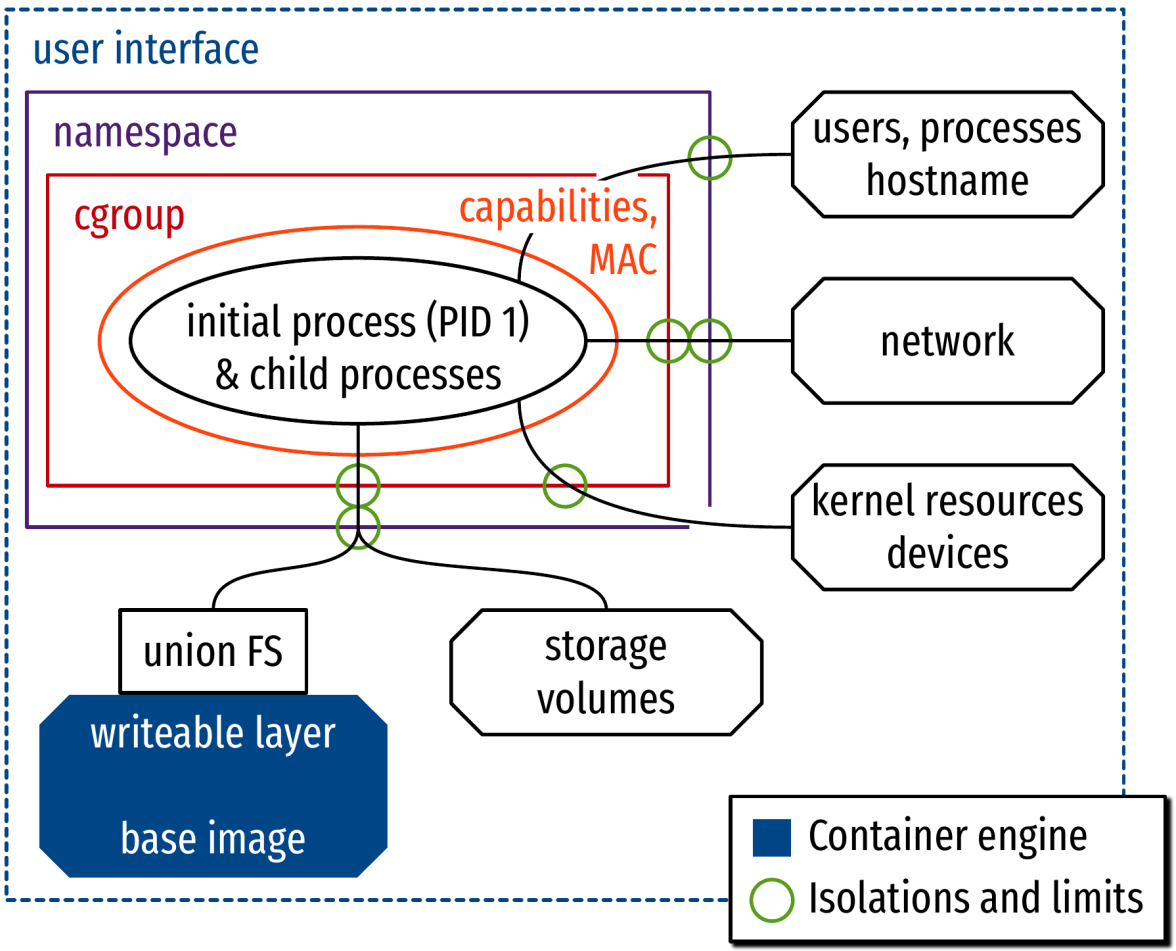


Illustration of a union filesystem and copy-on-write.

Low-level view of a container engine

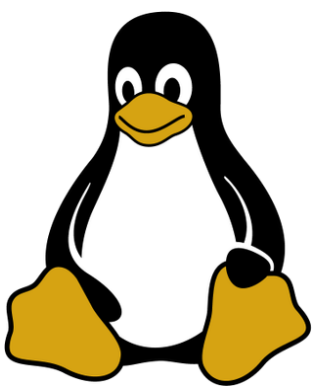


Low-level components and interface of a container engine.

- Most features that make a container, come from the Linux kernel!

Demo: namespaces and cgroups

- Spawn a new process in namespaces
- Put a process in control groups
  - Set limit and monitor resource usage
- Using the virtual filesystem interface
  - There are also syscalls



Linux logo.

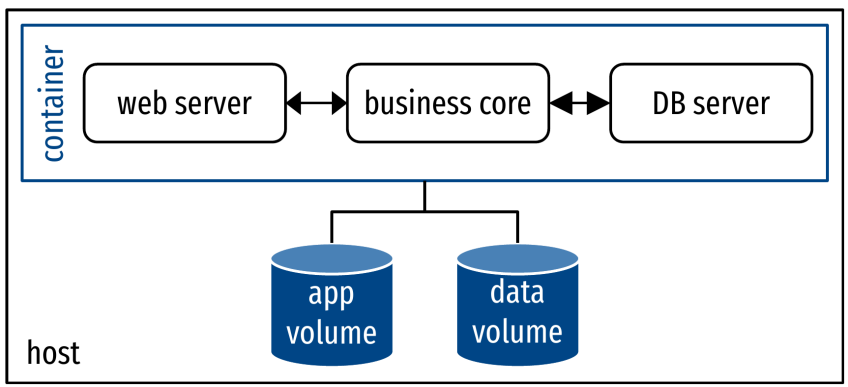
Containers for the cloud

1. Application architecture in the cloud
2. Micro-services
3. Orchestration

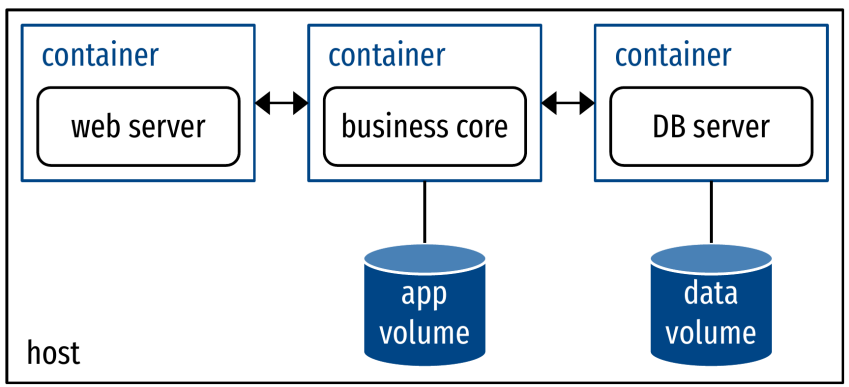
Cloud application architecture

- Historic pattern: **monolithic application**
  - All components are ad-hoc, tightly coupled
- Unfit for the cloud
  - Must manage all components at once for scalability, deployment, service quality
  - Hard to reconfigure
- New paradigm enabled by containers: **micro-services**

Micro-services



❌ Monolithic container.



✅ Composition of containers.

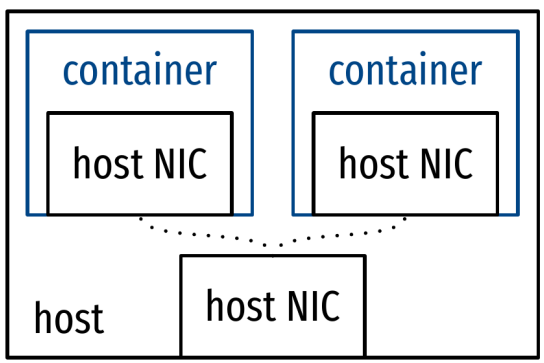
- Components as processes
  - Manual interfacing
    - Need in-container PID 1 (service manager) to run multiple processes
  - Cons of monolithic apps (*see previous slide*)

- **Components as containers**
  - Maximum reuse of images
  - High flexibility, clean configuration and interfacing
  - Fine-grained scalability

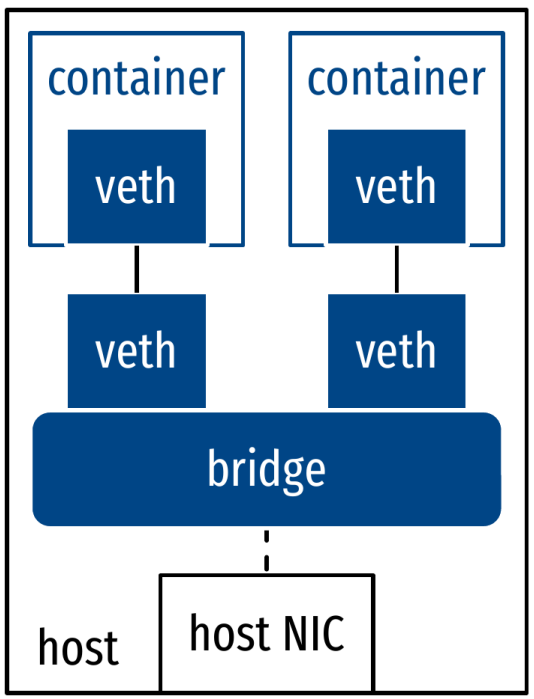
Networking for micro-services

- Configuration of networking by the container runtime
  - **Dedicated links** between component containers
  - Controlled link to the outside world
- Network drivers:
  - Host: expose host network devices to the container (no isolation)
  - Bridge: local virtual network
    - May be exposed to the outside world via virtual routing
  - Overlay: inter-host inter-container network
  - *None: no networking at all*

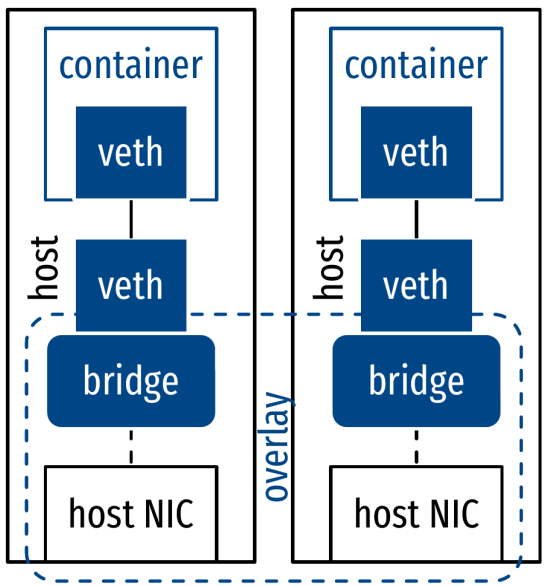
Networking for micro-services: illustrations



Host.



Bridge.



Overlay.

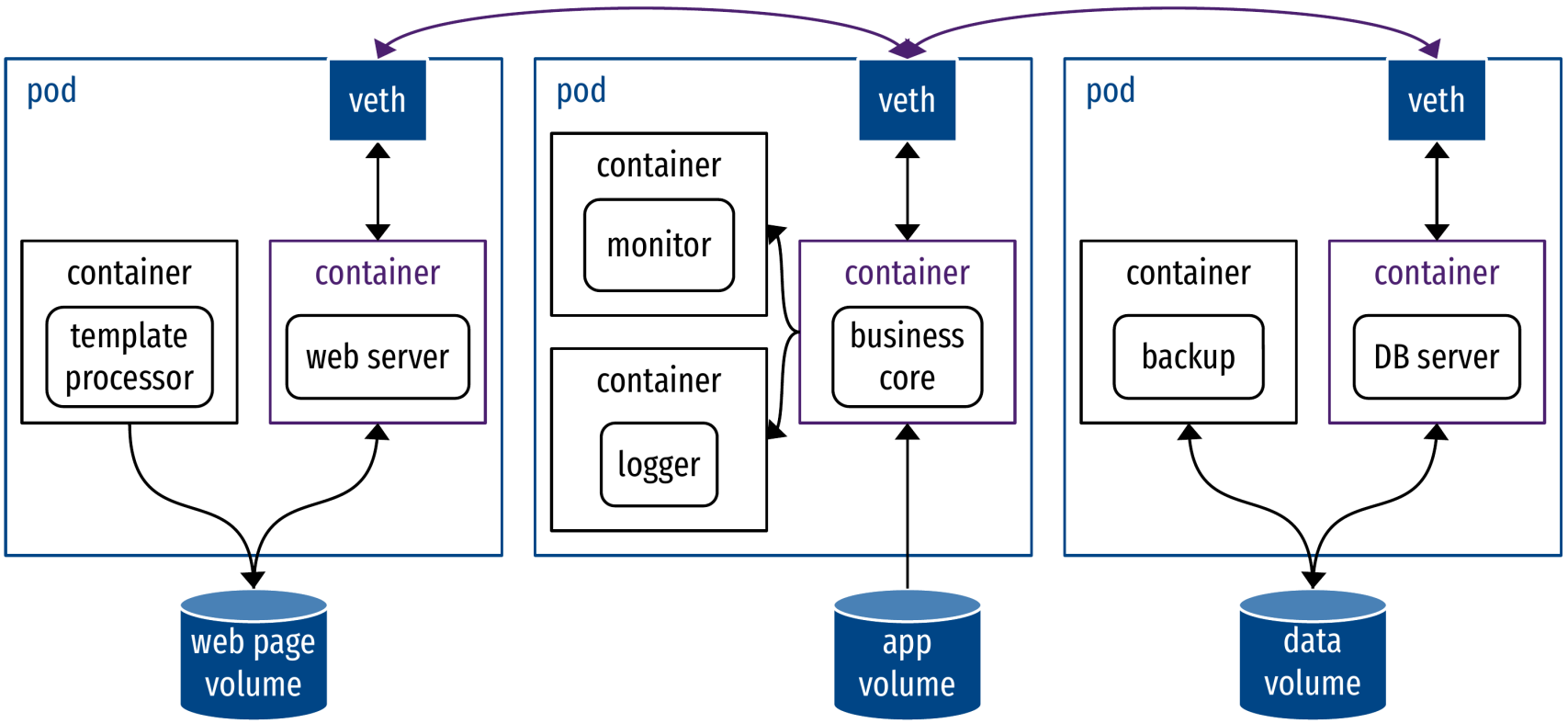
Orchestration

- Composition: build applications as micro-services
  - Roughly: manage multiple containers as one application
  - Example: Docker Compose
- **Orchestration**: manage micro-services
  - Deployment
  - Distribution
  - Replication
  - Load-balancing
  - Availability
  - Rolling updates
  - …
- Orchestration exposes higher-level interfaces to the features of composition
  - In the end, the orchestrator is the user front-end
- Examples: Kubernetes, Docker Swarm
- Abstraction of management unit: the **pod**

Orchestration: scheduling

- Manual criteria: **filters**
  - Handle host heterogeneity
    - Settings of container runtime, host OS…
  - Container affinity: force placement for resource access
    - Image availability, volume placement, other container…
- **Strategies for deployment** on physical hosts
  - Spread: balance load over hosts
  - Binpack: colocate as much as possible
- Handle colocation of tightly-coupled containers: **pods**
  - Containers in a pod share the same network namespace and same volumes
  - Pod = service container + helper (sidecar) containers (logging, interfacing…)

Orchestration of pods



Application architecture with pods.

Demo: Kubernetes

- Create and use a pod
- Create and use a deployment
  - Scalability
  - Roll-out

Kubernetes logo.

Kubernetes application: example of `deployment.yaml`

```yaml
kind: Deployment
# [ ... ]
spec:
  # Scalability: set number of replicas.
  replicas: 3
  selector:
    matchLabels:
      app: simpleserver
  template:
    metadata:
      labels:
        app: simpleserver
    spec:
      # Pod: composition of containers.
      containers:
      - name: pythonserver
        image: python:simpleserver
        resources:
          requests:
            cpu: 0.5
```

Example of deployment description file.

Operating system-level virtualization

- Virtualize the OS instead of the hardware
  - **Containers:** simpler, lighter, faster
    - Not safer!
- Based on the Linux kernel (LinuX Containers, LXC): namespaces, cgroups, etc.
  - Container engines wrap those features and deliver unified specifications
  - Container runtimes bring usability, networking, development processes…
- Enabling new cloud-native application architecture: **micro-services**
  - Compositions of containers managed by orchestrators