Containerd From The Bottom Up

A reader-grade tour of containerd, runc, namespaces, cgroups, and the Linux primitives behind every running container.

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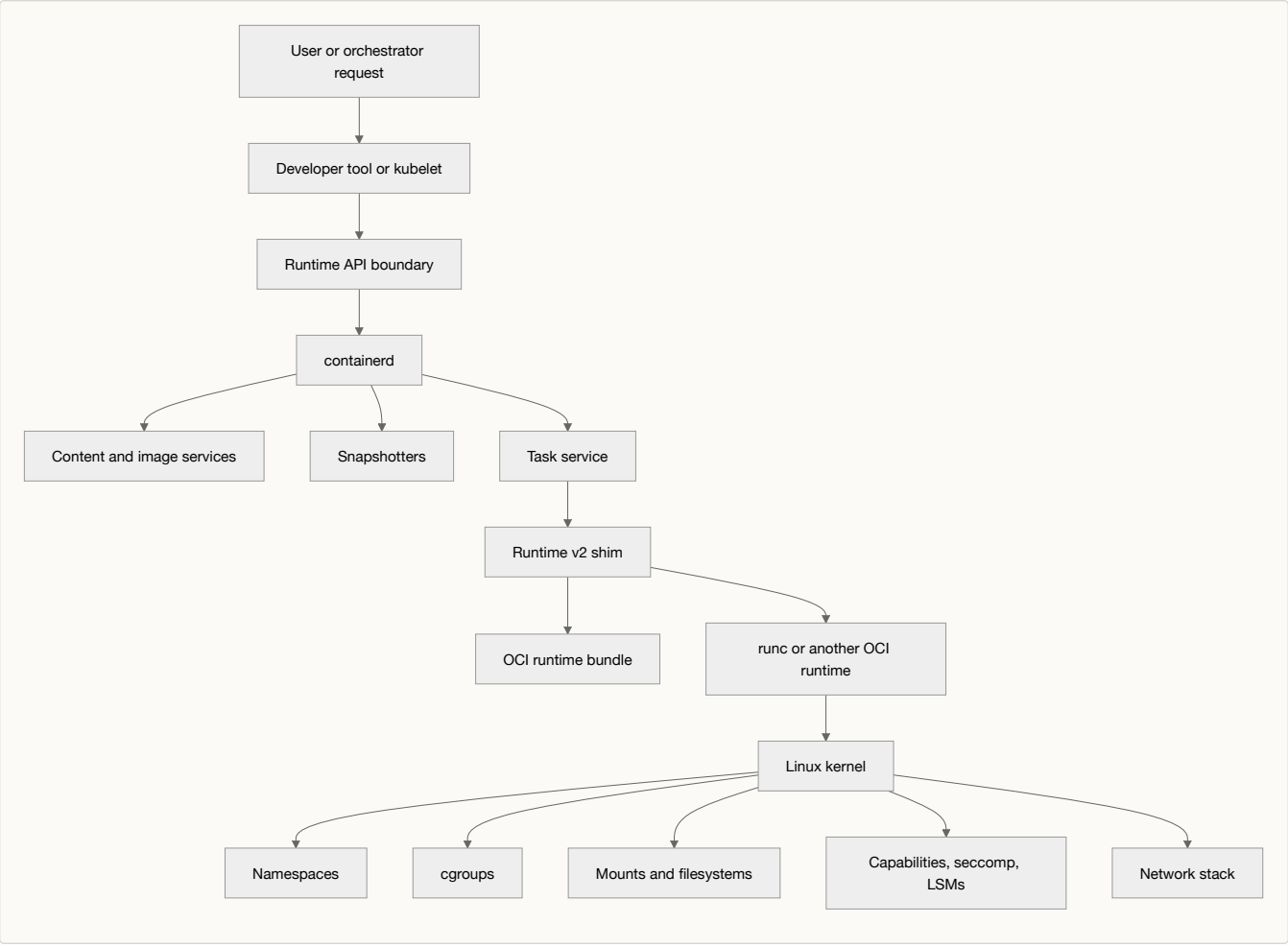
PART I — ORIENTATION

Chapter 1: The Container Stack Map

The word "container" gets used at every layer of the stack. A `docker run` command is a "container." A Kubernetes `Pod` "contains" containers. `runc` "creates a container." A `clone3(2)` call with namespace flags creates something the kernel does not call a container at all. The same word names a developer workflow, a Kubernetes resource, a runtime command, and a kernel construction — and people use the meanings interchangeably. That is how the same conversation can be technically correct on every line and still leave the room confused.

This book walks the runtime stack from the kernel up: namespaces and cgroups (control groups) and mount setup, the OCI (Open Container Initiative) runtime spec and `runc`, the runtime v2 shim, containerd's content store and snapshotters and task service, the Container Runtime Interface (CRI), and the Kubernetes objects that finally land on those primitives. The map below is what the rest of the chapters fill in.

A container system turns a request — typed by a developer or issued by an orchestrator — into a Linux process running with a configured environment. Along the way image references become local content, image layers become a mountable filesystem, runtime metadata becomes an OCI spec, and that spec becomes kernel state: namespaces, cgroups, mounts, security policy, and a network stack.



Docker, Kubernetes, `nerdctl`, `ctr`, Podman, and direct containerd clients all enter the stack at different layers. What stays consistent is the delegation pattern: high-level tools express intent, lower layers produce content and runtime state, and the kernel enforces the result.

A Short History

Containers were not designed; they accreted over four decades of Unix work. The modern stack — kernel primitives at the bottom, an OCI runtime, a per-container shim, a daemon, an orchestrator API, and developer tooling at the top — is a record of which problem each generation solved and which it deferred to the next.

Filesystem Isolation: 1979 To 2005

Unix `chroot(2)` shipped in V7 in 1979. It changes the apparent root directory of a process so pathname resolution starts somewhere other than `/`. That is a useful primitive — it lets a sandbox or a build environment see a smaller filesystem — and it is not a container. `chroot` does not isolate process IDs, networking, IPC, users, or privileges. Root inside a `chroot` is root on the host, and a root process can break out of one without much effort.

FreeBSD jails (FreeBSD 4.0, March 2000) extended the idea into something closer to OS-level virtualization. A jail is `chroot` plus its own hostname, IP-binding constraints, restricted process visibility, and a privilege model that downgrades a jailed root. Solaris Zones (Solaris 10, February 2005) went further: separate process trees, separate networking stacks (with "exclusive-IP" zones added in 2007), and separate user spaces, all sharing one kernel. Both systems demonstrated, several years before Linux containers were practical, that "many isolated user spaces on one kernel" was a real production model.

Linux took longer. Through the 2000s the kernel grew the same set of capabilities one feature at a time, and the userland followed.

The Linux Kernel Catches Up: 2002 To 2020

Linux containers did not arrive as a single feature. The kernel grew the parts list across more than a decade:

Feature	Kernel	Year
POSIX capabilities	2.2	1999
Mount namespace	2.4.19	2002
SELinux	2.6.0	2003
seccomp (mode 1)	2.6.12	2005
UTS and IPC namespaces	2.6.19	2006
Process containers (cgroups)	2.6.24	2008
PID namespace	2.6.24	2008
Network namespace	2.6.24 onward	2008–2009
AppArmor	2.6.36	2010
seccomp-bpf	3.5	2012
User namespace	3.8	2013
OverlayFS	3.18	2014
cgroup v2	4.5	2016
cgroup namespace	4.6	2016
Time namespace	5.6	2020

A short gloss on each name in the table:

- **POSIX capabilities** — root-equivalent authority broken into ~40 individually grantable units (`CAP_NET_ADMIN` , `CAP_SYS_ADMIN` , etc.).

- **Namespaces** — kernel mechanism that gives a process a private view of one global resource (process IDs, mounts, network stack, hostname, IPC, user IDs, cgroup tree, time offsets).
- **cgroups (control groups)** — group processes into a hierarchy and account for or limit their CPU, memory, IO, and pids consumption.
- **SELinux and AppArmor** — Linux Security Modules (LSMs) that enforce mandatory access control. SELinux is label-based; AppArmor is path-based.
- **seccomp** — secure computing mode. The kernel feature that filters syscalls; `seccomp-bpf` lets userspace install a Berkeley Packet Filter program for the syscall decision.
- **OverlayFS** — kernel filesystem that stacks read-only layers under a writable upper layer; the standard backend for layered container images.

cgroups arrived under the name "process containers" — Google's Paul Menage and Rohit Seth proposed them in 2006, and they merged in 2.6.24 in 2008. The name was changed to avoid colliding with the rest of the kernel's "container" usage. (The collision lost anyway.)

Through this period, Linux had container parts but no consensus container. OpenVZ — an open-source OS-level virtualization system distributed as a separate kernel patch set — had been running production VPS hosting since 2005, but never made it to mainline. Google had been running Borg, its internal cluster manager, on cgroups since the late 2000s. Neither was something a developer could install on a laptop.

LXC, Docker, And libcontainer: 2008 To 2014

LXC — short for Linux Containers — was the first userspace toolkit to assemble Linux's accumulating namespace and cgroup features into a usable container model. LXC 0.1.0 shipped in August 2008. It drove the kernel directly, exposed a CLI (`lxc-create` , `lxc-start` , `lxc-attach`), and worked — but it left the workflow problems open. There was no standard image format, no layered build model, no registry, no portable way to "ship a container."

Docker (March 2013) closed the workflow gap. The original 2013 release used LXC underneath; what Docker added was the part above the kernel: a daemon (`dockerd`), a developer-facing CLI (`docker`), a layered image format with build instructions (`Dockerfile`), and a registry protocol (Docker Registry, later Distribution). Containers became commodity infrastructure within eighteen months of Docker's launch — not because the kernel changed, but because the workflow finally fit a developer's day.

Docker 0.9 (March 2014) replaced LXC with libcontainer, a Go library that drove the kernel directly through namespace and cgroup syscalls. The motivations were operational: independence from a separate userland project, the ability to manage namespaces and cgroups directly from Go, and a path to platform-independent execution drivers. libcontainer is the codebase that became `runc` .

CoreOS launched rkt (pronounced "rocket") in November 2014 with a different model: no central daemon, an `appc` (App Container) image format, and a process-per-invocation supervision shape. rkt did not survive as a runtime, but its existence pushed the ecosystem toward open, multi-vendor standards instead of Docker-defined ones.

Standards: OCI, 2015

The Open Container Initiative formed at DockerCon on June 22, 2015, under the Linux Foundation. The mandate was open specifications for container formats and runtimes; Docker donated runc (a brand-new extraction of libcontainer) as the reference implementation. OCI publishes three specifications, each versioned independently:

- **Runtime Specification** — what an OCI runtime consumes and how it behaves. Defines the OCI bundle format and the lifecycle commands.
- **Image Specification** — how images are packaged: manifests, image configs, layers, and digests.
- **Distribution Specification** — how images move through registries. Reached 1.0 in 2020 by formalizing Docker Registry HTTP API V2 as an open standard.

The three specs separate concerns the Docker daemon had bundled together: building, distributing, and running an image are now three contracts owned by three standards.

`runc` 1.0 took until June 2021. Real production deployments had been using pre-1.0 runc for years; the version number was an acknowledgement of stability, not a moment of arrival.

containerd Becomes Its Own Layer: 2015 To 2020

containerd started inside Docker in early 2015 as a refactor that pulled lifecycle and supervision out of `dockerd` and into a separate daemon. By December 2015 it was a public project; in March 2017 Docker donated it to the Cloud Native Computing Foundation (CNCF), the Linux Foundation sub-project that hosts Kubernetes; CNCF announced graduation on February 28, 2019.

The split mattered because Kubernetes — by then the dominant orchestrator — did not want to depend on Docker the product. containerd 1.0 (December 2017) gave Kubernetes a daemon focused on the work in the middle: pulling and storing image content, snapshot management, container metadata, task supervision, and runtime integration through shims. Docker remained the developer-facing product on top; containerd became reusable infrastructure underneath.

containerd's runtime v2 shim model (containerd 1.2, October 2018) is the boundary that lets a single daemon work with runc, crun (a C reimplementation of runc by Red Hat), gVisor (a Google userspace kernel that intercepts syscalls), Kata Containers (each container in a lightweight VM), Wasm (WebAssembly) runtimes, and Windows host process containers through one ttrpc API. ttrpc is a smaller-footprint variant of gRPC for local Unix-socket transport, designed for the per-container shim use case. Runtime v1 was deprecated in containerd 1.4 (September 2020); current installations are all v2.

Kubernetes And CRI: 2016 To 2022

Kubernetes shipped in 2014 carrying the vocabulary of Borg, Google's internal cluster manager that Kubernetes was modelled after — pods, controllers, schedulers — and an in-tree integration with Docker Engine. By late 2016 the in-tree integration had become a maintenance problem: every container-runtime change required a Kubernetes patch. The Container Runtime Interface (CRI) was the answer. CRI v1alpha shipped in Kubernetes 1.5 (December 2016) as a gRPC API kubelet calls, and any runtime that implements it can plug into Kubernetes.

CRI is also where the word "runtime" splits in two. From Kubernetes' point of view, a "container runtime" is anything that implements CRI: containerd (via its CRI plugin), CRI-O. From OCI's point of view, the "runtime" is what consumes an OCI bundle: runc, crun, youki, runsc, kata-runtime. Both meanings are correct; the rest of the book uses the precise term.

For several years kubelet talked to Docker through an in-tree adapter called dockershim, which presented Docker Engine as if it were a CRI runtime. dockershim was deprecated in Kubernetes 1.20 (December 2020) and removed in 1.24 (May 3, 2022). The change did not break Docker-built images — those are OCI images, identical to what any other tool produces — but it ended the special case where Kubernetes called Docker. Kubernetes nodes now talk to containerd or CRI-O directly.

Why The Stack Looks Like This

The current shape — kernel primitives, OCI runtime, runtime shim, containerd, CRI plugin, kubelet, Kubernetes API — is the residue of those decisions. Each layer marks a boundary that someone, at some point, had to redraw because the layer above wanted to be replaceable.

- The kernel stayed the kernel. Containers compose its primitives without changing them.
- OCI exists because Docker-defined formats were not the stable contract a multi-vendor ecosystem needed.
- runc exists because the kernel-driving code had to live in a small, language-agnostic binary that did not bundle a registry or a daemon.
- The runtime v2 shim exists because containerd needs to survive its own restarts without killing running workloads.
- containerd exists because Docker's product surface and Kubernetes' runtime needs are different problems.
- CRI exists because Kubernetes wanted to stop tracking individual runtime APIs.

That layering is what the rest of the book inspects. Most of the time the layers are invisible — a developer types `kubectl apply -f deploy.yaml` and a process starts somewhere — but when something breaks, "where in the stack" is the only question that matters.

"Runtime" Means Two Things

The CRI/OCI split appears at every layer of the stack from chapter 3 onward. It deserves its own definition table.

Phrase	Meaning	Examples
CRI runtime	A service kubelet calls over gRPC. Implements `RuntimeService` and `ImageService`.	containerd (via its CRI plugin), CRI-O
OCI runtime	A program that consumes an OCI bundle and produces a configured process.	runc, crun, youki, runsc, kata-runtime
containerd runtime plugin	containerd's configured runtime path; usually a runtime v2 shim binary.	`io.containerd.runc.v2`, `io.containerd.runhcs.v1`
Runtime v2 shim	The supervisor process between containerd and the OCI runtime.	`containerd-shim-runc-v2`, `containerd-shim-kata-v2`

A request from a Kubernetes pod walks all four. kubelet asks the CRI runtime (containerd), which delegates to a runtime v2 shim (`containerd-shim-runc-v2`), which calls the OCI runtime (`runc`).

The Layers, From The Top

Intent

A person types `docker run nginx`, or `nerdctl run nginx`, or `podman run nginx`, or applies a Kubernetes Deployment that eventually causes kubelet to ask for a pod. The interfaces differ; the intent is the same — run a process from an image with a particular filesystem, environment, network, and resource policy.

Developer-facing tools name containers, expose ports, attach logs, and hide the runtime machinery. Hiding it does not eliminate it; it means the tool is doing translation. `docker run nginx` becomes a registry pull, a snapshot prepare, a container record, a task create, a shim launch, a runc invocation, and a `clone3(2)` call. Everything from the second word onward is what the rest of the book is about.

Docker

Docker is a developer-facing product: a CLI (`docker`), a daemon (`dockerd`), and a set of workflows for images, containers, networks, and volumes. Since Docker 1.11 (April 2016), `dockerd` has not done its own container lifecycle work — it delegates to containerd, and containerd delegates to runc. A `docker run` command and "a container runtime" are two different things at two different layers; the daemon is the workflow tier, the runtime is what configures the kernel.

Docker is one entry point into the stack. `nerdctl` is a Docker-compatible CLI for containerd. Podman is a daemonless Docker-compatible CLI that drives runc directly through `conmon` (container monitor), a small per-container supervisor that plays the same role as containerd's shim. The entry points differ; the layers underneath are the same.

Kubernetes

Kubernetes does not exist to run a single container conveniently. It exists to manage desired state across many machines. A user declares that a workload should exist; controllers and the scheduler decide where it runs; kubelet on each node makes local runtime calls to create pods and containers.

kubelet talks to the runtime over CRI, a gRPC API defined in `k8s.io/cri-api`. The methods break into a `RuntimeService` (pod sandbox lifecycle, container lifecycle, exec, attach, port-forward, status, stats, logs) and an `ImageService` (list, status, pull, remove, filesystem usage). Anything kubelet wants the runtime to do crosses one of those two interfaces.

A pod is a Kubernetes-only concept; CRI invents a "pod sandbox" to represent it at the runtime layer. The sandbox holds the network namespace, runtime endpoint, labels, and (on Linux) a `pause` container that pins the namespaces while the pod's workload containers come and go. Chapter 13 walks the full sandbox lifecycle.

containerd

containerd is where image references become content, content becomes a snapshot, and a snapshot plus a spec becomes a running task — three boundaries the rest of the book follows.

It is a daemon with a graph of plugins: a content store for digest-addressed bytes, snapshotters for filesystem state, an image service for name-to-descriptor mapping, a container metadata store, a task service, runtime v2, a CRI plugin, an events service, and a leases service for protecting in-flight work from garbage collection. Clients reach each plugin through gRPC.

containerd also enforces a distinction that cuts through the rest of the book's vocabulary: a *container* is metadata — image, labels, snapshot key, runtime config, OCI spec — while a *task* is the live process derived from that metadata. A container can exist without a task. A task can exit while the container record stays. Untangling them is the first step toward understanding what the daemon is actually doing.

Images, Content, And Snapshots

When the user says "run nginx," nothing about that reference is yet usable. The reference is a name; the kernel needs a filesystem.

Producing one takes six steps:

1. resolve the reference to a manifest;
2. fetch the manifest, image config, and layer blobs from a registry;
3. store blobs by digest in the content store;
4. unpack the layers;
5. ask a snapshotter to prepare a mountable view, plus a writable layer for this container;
6. mount that view as the root for the process.

The content store and the snapshotter are deliberately separate concerns. The content store holds digest-addressed image data, immutable and shareable across containers and across images. The snapshotter turns layers into filesystem state. Image pulls can succeed even when unpacking fails; many containers can share one set of immutable layers; and garbage collection has to reason about content, snapshots, containers, and leases at once. Chapter 11 covers the whole pipeline.

Shims

In the runtime v2 model, containerd launches one shim process per container (or per pod sandbox); for the standard Linux runc path, the binary is `containerd-shim-runc-v2`. The shim owns runtime-specific behavior and the lifecycle of the actual container process: it invokes runc, manages the IO pipes, reaps the process, and reports the exit status back to containerd. On a host running one container, `pstree` shows the layering:

```
systemd
├── containerd
└── containerd-shim-runc-v2
    └── nginx        ← the workload
```

The shim is not a duplicate of containerd. It is the supervision boundary that lets containerd be restarted without killing running workloads — the shim keeps holding the workload's stdout, exit status, and signal path until the daemon reconnects. Runtime-specific code lives behind the shim v2 task API over ttrpc (a lightweight gRPC variant for local Unix-socket transport), so swapping runc for crun, gVisor, or Kata is a configuration change at the containerd layer, not a code change.

runc

runc is a low-level OCI runtime. Its job is to take an OCI bundle — a directory containing `config.json` and a root filesystem — and produce a configured process. It does not talk to registries, schedule pods, or host a developer workflow.

`config.json` describes everything the kernel needs to know: the process to run, environment and working directory, root filesystem path, mounts, namespaces to enter or create, cgroup settings, capabilities, seccomp filter, hooks, and annotations. runc translates that into Linux operations — `clone(2)` or `clone3(2)` with the right namespace flags, mount setup, cgroup writes,

credential and capability adjustments — and then `execve` s the configured process.

runc is one OCI runtime. crun is a C reimplementation maintained by Red Hat with lower memory and faster startup. youki is a Rust reimplementation. runsc (gVisor) intercepts syscalls in a userspace kernel for stronger isolation. kata-runtime runs each container inside a lightweight VM. All of them satisfy the same OCI bundle contract.

The Kernel

A container is built by configuring several Linux primitives at once:

- namespaces change what a process can see;
- cgroups account for and limit what it can use;
- mount setup determines what filesystem it sees as `/`;
- capabilities and seccomp reduce its authority;
- LSMs (AppArmor, SELinux) enforce mandatory access control;
- network namespaces and virtual devices route its traffic.

The kernel does not have a "container" type. It runs processes with credentials, mount tables, and namespace memberships — and the runtime configures those primitives so that, taken together, they behave like the abstraction the layers above promised.

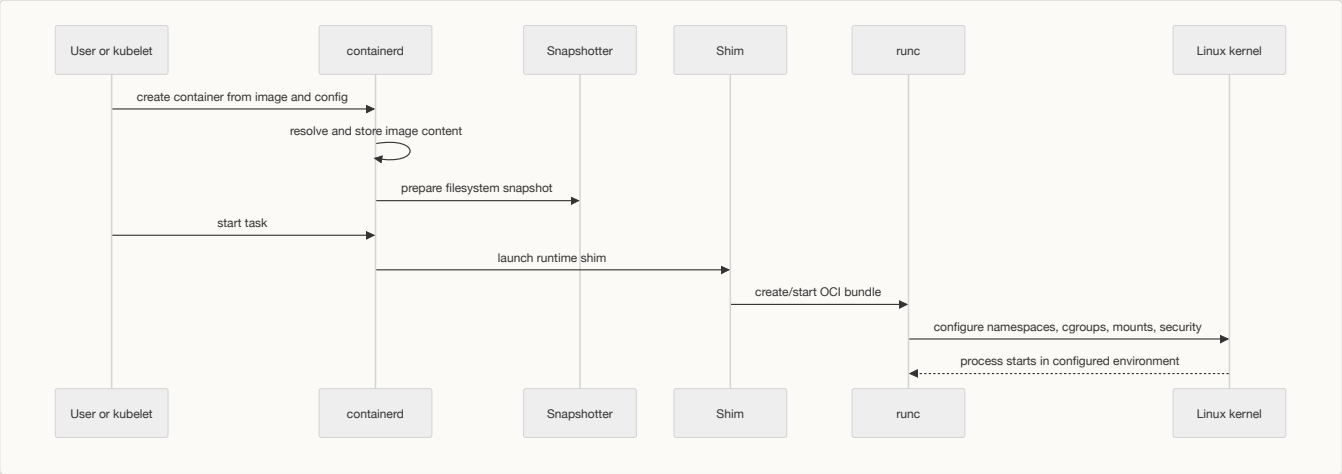
What "Container" Means At Each Layer

The same word names different objects at different layers. When two engineers disagree about containers, they are usually pointing at different rows of this table:

Layer	"A container" is...	The actual object
Kubernetes	An entry in a `Pod` spec.	A `Container` inside `PodSpec.containers`.
CRI	A runtime-level container, scoped to a pod sandbox.	A container ID returned by `RuntimeService.CreateContainer`.
containerd	Persistent metadata.	A row in the container metadata store: ID, image, snapshot key, runtime, OCI spec.
Runtime v2 / shim	A supervised task.	A task service ID with an attached shim process and runc state.
OCI	A bundle in the `created` or `running` state.	A directory with `config.json` plus a runtime state file.
Linux kernel	Nothing.	A process tree with namespace memberships, cgroup placement, mount table, credentials, and security policy.

Most "is X a container" arguments resolve once both speakers agree which row they mean.

Following One Request Down



The exact calls vary by client, runtime configuration, and host. The rest of Part I expands two of the diagram's nouns: chapter 2 zooms in on the kernel-side question — what a container actually is — and chapter 3 covers the contracts that hold the stack together: the OCI runtime spec and the runtime v2 shim API.

Sources And Further Reading

- Docker overview: https://docs.docker.com/get-started/docker-overview/
- Docker 0.9 / libcontainer announcement: https://www.docker.com/blog/docker-0-9-introducing-execution-drivers-and-libcontainer/
- Open Container Initiative: https://opencontainers.org/
- OCI Runtime Specification: https://github.com/opencontainers/runtime-spec
- OCI Image Specification: https://github.com/opencontainers/image-spec
- OCI Distribution Specification: https://github.com/opencontainers/distribution-spec
- containerd docs: https://containerd.io/docs/main/
- containerd graduation announcement: https://www.cncf.io/announcements/2019/02/28/cncf-announces-containerd-graduation/
- containerd runtime v2: https://github.com/containerd/containerd/blob/main/docs/runtime-v2.md
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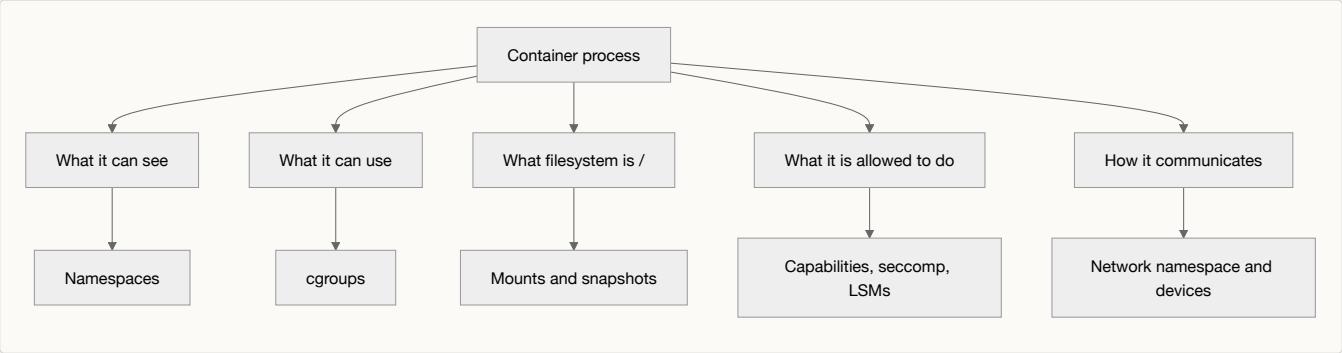
- runc README: https://github.com/opencontainers/runc
- LXC project: https://linuxcontainers.org/lxc/introduction/
- FreeBSD jail(8): https://man.freebsd.org/cgi/man.cgi?query=jail&sektion=8
- Solaris Zones introduction: https://docs.oracle.com/cd/E19044-01/sol.containers/817-1592/zones.intro-1/index.html

Chapter 2: What A Container Actually Is

A Linux container is a process — or a process tree — running with a deliberately configured environment. The kernel schedules it like any other process. What makes it a container is the configuration around it: what it can see, what it can use, which filesystem it sees as `/`, what authority it has, and how it reaches the network.



Why The Boundary Is Not A Hypervisor

VMs and containers both isolate workloads, but at different layers. A VM runs a guest kernel on hardware virtualization. A Linux container shares the host kernel — which is why startup is fast (process creation, not a boot) and why the container is tied to that kernel's version, config, and security state. A workload that needs a different kernel needs something more than a Linux container.

The container boundary is the assembled effect of namespaces, cgroups, mount setup, credentials, capabilities, seccomp, LSMs, device rules, and runtime policy. It is strong when the configuration is right, but its shape is nothing like a hypervisor's: a hypervisor isolates with a separate guest kernel and a virtual hardware interface, while a container is the host kernel applying scoping rules to one of its own processes. The practical consequence is that a kernel bug like CVE-2022-0185 (filesystem-context heap overflow) is a container-escape primitive; the same bug under a VM stops at the guest kernel.

Not An Image

An image is packaged content and metadata — in OCI terms, a manifest, an image config, and a set of layer blobs, all addressed by digest. It can sit in a registry or a local content store with no process running anywhere.

A container is what happens when that content is combined with runtime configuration to start a process. "Run an image" is shorthand for a fixed sequence: the runtime resolves the reference, fetches the manifest and layers, stores them by digest, hands them to a snapshotter that produces a writable root filesystem, and starts a process inside that filesystem under an OCI runtime spec. The image is an input. The container is the running result.

The Process At The Center

A container has an ordinary Linux process at its center, with everything any other Linux process has: a command, environment, credentials, file descriptors, signal handlers, parents and children, an exit status. The runtime does not replace any of that; it configures the world around it.

The consequences are mundane. When the configured process exits, the container's task is over. When it spawns children, the runtime and kernel track the whole tree. A signal from outside has to become a Linux signal delivered to the right PID. Bytes written to stdout have to land somewhere the runtime stack has wired up.

Namespaces: What The Process Can See

Namespaces wrap global system resources so a process sees a scoped instance of each one. Eight namespace types are relevant to containers:

- **mount** — the mount table;
- **PID** — the process ID space;
- **network** — interfaces, addresses, routes, firewall state, ports;
- **UTS** — hostname and domain name;
- **IPC** — System V IPC and POSIX message queues;
- **user** — UID and GID mappings;
- **cgroup** — the cgroup hierarchy view;
- **time** — offsets for `CLOCK_MONOTONIC` and `CLOCK_BOOTTIME` (added in Linux 5.6).

Inside a container, a process might believe it is PID 1; on the host it has another PID, and both are real within their respective views. Namespaces on their own do not limit memory, CPU, or process count, and an isolated mount namespace can still expose dangerous host paths if a careless bind mount puts them there.

cgroups: What The Process Can Use

cgroups organize processes into a hierarchy and attach resource controllers to it. Where namespaces govern visibility, cgroups govern consumption: memory limits and OOM behavior, CPU weights and quotas, cpuset placement, IO controls, pids limits, and the accounting that makes any of it observable.

Linux has shipped cgroup v2 since 4.5 (2016); systemd made it the default in v243 (2019), and major distributions followed by 2022 (RHEL 9). v2 is a unified hierarchy with one consistent controller model, replacing v1's per-controller hierarchies. On systemd hosts, runtimes ask systemd for a transient scope or slice over D-Bus and let systemd create the cgroup with `Delegate=yes`; the runtime itself never writes arbitrary paths under `/sys/fs/cgroup`.

The split to hold onto:

- namespaces answer *what world does this process see?*
- cgroups answer *what resources can this process group use?*

The Root Filesystem

Inside a container, `/` is almost never the host's `/`. It is a prepared root filesystem assembled from image layers and runtime mounts.

Producing it follows a fixed sequence: layers arrive as content; the snapshotter unpacks them and stacks them, typically with overlayfs; a writable upper layer is added for this container; the runtime sets up the mount table inside a fresh mount namespace; and `pivot_root(2)` swaps the prepared tree in as the new `/`. Bind mounts then expose specific host paths, tmpfs is mounted where needed, certain paths are masked or read-only, and device nodes are restricted.

The image is the repeatable base; the runtime decides what host-specific mounts, secrets, devices, and writable paths show up.

Security Controls: What The Process May Do

In Unix, visibility and permission are different problems. A container process can see a path it cannot read, run as UID 0 inside a user namespace while mapping to an unprivileged UID on the host, hold a shrunken set of capabilities, and have most of its syscalls denied by seccomp and most of its file accesses denied by AppArmor or SELinux.

The usual controls:

- **capabilities** — split root-equivalent authority into individually grantable pieces;

- **seccomp** — filter or block system calls;
- **AppArmor / SELinux** — apply mandatory access control policy;
- **user namespaces** — map UIDs and GIDs;
- **read-only and masked mounts** — limit filesystem exposure;
- **device cgroup rules** — control which device nodes work.

The boundary is the combined configuration. Dropping `CAP_NET_ADMIN` is fine for a web server but breaks a CNI plugin that needs to manage routes inside the netns; turning off seccomp's default deny list lets a workload call `keyctl(2)` again, which is fine for some images and a privilege-escalation vector for others.

Networking: How The Process Communicates

A container usually runs in its own network namespace, with its own loopback device, addresses, routes, firewall state, and ports. Connecting it to anything else is left to the runtime: typical solutions include veth pairs into a bridge, routed setups, NAT, overlay networks, eBPF datapaths, or direct device assignment.

Kubernetes treats this slightly differently. It creates one network namespace per pod sandbox, and every container in that pod runs inside the same namespace. This is why containers in a pod can talk to each other over `localhost` — they share the namespace.

The Container Network Interface (CNI) fits at this layer. CNI is a plugin specification, not a container or a runtime. The runtime creates (or receives) a network namespace, then invokes plugin binaries with `ADD` to set it up and `DEL` to tear it down. A concrete `ADD` call: containerd executes `/opt/cni/bin/bridge`, passes the namespace path in `CNI_NETNS` and a JSON config on stdin, and the bridge plugin creates a veth pair, moves one end into the namespace, attaches the other to a Linux bridge on the host, and delegates address allocation to an IPAM plugin. Part V walks through this in detail.

The Metadata Outside

The running process is only half the story. Outside it, the runtime tracks the image reference, labels and annotations, the snapshot key, the runtime name, the OCI spec, task status, the shim process, IO pipes and logs, exit status, and the leases that keep garbage collection from reclaiming content still in use.

This outside state is why containerd separates a *container* from a *task*. The container object is metadata that can exist without any process; the task is the live execution of that metadata.

A Thought Experiment

Take `/bin/sh` on a Linux host. Run it normally; it sees the host's process tree, mounts, network, and resource environment. Now change one thing at a time. The commands below add isolation in roughly the order a runtime does. Run them on a disposable Linux VM as root — each one mutates kernel state — and refer to chapter 4 onward for the flag-by-flag detail.

Swap the root filesystem (mount namespace plus `pivot_root`): `/` means something different.

```
# Build a tiny rootfs and enter a shell whose / is that directory.
mkdir -p /tmp/rootfs && docker export $(docker create alpine:3.20) | tar -x -C /tmp/rootfs
sudo unshare --mount --uts --pid --fork --mount-proc=/tmp/rootfs/proc \
  chroot /tmp/rootfs /bin/sh
# Inside: ls / shows alpine's layout, not the host's.
```

Add a UTS namespace: it gets its own hostname.

```
sudo unshare --uts -- /bin/sh -c 'hostname container-demo; hostname; exit'
hostname   # unchanged on the host
```

Add a PID namespace: it sees a process tree where it might be PID 1.

```
sudo unshare --pid --fork --mount-proc -- /bin/sh -c 'echo "I am PID $$"; ps -ef'
# I am PID 1
# UID  PID  PPID ... CMD
#   0    1     0 ... /bin/sh -c echo "I am PID $$"; ps -ef
```

Add a cgroup with limits: its memory and CPU are bounded and accounted.

```
sudo mkdir /sys/fs/cgroup/demo
echo "100M"     | sudo tee /sys/fs/cgroup/demo/memory.max
echo "50000 100000" | sudo tee /sys/fs/cgroup/demo/cpu.max   # 50% of one CPU
sudo unshare --pid --fork --mount-proc -- /bin/sh -c '
  echo $$ > /sys/fs/cgroup/demo/cgroup.procs
  cat /sys/fs/cgroup/demo/memory.current
'
sudo rmdir /sys/fs/cgroup/demo   # cleanup
```

Add a network namespace and a veth pair: it has its own network stack, plumbed to the host.

```
sudo ip netns add demo
sudo ip link add veth-h type veth peer name veth-c
sudo ip link set veth-c netns demo
sudo ip addr add 10.20.0.1/24 dev veth-h && sudo ip link set veth-h up
sudo ip -n demo addr add 10.20.0.2/24 dev veth-c
sudo ip -n demo link set veth-c up && sudo ip -n demo link set lo up
sudo ip netns exec demo /bin/sh -c 'ip addr; ping -c1 10.20.0.1'
sudo ip netns del demo && sudo ip link del veth-h 2>/dev/null
```

Drop capabilities, attach a seccomp profile, and apply an LSM policy: it has less authority even in a tree it appears to own.

```
# Capabilities: run /bin/sh with no caps in any set.
sudo capsh --drop=all --caps="" -- -c 'grep ^Cap /proc/self/status; id'

# Seccomp: deny mkdir(2) for this shell only (requires runc/docker for full profiles).
docker run --rm --security-opt seccomp=<(echo '{
  "defaultAction":"SCMP_ACT_ALLOW",
  "syscalls":[{"names":["mkdir","mkdirat"],"action":"SCMP_ACT_ERRNO"}]
}') alpine:3.20 sh -c 'mkdir /tmp/x || echo "mkdir blocked"'

# LSM: confine /bin/sh under the docker-default AppArmor profile.
docker run --rm --security-opt apparmor=docker-default alpine:3.20 \
  sh -c 'cat /proc/self/attr/current'
# docker-default (enforce)
```

Each command on its own is a small kernel call. Stacked, they are what a runtime hands the kernel when it starts a container.

A Working Definition

The word *container* gets attached to all of these: a tarball, an image in a registry, a `chroot`, a single namespace or cgroup, a `docker run` command, a Kubernetes pod, even a VM. Each names a real part of the picture, and none of them is the whole thing. Mistaking the part for the whole is how the word loses meaning.

> *A container is a process or process tree, started from packaged content and a runtime spec, isolated and constrained by host kernel primitives, and tracked by metadata that lives outside it.*

Chapter 3 picks up the contracts that hold these pieces together: the OCI runtime spec and the runtime v2 shim API.

Sources And Further Reading

- Linux namespaces: https://man7.org/linux/man-pages/man7/namespaces.7.html
- Linux cgroups: https://man7.org/linux/man-pages/man7/cgroups.7.html
- Linux cgroup v2 docs: https://kernel.org/doc/html/next/admin-guide/cgroup-v2.html
- OCI Runtime Specification: https://github.com/opencontainers/runtime-spec
- OCI Image Specification: https://github.com/opencontainers/image-spec
- CNI specification: https://www.cni.dev/docs/spec/

Chapter 3: Standards — OCI and Runtime v2

Each arrow is a different contract. CRI is owned by Kubernetes. Runtime v2 is owned by containerd. The OCI runtime spec is owned by the OCI. They were designed at different times by different groups.

What OCI Is

The Open Container Initiative is a Linux Foundation project formed at DockerCon on June 22, 2015. Its mandate is to publish open specifications for container formats and runtimes. The point is interoperability: a runtime, a registry, or a builder should be replaceable without rewriting everything above it.

OCI publishes three specifications, each versioned independently:

- **Runtime Specification** — what a runtime consumes and how it behaves.
- **Image Specification** — what an image is.
- **Distribution Specification** — how images move through registries.

The Runtime and Image specs were the original two. The Distribution spec, derived from Docker's Registry HTTP API V2, reached 1.0 in 2020 and turned an existing de facto standard into an open one.

This chapter focuses on the Runtime Specification.

The OCI Runtime Specification

The runtime spec defines two artifacts and a small lifecycle.

The Bundle

A **bundle** is a directory on disk containing two things: a `config.json` file and a root filesystem the runtime will use as `/`.

`config.json` describes the desired environment in fields that map to the chapter 2 model:

- `process` — args, env, cwd, user, capabilities, rlimits, terminal, `noNewPrivileges`.
- `root` — path to the root filesystem and a `readonly` flag.
- `mounts` — destination, type, source, options. The mount table the runtime should set up before exec.
- `hostname`.
- `linux` — the Linux-specific block: namespaces to enter or create, UID and GID mappings, devices, `cgroupsPath`, `resources` (per-controller cgroup settings), `seccomp` filter, `maskedPaths` and `readonlyPaths`, `rootfsPropagation`, sysctls.
- `hooks` — code to run at fixed points in the lifecycle.
- `annotations` — opaque key/value metadata.

`ociVersion` pins the spec version the config targets; runc rejects bundles whose major version it does not recognize.

A trimmed but realistic `config.json` — the kind of file `runc spec` generates and the shim hands runc — looks like this:

```
{
  "ociVersion": "1.2.0",
  "process": {
    "terminal": false,
    "user": { "uid": 0, "gid": 0 },
    "args": ["/bin/sh"],
    "env": [
      "PATH=/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin",
      "TERM=xterm"
    ],
    "cwd": "/",
    "capabilities": {
      "bounding":  ["CAP_AUDIT_WRITE", "CAP_KILL", "CAP_NET_BIND_SERVICE"],
      "effective": ["CAP_AUDIT_WRITE", "CAP_KILL", "CAP_NET_BIND_SERVICE"],
      "permitted": ["CAP_AUDIT_WRITE", "CAP_KILL", "CAP_NET_BIND_SERVICE"]
    },
    "rlimits": [
      { "type": "RLIMIT_NOFILE", "hard": 1024, "soft": 1024 }
    ],
    "noNewPrivileges": true
  },
  "root": { "path": "rootfs", "readonly": true },
  "hostname": "runc",
  "mounts": [
    { "destination": "/proc", "type": "proc", "source": "proc" },
    { "destination": "/dev",  "type": "tmpfs", "source": "tmpfs",
      "options": ["nosuid", "strictatime", "mode=755", "size=65536k"] },
    { "destination": "/sys",  "type": "sysfs", "source": "sysfs",
      "options": ["nosuid", "noexec", "nodev", "ro"] }
  ],
  "linux": {
    "namespaces": [
      { "type": "pid" }, { "type": "network" }, { "type": "ipc" },
      { "type": "uts" }, { "type": "mount" }
    ],
    "uidMappings": [{ "containerID": 0, "hostID": 100000, "size": 65536 }],
    "gidMappings": [{ "containerID": 0, "hostID": 100000, "size": 65536 }],
    "resources": {
      "memory": { "limit": 268435456 },
      "cpu":    { "shares": 512, "quota": 50000, "period": 100000 },
      "devices": [{ "allow": false, "access": "rwm" }]
    },
    "maskedPaths":  ["/proc/kcore", "/proc/keys", "/sys/firmware"],
    "readonlyPaths": ["/proc/asound", "/proc/bus", "/proc/sys"],
    "seccomp": { "defaultAction": "SCMP_ACT_ERRNO" }
  }
}
```

Every chapter-2 concept has a slot here: namespaces under `linux.namespaces`, cgroup limits under `linux.resources`, the rootfs under `root`, capabilities and `noNewPrivileges` under `process`, mounts and masked paths in their own sections. Generate a fully-populated default in any directory with `runc spec`, then edit it down — that is the path most runtime work takes.

The Lifecycle

A compliant OCI runtime exposes five lifecycle commands:

- `create` — set up namespaces, mounts, cgroups, security policy. Stop at the entry point of the container's init process and wait. The user process is not yet running.
- `start` — exec the user process.
- `state` — report the container's status as JSON: `id`, `status`, `pid`, `bundle`.
- `kill` — send a signal.

- `delete` — release any state retained by the runtime.

`create` and `start` are split so the caller can do work between resource setup and process execution: attach IO, set up a network namespace from outside, run hooks. That is also why containerd's shim uses the two-phase form rather than `runc run`.

Hooks

Hooks let external code run at fixed points in the container's lifecycle. The current spec defines five:

- `createRuntime` — runs in the runtime's namespace, after namespaces are created but before `pivot_root`.
- `createContainer` — runs inside the container's namespace, before `pivot_root`.
- `startContainer` — runs inside the container's namespace, just before `exec`.
- `poststart` — after the user process starts.
- `poststop` — after the user process exits.

There is also a `prestart` hook that was deprecated in spec 1.0.2 in favor of the more granular hooks above; runtimes still support it for compatibility. Hooks are how networking, GPU device injection, and a lot of runtime extension behavior get wired in without modifying the runtime itself.

OCI Runtimes In Practice

An OCI runtime is anything that consumes a valid bundle and implements those lifecycle commands. The interchangeability is the point: the layers above the runtime — containerd, Docker, Kubernetes — pick a runtime by configuration, not by code.

The common implementations:

- **runc** (Go) — the reference implementation, donated by Docker; uses libcontainer for the Linux setup.
- **crun** (C) — smaller and faster than runc; lower memory and quicker startup; maintained by Red Hat.
- **youki** (Rust) — runc-equivalent semantics in a different language.
- **runsc** (gVisor) — Google's user-space kernel; intercepts syscalls in a sandbox process. Trades performance for a stronger isolation boundary.
- **kata-containers** — runs each container inside a lightweight VM; OCI-compatible from the caller's perspective.
- **nvidia-container-runtime** — a thin wrapper around runc that injects GPU devices via a hook.

Containerd's Runtime v2

containerd does not exec the OCI runtime directly. It launches a **shim** per task, and the shim drives the runtime on its behalf. This is the runtime v2 model, defined in `docs/runtime-v2.md` in the containerd repo.

Why The Shim Exists

If containerd were the direct parent of every container process, three things would break:

1. **Restarting containerd would kill containers.** When the parent dies, the children either die with it or are reparented to init.
2. **IO and exit handling would leak into containerd.** Stdin/stdout pipes, exit notification, and signal forwarding are runtime-specific.
3. **Runtime swaps would require daemon changes.** With the shim contract, swapping runc for crun is a configuration change.

v1 Versus v2

The original v1 shim was defined inside containerd and predated a stable wire protocol. Runtime v2 is a versioned API: the shim binary speaks a defined ttrpc Task service, and any runtime can be wrapped behind it without touching containerd. v2 also supports a single shim serving multiple containers — typically one shim per pod sandbox in CRI mode — which cuts per-container overhead in Kubernetes.

containerd 1.0 (2017) shipped v1; 1.4 (2020) deprecated it; v2 is what every current installation uses.

Naming

A v2 shim is identified by a name like `io.containerd.runc.v2`. The binary name is the same string with dots replaced by dashes: `containerd-shim-runc-v2`. containerd resolves the name to a binary on `$PATH` when starting a task.

The shims you are likely to see:

Runtime name	Binary	Purpose
`io.containerd.runc.v2`	`containerd-shim-runc-v2`	Standard Linux runc path
`io.containerd.runhcs.v1`	`containerd-shim-runhcs-v1`	Windows HCS
Vendor-specific	`containerd-shim-kata-v2`, `containerd-shim-runsc-v1`, etc.	Kata, gVisor, Firecracker

The Wire Protocols

The four arrows in this chapter's opening diagram each use a different transport. Walking from top to bottom:

CRI gRPC: kubelet → containerd. The kubelet calls containerd over a Unix domain socket — `/run/containerd/containerd.sock` by default — using the `RuntimeService` and `ImageService` definitions in `cri-api`. These are full gRPC over HTTP/2: requests like `RunPodSandbox`, `CreateContainer`, and `StartContainer` are unary, while `Attach`, `Exec`, and `PortForward` use streaming. The kubelet picks the socket up from `--container-runtime-endpoint`; the path is the only handshake.

ttrpc Task service: containerd → shim. Once a task exists, containerd talks to its shim over **ttrpc** — a slimmer gRPC variant maintained at `github.com/containerd/ttrpc`. The protobuf definitions are gRPC-shaped, but the wire skips HTTP/2: framed protobuf over a Unix socket, no streaming, smaller binary, smaller memory. ttrpc fits here because shims are cheap and there is one per workload (or per pod) — a full HTTP/2 stack per shim would cost more than the shim itself. The Task service the shim implements covers the operations a daemon needs:

- `Create`, `Start`, `Delete` — task lifecycle.
- `Exec`, `Kill`, `ResizePty`, `CloseIO` — interactive control.
- `State`, `Pids`, `Wait`, `Stats` — status and observation.
- `Pause`, `Resume`, `Update`, `Checkpoint` — runtime control.
- `Connect`, `Shutdown` — shim-level lifecycle.

When the shim is sandbox-aware (i.e. it can host a Kubernetes pod), a separate Sandbox service sits alongside Task.

Events: shim → containerd, via a publish binary. Containers produce asynchronous events — `TaskExit`, `TaskOOM`, `TaskCreate` — that the shim has to push back to containerd. Rather than open a second long-lived ttrpc connection, the shim invokes a small binary it was given at startup. containerd execs the shim with `-publish-binary /usr/local/bin/containerd` and `-address <main socket>`; the shim runs `containerd publish --topic=/tasks/exit --namespace=<ns>` for each event, with a serialized protobuf envelope on stdin. The publish binary is a thin client that forwards the event over ttrpc to containerd's Events service and exits. From the shim's perspective, an event is one `fork` / `exec`.

OCI runtime CLI: shim → runc. The shim does not link runc as a library. It writes the bundle to disk and invokes runc as a subprocess for each lifecycle step: `runc create`, `runc start`, `runc kill`, `runc delete`. The "protocol" is the CLI — arguments and exit codes — with several out-of-band channels:

- **stdio** is plumbed through inherited file descriptors. When `process.terminal` is true, runc allocates a pseudo-terminal and sends the master fd to the shim over a Unix socket whose path the shim passes as `--console-socket`.
- **The bundle directory** is the input. runc reads `config.json` and the rootfs from it; the path is the last positional argument to `runc create`.

- **The pid file** (`--pid-file`) is where runc writes the init process's host PID after `create` returns. The shim opens it, reads the PID, and uses `wait4(2)` (or pidfd) to detect exit.
- **The state directory** (default `/run/runc/<id>/`) holds runc's own `state.json` for each container, so subsequent `runc kill` or `runc delete` calls find the container without the shim having to keep any in-memory handle.

Part III walks through the runc side of these calls in detail.

The Startup Handshake

containerd starts a shim by execing its binary with the subcommand `start` and a fixed set of flags: `-namespace` (a containerd namespace, not a Linux one), `-id` (the task id), `-address` (containerd's main ttrpc socket), and `-publish-binary` (the events client). The shim then:

1. Creates its own ttrpc socket — a Unix abstract socket under containerd's state directory, e.g. `/run/containerd/s/<random>` .
2. Forks itself; the child runs the ttrpc server, the parent prints the socket address on stdout and exits.
3. containerd reads the address, dials it, and from then on drives the Task service over ttrpc.

The shim process — not containerd — is the parent of the container's init process. Containerd holds a ttrpc connection to the shim, the shim holds the runc invocations and the init PID, and runc has already exited by the time `Start` returns. If containerd restarts, the shim keeps running and keeps holding the container; on reconnect, containerd dials the existing socket and resumes management without restarting the workload.

Part III opens up the OCI runtime spec and runc. Part IV opens up containerd, which is where CRI on top and runtime v2 underneath both meet.

Sources And Further Reading

- OCI homepage: https://opencontainers.org/
- OCI Runtime Specification: https://github.com/opencontainers/runtime-spec
- OCI Image Specification: https://github.com/opencontainers/image-spec
- OCI Distribution Specification: https://github.com/opencontainers/distribution-spec
- runc: https://github.com/opencontainers/runc
- crun: https://github.com/containers/crun
- youki: https://github.com/containers/youki
- gVisor: https://gvisor.dev/
- Kata Containers: https://katacontainers.io/
- containerd runtime v2: https://github.com/containerd/containerd/blob/main/docs/runtime-v2.md
- containerd ttrpc: https://github.com/containerd/ttrpc

PART II — LINUX PRIMITIVES

Chapter 4: Namespaces

A **namespace** is a kernel-maintained, reference-counted set of resources that a process sees as the global instance of those resources. Two processes in the same namespace share the same view; two processes in different namespaces of the same type see disjoint views, even though they are running on the same machine and the same kernel. The kernel keeps one namespace per *type* (mount, PID, network, ...) per *task*, and exposes membership through the `nsproxy` struct attached to every task.

Containers exist because Linux generalized this idea across eight different kinds of resource and gave userspace a way to compose them. A process inside a container has its own PID namespace (so it sees `init` as PID 1 and cannot signal anything outside), its own mount namespace (so its `/etc/hosts` is not the host's), its own network namespace (its own loopback, route table, sockets, iptables rules), and so on. The container appears to be a small Linux system because, from its own viewpoint, it is one. Nothing about the kernel changes; only the views do.

Two things namespaces do *not* do are worth saying up front. They do not isolate resource consumption — a process in its own PID namespace can still allocate every byte of host memory, which is what cgroups (chapter 5) are for. And they do not enforce policy beyond visibility — a process that can see a resource and has the capabilities to act on it will succeed, which is what capabilities, seccomp, and MAC (chapter 7) compose with namespaces to constrain.

> ***Safety:*** *the commands below mutate kernel state and most need root. Use a disposable Linux VM. Examples here were checked on Ubuntu 24.04 with kernel 6.8 and the `util-linux` package supplying `unshare`, `nsenter`, and `lsns`.*

The Eight Types

Linux ships eight namespace types, each gated by a `CLONE_NEW*` flag passed to `clone(2)` or `unshare(2)`. The order they were added matters: a runtime targeting kernel 6.x can use all eight; older kernels miss the later ones.

Type	Flag	Linux	What it isolates
Mount	`CLONE_NEWNS`	2.4.19 (2002)	The mount table
UTS	`CLONE_NEWUTS`	2.6.19 (2006)	Hostname, NIS domain name
IPC	`CLONE_NEWIPC`	2.6.19 (2006)	System V IPC, POSIX message queues
PID	`CLONE_NEWPID`	2.6.24 (2008)	Process ID number space
Network	`CLONE_NEWNET`	2.6.24 (2008)	Net devices, addresses, routes, ports, netfilter
User	`CLONE_NEWUSER`	3.8 (2013)	UID/GID mappings, namespaced privilege
Cgroup	`CLONE_NEWCGROUP`	4.6 (2016)	View of the cgroup root
Time	`CLONE_NEWTIME`	5.6 (2020)	`CLOCK_MONOTONIC` and `CLOCK_BOOTTIME` offsets

`CLONE_NEWNS` predates the era when "namespaces" became plural — the flag still creates a *mount* namespace, despite the historical name. The mount namespace was the first one because mount-table virtualization was the original motivation; everything else followed.

User namespaces are the special one. A process can hold root-equivalent capabilities inside a user namespace it created without holding any host-level privilege, which is the basis of every rootless container runtime. They also redefine what "privilege" means everywhere else — capabilities apply only within the user namespace that owns the resource being acted on. The user namespace section below covers the consequences.

Creating, Joining, Leaving

Three syscalls do almost all the work:

- **`clone(2)`** / **`clone3(2)`** — create a child process with one or more `CLONE_NEW*` flags. The child starts in the new namespace(s); the parent stays where it was. This is the path containers actually take: runc calls `clone3` with the right flags, and the child becomes the container init.
- **`unshare(2)`** — move the *current* process into freshly-created namespaces. Same flag set as `clone`. Useful when you want to change membership without forking.
- **`setns(2)`** — join an existing namespace via a file descriptor. The fd usually comes from `/proc/<pid>/ns/<type>` or from a bind mount of one of those symlinks.

A namespace exists as long as something holds a reference to it. References come from three places: a process whose `nsproxy` points at it, an open file descriptor on its `/proc/<pid>/ns/<type>` symlink, or a bind mount of that symlink elsewhere in the filesystem. When the last reference goes away, the kernel destroys the namespace and reclaims its resources. This is why `ip netns add foo` bind-mounts the network namespace under `/var/run/netns/foo`: the bind mount keeps the namespace alive so a CNI plugin can configure it before any container process exists inside.

Two processes share a namespace exactly when their `/proc/<pid>/ns/<type>` symlinks resolve to the same inode. The inode number is the namespace's identity.

What Lives In `/proc/<pid>/ns/`

```
ls -l /proc/self/ns/
# lrwxrwxrwx 1 me me 0 ... cgroup -> 'cgroup:[4026531835]'
# lrwxrwxrwx 1 me me 0 ... ipc    -> 'ipc:[4026531839]'
# lrwxrwxrwx 1 me me 0 ... mnt    -> 'mnt:[4026531840]'
# lrwxrwxrwx 1 me me 0 ... net    -> 'net:[4026531992]'
# lrwxrwxrwx 1 me me 0 ... pid    -> 'pid:[4026531836]'
# lrwxrwxrwx 1 me me 0 ... pid_for_children -> 'pid:[4026531836]'
# lrwxrwxrwx 1 me me 0 ... time   -> 'time:[4026531834]'
# lrwxrwxrwx 1 me me 0 ... time_for_children -> 'time:[4026531834]'
# lrwxrwxrwx 1 me me 0 ... user   -> 'user:[4026531837]'
# lrwxrwxrwx 1 me me 0 ... uts    -> 'uts:[4026531838]'
```

The `_for_children` entries apply to processes the current process spawns. PID and time namespace changes take effect at the next `fork(2)`, not immediately, so the kernel exposes both the current value and the value newly-forked children will inherit. This is why `unshare --pid` requires `--fork` — the calling process cannot move into the new PID namespace itself; it must fork a child that becomes PID 1.

The same information in tabular form:

```
lsns
```

`lsns` walks `/proc/*/ns/` and groups processes by namespace; it is the easiest way to figure out which container is using which namespace in a debug session.

Creating Namespaces With `unshare`

`unshare(1)` is the user-space wrapper for `unshare(2)`. It creates new namespaces and execs a command inside them.

A UTS namespace needs `CAP_SYS_ADMIN` to create directly:

```
sudo unshare --uts -- bash -c 'hostname inside; hostname'
# inside
hostname
# (unchanged on host)
```

To get the same behavior unprivileged, wrap it in a user namespace — the one namespace that does not require pre-existing privilege to create:

```
unshare --user --map-root-user --uts -- bash -c 'hostname inside; hostname'
# inside
hostname
# (unchanged on host)
```

`--map-root-user` writes a UID/GID mapping that maps the caller to UID 0 inside the new user namespace. The shell believes it is root; from the host it is the same unprivileged process.

PID Namespace And The PID 1 Problem

A new PID namespace makes the first process inside it PID 1.

```
sudo unshare --pid --fork --mount-proc -- bash -c 'echo "pid: $$"; ps -ef'
# pid: 1
# UID  PID  PPID ... CMD
#   0    1     0 ... bash -c echo "pid: $$"; ps -ef
#   0    2     1 ... ps -ef
```

`--fork` is required because the calling process cannot move into the new PID namespace itself; it must fork a child that becomes PID 1. `--mount-proc` remounts `/proc` inside the new mount namespace so `ps` reflects the new PID space.

PID namespaces are **hierarchical**: every process in a child namespace also has a PID in the parent and in every ancestor up to the root. The host can see and signal container processes by their host PIDs; the container cannot see host processes at all. PIDs are translated when crossing the boundary — the same task is, say, host-PID 24891 and container-PID 1.

PID 1 is special, and the special treatment is the reason container processes routinely fail to exit on `docker stop` or `kubectl delete pod`. Two kernel rules apply only to PID 1 in its namespace:

- **Default signal handlers do not run.** `SIGTERM`, `SIGINT`, and friends are silently dropped unless PID 1 has installed a handler. `SIGKILL` and `SIGSTOP` are exceptions because the kernel cannot block them.
- **Orphaned descendants get reparented to PID 1.** When PID 1 fails to `wait(2)` on them, they become zombies that pile up indefinitely.

To see the failure:

```
sudo unshare --pid --fork --mount-proc -- bash -c '
  echo "pid 1 = $$"
  while :; do sleep 1; done
'
# In another terminal:
# kill -TERM <pid-of-the-bash-process-on-host>
# bash continues running
```

The kernel will not deliver the default-action `SIGTERM`. Container runtimes work around this by injecting a tiny init like `tini` or `dumb-init` that installs handlers, forwards signals to its children, and reaps zombies on their behalf. Docker has had `--init` for this since 1.13; Kubernetes pods that don't ship their own init usually need one in the image, or a sidecar approach.

Mount Namespaces And Propagation

A mount namespace governs which mounts a process sees. To watch a mount appear and disappear:

```
sudo unshare --mount -- bash
# Inside the new namespace:
mount -t tmpfs tmpfs /mnt
mount | grep /mnt
# tmpfs on /mnt type tmpfs (rw,relatime)
exit
# Back on the host:
mount | grep /mnt
# (nothing)
```

The host never saw the mount, because the mount namespace's mount table is private. A mount namespace governs *mounts*, not *inodes*: bind-mount the host's `/etc/passwd` into a container's mount namespace and the container reads the host's file regardless of its mount view. The boundary is the mount table, not the data.

The catch is **propagation**. Each mount in a mount namespace has one of four propagation types:

- **shared** (`MS_SHARED`) — events propagate to peers in the same propagation group.
- **private** (`MS_PRIVATE`) — no propagation.
- **slave** (`MS_SLAVE`) — receives events from a master, does not send.
- **unbindable** (`MS_UNBINDABLE`) — like private, plus cannot be the source of a bind mount.

Many distributions ship `/` as `shared`. A new mount namespace inherits the propagation of its source, which would mean a container's mount events propagate back to the host's peers. Default `unshare --mount` makes the new namespace's root `private` to prevent that:

```
findmnt -o TARGET,PROPAGATION /
# TARGET PROPAGATION
# /      shared
```

When runc sets up a container, it sets the new mount namespace's root to `private` (or whatever `linux.rootfsPropagation` requests), then mounts the rootfs and special filesystems before `pivot_root(2)` swaps it in. Chapter 6 walks through that sequence. Kubernetes' `mountPropagation` field maps directly: `HostToContainer` is `rslave`, `Bidirectional` is `rshared`, the default is `rprivate`.

Network Namespaces

Each network namespace is a complete, independent network stack: its own loopback (down by default), its own list of network devices, its own routing table, its own neighbor table, its own netfilter rules, its own sockets, and its own per-namespace sysctls (most of `net.*` is namespaced in modern kernels). Two namespaces cannot accidentally share a port because they do not share a port table.

`ip netns` is the convenient subcommand. Unlike `unshare`, `ip netns add` keeps the namespace alive after the calling process exits by bind-mounting it to `/var/run/netns/<name>`:

```
sudo ip netns add demo
sudo ip netns list
# demo
ls /var/run/netns/
# demo
```

```
sudo ip netns exec demo ip link
# 1: lo: <LOOPBACK> mtu 65536 state DOWN ...
sudo ip netns exec demo ip link set lo up
sudo ip netns exec demo ping -c1 127.0.0.1
```

When a network device is moved into a namespace it loses its address configuration; addresses, routes, and firewall state must be reapplied inside the new namespace.

Connecting two namespaces requires a virtual link. The classic recipe is a `veth` pair — a kernel-provided cable with two ends, where one end goes into each namespace:

```
sudo ip netns add a
sudo ip netns add b

sudo ip link add va type veth peer name vb
sudo ip link set va netns a
sudo ip link set vb netns b

sudo ip -n a link set lo up
sudo ip -n b link set lo up
sudo ip -n a link set va up
sudo ip -n b link set vb up

sudo ip -n a addr add 10.10.0.1/24 dev va
sudo ip -n b addr add 10.10.0.2/24 dev vb

sudo ip netns exec a ping -c1 10.10.0.2
```

This is one bridge away from the standard container networking pattern: replace `vb` going into namespace `b` with `vb` attached to a host bridge, and add NAT rules. Part 6 covers the bridge-based and CNI flows in detail.

Joining An Existing Namespace With `nsenter`

`nsenter(1)` calls `setns(2)` on a target namespace and execs a command. To run a command inside a process's mount namespace:

```
pgrep -f some-container-process
sudo nsenter -t <pid> -m -p -- ls /proc
```

`kubectl exec`, `crictl exec`, and `docker exec` all reduce to a `setns` chain plus an `exec`. The reason it has to chain in a specific order is that some namespace transitions invalidate previously-set state — notably, joining a mount namespace makes paths from the old namespace unresolvable, so PID namespace switches that need to read `/proc` must come first.

A subtle gotcha: `setns(2)` for PID and mount namespaces was historically restricted on multithreaded processes, because Go programs (containerd, runc) cannot safely call it from arbitrary goroutines. runc works around this by doing all its namespace setup in a small C shim (`libcontainer/nsenter/nsexec.c`) that runs *before* the Go runtime starts.

User Namespaces And Privilege Scoping

User namespaces are the conceptual hinge of the chapter. Most other namespace types are *owned* by a user namespace, and capabilities held by a process apply only within the user namespace that owns the resource being acted on. That is what makes namespaces composable: an unprivileged user can create a user namespace, gain `CAP_SYS_ADMIN` inside it, and then create mount or network namespaces from inside that user namespace — because those new namespaces are owned by the user namespace where the user has `CAP_SYS_ADMIN`.

To create one and observe the mapping:

```
unshare --user --map-root-user -- bash -c '
  echo "id inside: $(id)"
  cat /proc/self/uid_map
'
# id inside: uid=0(root) gid=0(root) groups=0(root)
# 0          1000          1
```

The mapping reads as `<inside-uid> <outside-uid> <length>`. UID 0 inside maps to UID 1000 outside, for one UID. The shell believes it is root inside; from the host it is the same unprivileged user.

A user namespace gives root-equivalent capabilities only over resources owned by *that* user namespace. Try to do something that requires actual host root:

```
unshare --user --map-root-user -- bash -c '
  mount -t tmpfs tmpfs /mnt
'
# mount: /mnt: permission denied. (only privileged user can mount)
```

The mount fails because the host's mount namespace is owned by the *initial* user namespace, where the calling user is just UID 1000. The same `CAP_SYS_ADMIN`, scoped to a freshly-created mount namespace owned by the new user namespace, is enough to mount things there:

```
unshare --user --map-root-user -- bash -c '
  unshare --mount -- bash -c "mount -t tmpfs tmpfs /mnt && echo mounted"
'
# mounted
```

This distinction — capabilities-scoped-to-the-owning-user-namespace — is the source of most "I have root in the container, why doesn't this work?" confusion. The capability is real; it just does not apply to host-owned objects.

For unprivileged users to map UIDs other than their own, they need `newuidmap(1)` and `newgidmap(1)` (setuid helpers from `shadow-utils`) and entries in `/etc/subuid` and `/etc/subgid`:

```
grep "^$(whoami):" /etc/subuid /etc/subgid
# /etc/subuid:me:100000:65536
# /etc/subgid:me:100000:65536
```

These say: the user `me` may map host UIDs 100000 through 165535 inside any user namespace they own. This is what gives a rootless container a 64K-UID range to allocate inside. Writing to `gid_map` from an unprivileged user also requires writing `deny` to `/proc/<pid>/setgroups` first, to prevent privilege escalation via supplementary group manipulation — a kernel-side check added after a 2014 CVE.

Time Namespaces

Time namespaces are the youngest of the eight (Linux 5.6, March 2020) and the most limited. They offset only `CLOCK_MONOTONIC` and `CLOCK_BOOTTIME`. `CLOCK_REALTIME` is shared with the host and cannot be changed per-namespace, which means containers cannot lie about the wall-clock time — only about how long they have been running.

```
sudo unshare --time --fork -- bash -c '
  echo "Before offset:"
  cat /proc/uptime
  # Apply offsets via /proc/<pid>/timens_offsets.
  # Format: <clock_id> <secs> <nanosecs>
  # CLOCK_MONOTONIC=1, CLOCK_BOOTTIME=7
  echo "1 -100 0" > /proc/$$/timens_offsets
  echo "After offset:"
  cat /proc/uptime
'
```

`timens_offsets` must be written before any process executes inside the namespace, which is why runtimes write it in the brief window after `unshare(CLONE_NEWTIME)` and before `exec`. The use case is checkpoint/restore (CRIU) — a restored process needs `CLOCK_MONOTONIC` to appear continuous across the freeze, even though wall time has advanced.

Putting It Together: A Hand-Rolled Container

The same assembly without runc: a shell with its own user, PID, mount, UTS, IPC, and net namespaces, and an Alpine rootfs as `/`.

```
# Get a small rootfs.
mkdir alpine-rootfs
docker export $(docker create alpine:3.20) | tar -C alpine-rootfs -xf -

# Run a shell in fresh namespaces with that as /.
sudo unshare \
  --user --map-root-user \
  --pid --fork --mount-proc \
  --mount --uts --ipc --net \
  -- chroot alpine-rootfs /bin/sh

# Inside:
# / # hostname
# (empty -- new UTS namespace)
# / # ps
# PID   USER     TIME  COMMAND
#     1 root      0:00 /bin/sh
#     2 root      0:00 ps
# / # ls /
# bin etc lib mnt proc root sbin sys tmp usr var
```

This is intentionally crude. There is no cgroup, no seccomp, no capability dropping, no `pivot_root` (just `chroot`, which is escapable), no IO or signal supervision, no networking inside the new netns. What it does demonstrate is the order of namespace creation: user namespace first (so the rest can be created unprivileged), then PID with `--fork` (so the calling shell does not need to enter it), then the rest. Stacking flags on a single `unshare` call is also how runc does it — one syscall, all the namespaces at once, an atomic transition into the new state.

OCI Mapping

The runtime spec's `linux.namespaces` array names which namespaces to enter or create. Each entry is `{type, path}`; if `path` is set, the runtime calls `setns(2)` on it instead of creating a new one.

This is how Kubernetes shares a pod's network namespace across containers — every container in the pod has its config's `network` entry pointing at the same `/proc/<pid>/ns/net` path. The first container creates the namespace; the rest join it. The pod sandbox container (the "pause container") exists primarily to hold that namespace open — it bind-mounts it so the namespace survives the death of any individual container.

`linux.uidMappings` and `linux.gidMappings` carry the user-namespace ID mappings. `linux.timeOffsets` carries the time-namespace clock offsets.

Where This Goes

Namespaces by themselves do not constrain CPU or memory and do not prevent a process from forking until the host runs out of process slots. The next chapter — cgroups v2 — covers the resource side.

Sources And Further Reading

- `namespaces(7)`: https://man7.org/linux/man-pages/man7/namespaces.7.html
- `unshare(1)`: https://man7.org/linux/man-pages/man1/unshare.1.html
- `nsenter(1)`: https://man7.org/linux/man-pages/man1/nsenter.1.html
- `user_namespaces(7)`: https://man7.org/linux/man-pages/man7/user_namespaces.7.html
- `pid_namespaces(7)`: https://man7.org/linux/man-pages/man7/pid_namespaces.7.html
- `mount_namespaces(7)`: https://man7.org/linux/man-pages/man7/mount_namespaces.7.html
- `network_namespaces(7)`: https://man7.org/linux/man-pages/man7/network_namespaces.7.html
- `time_namespaces(7)`: https://man7.org/linux/man-pages/man7/time_namespaces.7.html
- `cgroup_namespaces(7)`: https://man7.org/linux/man-pages/man7/cgroup_namespaces.7.html
- Linux shared subtree docs: https://www.kernel.org/doc/Documentation/filesystems/sharedsubtree.txt
- OCI Runtime Spec, namespaces: https://github.com/opencontainers/runtime-spec/blob/main/config-linux.md#namespaces
- runc nsenter C source: https://github.com/opencontainers/runc/blob/main/libcontainer/nsenter/nsexec.c

Chapter 5: Cgroups v2

Namespaces decide what a process can see. **Cgroups** — *control groups* — decide what it can use. The two pair up because isolation alone is not enough: a container with its own PID, mount, and network namespaces can still allocate every byte of the host's memory, spin every core to 100%, and fork until the kernel runs out of process slots. Cgroups close that gap by attaching kernel resource controllers to a tree of process groups, so every limit and accounting decision applies to a defined subset of the system instead of to the host as a whole.

The production failure mode this exists to prevent is concrete. One pod's Java heap doubles overnight after a config change, the JVM walks the host into swap, every other pod on the node misses its liveness probe, the kubelet declares the node unhealthy, and the workload reschedules onto a peer that promptly suffers the same fate. Without a per-cgroup `memory.max`, "noisy neighbor" is "all neighbors die." The rest of this chapter is about how the kernel actually accounts for and enforces those limits, why the interface looks the way it does, and what every file under `/sys/fs/cgroup` is for.

> ***Safety:*** *writing to `/sys/fs/cgroup` requires root. The example that triggers an OOM kill is harmless on a VM but will cause a real OOM event in the kernel log. Use a disposable Linux VM. Examples were checked on Ubuntu 24.04 with kernel 6.8 and systemd 255 in cgroup v2 unified mode.*

v1 And v2: What Changed And Why

Cgroups began as "process containers," a 2006–2007 patch series from Paul Menage and Rohit Seth at Google, renamed at merge to avoid clashing with the Solaris term. The v1 patch landed in Linux 2.6.24 in January 2008. Its design choice was **multiple hierarchies**: every resource controller (cpu, memory, io, pids, …) got its own directory tree, and a process could sit at a different position in each tree. You could place process *X* in a CPU cgroup that capped it at one core while simultaneously placing it in a memory cgroup that gave it 32 GB. Flexible, in principle.

In practice the multi-hierarchy model produced three persistent problems. **Incoherent attribution** was the worst of them. The page cache and writeback paths need memory and I/O accounting to agree about which group an allocation belongs to: a write that dirties a page is a memory event when the page is allocated and an I/O event when the page is written back, possibly minutes later by an unrelated kernel thread. In v1, a process could be in a memory cgroup of one shape and an `io` (then `blkio`) cgroup of a completely different shape. The kernel charged the dirty page to one group and the writeback I/O to another. Throttling either side did not throttle the workload that actually caused the load, and limits could be over- or under-counted. The kernel docs eventually documented this as "v1 cannot do meaningful page-cache writeback accounting," which is a kind way to put it.

Delegation was unsafe. Handing a subtree to an unprivileged manager required reasoning about every controller hierarchy independently, and v1 had no kernel-side notion of what a delegated manager was allowed to do. **Single-writer collisions with systemd** were the third: once systemd took over the cgroup tree on most distros, two managers writing to the same v1 controllers raced, and the cgroup core had no notion of ownership.

Cgroup **v2** merged in Linux 4.5 (March 2016) and became the default unified mode in Fedora 31 (2019), Debian 11 (2021), Ubuntu 21.10 (2021), and RHEL 9 (2022). Kubernetes flipped the v2 default in 1.25 (2022). The redesign is built around three principles. **Single hierarchy:** every cgroup is a node in one tree, and a process belongs to exactly one cgroup. **Top-down enablement:** controllers are not "in" a cgroup by default; the parent enables them for children by writing into its `cgroup.subtree_control`. **Coherent accounting:** because every controller sees the same hierarchy, the page-cache problem disappears — memory and I/O charges land on the same node. The model trades v1's per-controller flexibility for coherence, and the flexibility was, in practice, almost never useful and almost always confusing.

The rest of this chapter assumes v2. A few v1 oddities (separate `devices.allow` files, the `freezer` subsystem, `net_cls` / `net_prio`) are gone or replaced; the substitutes are noted as they come up.

Why A Pseudo-Filesystem

The cgroup API could have been a syscall. Instead the kernel exposes the entire interface as a virtual filesystem mounted at `/sys/fs/cgroup`: every cgroup is a directory, every knob is a file, and configuration happens with `mkdir`, `echo`, and `cat`. The choice is deliberate and pays off in five places.

A directory tree is the natural shape for a hierarchy of process groups, so the API matches the underlying object. UNIX file permissions already exist for restricting who can read or write what, which means **delegation comes for free**: `chown` a subtree to an unprivileged user and they own everything below it without any new access-control code in the kernel. The interface is **introspectable from any language** — no libc binding, no syscall numbers, just `read(2)` and `write(2)` against paths. Each kernel-side write is **atomic per line**, so scripts can edit a knob without partial-state races. And `cgroup.events` is **inotify-watchable**, which lets userspace react to a cgroup becoming empty without polling.

The cost is a slightly unusual UX: configuring kernel resource policy with shell redirects feels like a hack the first time. But everything in this chapter is `mkdir`, `echo`, and `cat`, and that is the point.

The Charging Model

Limits and accounting need a verb. The kernel calls it **charging**. When code on behalf of a process allocates a tracked resource — a page of memory, a process slot, a millisecond of CPU — the kernel walks from the calling task to the cgroup it belongs to (`task->cgroups`, a per-task pointer) and increments a counter on that cgroup. When the resource is released, the counter decrements. Limits are enforced on the increment: if the new value would exceed the cgroup's `*.max`, the operation either fails (`ENOMEM`, `EAGAIN`) or triggers reclaim, depending on the controller.

Charging is **hierarchical**. Every charge against a leaf is also charged against every ancestor up to the root. That is what `cgroup.subtree_control` and the unified hierarchy buy: parents see the sum of their children's usage, and a parent limit constrains the total of everything beneath it. A pod-level `memory.max` of 4 GB is enforced even if the pod's containers individually have no limit, because every page they allocate is charged to the pod cgroup as well.

A few concrete examples make the abstraction tangible:

- **Memory.** `mm/memcontrol.c` calls `try_charge` on every page allocation that should count against the calling task's memory cgroup. If the new charge would exceed `memory.max`, the kernel attempts direct reclaim inside the cgroup. If reclaim cannot free enough, the OOM killer fires *inside the cgroup* and picks a victim from its processes.
- **CPU.** The scheduler tracks CPU time per scheduler entity. With the cpu controller enabled, every cgroup gets its own entity in the runqueue, and the scheduler updates `cpu.stat` with the cycles consumed. `cpu.max` adds a bandwidth controller (CFS/EEVDF bandwidth) that throttles the cgroup when it has used its quota for the current period.
- **PIDs.** `kernel/cgroup/pids.c` increments the cgroup's `pids.current` inside `fork(2)`, after the new task is allocated but before it is visible. If `pids.current` would exceed `pids.max`, `fork` returns `EAGAIN`.
- **I/O.** Block-layer accounting attaches a charge to every BIO submitted on behalf of a process, with the calling cgroup recorded in the BIO. The block scheduler and writeback path use that to attribute throttling and weight.

Two consequences fall out of the charging model that are worth holding in mind. First, **a process's cgroup is sticky to its work, not just to its identity**: a kernel thread doing writeback on behalf of a user process is charged to the user's cgroup, because the BIO carries the original task's cgroup pointer. Second, **moving a process between cgroups does not retroactively re-charge anything**. Already-allocated pages stay charged to the original cgroup until they are freed. Restarting a heavy process is sometimes the only way to re-attribute its memory.

Confirm v2 Is Active

The unified hierarchy is mounted as `cgroup2` at `/sys/fs/cgroup`:

```
mount | grep cgroup2
# cgroup2 on /sys/fs/cgroup type cgroup2 (rw,nosuid,nodev,noexec,relatime,nsdelegate,memory_recursiveprot)
```

If you also see `cgroup` mounts at `/sys/fs/cgroup/<controller>/`, the system is in legacy v1 or hybrid mode and the rest of this chapter does not apply directly. To force unified mode, set `systemd.unified_cgroup_hierarchy=1` on the kernel command line and reboot.

The two mount options worth knowing about are `nsdelegate` (treats a cgroup namespace boundary as a delegation point — the namespace's root cgroup is the limit of what processes inside the namespace can climb above) and `memory_recursiveprot` (makes `memory.low` and `memory.min` apply recursively down the subtree, the version of these knobs everyone actually wants).

Walk The Tree

Every directory under `/sys/fs/cgroup` is a cgroup. The root is `/sys/fs/cgroup` itself.

```
ls /sys/fs/cgroup/ | head
# cgroup.controllers
# cgroup.max.depth
# cgroup.max.descendants
# cgroup.procs
# cgroup.subtree_control
# cgroup.threads
# cpu.pressure
# cpu.stat
# init.scope
# io.pressure
# ...
cat /sys/fs/cgroup/cgroup.controllers
# cpuset cpu io memory hugetlb pids rdma misc
```

`cgroup.controllers` lists what is *available* to this cgroup; `cgroup.subtree_control` lists what is *enabled* for children:

```
cat /sys/fs/cgroup/cgroup.subtree_control
# cpuset cpu io memory pids
```

A controller has to be enabled by the parent before child cgroups can use it. That is the **top-down constraint**: parents enable, children inherit, and a non-root cgroup with processes in it cannot enable controllers in its own `subtree_control` (more on that below). To see how systemd has shaped the tree:

```
systemd-cgls --no-pager | head -30
```

The standard layout: `system.slice/` for system services, `user.slice/user-<uid>.slice/` for user sessions, and (when present) `kubepods.slice/` or `machine.slice/` for orchestrated workloads.

Make A Cgroup By Hand

A new cgroup is just a `mkdir`. The kernel synthesizes a standard set of files inside automatically:

```
sudo mkdir /sys/fs/cgroup/demo
ls /sys/fs/cgroup/demo/
# cgroup.controllers   cgroup.events     cgroup.freeze   cgroup.kill
# cgroup.max.depth     cgroup.max.descendants            cgroup.procs
# cgroup.stat          cgroup.subtree_control            cgroup.threads
# cgroup.type          cpu.pressure      cpu.stat
# io.pressure          memory.pressure
```

Every cgroup, regardless of which controllers are enabled, gets the **`cgroup.*` files**. Each one has a job:

- **`cgroup.procs`** — PIDs in this cgroup. Read it to list members; write a PID to it to move that process into the cgroup. Atomic: a write moves the process out of its previous cgroup as it places it.
- **`cgroup.threads`** — like `cgroup.procs` but for individual TIDs. Only meaningful when `cgroup.type` is `threaded`.
- **`cgroup.controllers`** — controllers available to *this* cgroup, inherited from the parent's `cgroup.subtree_control`. Read-only.
- **`cgroup.subtree_control`** — controllers enabled for *child* cgroups of this one. Written as a diff: `+memory +pids -io`. The diff syntax is what makes scripts safe — you do not need to know the existing state to add a controller.
- **`cgroup.events`** — readable, with two keys (`populated` 0/1, `frozen` 0/1). Set up an `inotify(7)` watch on this file to be notified when the cgroup empties out — that is how runtimes know a container has fully exited without polling `cgroup.procs`.
- **`cgroup.type`** — usually `domain` (the standard "contains processes" mode). `threaded` switches to per-thread cgroup membership; `domain threaded` is the threaded-root marker. `domain invalid` means the cgroup is currently in a state controllers cannot handle (typically a transitional state inside a threaded subtree).
- **`cgroup.stat`** — counts of descendant cgroups, in two flavors: `nr_descendants` (live) and `nr_dying_descendants` (released but not yet freed because they still hold charged resources, usually pinned page-cache pages).
- **`cgroup.freeze`** — write `1` to suspend every process in the cgroup at the next safe point; write `0` to thaw. Replaces v1's separate freezer controller. Useful for snapshotting and for safely moving processes that the runtime does not want running during the move.
- **`cgroup.kill`** — write `1` to atomically `SIGKILL` every process in the cgroup, all at once, with no race window for a forking child to escape. Added in Linux 5.14 (August 2021); described in detail later.
- **`cgroup.max.depth`**, **`cgroup.max.descendants`** — caps on hierarchy size, defending against runaway cgroup creation by buggy or malicious tenants.

Three additional files appear unconditionally because the kernel always tracks them, even with no controller enabled: **`cpu.stat`** (CPU accounting in microseconds), and **`cpu.pressure`**, **`memory.pressure`**, **`io.pressure`** — the **PSI** files described later in the chapter.

Controller-specific files (like `memory.max`, `cpu.weight`, `pids.max`) appear only after the parent enables that controller in `cgroup.subtree_control`. To enable more for `demo`, write the diff to the parent — in this case `/sys/fs/cgroup` itself:

```
echo "+memory +pids" | sudo tee /sys/fs/cgroup/cgroup.subtree_control > /dev/null
ls /sys/fs/cgroup/demo/ | grep -E '^memory\.|^pids\.' | head
# memory.current
# memory.events
# memory.high
# memory.low
# memory.max
# memory.peak
# memory.stat
# memory.swap.current
# pids.current
# pids.events
# pids.max
```

Enabling a controller for *children* does not enable it for the cgroup itself — that is what "top-down" means in practice. The kernel docs phrase it as: a controller is propagated *into* a cgroup's resource files by the parent's `subtree_control`, and is propagated *out* of that cgroup to its descendants by its own `subtree_control`. A cgroup with no children has no reason to enable anything in its `subtree_control`.

Move A Process In

Put a process into a cgroup by writing its PID to `cgroup.procs`:

```
sudo sh -c 'sleep 600 & echo $! > /sys/fs/cgroup/demo/cgroup.procs; wait'
# In another terminal:
cat /sys/fs/cgroup/demo/cgroup.procs
# 12345
```

A process can only be in one cgroup at a time. Writing its PID to a different cgroup's `cgroup.procs` moves it atomically. `cgroup.threads` works the same way for individual threads, on cgroups whose `cgroup.type` is `threaded`.

The move is a write of *the calling task's* membership, not a deep copy of state. As noted in the charging section, already-allocated memory stays charged to the original cgroup until it is freed.

Memory: Limits, Reclaim, OOM

The memory controller is the most consequential one to get right and the easiest to misconfigure. Start with what `memory.max` actually counts. In v2 the answer is "the cgroup's full memory footprint, including kernel allocations made on its behalf." Concretely, the controller charges:

- **Anonymous pages** (heap, stack, malloc-backed memory).
- **File-backed pages** that the cgroup is the first to fault into the page cache.
- **Kernel objects** the cgroup forced into existence: slab caches (dentries, inodes, kmalloc), socket buffers, page-table memory, percpu allocations.

What it does *not* count: pages already charged to a different cgroup that this one is also reading (the first reader gets the charge), and `tmpfs` mounts that are charged to whoever wrote the file.

Set a small limit, run a process that allocates more, and watch the kernel kill it within the cgroup:

```
sudo mkdir -p /sys/fs/cgroup/oom-demo
echo "+memory" | sudo tee /sys/fs/cgroup/cgroup.subtree_control > /dev/null
echo 50M | sudo tee /sys/fs/cgroup/oom-demo/memory.max > /dev/null

sudo sh -c 'echo $$ > /sys/fs/cgroup/oom-demo/cgroup.procs; \
  exec python3 -c "x=bytearray(200*1024*1024); print(\"alive\")"'
# Killed
echo $?
# 137  (128 + SIGKILL)
```

Confirm the kill was scoped to the cgroup:

```
cat /sys/fs/cgroup/oom-demo/memory.events
# low 0
# high 0
# max 1         <- count of allocations rejected/throttled at memory.max
# oom 1         <- count of OOM events
# oom_kill 1    <- count of processes killed
```

The sequence is: an allocation request would push `memory.current` past `memory.max`; the kernel calls `try_charge`, which triggers reclaim inside the cgroup; reclaim cannot free enough (this Python is allocating anonymous memory, which can only be reclaimed via swap, and there is none); the cgroup-scoped OOM killer fires and chooses a victim from the cgroup's processes by `oom_score_adj`. The host's `oom_score` for unrelated processes is irrelevant.

By default the OOM killer kills one process. Setting `memory.oom.group = 1` makes it kill *every* process in the cgroup, useful for "all-or-nothing" workloads where a partially-killed pod is worse than a fully-killed one — the most common Kubernetes example is a pod whose containers depend on each other and would deadlock if one died. Setting `oom_score_adj` per-process is how you tell the killer which process to prefer or avoid.

`memory.high` is the softer counterpart. The kernel throttles the cgroup's allocations and forces reclaim when usage exceeds the threshold, but does not kill anything:

```
echo 30M | sudo tee /sys/fs/cgroup/oom-demo/memory.high > /dev/null
```

A typical pattern is `memory.high` set slightly below `memory.max`, so reclaim and throttling kick in before the hard limit is hit and the workload has time to react (drop a cache, finish a request, gc) before the OOM killer becomes inevitable.

`memory.low` and `memory.min` work the other direction: they protect a cgroup from reclaim. A cgroup below `memory.low` is skipped by reclaim under normal pressure (other cgroups are reclaimed first); `memory.min` is a hard floor — the kernel will not reclaim below it even under memory pressure. `memory_recursiveprot` makes both apply recursively, which is what you want when the protection should hold for the whole subtree, not just the immediate cgroup.

For deeper accounting, read `memory.stat`:

```
cat /sys/fs/cgroup/oom-demo/memory.stat | head
# anon                 ...
# file                 ...
# kernel               ...
# kernel_stack         ...
# pagetables           ...
# percpu               ...
# sock                 ...
# vmalloc              ...
# slab                 ...
# slab_reclaimable     ...
# slab_unreclaimable   ...
```

`memory.peak` (Linux 5.19, July 2022) records the high-water mark — useful for sizing because `memory.current` only shows the right-now value. Without it, catching the peak required polling.

CPU: Weight And Quota

Two CPU files do almost all the work:

- **`cpu.weight`** — proportional share, applied when CPUs are oversubscribed. Default 100. Range 1–10000. Higher is more share.
- **`cpu.max`** — `<quota> <period>` in microseconds. Default `max 100000`, meaning unlimited.

`cpu.weight` is a scheduler weight. The Linux scheduler (CFS through 6.5; **EEVDF** from 6.6 onward, October 2023) treats every cgroup with the cpu controller enabled as a hierarchical scheduler entity, and distributes time at each level in proportion to weight. Two cgroups under the same parent with weights 100 and 200 get one-third and two-thirds of the parent's CPU share when both are runnable. With no contention — say only one of them is busy — weight does nothing; the busy one gets all the CPU it can use up to `cpu.max`.

`cpu.max` is the CFS **bandwidth controller**. It enforces a hard cap by tracking how much CPU time the cgroup has consumed in the current period, throttling it once the quota is reached, and untrottling it at the start of the next period:

```
sudo mkdir -p /sys/fs/cgroup/cpu-demo
echo "+cpu" | sudo tee /sys/fs/cgroup/cgroup.subtree_control > /dev/null
echo "50000 100000" | sudo tee /sys/fs/cgroup/cpu-demo/cpu.max > /dev/null

sudo sh -c 'echo $$ > /sys/fs/cgroup/cpu-demo/cgroup.procs; \
  exec timeout 5 sh -c "while :; do :; done"'

cat /sys/fs/cgroup/cpu-demo/cpu.stat
# usage_usec     2500000
# user_usec      2500000
# system_usec       0
# nr_periods      ~50
# nr_throttled    ~50
# throttled_usec ~2500000
```

`50000 100000` means "50 ms of CPU time per 100 ms period," i.e. 0.5 cores. `nr_throttled` shows the cgroup hit its quota every period; `throttled_usec` is how long it sat paused. Kubernetes' CPU throttling alerts read these counters. The pathology to watch for is **tail-latency throttling**: a low-`cpu.max` workload that is mostly idle but bursty can blow through its quota in the middle of a request, sit throttled for the rest of the period (up to 100 ms), and miss its SLO. Latency-sensitive Kubernetes workloads sometimes drop `cpu.max` entirely and rely on `cpu.weight` plus capacity planning instead, accepting that one bad neighbor can slow them down rather than guaranteeing one will block them at every period boundary.

The Kubernetes CPU model maps directly: `requests.cpu` becomes `cpu.weight` (rescaled), `limits.cpu` becomes `cpu.max`. Setting `requests` without `limits` is what gives you weight without bandwidth throttling.

I/O: Bandwidth And Weighted Sharing

The io controller exposes two knobs, keyed per block device:

- **`io.max`** — bandwidth cap, written as `<major>:<minor> rbps=<bytes/s> wbps=<bytes/s> riops=<n> wiops=<n>`. Each field defaults to `max`.
- **`io.weight`** — proportional share among cgroups contending for the same device. **Requires the bfq I/O scheduler**; on the default `mq-deadline` or `none` schedulers, `io.weight` is silently ineffective.

`io.stat` reports per-device usage:

```
cat /sys/fs/cgroup/system.slice/io.stat
# 8:0 rbytes=... wbytes=... rios=... wios=... dbytes=... dios=...
```

Two complications make I/O accounting harder than memory or CPU. Writeback is asynchronous: a process dirties a page in memory, and the actual disk write happens later, possibly by a kernel thread on a different CPU. v2's coherent hierarchy is what makes this attributable — the BIO carries the original cgroup, and the writeback charge lands on the same node as the memory charge for the dirty page. v1 famously could not do this. The other complication is that filesystem journal traffic is shared across cgroups; some of it cannot be cleanly attributed to any one cgroup, and the kernel charges it to the root.

Limit Process Count

Forks happen all the time. A bug or attack can exhaust the host's pid space; `pids.max` defends against it:

```
sudo mkdir -p /sys/fs/cgroup/pid-demo
echo "+pids" | sudo tee /sys/fs/cgroup/cgroup.subtree_control > /dev/null
echo 5 | sudo tee /sys/fs/cgroup/pid-demo/pids.max > /dev/null

sudo sh -c 'echo $$ > /sys/fs/cgroup/pid-demo/cgroup.procs; \
  for i in 1 2 3 4 5 6 7 8; do \
    sleep 30 & echo "started $!"; \
  done'
# After the limit:
# sh: fork: retry: Resource temporarily unavailable
```

`pids.events` records the rejections:

```
cat /sys/fs/cgroup/pid-demo/pids.events
# max 4   <- count of fork rejections
```

The check is inside `fork(2)`: the kernel allocates the new task struct, then attempts to charge `+1` against the cgroup's `pids.current`. If the new value would exceed `pids.max`, the allocation is undone and `fork` returns `EAGAIN`. This is the same charging path described earlier — the cgroup is debited at the moment the kernel commits to the new resource.

Pressure: PSI

Utilization is a misleading metric for resource health. A CPU pegged at 100% is not under pressure if every task that wants the CPU is currently getting it. A CPU at 40% is under pressure if there are queued tasks waiting their turn. **PSI** (Pressure Stall Information) measures the second condition — time spent stalled, not time spent busy — and exposes it per-cgroup in `cpu.pressure`, `memory.pressure`, and `io.pressure`:

```
cat /sys/fs/cgroup/oom-demo/memory.pressure
# some avg10=0.00 avg60=0.00 avg300=0.00 total=0
# full avg10=0.00 avg60=0.00 avg300=0.00 total=0
```

`some` is "at least one task in the cgroup was stalled on this resource." `full` is "every task in the cgroup was stalled" — strictly worse, because the cgroup made no progress. The `avg` numbers are 10-, 60-, and 300-second moving averages of the percentage of wall time stalled. `total` is a microsecond counter useful for delta-style monitoring.

PSI was added in Linux 4.20 (December 2018). Facebook's `oomd` and the kernel's PSI-aware reclaim were the original consumers; the most useful threshold most operators reach for is "memory.pressure full > 5% over 60s = act now," because by the time RSS hits the limit it is already too late.

"No Internal Processes" In Practice

A non-root cgroup cannot both contain processes *and* have controllers enabled in its `subtree_control` that propagate to children. To see the rule fire:

```
sudo mkdir -p /sys/fs/cgroup/parent/child
sudo sh -c 'echo $$ > /sys/fs/cgroup/parent/cgroup.procs'
echo "+memory" | sudo tee /sys/fs/cgroup/parent/cgroup.subtree_control
# tee: /sys/fs/cgroup/parent/cgroup.subtree_control: Device or resource busy
```

Move the process out first, then the write succeeds:

```
sudo sh -c 'echo $$ > /sys/fs/cgroup/parent/child/cgroup.procs'
echo "+memory" | sudo tee /sys/fs/cgroup/parent/cgroup.subtree_control
# +memory
```

The reason is the charging model: if a parent contained both processes and child cgroups with the same controllers enabled, the kernel would have to choose whether the parent's processes count against the parent's limits in isolation, against the children's, or both — and however it chose, some configurations would produce contradictions. v1 tried to be clever and produced exactly the contradictions described earlier. v2 simply forbids the configuration. Containers always sit in **leaf cgroups** for this reason: the runtime creates a hierarchy of intermediate cgroups (slice → kubepods → pod → container), each of which has children but no processes, and puts the container's processes only in the leaf.

Killing A Cgroup Atomically

`cgroup.kill` is the right way to terminate a container. Writing `1` to it sends `SIGKILL` to every process in the cgroup, all at once, in a single kernel transaction:

```
sudo mkdir -p /sys/fs/cgroup/kill-demo
sudo sh -c 'sleep 9999 & sleep 9999 & sleep 9999 & wait' &
# Move them in:
for pid in $(pgrep -P $! sleep); do echo $pid | sudo tee /sys/fs/cgroup/kill-demo/cgroup.procs; done

# Atomic kill:
echo 1 | sudo tee /sys/fs/cgroup/kill-demo/cgroup.kill
# All sleeps are now gone; cgroup.procs is empty.
```

Without `cgroup.kill`, the userspace alternative is "list `cgroup.procs`, send `SIGKILL` to each, repeat until empty." The race window in that loop is real: a process inside the cgroup can `fork(2)` between the listing and the kill, and the new child escapes the first round. If it forks fast enough you have an unkillable cgroup. `cgroup.kill` is implemented in the kernel as "hold the cgroup mutex, walk every task, signal it, then return," which closes the race entirely. It is one of the small features that made container shutdown in Kubernetes substantially less flaky after Linux 5.14 (August 2021).

`cgroup.freeze` is the related primitive for the not-quite-kill case: write `1` to suspend every process at the next safe point, do whatever the runtime needs to do, write `0` to thaw. Snapshotting a process tree, moving processes between cgroups without races, and detaching for live migration all use it.

The Cgroup Namespace From Inside A Container

Containers see a different `/sys/fs/cgroup` from the host. Cgroup namespaces, added in Linux 4.6 (May 2016), virtualize the cgroup tree the same way mount namespaces virtualize the mount table: a process inside a cgroup namespace sees its own cgroup as `/`, and any path it reads from `/proc/self/cgroup` is relative to that root.

```
# Host:
cat /proc/self/cgroup
# 0::/user.slice/user-1000.slice/session-3.scope

# Inside a container:
docker run --rm alpine:3.20 cat /proc/self/cgroup
# 0::/
```

The container does not see "I am at `/system.slice/docker-<id>.scope`"; it sees "I am at `/`." The runtime mounts a fresh `cgroup2` filesystem at `/sys/fs/cgroup` inside the namespace, and the kernel renders the tree relative to the namespace's root. From the host, the same cgroup is still at its real path; the namespace is purely a per-process view.

The `nsdelegate` mount option pairs with this: it makes the cgroup namespace boundary act as a delegation point, so a process inside the namespace cannot move itself or other processes above its own root cgroup, even if it has the file permissions to do so. Without `nsdelegate`, a privileged process inside a container could in principle write to `cgroup.procs` of an ancestor and escape — `nsdelegate` makes that an `EPERM`.

systemd Owns The Tree

On systemd-managed hosts (most production Linux), systemd owns the cgroup tree. The kernel enforces a single-writer model per cgroup directory — if two processes both manage the same cgroup, one will lose. systemd's answer is **delegation**: it creates a parent with `Delegate=yes`, marks it as owned by another manager, and stops touching what is underneath.

`systemd-run` is the convenient way to launch a transient unit and observe its cgroup placement:

```
sudo systemd-run --slice=demo.slice --unit=oneshot.service --scope sleep 60 &
systemctl status oneshot.service
# Look for "CGroup: /demo.slice/oneshot.service"
cat /sys/fs/cgroup/demo.slice/oneshot.service/cgroup.procs
# <pid of sleep>
```

When containerd is configured with the `systemd` cgroup driver, it does not write cgroup files directly. It asks systemd over D-Bus to create a transient scope for each container shim, and lets systemd populate the resource files. The OCI `linux.cgroupsPath` in this mode is a systemd path:

```
kubepods-besteffort.slice:cri-containerd:<container-id>
```

read as `<slice>:<prefix>:<id>`. The runtime creates a transient scope `cri-containerd-<id>.scope` under `kubepods-besteffort.slice/`.

The "cgroup driver" config in containerd, kubelet, and runc must agree. A common production failure: kubelet uses `systemd`, containerd uses `cgroupfs`, and pods fail to start because each side is trying to create cgroups the other does not see.

Delegation Enables Rootless

cgroup v2's delegation model is what gives a rootless container resource limits. Without v2 delegation, only the root user could write to cgroup files, and rootless containers would have no enforced limits. systemd creates a delegated subtree under `user.slice/user-<uid>.slice/user@<uid>.service/` and grants the user ownership:

```
ls -ld /sys/fs/cgroup/user.slice/user-1000.slice/user@1000.service
# drwxr-xr-x 2 1000 1000 ... user@1000.service
```

Inside the delegated subtree, the user can `mkdir`, write `+cpu +pids +memory` to `subtree_control` (subject to what systemd enabled at the boundary), and place processes — without root.

```
# As an unprivileged user:
mkdir /sys/fs/cgroup/user.slice/user-$(id -u).slice/user@$(id -u).service/me-demo
echo $$ > /sys/fs/cgroup/user.slice/user-$(id -u).slice/user@$(id -u).service/me-demo/cgroup.procs
```

Rootless podman, buildah, and rootless containerd put their containers under this kind of subtree.

Device Access Is BPF, Not Files

cgroup v2 does not have `devices.allow` or `devices.deny` files. Device access policy is enforced by an eBPF program of type `BPF_PROG_TYPE_CGROUP_DEVICE` attached to the cgroup. runc compiles the OCI `linux.resources.devices` list into a BPF program at container start, and the kernel runs that program on every device-class operation: the program returns 0 (deny) or 1 (allow) per syscall.

To see the attached program on a running container's cgroup:

```
sudo bpftool cgroup tree | head
# CgroupPath
# ID       AttachType      AttachFlags     Name
# /sys/fs/cgroup/system.slice/docker-<id>.scope
#     12  cgroup_device                   <prog-name>
```

v1 exposed device policy as `devices.allow` and `devices.deny` files; v2 exposes nothing in the cgroup directory. Tooling that walked the v1 files has to load the BPF program with `bpftool cgroup show` instead.

OCI Resource Mapping

The relevant `linux.resources` fields in `config.json` and where they land:

OCI field	v2 file
`memory.limit`	`memory.max`
`memory.reservation`	`memory.low`
`memory.swap`	`memory.swap.max`
`cpu.shares`	`cpu.weight` (rescaled from 1024 → 100 default)
`cpu.quota` / `cpu.period`	`cpu.max`
`cpu.cpus` / `cpu.mems`	`cpuset.cpus` / `cpuset.mems`
`pids.limit`	`pids.max`
`blockIO.weight`, `throttleReadBpsDevice`, etc.	`io.weight`, `io.max`
`devices`	BPF program attached via `BPF_PROG_TYPE_CGROUP_DEVICE`

The remap from v1 names to v2 files is the runtime's job, not the user's. The OCI spec keeps the v1-style names for compatibility; runc, crun, and youki translate.

Where This Goes

The next chapter covers the rootfs: content addressing, snapshotters, and how runc gets a process to see a custom `/`. Cgroups reappear in chapter 7 when the device cgroup BPF program comes up under the security boundary.

Sources And Further Reading

- Linux cgroup v2 admin docs: https://kernel.org/doc/html/next/admin-guide/cgroup-v2.html
- `cgroups(7)`: https://man7.org/linux/man-pages/man7/cgroups.7.html
- systemd cgroup delegation: https://systemd.io/CGROUP_DELEGATION/
- PSI docs: https://docs.kernel.org/accounting/psi.html
- BPF cgroup device program: https://docs.kernel.org/bpf/prog_cgroup_device.html
- CFS bandwidth control: https://docs.kernel.org/scheduler/sched-bwc.html
- EEVDF scheduler (Linux 6.6): https://lwn.net/Articles/925371/
- `cgroup.kill` (Linux 5.14): https://lwn.net/Articles/855286/
- OCI runtime spec, Linux resources: https://github.com/opencontainers/runtime-spec/blob/main/config-linux.md#control-groups

Chapter 6: Container Filesystems

A container needs its own `/`. The processes inside should see an Alpine root or a Debian root, not whatever the host happens to be running, and writes inside should not leak back out. The naive way to deliver that — give every container a private copy of a full root filesystem — is what this chapter exists to avoid.

A 200 MB Alpine image starting ten containers would burn 2 GB of disk for ten near-identical trees. A Debian-based image starting the same ten would burn 5 GB. Pulling each of those copies once per host, every time the image moves, makes startup a download problem instead of a process-creation problem. Real systems do not work that way. They share the bytes that are common between images, store each unique blob exactly once, and give every running container a thin writable layer that captures only the changes it makes. The whole chapter is about the mechanics of that idea.

> ***Safety:*** *the OverlayFS and* `pivot_root` *examples mutate kernel mount state and need root. The image-inspection examples are safe and read-only. Use a disposable Linux VM for the privileged sections. Examples were checked on Ubuntu 24.04 with kernel 6.8 and* `containerd` *1.7.*

The Mental Model: Stacked, Content-Addressed, Copy-On-Write

Three ideas, each pulling its weight:

Stacked. A container's root filesystem is built by stacking directories. The bottom is the base layer (Alpine's `/bin`, `/etc`, `/lib`, ...). On top of that, each `RUN` or `COPY` in a Dockerfile adds another directory containing only the files that step changed. The final stack — read top-to-bottom, with upper entries hiding lower ones of the same name — is what the process sees as `/`. Two images sharing the same Alpine base share the same bottom directory on disk.

Content-addressed. Every layer is identified by the SHA-256 of its bytes. Two layers with identical content have identical digests, so the storage layer deduplicates by construction: you never store the same layer twice, regardless of which images reference it. The image manifest is just a list of digests.

Copy-on-write. The stacked layers are read-only. The container gets one extra writable directory on top. A read falls through the stack until it finds the file; a write to a previously-untouched file copies it up into the writable layer first, then modifies the copy. The lower layers are never touched. When the container exits, throwing away the writable layer throws away every change.

Linux gives all three of these to userspace through **OverlayFS**, a kernel filesystem that takes a list of directories and presents them as a merged view. The container runtime arranges the directories; OverlayFS does the merging. Once the mental model is clear, the rest of the chapter is just naming the pieces and showing where each one lives on disk.

How OverlayFS Merges Directories

OverlayFS takes four arguments at mount time:

- **`lowerdir`** — a colon-separated list of read-only directories. Read right-to-left: the last entry is the bottom of the stack, the first is the top.
- **`upperdir`** — the single writable directory. All changes land here.
- **`workdir`** — an empty scratch directory the kernel uses for atomic operations. Must live on the same filesystem as `upperdir`.
- The mount point itself, sometimes called **`merged`** — what processes actually see.

The merging rule is simple: for any path, the kernel returns the entry from the topmost layer that has it, with the writable upper layer on top of every lower. A write to a file that exists only in a lower layer triggers a **copy-up**: the kernel copies the file into `upperdir` and applies the write there. A delete is encoded as a **whiteout** — a character device with major:minor 0:0 in `upperdir`, which OverlayFS interprets as "hide the entry of this name in any lower layer." Deleting an entire directory's lower contents uses an **opaque marker**, the `trusted.overlay.opaque="y"` xattr on a directory in `upperdir`, which says "ignore everything below this directory."

You do not have to take this on faith. Mount one yourself.

Build An Overlay By Hand

```
sudo mkdir -p /tmp/ov/{lower1,lower2,upper,work,merged}

# Lower1 = base layer
echo "from lower1" | sudo tee /tmp/ov/lower1/file-a > /dev/null
echo "lower1 only" | sudo tee /tmp/ov/lower1/file-b > /dev/null

# Lower2 = stacked above lower1
echo "from lower2 (overrides lower1)" | sudo tee /tmp/ov/lower2/file-a > /dev/null

# Stack them. Order is right-to-left: lower1 is the bottom, lower2 is on top of it.
sudo mount -t overlay overlay \
  -o lowerdir=/tmp/ov/lower2:/tmp/ov/lower1,upperdir=/tmp/ov/upper,workdir=/tmp/ov/work \
  /tmp/ov/merged

cat /tmp/ov/merged/file-a   # from lower2 (overrides lower1)
cat /tmp/ov/merged/file-b   # lower1 only
```

`file-a` exists in both lower layers; the merged view shows the upper of the two. `file-b` exists only in `lower1`; it shows through unchanged. Now write through the merged view and watch the change land in `upperdir`, not in either lower:

```
echo "appended" | sudo tee -a /tmp/ov/merged/file-a > /dev/null
ls /tmp/ov/upper/
# file-a
diff /tmp/ov/upper/file-a /tmp/ov/lower2/file-a
# differs: upper has the appended line; lower2 is untouched
```

That is a copy-up. The first write to `file-a` copied it from `lower2` to `upper`, then appended. The lower layers are byte-for-byte the same as before. Delete `file-b` from the merged view to see the whiteout:

```
sudo rm /tmp/ov/merged/file-b
ls /tmp/ov/merged/        # file-a
ls -la /tmp/ov/upper/     # c--------- 0 0 ... file-b
```

A character device with mode `0` and major:minor `0:0`. That is OverlayFS's whiteout. The lower-layer `file-b` still exists; the upper-layer character device hides it. Clean up:

```
sudo umount /tmp/ov/merged
sudo rm -rf /tmp/ov
```

That is the entire kernel mechanism a container's root filesystem rides on. The rest of the chapter is about how layers get into `lowerdir` in the first place, and how `merged` becomes `/` for the container process.

What An OCI Image Is

An OCI image is the on-the-wire and on-disk format for shipping the layers a snapshotter will eventually unpack. It is a content-addressed bundle: one **manifest**, one **image config**, and an ordered list of **layer blobs**, each addressed by SHA-256 digest. The easiest way to see the structure is to pull an image into an OCI layout directory:

```
sudo apt-get install -y skopeo jq
skopeo copy docker://alpine:3.20 oci:./alpine-oci:3.20
ls alpine-oci/
# blobs/  index.json  oci-layout
```

`oci-layout` is a marker file. `index.json` is the entry point: for a single-arch image it points at one manifest; for a multi-arch image it points at an image index that selects per `{architecture, os}`. The manifest in turn names a config blob and a list of layers, each as a `{mediaType, digest, size}` descriptor. Walk the chain:

```
# index.json -> manifest digest
MANIFEST_DIGEST=$(jq -r '.manifests[0].digest' alpine-oci/index.json | sed 's/sha256://')

# manifest -> config digest and layer digests
jq '{config: .config.digest, layers: [.layers[].digest]}' \
  alpine-oci/blobs/sha256/$MANIFEST_DIGEST

# config -> rootfs.diff_ids
CONFIG_DIGEST=$(jq -r '.config.digest' alpine-oci/blobs/sha256/$MANIFEST_DIGEST | sed 's/sha256://')
jq '.rootfs' alpine-oci/blobs/sha256/$CONFIG_DIGEST
# {
#   "type": "layers",
#   "diff_ids": ["sha256:..."]
# }
```

Three different SHA-256 digests appear in this chain, and confusing them is the source of most layer-mismatch and snapshot-deduplication bugs:

- **Manifest layer digest** — SHA-256 of the *compressed* layer bytes (gzip or zstd). This is what the registry serves and what the manifest references. The pull path verifies it.
- **DiffID** — SHA-256 of the *uncompressed* tar. Listed in the image config's `rootfs.diff_ids`. Identifies the layer's content independent of how it was compressed in transit.
- **ChainID** — a recursive hash defined as `ChainID(L0) = DiffID(L0)` and `ChainID(Ln) = SHA256("ChainID(Ln-1) DiffID(Ln)")`. Identifies a *stack* of layers. Snapshotters key snapshots by ChainID, which is why two images sharing the same Alpine base share one on-disk snapshot for that stack instead of two.

To verify a layer's DiffID by hand:

```
LAYER_DIGEST=$(jq -r '.layers[0].digest' \
  alpine-oci/blobs/sha256/$MANIFEST_DIGEST | sed 's/sha256://')
zcat alpine-oci/blobs/sha256/$LAYER_DIGEST | sha256sum
# Should match diff_ids[0] in the image config.
```

If the registry's compressed-layer digest does not produce a tar whose uncompressed SHA-256 matches the config's DiffID, the snapshotter refuses to use the result. Two independent verification points keep the bytes honest end to end.

Layer Tar Conventions

A layer is a tar archive representing the *diff* between this layer and the one below it. Two encoded modifications give the diff its semantics:

- A file `<dir>/.wh.<name>` is a **whiteout**: it deletes `<name>` from any lower layer.
- A file `<dir>/.wh..wh..opq` is an **opaque marker**: lower layers' contents of `<dir>` are entirely hidden.

Notice the disconnect: the OCI layer format encodes deletion as a tar entry with a magic name; OverlayFS encodes it as a character device with major:minor 0:0. Neither side knows about the other. The unpacker translates between the two during snapshot creation.

To see whiteouts in a real image, build one that deletes a file:

```
mkdir build && cat > build/Dockerfile <<'EOF'
FROM alpine:3.20
RUN rm /etc/motd
EOF
docker buildx build --output type=oci,dest=motd.tar build/
mkdir motd-oci && tar -C motd-oci -xf motd.tar

MANIFEST=$(jq -r '.manifests[0].digest' motd-oci/index.json | sed 's/sha256://')
TOP_LAYER=$(jq -r '.layers[-1].digest' motd-oci/blobs/sha256/$MANIFEST | sed 's/sha256://')

zcat motd-oci/blobs/sha256/$TOP_LAYER | tar -tvf - | grep -E '\.wh\.|motd'
# -rw-r--r-- 0/0 0 ... etc/.wh.motd
```

The zero-byte `etc/.wh.motd` is `RUN rm /etc/motd` reduced to a tar entry the snapshotter can apply.

Content Store: Where The Bytes Live

When containerd pulls an image, it stores every blob — manifests, configs, and compressed layers alike — in its **content store**, addressed by digest:

```
/var/lib/containerd/io.containerd.content.v1.content/
  blobs/sha256/<digest>     # the actual bytes
  ingest/<id>/              # in-flight uploads
```

```
sudo ls /var/lib/containerd/io.containerd.content.v1.content/blobs/sha256/ | head
sudo ctr content ls | head
```

The content store does not know what any blob means. It stores opaque bytes and verifies them on read. Meaning lives in the **image service**, which tracks the human-readable mapping `alpine:3.20 -> sha256:<manifest>` and follows the manifest to its config and layers. Splitting "store the bytes" from "track what bytes belong to which image" is what lets garbage collection and lazy fetching coexist with normal pulls.

Garbage collection treats content and snapshots together. A blob is **reachable** if some image, lease, or snapshot references it; everything else is collectable. **Leases** keep arbitrary content alive during in-flight operations — a pull holds a lease over its blobs until the unpack finishes:

```
sudo ctr leases ls
```

Snapshotters: From Blobs To Mountable Directories

Compressed tar blobs are not a filesystem. Some component has to decompress each layer, lay its contents out as a directory, translate `.wh.*` markers into the filesystem's native deletion form, and produce a `lowerdir`-ready tree. That component is the **snapshotter**.

containerd defines a snapshotter interface; plugins implement it. The default on Linux is the OverlayFS snapshotter. The interesting operations are:

- `Prepare(key, parent)` — produce a writable snapshot whose lower layers are the chain rooted at `parent`. Returns the mount config the runtime should apply.
- `View(key, parent)` — same, but read-only.
- `Commit(name, key)` — finalize a `Prepare` result as a new immutable layer named `name` (typically a ChainID).

Unpacking a multi-layer image is a sequence of `Prepare` → write the layer's tar contents → `Commit`, repeated for each layer in order. The final container gets one more `Prepare` on top, and this one stays writable for the lifetime of the container.

Three kinds of snapshot fall out of this:

- **Committed** — immutable, named by ChainID, produced by unpacking one layer on top of another.
- **Active** — writable, used as the upper layer for a running container.
- **View** — read-only checkout of a committed chain, used by tools that just need to read.

```
sudo ctr snapshot ls | head
# KEY                                                PARENT                                                KIND
# sha256:abcd... (chainID for layer 0)
Committed
# sha256:efgh... (chainID for layer 0+1)             sha256:abcd...
Committed
# k8s.io/12/<container-id>                           sha256:efgh...                                        Active
```

The on-disk layout of the OverlayFS snapshotter:

```
/var/lib/containerd/io.containerd.snapshotter.v1.overlayfs/
  metadata.db
  snapshots/<id>/fs/        # the layer's directory, fed to OverlayFS as lower or upper
  snapshots/<id>/work/      # OverlayFS work dir (active snapshots only)
```

`fs/` is the data; `work/` is the kernel's scratch space for atomic operations, required to be on the same filesystem as the upper layer. `metadata.db` is a BoltDB file mapping snapshot keys to their parents and disk locations.

Other snapshotter implementations exist for other use cases:

- **`native`** copies entire layers instead of stacking. Used when OverlayFS is unavailable; very inefficient.
- **`btrfs`** uses btrfs subvolumes and snapshots; faster commits, requires a btrfs filesystem.
- **`zfs`** does the same on ZFS.
- **`stargz`** / **`soci`** support lazy fetching: the snapshotter mounts a layer before its bytes have finished downloading, by parsing the gzip or zstd index and serving on demand. Important for cold-start with large images.

The interchangeability is the same trick OCI runtimes pull a level up: containerd does not care which snapshotter is configured, as long as it implements the interface.

Mount Setup In runc

When runc starts a container, it has a snapshot from containerd and a `config.json` with a `mounts` array. Inside a fresh mount namespace, it executes a fixed sequence:

1. Make the new mount namespace's root mount private to prevent propagation back to the host.
2. Mount the rootfs (the OverlayFS the snapshotter returned).
3. Mount the special filesystems described in `config.json`'s `mounts` array.
4. Create device nodes (bind from host) and link standard ones (`/dev/stdin` → `/proc/self/fd/0`, etc.).
5. Apply `linux.maskedPaths` (bind `/dev/null` over them).
6. Apply `linux.readonlyPaths` (remount as read-only).
7. `pivot_root(2)` to swap the prepared rootfs in as `/`.
8. Unmount and remove the old root.
9. Set propagation on `/` per `linux.rootfsPropagation`.

The order is fixed because `pivot_root(2)` has constraints: the new and old roots must be on different mounts and neither may be shared, and the old root must be reachable as a directory under the new root. Step 1 makes propagation private, step 2 mounts the new root, and steps 3–6 happen before pivot because the runtime can still name host paths during setup.

Watching it from outside is awkward — the work happens between `clone(2)` and `execve(2)` of the user process — but the kernel-side view is easy to inspect after the container has started:

```
docker run --rm -d --name demo alpine:3.20 sleep 600
PID=$(docker inspect -f '{{.State.Pid}}' demo)
sudo cat /proc/$PID/mountinfo
# 1 0 0:34 / / rw,relatime master:1 - overlay overlay rw,lowerdir=...
# 2 1 0:35 / /proc rw,nosuid,nodev,noexec,relatime - proc proc ...
# ...
docker stop demo
```

The first line is the rootfs — an OverlayFS mount with a `lowerdir` chain corresponding to the image's layers and an `upperdir` corresponding to the snapshotter's active snapshot. The rest are the special filesystems from step 3. The runc source for this lives in `libcontainer/rootfs_linux.go`; the OCI spec describes the requirements in `runtime-linux.md`.

`pivot_root` Versus `chroot`

The classic Unix way to change a process's root is `chroot(2)`: it sets the calling process's root directory to a path. It is also famously escapable. A process with an open file descriptor to a directory outside the chroot, or with `CAP_SYS_CHROOT`, can climb back out. `chroot` rewrites the process's view of `/`, but it does not unmount the old root or move it out of reach.

`pivot_root(2)` is what containers actually use, and the difference matters. `pivot_root(new_root, put_old)` atomically swaps the *mount namespace's* root: `new_root` becomes `/`, and the previous `/` is moved to `put_old`. Once that swap is done, the runtime unmounts `put_old` so the old root is no longer reachable at all — not by file descriptor, not by `..`, not by climbing out of a chroot. The container's process literally cannot name the host root through the filesystem after step 8 above.

To see the swap in isolation, without runc in the way:

```
sudo unshare --mount -- bash
# Inside the new mount namespace:

mkdir -p /tmp/newroot/{old,bin,proc,sys,dev}
mount -t tmpfs tmpfs /tmp/newroot       # placeholder rootfs
cp /bin/busybox /tmp/newroot/bin/

# pivot_root requires / to be private and the new root to be a separate mount.
mount --make-rprivate /
mount --bind /tmp/newroot /tmp/newroot

cd /tmp/newroot
pivot_root . old

# After this, `.` is the new /; `/old` is the old root.
exec /bin/busybox sh
ls /old
# usr  etc  var  ...   (the host's old root, still reachable)

umount -l /old
ls /
# bin  old  proc  sys  dev   (now without the host's root visible)
```

This is exactly what runc does, with one important addition: runc unmounts the old root *before* exec'ing the user process so the container cannot even briefly see the host. The example above leaves it mounted long enough to inspect.

OCI Mounts In Practice

The `mounts` array in `config.json` is what the runtime applies in step 3 above. Each entry has `destination`, `type`, `source`, and `options`. The conventional default set:

Destination	Type	Source	Notes
`/proc`	`proc`	`proc`	Reflects PID namespace. Required for `ps`, `/proc/self/`.
`/dev`	`tmpfs`	`tmpfs`	`mode=755`.
`/dev/pts`	`devpts`	`devpts`	`newinstance,ptmxmode=0666`.
`/dev/shm`	`tmpfs`	`shm`	`mode=1777,size=65536k`.
`/dev/mqueue`	`mqueue`	`mqueue`	Matches IPC namespace.
`/sys`	`sysfs`	`sysfs`	Often `ro` for non-privileged.
`/sys/fs/cgroup`	`cgroup2`	`cgroup`	Read-only bind, view limited by cgroup namespace.

Bind mounts (`type: bind`, `source: <host-path>`) are how host paths show up inside containers — Docker volumes, Kubernetes hostPath, and secret mounts all use them. The `options` field controls propagation: `rprivate` (default) does not propagate; `rslave` accepts host changes; `rshared` propagates both ways. Kubernetes' `mountPropagation: HostToContainer` corresponds to `rslave`; `Bidirectional` corresponds to `rshared`.

```
docker run --rm -d --name demo -v /tmp:/host-tmp alpine:3.20 sleep 600
PID=$(docker inspect -f '{{.State.Pid}}' demo)
sudo cat /proc/$PID/mountinfo | grep host-tmp
# .../tmp /host-tmp rw,relatime - ext4 /dev/...
docker stop demo
```

Rootless OverlayFS

OverlayFS uses `trusted.*` xattrs for opaque markers and redirects, and writing `trusted.*` requires `CAP_SYS_ADMIN` *on the host*. That is why, until recently, rootless OverlayFS did not work. Linux 5.11 added support for OverlayFS in user namespaces; on older kernels, rootless tooling (rootless Docker, podman) falls back to `fuse-overlayfs`, a userspace reimplementation that uses `user.*` xattrs and accepts the performance cost.

```
podman info --format '{{.Store.GraphDriverName}}'
# overlay (kernel) or overlay (fuse-overlayfs)
```

Where This Goes

The next chapter covers the security controls that compose with the filesystem to form the full container boundary — capabilities, seccomp, MAC, masked paths. The masked paths in particular layer on top of the mount setup described here: they are bind mounts performed after the OCI mount table is in place.

Sources And Further Reading

- OCI Image Specification: https://github.com/opencontainers/image-spec
- OCI image layout: https://github.com/opencontainers/image-spec/blob/main/image-layout.md
- OCI image layer format: https://github.com/opencontainers/image-spec/blob/main/layer.md
- containerd content flow: https://github.com/containerd/containerd/blob/main/docs/content-flow.md
- containerd snapshotter docs: https://containerd.io/docs/2.2/snapshotters/readme/
- Linux OverlayFS: https://www.kernel.org/doc/html/latest/filesystems/overlayfs.html
- `pivot_root(2)`: https://man7.org/linux/man-pages/man2/pivot_root.2.html
- `mount(2)`: https://man7.org/linux/man-pages/man2/mount.2.html
- runc rootfs setup: https://github.com/opencontainers/runc/blob/main/libcontainer/rootfs_linux.go

Chapter 7: Security Boundaries

A container is not a hypervisor. It is a process — or a tree of processes — running directly on the host kernel, separated from everything else by a stack of independently-tunable Linux subsystems. The security boundary is the *composition* of those subsystems: namespaces shape what the process sees, capabilities and seccomp shape what it can ask the kernel to do, MAC policy gates the operations the kernel would otherwise allow, masked paths plug the holes that namespaces cannot, and cgroups bound the damage if something else fails. None of these is "the security model." The model is the layered effect, and the cost of `--privileged` is removing several layers at once.

The chapter walks the layers in roughly the order the kernel applies them, with one section per control. The framing to keep in mind throughout: every layer is **defense in depth**. A misconfiguration or a bypass of one layer should leave the others holding.

> ***Safety:*** *most examples need root. The seccomp and capabilities demonstrations are harmless on a VM. The MAC examples assume the relevant LSM is already loaded and configured by the distribution. Use a disposable Linux VM. Examples were checked on Ubuntu 24.04 (AppArmor) and a Fedora 40 VM (SELinux).*

What The Controls Are For

Three threat classes shape the controls:

1. **Container → host escape** — a process inside the container gaining privileges or visibility on the host.
2. **Container → container interference** — one container reading another's data, signaling its processes, or starving its resources.
3. **Container → external resource abuse** — a container performing actions outside its intended scope.

Capabilities and seccomp limit (1) and (3). MAC (AppArmor, SELinux) covers (1) and (2). User namespaces strengthen (1) at the cost of operational complexity. Cgroups address resource starvation in (2). No single control covers everything; the next sections cover each one, then the chapter returns to what `--privileged` actually loosens.

Linux Capabilities

Capabilities split the historical "root or not" privilege model into roughly forty independently-grantable units. `CAP_NET_ADMIN` lets a process configure interfaces; `CAP_SYS_TIME` lets it set the system clock; `CAP_NET_BIND_SERVICE` lets it bind ports below 1024. A non-root process with the right capability can do the corresponding privileged operation; a root-equivalent process *without* that capability cannot. The model exists because "root" was always a coarse abstraction — a daemon that needs to bind port 80 should not also be able to load kernel modules.

Every process has **five capability sets**, each a 64-bit bitmap, and the rules for how they evolve across `execve(2)` are the part that takes the most time to internalize:

- **Permitted (P)** — the upper bound on what the process can hold effective. Capabilities can be moved from P to E, but never gained outside of P (except via exec of a file with file capabilities, subject to the bounding set).
- **Effective (E)** — what is currently checked on every privileged operation. Always a subset of P.
- **Inheritable (I)** — preserved across `execve` *only* when the new file's inheritable set permits it. Largely a legacy mechanism whose modern replacement is the ambient set.
- **Bounding (B)** — a hard upper bound. Capabilities cannot be added beyond B during the process's lifetime, even by exec'ing a setuid binary or one with file capabilities. **This is the set runtimes actually configure for a container.**
- **Ambient (A)** — added in Linux 4.3 (2015). Preserved across `execve` for non-privileged binaries. An ambient bit must be in both P and I; it then gets added to P, E, and I after exec. This is what lets a container's init process pass capabilities to its children without relying on file capabilities.

The bounding set is the bound on a container's lifetime privilege. A container with bounding set `{CHOWN, DAC_OVERRIDE, FOWNER, ...}` can never gain a capability outside that set, regardless of what setuid binaries or file-capabilities-bearing executables it runs. Setting the bounding set is the runtime's job; reading the current state back is yours.

```
# What capabilities does the current shell have?
grep ^Cap /proc/self/status
# CapInh: 0000000000000000
# CapPrm: 0000000000000000
# CapEff: 0000000000000000
# CapBnd: 000001fffffffff
# CapAmb: 0000000000000000
```

Five hex bitmaps, one per set. For an unprivileged shell, the bounding set is "all caps known to this kernel" because a setuid root binary could push more in. For a runc-launched container the bounding set is restricted to the OCI `process.capabilities.bounding` list.

Decode the bitmaps with `capsh`:

```
capsh --decode=000001fffffffff
# 0x000001fffffffff=cap_chown,dac_override,...,cap_checkpoint_restore
```

To see the difference inside a container:

```
docker run --rm alpine:3.20 sh -c 'grep ^Cap /proc/self/status'
# CapInh: 0000000000000000
# CapPrm: 00000000a80425fb
# CapEff: 00000000a80425fb
# CapBnd: 00000000a80425fb
# CapAmb: 0000000000000000

docker run --rm alpine:3.20 sh -c '
  apk add -q libcap
  capsh --decode=$(grep ^CapBnd /proc/self/status | cut -f2)
'
# 0x00000000a80425fb = cap_chown,dac_override,fowner,fsetid,kill,setgid,
# setuid,setpcap,net_bind_service,sys_chroot,mknod,audit_write,setfcap
```

Thirteen capabilities — the conventional default container set. Notably absent: `CAP_SYS_ADMIN`, `CAP_NET_ADMIN`, `CAP_SYS_PTRACE`, `CAP_SYS_TIME`, `CAP_NET_RAW`, `CAP_SYS_MODULE`. The container's "root" cannot configure interfaces, load kernel modules, or set the clock. Compare with `--privileged`:

```
docker run --rm --privileged alpine:3.20 sh -c 'grep ^CapBnd /proc/self/status'
# CapBnd: 000001fffffffff   <- everything
```

`--privileged` clears the bounding set, drops the seccomp profile, removes the AppArmor or SELinux profile, and gives the device cgroup a wildcard rule. It is the easiest way to make a container "work," and it removes most of what made it a container.

File Capabilities And `noNewPrivileges`

Capabilities can also live on executables as the `security.capability` xattr:

```
sudo apt-get install -y libcap2-bin
getcap -r /usr/bin /usr/sbin 2>/dev/null | head
# /usr/bin/ping cap_net_raw=ep
# /usr/bin/newuidmap cap_setuid+ep
# /usr/bin/newgidmap cap_setgid+ep
```

When `ping` is exec'd, its file capabilities become permitted+effective on the new process. This is how a non-root user can `ping` despite needing `CAP_NET_RAW` — the binary brings the capability with it. The same mechanism is a privilege-escalation primitive in the wrong hands: a buggy setuid binary inside a container can become a way out.

`noNewPrivileges` is a one-bit `prctl(2)` switch, set with `prctl(PR_SET_NO_NEW_PRIVS, 1)`, that closes that path. Once set, the process cannot gain privileges via `execve`: setuid bits are ignored, file capabilities are ignored, AppArmor profile transitions are blocked. The bit is one-way; it cannot be cleared once set, and it is inherited across `fork(2)` and `execve(2)`.

```
# A non-privileged shell. ping works because of file capabilities.
ping -c1 127.0.0.1 > /dev/null && echo "ping ok"
# ping ok

# Set no_new_privs, then exec ping. File capabilities are ignored.
exec setpriv --no-new-privs ping -c1 127.0.0.1
# ping: socktype: SOCK_RAW
```

OCI containers default to `noNewPrivileges: true`. It is a near-zero-cost defense against an entire class of escalation, and most container workloads do not need privilege transitions across exec.

Seccomp

Seccomp ("secure computing mode") is a syscall filter. The kernel runs an attached BPF program on every syscall, the program inspects the syscall number and arguments, and returns an action. The actions that matter are `SECCOMP_RET_ALLOW` (proceed normally), `SECCOMP_RET_ERRNO(n)` (fail the syscall with errno *n*), `SECCOMP_RET_KILL_PROCESS` (kill the process), and `SECCOMP_RET_USER_NOTIF` (hand the syscall to a user-space supervisor — used by gVisor, podman's user-namespace fallback, and other userland implementations of restricted syscalls).

The architecture is worth holding in mind. Seccomp is a **layer between userspace and the syscall entry point**: the program runs after the kernel decodes the syscall number but before any syscall logic executes. It cannot block kernel actions taken on the process's behalf (page faults, signal delivery), only deliberate syscalls. It also cannot dereference pointer arguments — the program sees raw register values — which is why filters work on syscall numbers and flag arguments rather than on path strings. Ksyscalls like `mount`'s path are off-limits to seccomp; AppArmor and SELinux are how you filter on paths.

A small example using `libseccomp`:

```
sudo apt-get install -y libseccomp-dev gcc

cat > /tmp/seccomp-demo.c <<'EOF'
#include <seccomp.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/utsname.h>

int main(void) {
    scmp_filter_ctx ctx = seccomp_init(SCMP_ACT_ALLOW);
    seccomp_rule_add(ctx, SCMP_ACT_ERRNO(EPERM), SCMP_SYS(uname), 0);
    seccomp_load(ctx);
    seccomp_release(ctx);

    char buf[1024];
    if (gethostname(buf, sizeof buf) < 0) {
        perror("gethostname");
    } else {
        printf("hostname: %s\n", buf);
    }

    struct utsname u;
    if (uname(&u) < 0) {
        perror("uname");
    } else {
        printf("uname: %s\n", u.sysname);
    }
    return 0;
}
EOF

gcc /tmp/seccomp-demo.c -lseccomp -o /tmp/seccomp-demo
/tmp/seccomp-demo
# hostname: <something>
# uname: Operation not permitted
```

`gethostname(2)` is allowed, `uname(2)` is forced to return `EPERM`. The OCI spec's `linux.seccomp` field describes the same filter as JSON; runc compiles it to BPF before exec. Docker and containerd ship a default profile that blocks roughly fifty syscalls, including `kexec_load`, `keyctl`, `add_key`, `init_module`, `mount`, `umount2`, `swapon`, `clock_settime`, and `reboot`. The full profile is at `containerd/contrib/seccomp/seccomp_default.go` (or `moby/profiles/seccomp/default.json` for the Docker copy).

Seccomp interacts with `noNewPrivileges`: loading a non-trivial seccomp filter requires either `CAP_SYS_ADMIN` *or* `noNewPrivileges`. The latter is what containers use, because requiring `CAP_SYS_ADMIN` to set up a sandbox would defeat the point. The kernel's reasoning is that without `noNewPrivileges`, a seccomp filter could prevent a setuid binary from dropping privileges correctly — so the kernel forbids the combination.

To inspect the filter on a running container:

```
docker run --rm -d --name demo alpine:3.20 sleep 600
PID=$(docker inspect -f '{{.State.Pid}}' demo)
grep -E 'Seccomp|^Sec' /proc/$PID/status
# Seccomp:        2
# Seccomp_filters: 1
docker stop demo
```

`Seccomp: 2` is `SECCOMP_MODE_FILTER`. `Seccomp_filters: 1` is the number of attached BPF programs.

Mandatory Access Control: Path-Based Versus Label-Based

Capabilities and seccomp constrain *the calling process*. **MAC** — Mandatory Access Control — constrains *every operation* against system policy, regardless of the calling process's capabilities and regardless of the file's UNIX permissions. MAC is the layer that says "even if DAC and capabilities would have allowed this, the policy disallows it."

Linux ships two MAC implementations, distros pick one, and they take fundamentally different approaches to the same problem:

- **AppArmor** is **path-based**. A profile names paths and operations: "this profile may read `/etc/passwd`, may not write `/etc/shadow`." Paths are the policy primitive.
- **SELinux** is **label-based**. Every file and process has a security label (`user:role:type:level`), and policy says which labels can act on which other labels. Paths are an indirection — the label is what matters.

The trade-off is the usual one: paths are obvious and easy to reason about but break under bind mounts and renames; labels are precise and stable but require labeling every file and a policy to manage them. AppArmor is easier to pick up and deploy; SELinux is stricter and harder to bypass with creative filesystem manipulation. Distros pick one because the kernel's LSM framework historically allowed only one major MAC LSM at a time (modern stacking changes this for some LSM combinations, but path-versus-label is still one or the other in practice).

AppArmor (Ubuntu/Debian)

```
# Confirm AppArmor is enabled.
sudo aa-status | head
# apparmor module is loaded.
# 70 profiles are loaded.

# Find the profile a running container is using.
docker run --rm -d --name demo alpine:3.20 sleep 600
PID=$(docker inspect -f '{{.State.Pid}}' demo)
sudo cat /proc/$PID/attr/current
# docker-default (enforce)
docker stop demo
```

Inside `docker-default`, writes to `/proc/sys`, `/proc/sysrq-trigger`, `/sys/kernel`, and most of `/sys` are denied. Mount operations are blocked except for the ones the runtime itself sets up before the profile attaches. Try writing to a kernel parameter from inside a default-profile container:

```
docker run --rm alpine:3.20 sh -c 'echo 1 > /proc/sys/kernel/sysrq'
# sh: can't create /proc/sys/kernel/sysrq: Permission denied
```

Without AppArmor, this would be allowed if the container had `CAP_SYS_ADMIN` (it doesn't by default), or if the kernel parameter happened to be writable for non-root (it isn't here). The AppArmor profile is the layer denying it.

Per-pod AppArmor profiles in Kubernetes use `securityContext.appArmorProfile` (since 1.30, GA). The named profile must already be loaded on the node — Kubernetes does not ship profiles, only references them.

SELinux (RHEL/Fedora)

```
# On a Fedora/RHEL host with SELinux in enforcing mode:
getenforce
# Enforcing

# Process contexts.
ps -eZ | head
# system_u:system_r:init_t:s0   1 ?  init
# ...

# Container process context.
podman run --rm -d --name demo registry.access.redhat.com/ubi9/ubi-minimal sleep 600
PID=$(podman inspect -f '{{.State.Pid}}' demo)
sudo cat /proc/$PID/attr/current
# system_u:system_r:container_t:s0:c123,c456
podman stop demo
```

The process type `container_t` is the policy bucket for normal containers. The `:s0:c123,c456` suffix is **MCS** (Multi-Category Security): each container gets a unique pair of categories, and the policy permits access only when the categories of subject and object match. Two containers running as the same `container_t` cannot read each other's files because their MCS labels differ — one of the cleanest examples of label-based MAC's strengths, because the kernel does not have to track which paths belong to which container, only which categories.

To see the file labels under a container's rootfs:

```
sudo ls -lZ /var/lib/containers/storage/overlay/<id>/diff/etc/ | head
# system_u:object_r:container_file_t:s0:c123,c456 ...
```

`container_file_t` is the policy bucket for container-managed files. The MCS pair matches the process's, which is what makes the access decision come out "allowed."

When SELinux denies an action that DAC and capabilities would allow, the audit log records it:

```
sudo ausearch -m AVC -ts recent | tail
# type=AVC msg=audit(...): avc:  denied  { read } for  pid=...
#   scontext=...:container_t:s0:c123,c456
#   tcontext=...:container_file_t:s0:c789,c012
#   tclass=file
```

An AVC denial line tells you which container (the categories), which kind of object (the type), and which permission the policy was missing (the action).

User Namespaces As A Security Boundary

User namespaces let a process hold root-equivalent capabilities inside the namespace without holding any host-level privilege. The chapter on namespaces showed how to create one; here is what the security implication looks like.

```
# Inside a user namespace where I am "root":
unshare --user --map-root-user -- bash -c '
  # Try to mount the host /proc.
  mount -t proc proc /mnt 2>&1
  # mount: /mnt: permission denied. (only privileged user can mount)

  # But create a new mount namespace - mount in there works:
  unshare --mount -- bash -c "mount -t tmpfs tmpfs /mnt && echo mounted"
  # mounted
'
```

The `CAP_SYS_ADMIN` the inner shell holds applies *to resources owned by its user namespace*. Mount namespaces created from inside that user namespace are owned by it; the host's mount namespace is not. A compromise that escalates to root inside such a container lands at an unprivileged host UID instead of host root — the threat-model improvement rootless containers exist for.

Kubernetes has `spec.hostUsers: false` (beta in 1.30, on track for GA) to give every pod its own user namespace. Inside, the pod's processes appear to run as their requested UIDs; outside, those UIDs map to a high-numbered host UID range (e.g. 100000–165535). A compromise that escalates to "root" inside the pod gets host UID 100000, which on the host is unprivileged.

Caveats:

- The rootfs has to be `chown`-ed to match the namespace's mapping, or **idmap mounted** (Linux 5.12+) so the kernel performs the translation at access time without rewriting on-disk ownership.
- File capabilities, ACLs, and `setuid` binaries on shared filesystems still run as the namespace-mapped UID, which is usually fine but occasionally surprising.
- Historically, several CVEs in setuid helpers like `newuidmap` allowed user-namespace escapes. Distros are conservative about which setuid binaries they ship for this reason.

Masked And Read-Only Paths

`/proc` and `/sys` aggregate host-wide information that the PID and mount namespaces do not isolate. Two OCI fields plug the leaks:

- `linux.maskedPaths` — runc bind-mounts `/dev/null` over files and an empty `tmpfs` over directories. The OCI spec requires the path be inaccessible, not the specific mechanism.
- `linux.readonlyPaths` — remount the path read-only.

The default masked set in most runtimes:

```
/proc/asound
/proc/acpi
/proc/kcore
/proc/keys
/proc/latency_stats
/proc/timer_list
/proc/timer_stats
/proc/sched_debug
/proc/scsi
/sys/firmware
/sys/devices/virtual/powercap
```

Default read-only:

```
/proc/bus
/proc/fs
/proc/irq
/proc/sys
/proc/sysrq-trigger
```

To verify:

```
docker run --rm alpine:3.20 sh -c 'cat /proc/kcore' 2>&1 | head
# (no output -- /dev/null is mounted over it)

docker run --rm alpine:3.20 sh -c 'echo 1 > /proc/sysrq-trigger' 2>&1
# sh: can't create /proc/sysrq-trigger: Read-only file system
```

The list looks arbitrary at first glance and reads more naturally as a history of disclosures. Each entry was added in response to something specific:

- `/proc/kcore` is a pseudo-file that exposes physical RAM. With `CAP_SYS_RAWIO` a process can read kernel memory through it, including secrets and pointers that defeat KASLR. Masked unconditionally because the cost of accidentally leaving it readable is catastrophic.
- `/proc/keys` lists kernel keyrings, which can include credentials.
- `/proc/sched_debug` and `/proc/timer_list` were shown to leak kernel pointers that defeat KASLR.
- `/proc/sysrq-trigger` accepts single-character commands that crash, reboot, or sync the host. Read-only, not masked, because programs sometimes check for its existence.
- `/proc/sys` is the runtime-tunable kernel parameter tree. Read-only because the per-namespace knobs are a small subset; most of the tree affects the host.
- `/sys/firmware` exposes ACPI and firmware-tunable settings that should never be reachable from a workload.

Any new `/proc` or `/sys` interface that exposes host state is a candidate for the masked list. Treat the list as a defense in depth atop seccomp and capabilities: a container that should not need any of these would be fine without them, but masking them removes the failure mode where some other layer slips.

Device Access (cgroup v2 + eBPF)

cgroup v2 has no `devices.allow` file. Device policy is enforced by an eBPF program of type `BPF_PROG_TYPE_CGROUP_DEVICE` attached to the cgroup. runc compiles the OCI `linux.resources.devices` list into BPF and attaches it. The kernel runs that program on every device-class operation (open, mknod, etc.) and uses the program's return value to allow or deny.

```
docker run --rm -d --name demo alpine:3.20 sleep 600
CGROUP=$(docker inspect -f '{{.HostConfig.CgroupParent}}/docker-{{.Id}}.scope' demo)

sudo bpftool cgroup tree /sys/fs/cgroup$CGROUP 2>/dev/null || \
  sudo bpftool cgroup tree | grep -A1 "$(docker inspect -f '{{.Id}}' demo | head -c12)"
# /sys/fs/cgroup/.../docker-<id>.scope
# ID  AttachType      AttachFlags     Name
# X   cgroup_device                   sd_devices
docker stop demo
```

Try to access a device that is not in the allow list:

```
docker run --rm alpine:3.20 sh -c '
  cat /dev/null > /dev/null  # allowed
  echo "null ok"
  cat /dev/sda 2>&1 | head -1  # not allowed
'
# null ok
# cat: /dev/sda: Operation not permitted
```

The kernel returns `EPERM` because the BPF program denies the open. Privileged containers attach a BPF program that allows everything (`a *:* rwm`).

The default device set is small: `/dev/null`, `/dev/zero`, `/dev/full`, `/dev/random`, `/dev/urandom`, `/dev/tty`, `/dev/console`, `/dev/ptmx`, all `rwm`. Anything else has to be explicitly added in `linux.resources.devices`.

Putting It Together

A non-privileged container's actual boundary, in roughly the order it is built:

1. **Namespaces** create separate views.

2. **Mount setup** with masked and read-only paths closes `/proc` and `/sys` leaks.
3. **Capability bounding set** strips kitchen-sink privileges.
4. `noNewPrivileges` prevents privilege gain across exec.
5. **Seccomp** filters dangerous syscalls (and is what unlocks loading the filter without `CAP_SYS_ADMIN`, paired with the previous step).
6. **AppArmor or SELinux** denies operations that DAC and capabilities would allow.
7. **Cgroup device BPF** restricts which devices work.
8. **Cgroups** bound resource consumption.
9. **User namespace mapping** (when enabled) makes container root unprivileged on the host.

Each layer is independently configurable. `--privileged` clears most of these layers at once, which is why it is rarely the right answer when a container does not work. The right reflex when a container needs more than the defaults allow is to add the *specific* capability, the *specific* device, the *specific* AppArmor profile transition — keeping every other layer in place.

Where This Goes

Part 3 picks up the OCI runtime side: how an OCI bundle is laid out, what `config.json` looks like in detail, and how runc translates the spec into the kernel state we have just spent four chapters cataloguing.

Sources And Further Reading

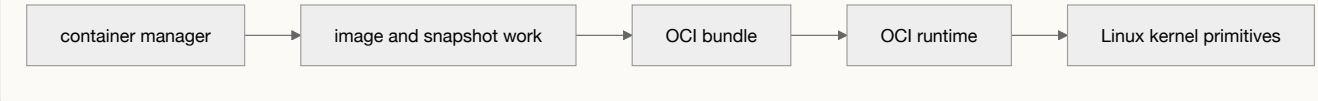
- `capabilities(7)`: https://man7.org/linux/man-pages/man7/capabilities.7.html
- `seccomp(2)`: https://man7.org/linux/man-pages/man2/seccomp.2.html
- Linux seccomp_filter docs: https://www.kernel.org/doc/html/latest/userspace-api/seccomp_filter.html
- AppArmor: https://gitlab.com/apparmor/apparmor/-/wikis/home
- SELinux project: https://github.com/SELinuxProject
- container-selinux: https://github.com/containers/container-selinux
- `prctl(2)` `PR_SET_NO_NEW_PRIVS`: https://man7.org/linux/man-pages/man2/prctl.2.html
- OCI runtime spec, capabilities: https://github.com/opencontainers/runtime-spec/blob/main/config.md#capabilities
- OCI runtime spec, seccomp: https://github.com/opencontainers/runtime-spec/blob/main/config-linux.md#seccomp
- Default Docker seccomp profile: https://github.com/moby/moby/blob/master/profiles/seccomp/default.json
- containerd seccomp default: https://github.com/containerd/containerd/blob/main/contrib/seccomp/seccomp_default.go
- BPF cgroup device program: https://docs.kernel.org/bpf/prog_cgroup_device.html
- idmap mounts: https://lwn.net/Articles/837566/

PART III — OCI AND RUNC

Chapter 8: OCI Runtime Bundles

An OCI runtime bundle is the local handoff between a higher-level manager and a low-level runtime: a directory containing `config.json` and the root filesystem the runtime will use as `/`.

By the time runc sees a bundle, containerd or another manager has already done the image work. Registry resolution, content download, layer unpacking, snapshot preparation, and mount calculation happen above the OCI runtime boundary. The runtime receives the result as local filesystem state plus a JSON spec.



containerd, CRI-O, Docker, and other managers prepare filesystem and metadata state in their own way, then hand a common bundle to runc, crun, youki, runsc, Kata, or another compatible implementation.

Bundle Layout

The OCI runtime spec defines a bundle as a directory with `config.json` at the root. The root filesystem is referenced by `root.path`; the spec does not require the rootfs directory to have one universal name, though `rootfs` is conventional.

The practical shape is:

```
bundle/
  config.json
  rootfs/
    bin/
    etc/
    proc/
    ...
```

`config.json` is the contract. It describes the process, root filesystem, mounts, namespaces, cgroups, hooks, annotations, and platform-specific settings. The root filesystem is the tree that should become `/` inside the container after the runtime sets up the mount namespace and switches root.

The top-level Go type generated for the runtime spec is a useful map of that contract:

```
type Spec struct {
    Version string `json:"ociVersion"`
    Process *Process `json:"process,omitempty"`
    Root *Root `json:"root,omitempty"`
    Mounts []Mount `json:"mounts,omitempty"`
    Hooks *Hooks `json:"hooks,omitempty" platform:"linux,solaris,zos"`
    Annotations map[string]string `json:"annotations,omitempty"`
    Linux *Linux `json:"linux,omitempty" platform:"linux"`
}
```

The OCI runtime spec is the authoritative document. Most implementations vendor the `runtime-spec/specs-go` types, so configs that round-trip through one tool tend to round-trip through the others.

Process And Root

The `process` object describes the program to execute. It includes `args`, `env`, `cwd`, user and group settings, capabilities, rlimits, terminal settings, `noNewPrivileges`, AppArmor and SELinux labels, scheduler fields, I/O priority, and CPU affinity. A minimal one looks like this:

```
"process": {
  "args": ["/bin/sh", "-c", "echo hello"],
  "env": ["PATH=/usr/bin"],
  "cwd": "/",
  "noNewPrivileges": true
}
```

The `root` object names the container root filesystem. `root.path` is interpreted relative to the bundle unless it is absolute. `root.readonly` asks the runtime to make the root filesystem read-only after setup; individual mounts still carry their own options.

```
"root": { "path": "rootfs", "readonly": false }
```

The runtime creates the namespace and mount state that make `process` and `root` true.

Mounts

The `mounts` array is ordered. That matters because later mounts can cover earlier paths. Each mount has a destination, type, source, and options:

```
"mounts": [
  { "destination": "/proc", "type": "proc", "source": "proc" },
  { "destination": "/data", "type": "bind", "source": "/var/data",
    "options": ["rbind", "ro"] },
  { "destination": "/tmp",  "type": "tmpfs", "source": "tmpfs",
    "options": ["mode=1777", "size=64m"] }
]
```

The three entries share one JSON shape and produce three very different kernel calls: a `proc` mount, a host-path bind, and a fresh tmpfs. A bind mount source can be absolute or relative to the bundle.

The spec defines the desired mount table without prescribing how the runtime achieves it. A runtime may use classic `mount(2)`, the file-descriptor mount API (`fsopen(2)`, `fsmount(2)`, `move_mount(2)`), idmapped mounts via `mount_setattr(2)`, or bind-mount fallbacks, depending on kernel support and user-namespace mode.

Linux Namespaces

The Linux-specific `namespaces` list names namespace types such as mount, PID, network, UTS, IPC, user, cgroup, and time. For each namespace type, the meaning of `path` is the key:

OCI namespace entry	Runtime behavior
Type present with no `path`	Create a new namespace of that type.
Type present with `path`	Join the namespace at that path, usually via `setns(2)`.
Type absent	Inherit the runtime's namespace of that type.

Duplicate namespace types are invalid.

`linux.namespaces` does not isolate anything by itself. It instructs the runtime which namespaces to create or join when it builds the container process — the kernel calls from Part II happen at that step, not at JSON-decode time.

Cgroups And Resources

`linux.cgroupsPath` describes where the container should live in the cgroup hierarchy. `linux.resources` describes controller settings: CPU, memory, block I/O, pids, hugepages, RDMA, device rules, and cgroup v2 `unified` settings not otherwise modeled by the spec.

The spec does not mandate one cgroup manager. A runtime can write cgroupfs directly, use systemd, or combine approaches depending on host configuration. For cgroup v2, delegation rules matter: ownership and writable files are constrained by the kernel's delegation model.

If a limit is expressed correctly in `config.json` but not visible in `/sys/fs/cgroup`, the failure is in the runtime's cgroup application path or the host manager interaction, not in the bundle format itself.

Hooks

Hooks run at defined points around container setup, each in a specific namespace context.

The current runtime spec defines:

- `createRuntime` - runs in the runtime namespace after environment creation and before `pivot_root` or an equivalent root switch.
- `createContainer` - runs in the container namespace after namespace setup and before `pivot_root` or equivalent.
- `startContainer` - runs in the container namespace before the user command executes.
- `poststart` - runs in the runtime namespace after the user process starts.
- `poststop` - runs in the runtime namespace after the container is deleted.

A hook entry is a process invocation, nothing more:

```
"hooks": {
  "createRuntime": [
    { "path": "/usr/local/bin/setup-net",
      "args": ["setup-net", "--bridge", "br0"],
      "timeout": 5 }
  ]
}
```

`prestart` is deprecated but still appears in implementations for compatibility. Hooks are a common place for device injection and runtime extensions: `nvidia-container-runtime` is a `createRuntime` hook that injects GPU device nodes and library bind mounts before runc switches root. Each hook is a single exec at a defined lifecycle point — no plugin discovery, no shared state.

Runtime State

The OCI runtime also has a state JSON format. `state` reports fields such as `ociVersion`, `id`, `status`, `pid`, `bundle`, and `annotations`. The core statuses are `creating`, `created`, `running`, and `stopped`.

The lifecycle verbs use that state model:

- `create` prepares the container environment and leaves the user-specified program not yet executed.
- `start` runs the user-specified program.
- `state` reports status.
- `kill` sends a signal.
- `delete` removes runtime state after the container is stopped.

The `create` / `start` split exists so a caller can do work between setup and execution: attach IO, pass file descriptors, run hooks, or coordinate external namespace setup.

What The Spec Leaves Open

The OCI runtime spec defines the bundle and lifecycle, not a particular process tree. runc, crun, youki, gVisor, and Kata can all keep an OCI-facing shape while making different implementation choices.

Those choices include:

- whether the runtime uses `pivot_root(2)`, `chroot(2)`, `MS_MOVE`, or newer mount strategies for root switching;
- whether cgroups are applied through cgroupfs or systemd;
- how the runtime orders `clone(2)`, `clone3(2)`, `unshare(2)`, and `setns(2)`;
- how mounts are realized on older kernels, in user namespaces, or with idmapped mount support;
- whether the isolation boundary is direct host Linux primitives, a userspace kernel, or a VM.

Chapter 9 follows runc's choices through this list.

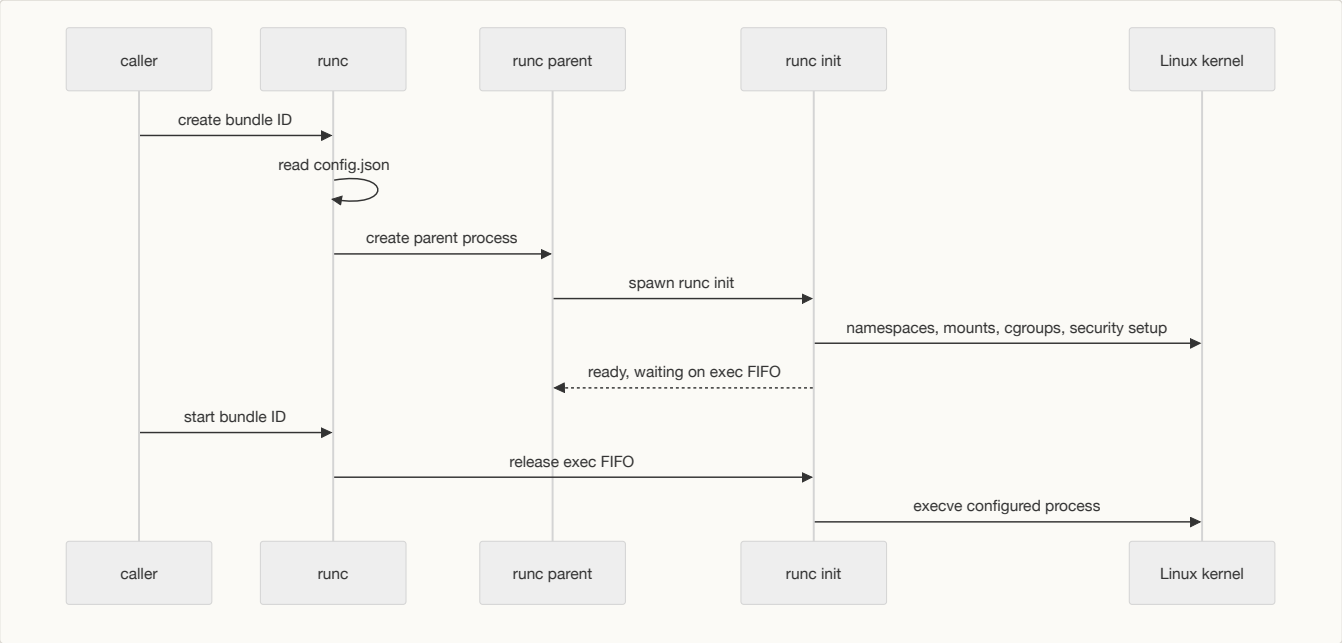
Sources And Further Reading

- OCI runtime bundle: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/bundle.md
- OCI runtime lifecycle: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/runtime.md
- OCI config: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/config.md
- OCI Linux config: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/config-linux.md
- OCI Go structs: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/specs-go/config.go
- `mount(2)`: https://man7.org/linux/man-pages/man2/mount.2.html
- `mount_setattr(2)`: https://man7.org/linux/man-pages/man2/mount_setattr.2.html
- `clone(2)`: https://man7.org/linux/man-pages/man2/clone.2.html
- `setns(2)`: https://man7.org/linux/man-pages/man2/setns.2.html
- `pivot_root(2)`: https://man7.org/linux/man-pages/man2/pivot_root.2.html

Chapter 9: runc Lifecycle

runc is containerd's default Linux runtime and the most common implementation of the OCI runtime contract. It takes the bundle from Chapter 8, turns `config.json` into libcontainer configuration, creates the requested Linux environment, and eventually calls `execve` for the configured process.

runc coordinates a parent process, an init process, namespace entry, cgroup placement, mount setup, hooks, seccomp, capabilities, labels, IO, state files, and cleanup. It is one implementation of the OCI runtime spec; crun, youki, runsc, and Kata are others.



`create` builds processes, namespaces, mounts, and cgroups but stops at the FIFO gate before `execve`; `start` releases the gate.

CLI Verbs

runc exposes the OCI lifecycle directly:

- `run` creates and starts a container in one command.
- `create` creates the container environment and leaves the configured program gated.
- `start` starts a container in the `created` state.
- `state` emits OCI state JSON.
- `kill` sends a signal.
- `delete` tears down a stopped or forcibly killed container.

The `run` command is convenient for humans. Container managers such as containerd use the two-phase `create` / `start` shape because it gives them a setup point between environment creation and process execution.

Reading The Bundle

runc starts by entering the bundle directory, opening `config.json`, decoding it into the OCI Go `Spec`, validating the process section, and converting the spec into libcontainer configuration.

The handoff from JSON to libcontainer is small:

```
if err = json.NewDecoder(cf).Decode(&spec); err != nil {
    return nil, err
}
return spec, validateProcessSpec(spec.Process)
```

From there runc translates the spec into libcontainer's model: namespaces, mounts, cgroups, devices, process settings, hooks, and runtime flags such as systemd cgroup mode, rootless mode, and no-pivot behavior.

The Parent And The Gate

For an init container, runc creates an exec FIFO before starting the container path:

```
if process.Init {
    if err := c.createExecFifo(); err != nil {
        return err
    }
}
```

The parent process then starts a cloned copy of `/proc/self/exe` running `runc init`. That init path receives pipes, bootstrap data, the init config, logging descriptors, and namespace setup instructions. runc marks unrelated file descriptors close-on-exec before starting `runc init`, a hardening detail added because leaked descriptors have produced container escapes in the past (CVE-2024-21626).

The FIFO is the gate. During `runc create`, the init process prepares the environment and waits. During `runc start`, runc releases that gate so the init path can continue to the final user process.

That gate is why `created` and `running` are different states: in `created`, namespaces, mounts, and cgroups exist and the init process is parked; the user-specified `execve` has not happened yet.

Namespace Entry

runc includes C namespace-entry code because namespace operations are sensitive to process and thread state. `setns(2)`, PID namespace creation, and clone ordering do not fit cleanly into an already-running multithreaded Go runtime.

The parent starts `runc init`, the C `nsenter` code handles low-level namespace entry and clone staging, and the Go init code reads `_LIBCONTAINER_*` environment variables and init config from pipes. From there the init path chooses standard init for a new container or setns init for `runc exec`.

crun and youki use different internal structures to satisfy the same OCI contract.

Root Filesystem Setup

The standard Linux init path prepares networking and routes, initializes labeling state, then prepares the root filesystem:

```
if err := setupNetwork(l.config); err != nil {
    return err
}
err := prepareRootfs(l.pipe, l.config)
```

`prepareRootfs` is where the bundle's root and mount declarations become a mount table inside the container's mount namespace. runc opens the rootfs, iterates configured mounts, creates device nodes when needed, sets up `/dev/ptmx` and `/dev` symlinks, runs parent-side hooks at the correct point, and switches root:

```
for _, m := range config.Mounts {
    if err := setupAndMountToRootfs(pipe, config, mountConfig, m); err != nil {
        return err
    }
}
err = pivotRoot(rootFd)
```

The full code path adds hardening around `/proc`, `/sys`, user-namespace device behavior, and read-only remounts. The mount list in `config.json` becomes kernel mount state, then `pivot_root(2)`, `MS_MOVE`, or `chroot(2)` swaps the prepared tree in as `/`.

Setup Order

runc's parent and init processes synchronize because setup order matters. The parent can apply cgroups before children escape placement, move configured network interfaces after it knows the child PID, run `prestart` and `createRuntime` hooks from the parent side, and pass file descriptors to the child. The child prepares the rootfs, runs container-side hooks, applies user and group settings, labels, capabilities, `noNewPrivileges`, seccomp, scheduler settings, I/O priority, and cwd checks close to the final exec.

That order is security-sensitive. A seccomp filter installed too early can block setup calls. A capability dropped too late gives more privilege to setup code than intended. A cwd outside the container root can become a host filesystem exposure.

Start, State, Kill, Delete

`start` only operates on a created container. It releases the exec FIFO so the init path can call `execve` for the configured program. `state` reports the OCI state fields from runc's stored state and live process information.

`kill` has more policy than a raw `kill(2)`. runc has special handling for `SIGKILL`, stopped and running states, cgroup process killing, and cases where the container does not have a private PID namespace. `delete --force` kills before teardown and must handle processes that may remain in the cgroup after the init process exits, especially when PID namespaces are shared.

A runtime owns the lifecycle state and teardown rules, not just the start path: `delete --force` reaps stragglers in the cgroup, and shared PID namespaces require killing the whole tree.

Other Runtime Answers

runc is the book's main implementation path, but the OCI contract allows different answers:

Runtime	What stays the same	What changes
crun	OCI bundle and lifecycle	C implementation and `libcrun` library-oriented design
youki	OCI bundle and lifecycle	Rust implementation and Rust abstractions for process, rootfs, cgroups, seccomp
gVisor `runsc`	OCI-facing command shape	Workload syscalls go through gVisor's userspace Sentry
Kata Containers	containerd/OCI-facing manager boundary	Workload runs inside a lightweight VM and guest agent

Part IV moves back up the stack to containerd, where image content, snapshots, container metadata, tasks, shims, and CRI all meet before the runtime ever receives a bundle.

Sources And Further Reading

- runc repository at checked commit: https://github.com/opencontainers/runc/tree/eb7eaf19b6eec5d1143b257057899e4a7b738c81
- runc CLI commands: https://github.com/opencontainers/runc/tree/eb7eaf19b6eec5d1143b257057899e4a7b738c81

- runc `config.json` loading: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/spec.go
- runc libcontainer setup: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/libcontainer/container_linux.go
- runc parent process sync: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/libcontainer/process_linux.go
- runc init dispatch: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/libcontainer/init_linux.go
- runc standard init: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/libcontainer/standard_init_linu
- runc rootfs setup: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/libcontainer/rootfs_linux.go
- runc nsenter C source: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/libcontainer/nsenter/nsexec.c
- OCI runtime lifecycle: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/runtime.md

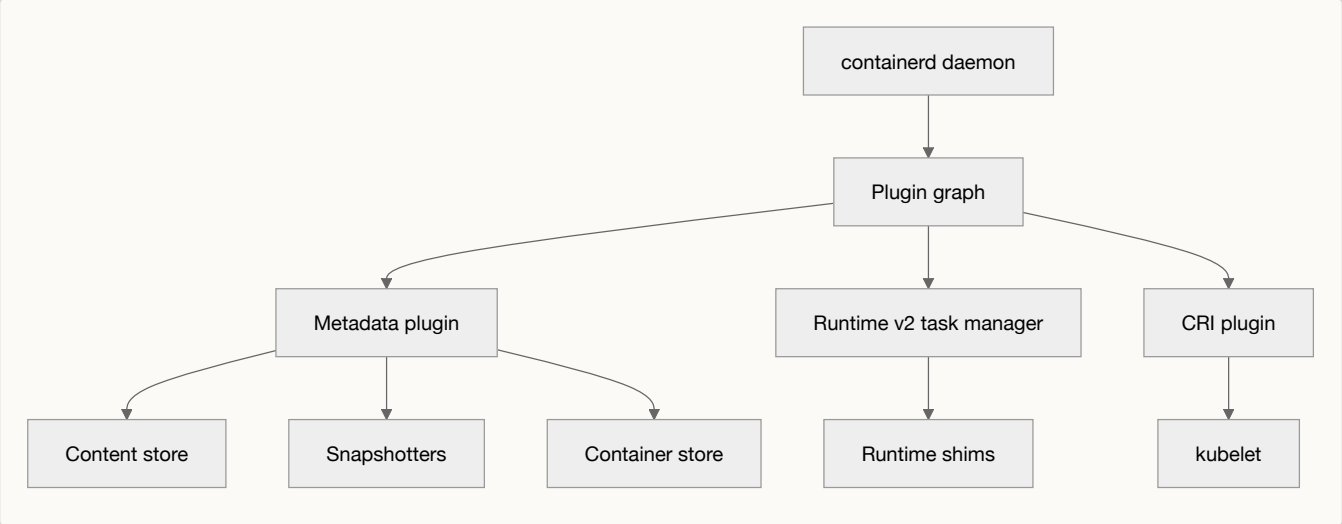
PART IV — CONTAINERD

Chapter 10: containerd Architecture

containerd is a daemon that hosts a plugin graph: content store, snapshotters, metadata, runtime v2, CRI, transfer, events, and services are all plugins, and clients reach each of them through a gRPC API.

To do that job it has to keep several kinds of state coordinated without collapsing them into one object: image references and descriptors, immutable content blobs, unpacked filesystem snapshots, persistent container metadata, live tasks, runtime shims, leases that protect work from garbage collection, and events that report what changed.

Those nouns carry weight for the rest of Part IV. A containerd *container* is a metadata object. A *task* is live execution. A *snapshot* is filesystem state managed by a snapshotter. *Content* is digest-addressed bytes, not a mounted root filesystem.



The Daemon As Plugin Host

The containerd daemon loads each configured plugin at startup, passing in a context with the root and state directories, daemon addresses, and the results of plugins it depends on. The startup loop in `cmd/containerd/server/server.go` is three lines of substance:

```
result := p.Init(initContext)
instance, err := result.Instance()
s.plugins = append(s.plugins, result)
```

Required plugins are tracked, so a missing core dependency fails startup instead of producing a half-wired daemon. Content, snapshotters, metadata, runtime v2, CRI, transfer, events, and services all show up as nodes in this graph.

The metadata plugin is the best anchor. It depends on content, events, and snapshots; at startup it opens `meta.db`, collects registered snapshotters, and builds a metadata database over the content store and snapshotter map. Images, containers, snapshots, and content can then be reasoned about together without being forced into one physical backend.

The metadata database stores names, records, labels, relationships, and namespace-scoped state. The content store stores blobs. Snapshotters own filesystem snapshot state. On disk under `/var/lib/containerd/`, the three stores live side by side:

```
io.containerd.metadata.v1.bolt/meta.db
io.containerd.content.v1.content/blobs/sha256/
io.containerd.snapshotter.v1.overlayfs/
```

Namespaces Are Metadata Partitions

containerd namespaces are not Linux namespaces. They do not call `unshare(2)` or `clone(2)` and they do not create process, mount, or network namespaces. They partition containerd's own metadata so one daemon can serve multiple consumers without mixing images, containers, leases, and snapshots.

CRI uses the `k8s.io` namespace. `ctr` defaults to `default`. Other clients pick their own. A single daemon can hold Kubernetes-managed objects and `ctr`-created objects at the same time, with each client seeing only the namespace it asks for.

A Linux PID namespace changes what processes can see. A containerd namespace changes where records are stored and looked up inside containerd. The two travel together by convention but not by mechanism: a process can run with no new Linux namespace and still belong to a containerd namespace, and a process can run inside many Linux namespaces while its metadata lives under `k8s.io`.

The Smart Client Model

containerd deliberately leaves higher-level work to clients. The plugin documentation calls this a smart-client model: if a step does not need to live in the daemon, the client does it before asking a service to do anything.

`ctr`, `nerdctl`, Docker, and CRI each resolve image names, choose snapshotters, build an OCI spec, attach labels, select runtime options, and pick a namespace before calling containerd. The same daemon serves all of them; it never sees how they differ.

The CRI plugin is a special case in that it runs inside the daemon, but it follows the same model: it translates Kubernetes CRI calls into containerd service calls and runtime choices. CRI is not a second runtime below containerd.

Core Services

The useful axis for learning containerd services is lifecycle responsibility:

Service	Responsibility
Content	Store immutable blobs and active ingestions by digest.
Images	Map names to OCI descriptor targets and keep image metadata.
Snapshots	Create active, view, and committed filesystem snapshots.
Containers	Store persistent container metadata: spec, image, runtime, snapshot key, labels, extensions.
Tasks	Manage live execution through runtime plugins and shims.
Leases	Protect content, snapshots, and metadata while work is in progress.
Events	Publish daemon and runtime lifecycle events.

The rows compose: image metadata points at content; unpacking content creates snapshots; a container record points at an image and a snapshot key; a task uses the container record to start live execution through runtime v2; a lease holds intermediate objects together while a pull or unpack is in flight; events tell observers what happened after requests return.

Keeping those responsibilities separate is what lets a single daemon serve several modes at once. An image can be pulled but not unpacked. A container can exist with no running task. A task can exit while the container metadata stays. A snapshot can outlive the image name that originally produced it, because a container or lease still references the chain.

Runtime v2 In The Architecture

Runtime v2 is the boundary between containerd's task service and runtime-specific process supervision. containerd starts or reconnects to a shim and talks to that shim over the runtime v2 task API. The common Linux path is `io.containerd.runc.v2`, implemented by the `containerd-shim-runc-v2` binary, which in turn drives `runc`.

The daemon never embeds the details of any specific runtime. The shim owns the runtime-specific work — invoking the OCI runtime, tracking exits, handling IO, publishing task events. That is why containerd can be restarted while existing tasks keep running under their shims, and why a different runtime can be slotted in by configuration alone.

The same boundary is why containerd has both synchronous calls and asynchronous events. A client calls `Start` and gets a response immediately, but the task's later exit arrives as an event. Runtime v2 defines task create, start, exit, delete, pause, resume, checkpoint, OOM, and exec events with ordering guarantees. A caller that only reads request responses misses task exits, OOM events, and any state change that happens after the synchronous call returns.

Where CRI Fits

The CRI plugin is a gRPC plugin inside containerd. It registers Kubernetes `RuntimeService` and `ImageService` servers on containerd's gRPC server and maps kubelet requests onto containerd services.

Kubelet gets a Kubernetes-shaped API and never has to know about containerd's image store, snapshotters, task service, leases, event monitor, or runtime v2 shims. It asks for a pod sandbox or a container start. The CRI plugin turns that into namespace-scoped containerd operations under `k8s.io`.

Four contracts stack on top of each other in the runtime path:

1. CRI sits between kubelet and containerd.
2. containerd services sit inside the daemon's own API surface.
3. Runtime v2 sits between containerd and the shim.
4. The OCI runtime spec sits between the shim and a runtime such as `runc`.

Each layer has its own vocabulary, and a word from one layer rarely means the same thing in another. The CRI runtime vs OCI runtime distinction from chapter 1 is the standing example.

Where This Goes

The rest of Part IV walks one object at a time across this graph. Chapter 11 takes image bytes from a reference into the content store and out through a snapshotter. Chapter 12 turns a container record into a task and a shim. Chapter 13 enters from the kubelet side and lands in the same containerd services.

Sources And Further Reading

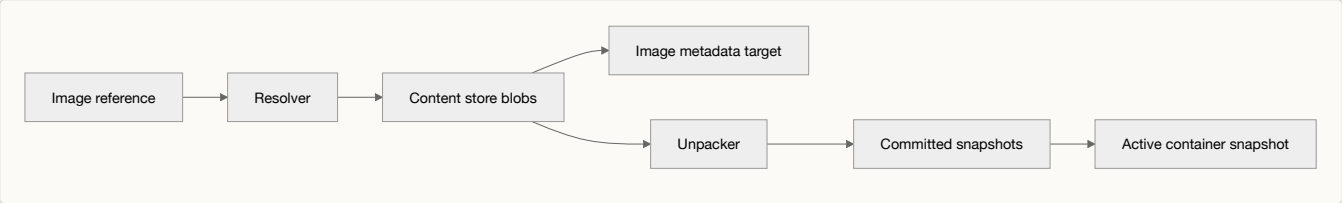
- containerd `v2.3.0` source: https://github.com/containerd/containerd/tree/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a
- Daemon plugin initialization: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/cmd/containerd/server/server.
- Metadata plugin: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/plugins/metadata/plugin.go
- Metadata DB: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/metadata/db.go
- Plugin docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/PLUGINS.md
- Feature docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/features.md
- Runtime v2 docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/runtime-v2.md

Chapter 11: Images, Content, And Snapshots

An image pull in containerd is four operations on four different things: name resolution, content download, image-metadata recording, and (optionally) layer unpacking through a snapshotter.

The four things are an **image reference**, the registry-style name a user types; **content blobs**, the digest-addressed bytes that make up manifests, configs, and layers; **image metadata**, which maps a name to an OCI descriptor target; and **snapshots**, which are filesystem states produced by applying layers in order.

The reason to keep them apart is that containerd can be in any of the partial states between them. Image metadata can exist without all the content being present. Content can exist without a mounted root filesystem. A snapshot chain can exist without a running process. A running task's writable layer is a separate object from the committed image layers it sits on top of.



The Content Store Is For Bytes

The content store is digest-addressed storage for immutable blobs: manifests, indexes, image configs, and compressed layers.

The interface in `core/content/content.go` is small enough to fit on one screen:

```
type Store interface {
    Manager
    Provider
    Ingester
}
```

`Provider` reads committed content by descriptor. `Ingester` handles active writes. `Manager` exposes metadata operations such as labels. An ingestion is invisible to readers until it is committed; after commit, callers can read the blob by digest and inspect or update its labels.

That commit boundary is the reason image pulls need leases. While a pull is running, containerd carries temporary blobs, partially traversed descriptors, and metadata that the garbage collector would happily delete if it ran in the gap. The pull path wraps the whole operation in a lease so the collector and the pull cannot race.

Image Metadata Is A Name To A Descriptor

The image store is not the image bytes. It maps a name to an OCI descriptor target — usually an image index or a manifest — and the content store holds whatever the descriptor points to.

The helpers around `images.Image` make the split visible. They resolve the image config, manifests, rootfs diff IDs, and size by walking the descriptor graph through a content provider. The image record is the named root of that graph; the content provider supplies the bytes at every node.

That split is why retagging an image is a metadata-only operation while fetching a missing layer is a content operation. It is also why deleting an image name does not delete the underlying blobs. The bytes might still be reachable from another image, a container, or a lease, and only the garbage collector — after looking at the whole reference graph — gets to decide.

Pulling An Image

A pull starts with a reference and a resolver, not with a download. The resolver locates the registry content. The fetcher walks the descriptor graph, downloading what it does not already have. The image service records a final image object at the end. If the caller asked for unpack, an unpacker is hooked into the traversal so layers are applied to the selected snapshotter as content arrives.

In containerd `v2.3.0` the path through `Client.Pull` does six things, in order:

1. wrap the operation in `WithLease`;
2. resolve the reference to a descriptor;
3. fetch content by walking the descriptor graph;
4. if `WithPullUnpack` is set, run the unpacker as part of the walk;
5. wait for unpack completion before creating the final image object;
6. reject Docker schema 1 manifests, which are no longer accepted as of containerd 2.1.

A pull is therefore a descriptor walk with content ingestion, optional unpack, metadata creation, and lease protection.

Snapshotters Are Filesystem State Machines

A snapshotter is a small state machine over filesystem snapshots, with three states — active, view, committed — and five operations:

- `Prepare` creates an active writable snapshot over a parent.
- `View` creates a read-only view.
- `Commit` records the changes in an active snapshot as a committed snapshot.
- `Mounts` returns mount instructions for a snapshot.
- `Remove` deletes active or committed state when no dependency holds it.

Image layers become committed snapshots; the container gets a new active writable snapshot on top of the committed chain at start time. That active snapshot is the container's writable layer. The image's committed layers stay immutable underneath it.

The default Linux backend is overlayfs, but the interface also has native, btrfs, zfs, blockfile, devmapper, Windows, and remote/lazy backends. Everything above this interface — containers, tasks, CRI — talks to "a snapshotter" without caring which one.

Unpack Connects Content To Snapshots

Unpacking is where image config and layer descriptors meet filesystem state. The unpacker reads the image config, lines layer descriptors up against the rootfs diff IDs, computes chain IDs, applies layers, and commits snapshots under stable names.

The core prepare/apply/commit loop in `core/unpack/unpacker.go` is three calls per layer:

```
mounts, err = sn.Prepare(ctx, key, parent, opts...)
diff, err := a.Apply(ctx, desc, mounts, ...)
err = sn.Commit(ctx, chainID, key, opts...)
```

Three identifiers travel together and must not be confused. The **descriptor digest** names the compressed blob in the content store. The **diff ID** names the uncompressed filesystem change after the layer is applied. The **chain ID** is a digest over the sequence of diff IDs up to and including the current layer; it becomes the snapshot key for the committed layer chain.

That is also why unpack waits for the image config. The config's `rootfs.diff_ids` is the source of truth for the uncompressed changes containerd expects. After applying a layer, containerd recomputes the diff ID and checks it against the config; only on a match does it commit the snapshot.

Garbage Collection References

Unpack also writes the labels that let the garbage collector cross from content into snapshots. After verifying a layer, unpack stamps the layer's content blob with a label for its uncompressed diff ID. After committing the chain, it stamps the image config with a snapshot GC reference label for the selected snapshotter, pointing at the final chain ID.

Without those labels, the collector cannot bridge the two stores. The content store and the snapshotter are separate systems with separate garbage; the labels are the edges that turn them into one reference graph. An image config points at a final chain ID, that chain ID depends on earlier committed snapshots, and the collector preserves the whole subgraph as long as anything reachable still references it.

Leases sit on top of that. A pull, unpack, or container-creation flow takes a lease to protect the in-progress set of content, metadata, and snapshots from collection until it has assembled a consistent result. Without leases, the collector would race the pull and delete in-progress objects.

From Image Chain To Container Rootfs

Committed snapshots for the image chain are not a running container; a client (or the CRI path) calls `Prepare` with the chain as parent, and task creation asks the snapshotter for mounts and passes them to runtime v2.

The full path from a typed reference to a mounted rootfs is seven steps:

1. Resolve an image reference.
2. Fetch descriptors and blobs into the content store.
3. Record image metadata pointing at the descriptor target.
4. Unpack layers into committed snapshots.
5. Prepare an active snapshot for the container.
6. Pass snapshot mounts to task creation.
7. Let the shim and runtime mount the root filesystem for execution.

No single object in that list is "the image" in every sense. The name, the bytes, the metadata, the committed chain, and the active rootfs are five different objects with five different lifetimes.

Where This Goes

A missing blob is a content problem. A missing unpacked root is a snapshot problem. A wrong tag is image metadata. A writable layer that will not mount is an active snapshot problem. A process that never starts is in the task and shim path — which is where chapter 12 picks up, with a container record that already knows which snapshot it owns and a task request that turns that record into live execution.

Sources And Further Reading

- containerd `v2.3.0` source: https://github.com/containerd/containerd/tree/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a
- Content flow docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/content-flow.md
- Content interfaces: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/content/content.go
- Image store and helpers: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/images/image.go
- Snapshotter interface: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/snapshots/snapshotter.go
- Pull path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/client/pull.go

- Unpacker: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/unpack/unpacker.go
- Snapshotter docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/snapshotters/README.n

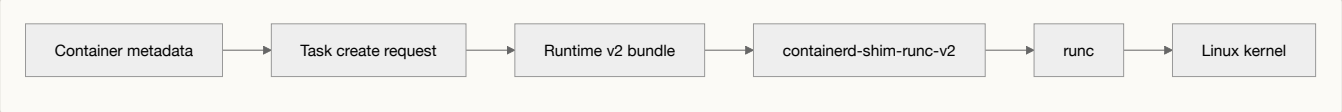
Chapter 12: Containers, Tasks, And Shims

In containerd, a container is not a running process. A container is persistent metadata; a task is live execution; a shim is the process boundary that lets containerd supervise that task without becoming the workload's direct parent.

That single distinction is why `ctr container ls` can list a container while `ctr task ls` shows nothing for it, and why `ctr task rm` leaves the container record in place. A container can exist with no task. A task can exit while the container record remains. Deleting a task is not the same operation as deleting the container metadata, and starting a task is not the same operation as creating the container record.

Word	containerd meaning	Concrete state
Container	Persistent metadata	ID, OCI spec, image, snapshot key, runtime, labels, extensions, sandbox ID
Task	Live execution	PID, status, IO, exec processes, runtime operations
Shim	Runtime supervisor	Task service endpoint, runtime calls, IO, exit handling, event publishing

The common Linux path is:



Container Metadata

A container record is the durable intent containerd needs later: runtime choice, image name, OCI spec, snapshotter, snapshot key, labels, extensions, and an optional sandbox ID. It is not an init process and it is not a cgroup.

The client-side `Container` interface reinforces the split. The metadata operations — `Info`, `Spec`, `Image`, `Update`, `Delete` — all stay on the metadata side; only `NewTask` crosses over into live execution. That is why `ctr container create` can return success while nothing is running on the host: the record exists, the process does not.

Task Creation

`Container.NewTask` turns a container record into a task service request. It creates or attaches IO, resolves snapshot mounts if the container has a snapshot key, carries runtime options across, and sends a `CreateTaskRequest` to the task service.

Strip the supporting code in `client/container.go` away and the call is two lines:

```
request := &tasks.CreateTaskRequest{ContainerID: c.id}
response, err := c.client.TaskService().Create(ctx, request)
```

The surrounding code builds IO, reads the container spec, asks the snapshotter for mounts, and fills runtime options before the request goes out — but a container record does not become a task until a client calls `NewTask`.

Starting is a separate boundary again. The client `Task` interface offers `Start`, `Kill`, `Pause`, `Resume`, `Exec`, `Pids`, `Checkpoint`, `Update`, `Metrics`, `Spec`, `Wait`, and `Delete`. `Create` prepares runtime state. `Start` runs the process. The split lets a runtime build a container's disk and IO state, optionally take a checkpoint, and only then begin execution.

Runtime v2 Bundles

Before a shim starts, the runtime v2 task manager builds a bundle directory on disk. A bundle is not an image layer and not part of the content store; it is per-task runtime state, scoped to one container.

`NewBundle` validates the task ID, creates the namespace-scoped state and work directories, creates a `rootfs` directory inside the bundle, links the work directory back in, and writes `config.json` when the request carries an OCI spec. The snapshot mounts from chapter 11 are activated into this same path.

That bundle is the handoff point between containerd metadata and a real OCI runtime. The shim is given enough information to ask runc to create the container without ever consulting the containerd database.

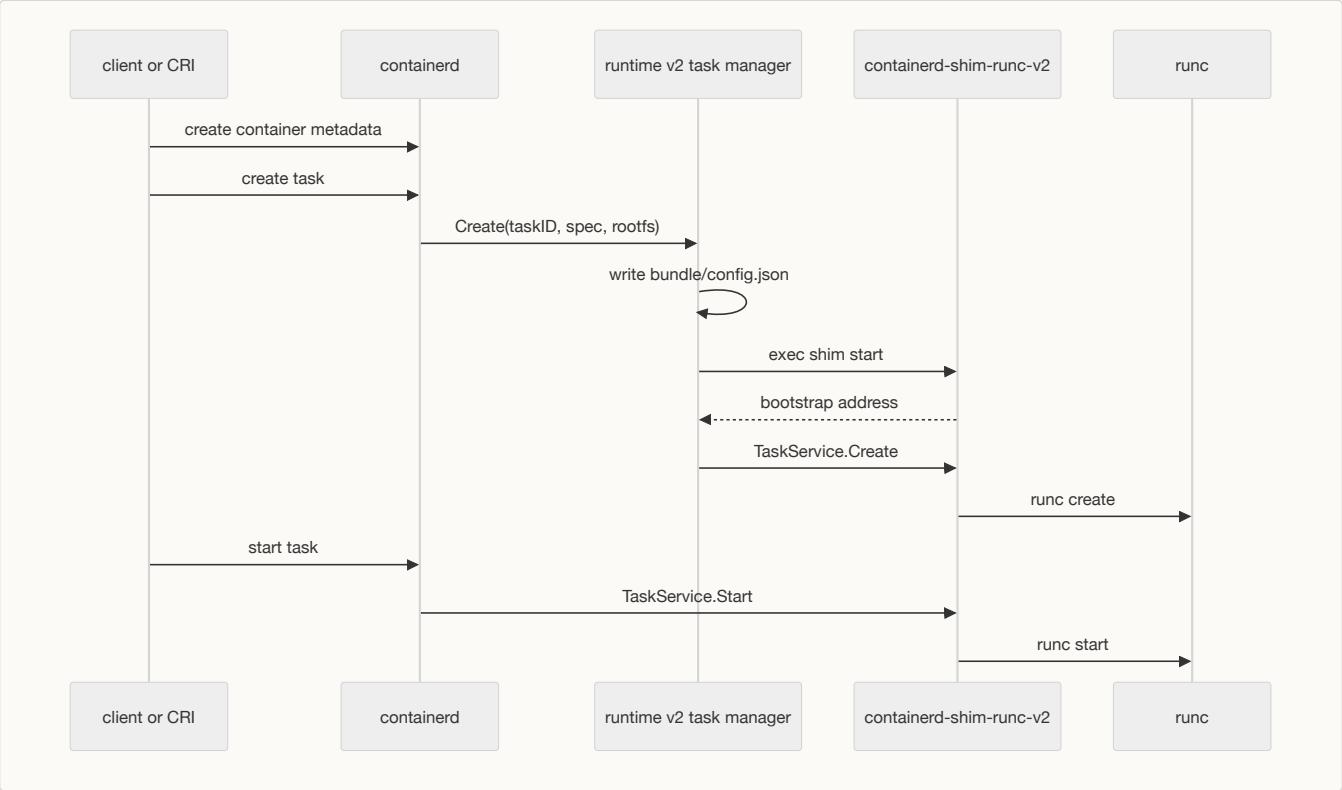
Starting Or Reconnecting To A Shim

The runtime v2 task manager creates the bundle, activates mounts, hands off to the shim manager to start or reconnect to a shim, validates the shim's runtime features, and calls the shim task client's `Create`.

Runtime names look like Java package paths: `io.containerd.runc.v2` is the canonical Linux/runc handler. The shim manager translates that to the binary name `containerd-shim-runc-v2`, finds it on `PATH`, executes it with the `start` action, parses the bootstrap address out of the response, connects over ttrpc (or gRPC, for shims that opt in), and persists the bootstrap data so containerd can reconnect to the same shim later.

This is the daemon-restart survival case from chapter 3, made concrete: the shim keeps supervising the workload across a containerd restart and reattaches when the daemon comes back.

The startup sequence looks like this:



Shim Grouping

"One shim per container" is a useful first approximation and not a rule. containerd 2.3 ships shim API version 3, and when a task belongs to a sandbox whose endpoint is reachable, the shim manager connects to the existing sandbox shim instead of starting another binary. If the endpoint is missing or its API version is older than the sandbox protocol, it falls back to launching a fresh shim.

The CRI sandbox path is the most visible place this matters: every container in a pod can share a single sandbox shim. What stays constant is that the shim is the runtime supervision boundary; how many shims there are depends on the runtime and sandbox configuration.

The runc Shim

`containerd-shim-runc-v2` is the runtime v2 task service for the standard Linux runc path. Its service object tracks containers and processes, watches OOM events, reaps exits, and publishes lifecycle events back to containerd.

On `Create`, the shim runs its runc container creation path: it converts the task request's mounts into process mounts, mounts the rootfs into the bundle's `rootfs` directory, writes runtime options, constructs the init process, and prepares a `runc create` invocation that carries the runtime root, bundle path, containerd namespace, runc binary name, and `systemd-cgroup` setting.

On `Start`, the shim calls the container's `Start` method and publishes a task-start or exec-start event. When the process exits, the shim picks the exit up through its wait handling and publishes a task-exit event. containerd never had to be the workload's direct parent to learn it died.

The snapshotter produced mounts in chapter 11; the task manager dropped them into the bundle path; the runc shim mounted the rootfs and handed runc an OCI bundle to create and start.

Events And Waiting

Task lifecycle is not only request and response. Callers can `Wait`, subscribe to events, or inspect status; runtime v2 shims publish task create, start, exit, delete, pause, resume, OOM, and exec events with defined ordering.

A `Start` can succeed and the process can exit a millisecond later. A client that only records the response from `Start` has observed the request, not the lifecycle. CRI, Docker, and `nerdctl` all rely on the wait and event paths to keep their own state honest.

Where This Goes

Chapter 13 stacks Kubernetes on top of all of that. Kubelet does not call runc — it calls CRI, and the CRI plugin builds sandboxes and containers in containerd that ride the same task-and-shim machinery this chapter just walked through.

Sources And Further Reading

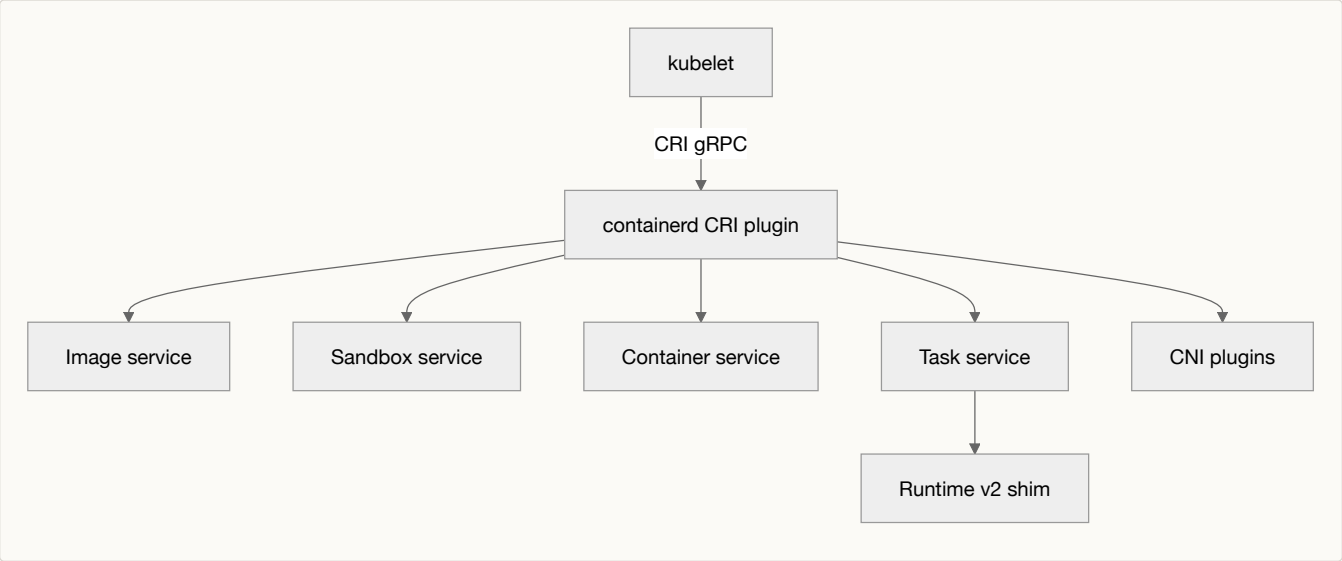
- Runtime v2 docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/runtime-v2.md
- Container metadata API: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/containers/containers.go
- Client container code: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/client/container.go
- Client task code: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/client/task.go
- Runtime v2 task manager: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/runtime/v2/task_manage
- Shim manager: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/runtime/v2/shim_manag
- Bundle handling: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/runtime/v2/bundle.go
- runc shim task service: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/cmd/containerd-shim-runc-v2/task/service.go

- runc shim container path:
  https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/cmd/containerd-shim-runc-v2/runc/container.go

Chapter 13: CRI And Kubernetes

Kubelet does not talk to `runc`. It talks to the Container Runtime Interface, and in containerd, CRI is an in-daemon plugin that translates Kubernetes runtime and image RPCs into containerd service calls.

Kubernetes has pods, pod sandboxes, runtime handlers, image pulls, container creates, exec, attach, port-forward, status, stats, and logs. containerd has namespaces, image metadata, content, snapshotters, containers, tasks, shims, leases, events, and runtime options.



Registration

The CRI plugin registers itself as a containerd gRPC plugin and pulls in a long dependency list — runtime, image, sandbox, NRI, event, service, lease, transfer, sandbox-store, and warning plugins. During init it builds an in-memory containerd client pinned to the `k8s.io` namespace, constructs the CRI service, and registers Kubernetes runtime and image servers on containerd's existing gRPC server.

The registration call in `plugins/cri/cri.go` is two lines:

```
runtime.RegisterRuntimeServiceServer(s, instrumented)
runtime.RegisterImageServiceServer(s, instrumented)
```

Everything kubelet ever sees of containerd flows through those two servers.

The `k8s.io` namespace is the second half of the boundary. Kubernetes-managed images, containers, sandboxes, leases, and snapshots all live in that one metadata partition. It does not isolate Linux processes — it keeps containerd records from colliding with whatever a developer creates by hand through `ctr` in the `default` namespace.

CRI Service State

CRI keeps a Kubernetes-shaped index over containerd state — sandbox stores, container name indexes, CNI state, stats — so kubelet can answer its own questions without round-tripping through containerd. containerd remains the source of truth for images, snapshots, and tasks; CRI keeps Kubernetes bookkeeping next to it. That is why CRI source can look larger than expected: it is preserving Kubernetes semantics on top of containerd objects that have their own.

The CRI API Shape

Kubernetes splits CRI into a runtime service and an image service. The runtime service covers pod sandbox operations, container operations, exec, attach, port-forward, status, stats, checkpointing, and runtime config. The image service covers image listing, status, pulls, removals, and filesystem usage.

The shape is visible in kubelet's own behavior. An image pull is a CRI image-service call. A workload container create is a runtime-service call. Starting that container is another runtime-service call. Inside containerd, those three calls land on the same image, snapshot, container, task, and shim machinery from chapters 11 and 12.

The same split is why `CreateContainer` does not start the workload. CRI inherits the OCI and containerd convention of keeping create and start as separate lifecycle steps; the API never had a "run" verb to begin with.

Pod Sandboxes

The first runtime object Kubernetes asks for is a pod sandbox. The pause container is the most visible piece; the sandbox is the metadata, network namespace, CNI result, runtime endpoint, labels, monitor state, and (on the default Linux path) the pause container itself.

`RunPodSandbox` does the Kubernetes-facing setup. In containerd `v2.3.0`, the source path runs through thirteen steps:

1. generate and reserve a sandbox name;
2. create a lease;
3. resolve the runtime handler;
4. store sandbox metadata;
5. create a network namespace unless host networking is requested;
6. run CNI setup;
7. create sandbox metadata through the sandbox service;
8. ensure the pause image exists;
9. start the sandbox;
0. save the sandbox endpoint, labels, and spec;
1. run NRI hooks;
2. mark the sandbox ready;
3. store the sandbox and start an exit monitor.

CNI gets its own chapter in Part V; for now it is enough that CRI runs CNI as part of `RunPodSandbox` and turns the result into containerd service calls.

The default pod-sandbox controller still creates a real containerd container and task for the sandbox image. It builds a sandbox container spec, prepares a snapshot, creates a container with runtime options, creates a task with null IO, waits on it, starts it, and records the PID. That sequence is the bridge between a Kubernetes pod sandbox and the container/task/shim model from chapter 12.

Image Pulls Through CRI

CRI `PullImage` starts as a Kubernetes image request, not a raw containerd pull. The CRI code normalizes the reference, picks a snapshotter from the pod sandbox or runtime handler context, and then drops into either the local client pull path or the transfer service.

On the local pull path, CRI passes a set of options that all show up again later:

- `WithPullUnpack`, so the image is unpacked into the chosen snapshotter;
- the snapshotter selection itself;

- labels for indexing and GC;
- download concurrency and rate limits;
- unpack-duplication suppression;
- optional layer-discard behavior.

That handover is why runtime handlers can affect image pulls. If a handler points at a non-default snapshotter, the image service needs the choice at pull time, because unpack has to land in the same filesystem backend the workload will eventually mount. Pulling for one snapshotter and starting on another is a common operational mistake and a hard one to debug after the fact.

Workload Container Creation

`CreateContainer` takes a pod sandbox ID and a container config. It checks the sandbox exists, resolves the already-pulled image, generates CRI metadata, builds an OCI spec using the sandbox's PID and network namespace state, prepares a new writable snapshot, attaches runtime and sandbox metadata, creates the containerd container, records CRI container state, and emits a container-created event.

It does not start the workload. `CreateContainer` prepares metadata, spec, snapshot state, and CRI bookkeeping; the user's process does not exist until `StartContainer` runs.

The snapshot step is where chapter 11's image work meets the workload. The image has already been pulled and unpacked into committed snapshots. `CreateContainer` calls `Prepare` for an active writable snapshot on top of that chain, and that active snapshot is what task creation will eventually hand to the shim as the root filesystem.

Workload Start

`StartContainer` is the live-execution step. It verifies the sandbox is ready, creates loggers and IO, carries the sandbox endpoint into task options when one exists, creates a containerd task, waits on it in the background, runs NRI start hooks, starts the task, records the PID and start time, launches an exit monitor, and emits a container-started event.

The single call crosses every layer Part IV has introduced:

1. kubelet calls CRI `StartContainer`;
2. CRI looks up its container and sandbox state;
3. CRI asks containerd to create a task for the container;
4. containerd runtime v2 builds the bundle and dials the shim;
5. the shim asks the OCI runtime to create and start the process;
6. CRI records the PID, monitors exit, and reports status back to kubelet.

kubelet never has to know how `io.containerd.runc.v2` becomes `containerd-shim-runc-v2`, where the bundle is written, or how snapshots are mounted into the rootfs.

Runtime Handlers

A runtime handler is the Kubernetes-facing name for a configured slice of containerd runtime behavior. Inside containerd it selects the runtime type, runtime options, snapshotter, sandboxer, runtime binary path, and IO mode, and it carries snapshotter information into the image service so pulls land in the right place.

Kubernetes should be able to ask for a runtime class — default, a VM-backed runtime such as Kata, an alternative such as crun — without constructing containerd runtime options by hand. The handler is the indirection that makes RuntimeClass a first-class Kubernetes object instead of an opaque config string.

The same handler is where most operational mistakes surface. A handler that names one snapshotter while the image was pulled and unpacked into another will fail at container start as a filesystem problem, not a configuration one. A handler that selects a sandbox-aware runtime pulls shim grouping and sandbox endpoints into task startup. Every field on a runtime handler changes a

concrete containerd behavior: snapshotter selection, runtime options, shim grouping for sandbox-aware runtimes.

Where This Goes

The stack reads cleanly in both directions. From kubelet down: CRI request → containerd services → runtime v2 shim → OCI runtime → kernel. From the kernel up: process and namespaces → OCI runtime → shim → containerd task → CRI container → Kubernetes pod. Part V picks up the pod's network namespace and shows how it gets wired into the host.

Sources And Further Reading

- Kubernetes CRI docs: https://kubernetes.io/docs/concepts/containers/cri/
- CRI API proto `v0.36.0` : https://github.com/kubernetes/cri-api/blob/v0.36.0/pkg/apis/runtime/v1/api.proto
- containerd CRI architecture docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/cri/architecture.md
- CRI plugin: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/plugins/cri/cri.go
- CRI runtime service: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/service.go
- CRI sandbox run path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/sandbox_r
- Pod sandbox controller: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/podsandbo
- CRI image pull path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/images/ima
- CRI container create path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/container_
- CRI container start path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/container_

PART V — NETWORKING

Chapter 14: Network Namespaces And Virtual Ethernet

Container networking is built out of three Linux primitives that exist on their own merits. **Virtual Ethernet pairs** (`veth`) give the kernel a way to wire two network devices back-to-back in software, like a patch cable that never leaves the kernel. **Linux bridges** are software Ethernet switches: any frame that comes in on one port leaves on the right port, with MAC learning and broadcast just like the metal box on a rack. **Network namespaces** give a process its own copy of the entire network stack — its own interfaces, IPs, routes, sockets, port numbers, and firewall rules.

A container is a process inside a network namespace. A container *talks* to the network because the namespace contains one end of a veth pair, the other end is on a bridge in the host namespace, and the bridge is wired to the rest of the world by routing or NAT. Every CNI plugin in the bridge family is some variation on that theme. The chapter takes the three primitives one at a time, with hands-on examples that work in isolation, and then composes them into a working two-container network from scratch.

> ***Safety:*** *every command below mutates kernel networking state and most need root. Use a disposable Linux VM. Examples were checked on Ubuntu 24.04 with kernel 6.8 and* `iproute2` *6.1.*

What A Network Namespace Holds

A network namespace is a separate, independent network stack. The `network_namespaces(7)` man page enumerates the pieces, but the list is more useful once you know what each piece does and why isolating it matters.

Network devices. Every interface lives in exactly one namespace at a time. `eth0` in one namespace and `eth0` in another are two unrelated devices; moving a device with `ip link set <dev> netns <ns>` is a literal handoff, not a copy. This is the foundation of everything else — with no devices, there is nothing to bind to, route through, or filter on.

The IPv4 and IPv6 protocol stacks. Each namespace has its own copy of the kernel's TCP/IP state: open sockets, the connection-tracking table (`conntrack`), neighbor caches (ARP for v4, NDP for v6), the Path MTU cache, and the tunables under `/proc/sys/net`. Two namespaces setting `tcp_keepalive_time` differently do not see each other; a connection-table-exhausting workload in one does not starve the other. The stack code is the same kernel; the *state* is per-namespace.

Routing tables. Each namespace has its own forwarding information base. A packet generated or received in namespace A is routed using A's tables only; A's `default via 10.0.0.1` says nothing about how B forwards. This is why two containers can each call `10.40.0.1` their default gateway without contradiction — the lookup happens in their own table.

Firewall rules. Netfilter (iptables/nftables) hooks are per-namespace. Rules installed inside a container's namespace filter only that namespace's traffic; the host's `iptables -L` does not see them, and they do not see the host's. CNI plugins exploit this directly — a per-pod ruleset stays scoped to the pod.

Port numbers. The TCP and UDP port spaces are per-namespace. Two containers can both `bind(0.0.0.0:80)` because the kernel checks for collisions inside the namespace's own port table; the host's port 80 is a third, independent slot.

The `/proc/net`, `/sys/class/net`, and `/proc/sys/net` views. Userspace tools — `ss`, `ip`, `iptables`, `sysctl` — read kernel state through these filesystems. The kernel makes them namespace-aware, so a process inside a namespace sees only its own interfaces, sockets, and sysctls. That is what lets `ip link` inside a container show only the container's devices without the tool needing to know about namespaces at all.

The abstract UNIX domain socket namespace. Abstract sockets — those with a leading null byte in their address, used by D-Bus and a handful of system services — are scoped to the network namespace rather than the filesystem. Path-based UNIX sockets (`/run/foo.sock`) live in the mount namespace instead. Most application code never notices, but system services that bind abstract names sometimes do.

The consequence of all of this is the rule worth memorizing: two namespaces cannot collide on a port and cannot accidentally route through each other, because they share neither the port table nor the route table.

What the namespace does *not* contain is also worth saying. It does not include the resolver — `/etc/resolv.conf` is a regular file in the mount namespace, and the runtime arranges it. It does not include process credentials, capabilities, or the user namespace's privilege rules; those compose with the network namespace but are independent of it (a process can be inside a network namespace while still being uid 0 in the host user namespace, or vice versa). And it does not, by itself, route anywhere. A fresh network namespace contains only a loopback interface, and that loopback is *down*. Until something puts an interface in and configures it, the namespace cannot send a packet.

The simplest demonstration is hand-rolled:

```
sudo ip netns add demo
sudo ip netns exec demo ip link
# 1: lo: <LOOPBACK> mtu 65536 qdisc noop state DOWN ...
sudo ip netns exec demo ip route
# (empty)
```

`ip netns add` does two things: it calls `unshare(CLONE_NEWNET)` to create the namespace, and it bind-mounts the namespace's `nsfs` inode under `/var/run/netns/demo` so the namespace persists past the calling process. That bind mount is what lets a CNI plugin configure a namespace before any container process exists inside it.

The rest of this chapter is about getting useful interfaces into that empty namespace and getting packets to flow through them.

veth Pairs: A Cable In The Kernel

A veth pair is two virtual Ethernet devices joined back-to-back. Whatever transmits on one end is received on the other. The pair has no protocol of its own, no encapsulation, no userspace forwarder; the kernel's `veth` driver simply hands the skb from one device to the other. The man page (`veth(4)`) is two paragraphs because there is not much to say beyond "it is a cable."

That simplicity is what makes veth the workhorse of container networking. A pair created on the host can have one end moved into a namespace; once moved, packets sent from inside the namespace come out on the host end, and the host's networking stack can do whatever it likes with them — switch them through a bridge, route them, hand them to an eBPF program, send them to a userspace agent. The container side does not need to know.

Build one and watch it work, no namespaces yet:

```
sudo ip link add veth-a type veth peer name veth-b
sudo ip addr add 10.20.0.1/24 dev veth-a
sudo ip addr add 10.20.0.2/24 dev veth-b
sudo ip link set veth-a up
sudo ip link set veth-b up

# Linux's reverse-path filter normally rejects this kind of self-connected
# topology because both addresses are on the same host. Disable it for the demo.
sudo sysctl -w net.ipv4.conf.all.rp_filter=2
sudo sysctl -w net.ipv4.conf.veth-a.rp_filter=0
sudo sysctl -w net.ipv4.conf.veth-b.rp_filter=0

ping -c1 -I veth-a 10.20.0.2
# 64 bytes from 10.20.0.2: icmp_seq=1 ttl=64 time=0.04 ms
```

Both ends are on the host, both have IPs, both are up. The ping leaves on `veth-a` and is received on `veth-b`. There is no switch in between — it is a literal cable. Tear it down:

```
sudo ip link del veth-a
# deleting one end removes the pair
```

The shape of every container network attachment is the same: a veth pair with one end relocated. Move `veth-b` into a namespace and the pair becomes a wire from inside the namespace out to the host. We will do exactly that in a few sections.

Linux Bridges: A Software Switch

A bridge is a software layer-2 switch. Each device added to the bridge becomes a *port*. Frames received on one port are forwarded to the appropriate port based on the destination MAC address; the bridge learns which port a MAC lives behind by remembering the source MAC of frames it sees. Broadcasts and unknown unicasts go to every port. This is the same model the rack-mounted switch under your desk uses; the only difference is that the cables are virtual.

Build one in isolation and prove the forwarding works:

```
# A bridge with two veth pairs plugged into it.
sudo ip link add br-demo type bridge
sudo ip link set br-demo up

sudo ip link add veth1a type veth peer name veth1b
sudo ip link add veth2a type veth peer name veth2b

# Plug the "a" ends into the bridge.
sudo ip link set veth1a master br-demo
sudo ip link set veth2a master br-demo
sudo ip link set veth1a up
sudo ip link set veth2a up
```

`master br-demo` enslaves the device to the bridge — the kernel installs a receive handler on the device that hands incoming frames to the bridge's forwarding logic. From here, any frame arriving on `veth1a` will be sent out `veth2a` if the destination MAC is on the other side, and broadcasts will go out both. Configure the "b" ends with addresses on the same subnet, bring them up, and the two ends can talk to each other through the bridge:

```
sudo ip addr add 10.30.0.1/24 dev veth1b
sudo ip addr add 10.30.0.2/24 dev veth2b
sudo ip link set veth1b up
sudo ip link set veth2b up

ping -c1 -I veth1b 10.30.0.2
# 64 bytes from 10.30.0.2: icmp_seq=1 ttl=64 time=0.05 ms
```

Watch the bridge learn:

```
bridge fdb show br br-demo
# <mac of veth1a>  dev veth1a master br-demo permanent
# <mac of veth2a>  dev veth2a master br-demo permanent
# <mac of veth1b>  dev veth1a master br-demo
# <mac of veth2b>  dev veth2a master br-demo
```

The first two entries are permanent — the bridge ports' own MACs. The last two are learned dynamically: when `veth1b` sent its ARP request through the bridge, the bridge saw the source MAC arrive on port `veth1a` and remembered it. The same thing a hardware switch does, in a kernel module. Tear it down:

```
sudo ip link del br-demo
sudo ip link del veth1a
sudo ip link del veth2a
```

Three things to internalize before we start adding namespaces. A bridge does not assign IPs to ports; the *devices* hold IPs, and the bridge forwards Ethernet frames between them. A bridge can itself hold an IP — `ip addr add 10.30.0.254/24 dev br-demo` — which makes the bridge a layer-3 entity for its subnet, the role it plays as the gateway in a container network. And a bridge does not by itself reach the outside world: forwarding decisions to anywhere outside the bridge subnet require routes and, usually, NAT.

Composing The Primitives: A Two-Container Network

Now compose. The pattern is one bridge in the host namespace, one veth pair per container with the host end on the bridge and the container end inside the container's network namespace, addresses on the namespaced ends, and a default route via the bridge's gateway IP. That is the shape every CNI bridge plugin produces.

Two namespaces, two veth pairs, one bridge:

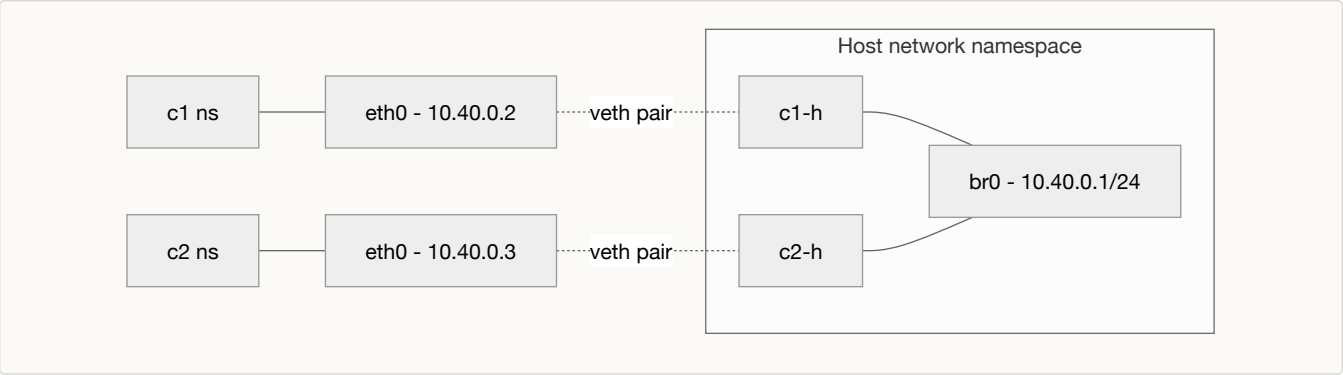
```
# Bridge with a gateway IP for the container subnet.
sudo ip link add br0 type bridge
sudo ip addr add 10.40.0.1/24 dev br0
sudo ip link set br0 up

# Container namespaces.
sudo ip netns add c1
sudo ip netns add c2

# A veth pair per container. The "h" end stays on the host bridge;
# the "c" end goes into the container namespace and is renamed to eth0
# so the container sees a familiar interface name.
sudo ip link add c1-h type veth peer name c1-c
sudo ip link add c2-h type veth peer name c2-c

sudo ip link set c1-h master br0
sudo ip link set c2-h master br0
sudo ip link set c1-h up
sudo ip link set c2-h up

sudo ip link set c1-c netns c1
sudo ip link set c2-c netns c2
sudo ip -n c1 link set c1-c name eth0
sudo ip -n c2 link set c2-c name eth0

# Configure the namespaced ends.
sudo ip -n c1 addr add 10.40.0.2/24 dev eth0
sudo ip -n c2 addr add 10.40.0.3/24 dev eth0
sudo ip -n c1 link set lo up
sudo ip -n c2 link set lo up
sudo ip -n c1 link set eth0 up
sudo ip -n c2 link set eth0 up

# Default route via the bridge gateway.
sudo ip -n c1 route add default via 10.40.0.1
sudo ip -n c2 route add default via 10.40.0.1
```

Verify the two "containers" can reach each other and the gateway:

```
sudo ip netns exec c1 ping -c1 10.40.0.3
# 64 bytes from 10.40.0.3: icmp_seq=1 ttl=64 time=0.06 ms
sudo ip netns exec c1 ping -c1 10.40.0.1
# 64 bytes from 10.40.0.1: icmp_seq=1 ttl=64 time=0.05 ms
```

Trace what just happened. From inside `c1`, the kernel selected `eth0` as the output device based on the route to `10.40.0.0/24`, did neighbor resolution for `10.40.0.3`, and transmitted the frame on `eth0` (the namespaced end of `c1`'s veth pair). The pair delivered the frame to `c1-h` on the host. `c1-h` is a port on `br0`, so the bridge's forwarding logic ran: looked up the destination MAC, found it on port `c2-h`, transmitted the frame there. The pair delivered it to `eth0` inside `c2`. The namespace, the veth, and the bridge each did exactly the job their man page promises, and together they implement container networking.

This is the topology:



Routes, Forwarding, And Masquerade

The two-container setup so far reaches itself but cannot reach the outside world. Three changes are needed. The host needs to forward packets between interfaces (off by default for safety). The container subnet needs to be NATed at the host's egress interface, because no router upstream of the host knows how to reach `10.40.0.0/24`. And the host needs return-path routing for any traffic heading back to that subnet.

```
sudo sysctl -w net.ipv4.ip_forward=1
sudo iptables -t nat -A POSTROUTING -s 10.40.0.0/24 ! -o br0 -j MASQUERADE

sudo ip netns exec c1 ping -c1 1.1.1.1
# 64 bytes from 1.1.1.1: icmp_seq=1 ttl=57 time=8.3 ms
```

That is **masquerade**: as packets leave the host on its real upstream interface, iptables rewrites their source address to the host's address, and the reply comes back to the host where the conntrack table recognizes it and rewrites the destination back to the container's address. The container has external connectivity without anyone outside knowing the container subnet exists.

Two things this hides that show up at scale. Masquerade defeats source-based policy upstream — every container looks like the host. And the conntrack table is finite: at very high connection rates, container-to-external traffic can exhaust it. Kubernetes' cluster networking promises pod-to-pod *without* NAT precisely to avoid these problems within the cluster; pod-to-external still typically uses some form of NAT or proxy.

CNI Plugins Do Exactly This

A CNI ADD invocation against the bridge plugin produces the same shape we just built by hand. The runtime hands the plugin a path to the container's network namespace; the plugin creates a veth pair, moves one end into that namespace path, attaches the other end to a configured bridge, calls the IPAM plugin to allocate an address, configures the address and a default route inside the namespace, and optionally installs a masquerade rule. The plugin returns JSON describing what it did. Chapter 15 walks the contract; the takeaway here is that the kernel work is what we have already done, and the plugin is mostly orchestration around `ip link add type veth` and friends.

When the container exits, the runtime calls CNI DEL. The plugin reverses the operations: deletes the veth pair (which destroys both ends), releases the IP back to IPAM, and removes any masquerade rule it owns. Because the namespace itself is owned by the runtime, the plugin does not delete it; the runtime tears down the namespace when the container's last process exits.

Cleanup

Tear down the demo before moving on:

```
sudo iptables -t nat -D POSTROUTING -s 10.40.0.0/24 ! -o br0 -j MASQUERADE
sudo ip netns del c1
sudo ip netns del c2
sudo ip link del br0
# veth pairs were owned by the namespaces; deleting the namespaces
# removed them, except for any host-side ends still on the bridge,
# which are removed when the bridge is deleted.
```

DNS Is A Separate Problem

A network namespace gives a process its own network stack. It does not give it its own resolver. DNS in a container comes from `/etc/resolv.conf` inside the container's mount namespace — a regular file, written by the runtime. Kubernetes layers cluster DNS on top of that: kubelet writes `/etc/resolv.conf` to point at the cluster DNS service IP, and the cluster DNS add-on (CoreDNS) answers lookups for services and pods. The CNI plugin can return DNS information in its result, but that does not, by itself, configure resolution; the runtime has to act on it.

Where This Goes

The next chapter covers the CNI contract in detail — how the runtime invokes plugins, what each plugin field means, and how chains compose. Chapter 16 then covers the Kubernetes pod networking model: how the kubelet uses CNI, how pod IPs are allocated, and what the cluster's reachability promises are.

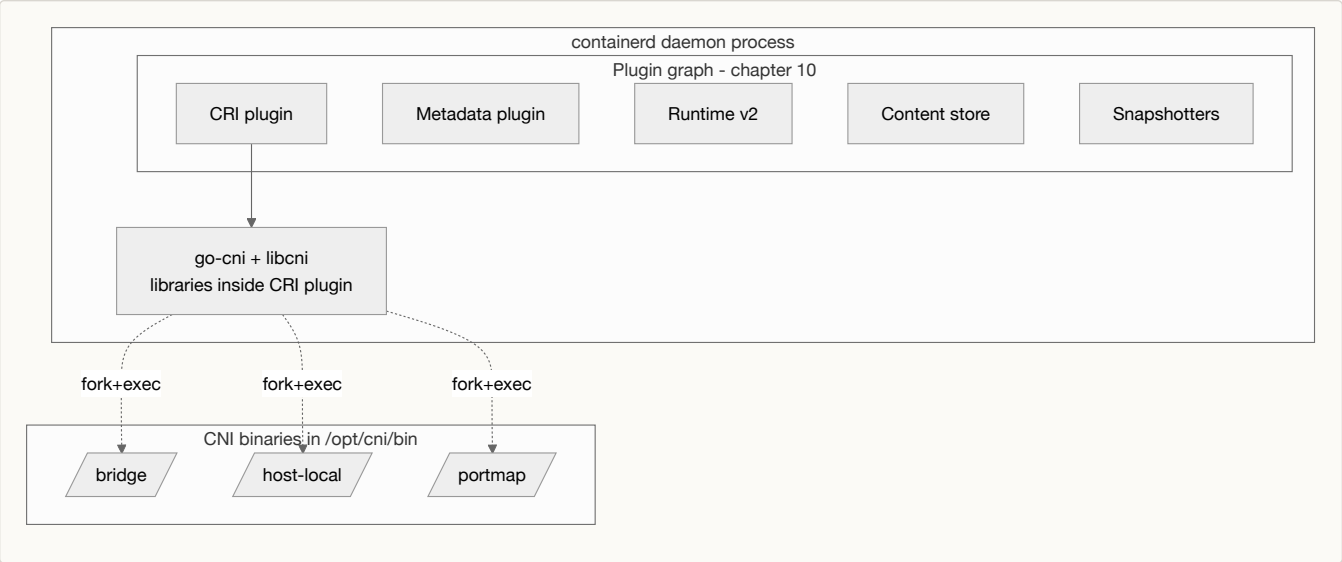
Sources And Further Reading

- `network_namespaces(7)`: https://man7.org/linux/man-pages/man7/network_namespaces.7.html
- `veth(4)`: https://man7.org/linux/man-pages/man4/veth.4.html
- `ip-netns(8)`: https://man7.org/linux/man-pages/man8/ip-netns.8.html
- `ip-link(8)`: https://man7.org/linux/man-pages/man8/ip-link.8.html
- `bridge(8)`: https://man7.org/linux/man-pages/man8/bridge.8.html
- `arp(7)`: https://man7.org/linux/man-pages/man7/arp.7.html
- `rtnetlink(7)`: https://man7.org/linux/man-pages/man7/rtnetlink.7.html
- Linux kernel veth driver: https://github.com/torvalds/linux/blob/master/drivers/net/veth.c
- Linux kernel bridge code: https://github.com/torvalds/linux/tree/master/net/bridge
- Linux kernel network namespace setup: https://github.com/torvalds/linux/blob/master/net/core/net_namespace.c
- Linux kernel `struct net`: https://github.com/torvalds/linux/blob/master/include/net/net_namespace.h
- CNI bridge plugin: https://github.com/containernetworking/plugins/blob/main/plugins/main/bridge/bridge.go
- Kubernetes networking model: https://kubernetes.io/docs/concepts/services-networking/

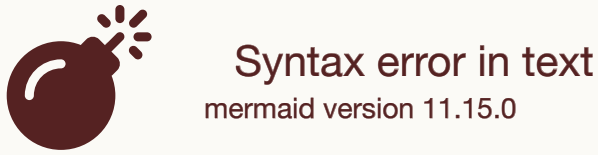
Chapter 15: CNI

When kubelet asks containerd to run a pod, containerd has to attach a network namespace to a network before any workload container starts. It does not perform that work itself. It calls a separate executable on disk — a **CNI plugin** — and lets the plugin create interfaces, allocate addresses, install routes, and report back. **CNI**, the Container Network Interface, is the protocol that makes that handoff possible.

The word "plugin" is overloaded here, and it is worth pinning down before anything else. Chapter 10 described containerd as a daemon hosting a **plugin graph** — content, snapshotters, metadata, runtime v2, CRI, and the rest — where each plugin is a Go object loaded into the daemon at startup. CNI plugins are *not* part of that graph. They are external executables on disk, spawned as child processes. The connection point between the two worlds is the **CRI plugin** inside containerd: when kubelet asks it for a pod sandbox, it uses the `go-cni` library (which wraps the upstream `libcni`) to find and `fork+exec` CNI plugin binaries from `/opt/cni/bin`.



That is the static picture: CNI plugins live outside containerd, and one branch of the CRI plugin reaches them. The dynamic picture — what happens at runtime, in what order, with what data — is this:



Five components, three of them on the containerd side and two of them plugin binaries. **containerd CRI** is the call site — it received `RunPodSandbox` from kubelet, created the network namespace as a bind-mounted file under `/var/run/netns/`, and now needs that namespace populated with an interface, an IP, and routes. **go-cni** is containerd's adapter, a small library in containerd's own repository that wraps libcni behind an interface shaped for the sandbox lifecycle: `Setup`, `Remove`, `Check`. **libcni** is the upstream CNI library from `containernetworking/cni`. It owns plugin discovery, configuration parsing, the invocation protocol, result caching, and GC. The **plugin binaries** are independent programs in `/opt/cni/bin`, none of them linked into containerd.

Plugin binaries come in three roles, distinguished by where they sit in a chain. **Main plugins** like `bridge`, `ipvlan`, and `macvlan` are first in the chain and create the attachment from nothing — they receive an empty namespace and populate it with an interface. **IPAM plugins** like `host-local` and `dhcp` are invoked recursively by a main plugin, not by the runtime; they own address allocation and nothing else. **Decorator plugins** like `portmap` and `bandwidth` come after the main plugin in the chain, read the

upstream plugin's result, and add behavior around the existing attachment without creating one of their own. The diagram shows one of each main–IPAM pair: bridge is the main plugin and host-local is its IPAM. A chain that also included portmap would run it as a third step after bridge returned.

The data crossing each boundary is small. Between go-cni and libcni it is a single Go function call:

```
r, err := n.cni.AddNetworkList(ctx, n.config, ns.config(n.ifName))
```

`n.config` is the parsed `.conflist`; `ns.config(n.ifName)` packages the sandbox ID, the netns path, and the interface name into the runtime arguments libcni expects; the return value is the CNI result containerd CRI caches on the sandbox. Between libcni and a plugin binary the boundary widens into a UNIX process invocation: a handful of environment variables for the per-call arguments, JSON on stdin for the configuration body, JSON on stdout for the result, and an exit code for success or failure. The bridge plugin in the diagram is itself a CNI runtime to the host-local plugin — it re-invokes the same protocol against the address allocator named in its `ipam` block. Delegation is recursion, not a separate mechanism.

CNI itself is small. It defines three things and stops. A **configuration schema** says what JSON the runtime hands the plugin. An **invocation protocol** says how the runtime starts the plugin and what it puts in the environment. A **result schema** says what the plugin writes back on stdout. The shape of the data path — bridge, overlay, eBPF, cloud routes — is whatever the plugin chooses; CNI does not care. That separation is what lets `containerd`, CRI-O, and any other runtime ship against dozens of network implementations without linking any of them in.

The rest of this chapter walks each piece of the protocol in turn — config, invocation, operations, chains — and ties the bridge plugin back to the hand-rolled network from chapter 14.

> ***Version pin:*** *this chapter tracks* `containernetworking/cni` `v1.3.0`, `containernetworking/plugins` `v1.9.1`, *and* `containerd/go-cni` `v1.1.13`, *which together implement CNI spec* `1.1.0`. *The spec version and the library tags move independently.*

What A CNI Configuration Looks Like

A CNI configuration describes a *network*: a name, plus an ordered chain of plugins that act on every attachment to that name. The runtime does not learn about networks from code — it reads configurations off disk, indexes them by name, and walks the matching chain when something asks to attach a namespace. Multiple networks can coexist on the same node; nothing in the protocol forces a one-to-one mapping between runtimes and networks. The configuration is the deployment contract: change the file and you change the network shape without rebuilding the runtime.

The file lives under `/etc/cni/net.d`, named `*.conflist` for a chain or `*.conf` for a single plugin. A typical containerd-on-Kubernetes node has one `.conflist` and no other CNI files.

A representative bridge-and-portmap chain:

```
{
  "cniVersion": "1.0.0",
  "name": "k8s-pod-network",
  "plugins": [
    {
      "type": "bridge",
      "bridge": "cni0",
      "isGateway": true,
      "ipMasq": true,
      "ipam": { "type": "host-local", "subnet": "10.244.0.0/16" }
    },
    {
      "type": "portmap",
      "capabilities": { "portMappings": true }
    }
  ]
}
```

The list-level fields are small. `cniVersion` is the spec version the runtime should obey when walking this list. `name` identifies the network — multiple `.conflist` files can coexist, and the runtime picks by name. `plugins` is the ordered chain. `disableCheck` and `disableGC` opt the list out of those maintenance operations; the optional `cniVersions` array advertises additional versions the chain supports.

Inside each plugin object, `type` is the binary name. The runtime resolves it against `CNI_PATH` (usually `/opt/cni/bin`) and executes whatever it finds. Every other field is the plugin's business: `bridge` and `isGateway` mean something to the bridge plugin and nothing to portmap; `ipam` is a nested config that the main plugin will delegate to another binary; `capabilities` is the plugin's request for runtime-supplied data such as port mappings or bandwidth limits. The spec calls out a few well-known keys — `ipMasq`, `ipam`, `dns`, `capabilities` — but they are conventions, not required fields.

The word "container" in the spec is broader than the Linux sense. It means *a network isolation domain being attached to a network*. On Linux that is a network namespace path, but CNI is not Linux-only and the protocol is not pinned to namespaces.

Invocation: Environment In, JSON Out

CNI's invocation protocol is the shape a CGI handler would have if you took it out of HTTP. The runtime treats the plugin as an opaque executable and reaches it through exactly the surfaces every process already has: environment variables for the per-call arguments, stdin for the configuration body, stdout for the structured reply, exit code for success or failure. Nothing else crosses the boundary — no shared memory, no library linkage, no language requirement, no version negotiation outside the JSON itself.

That choice is what makes CNI portable. A plugin can be written in any language. It can run in a different security context than the runtime, because it is a fresh process. It can be replaced on disk without restarting anything that does not have a call in flight. And the protocol can be reproduced by hand: print the environment, capture the stdin, run the binary in a shell.

libcni packs the call into environment variables:

```
"CNI_COMMAND="+args.Command,
"CNI_NETNS="+args.NetNS,
"CNI_IFNAME="+args.IfName,
```

The full set is `CNI_COMMAND` (the verb), `CNI_CONTAINERID` (the runtime's opaque ID for the attachment), `CNI_NETNS` (a path the plugin can `setns(2)` into, or omit for non-Linux), `CNI_IFNAME` (the interface name the plugin should create inside the namespace), `CNI_ARGS` (a `;`-separated bag the runtime can use for free-form labels), and `CNI_PATH` (where to find further plugin binaries, since IPAM delegation re-invokes this same protocol).

After the binary exits, libcni decodes the bytes against the requested result version:

```
stdoutBytes, err := exec.ExecPlugin(ctx, pluginPath, netconf, args.AsEnv())
return create.Create(resultVersion, fixedBytes)
```

The result is a structured object — interfaces, IPs, routes, DNS — versioned so that an older runtime can still consume output produced by a newer plugin. Errors are structured CNI error objects, not free-form text on stderr; that is what lets a runtime distinguish "plugin not found" from "IPAM exhausted."

This is why a CNI plugin does not have to be linked into containerd, kubelet, or any runtime. It has to be executable, discoverable, and able to speak environment variables plus JSON.

Operations And Ownership

Every CNI verb is one half of a state-ownership pair. The plugin can create kernel state — interfaces, addresses, routes, firewall rules, IPAM files — but the runtime is the only thing that knows when a namespace has gone away, when the configured chain has changed, or when a cached attachment no longer corresponds to any live pod. The verbs exist so the runtime can tell the plugin which of those things just happened, and the plugin can do the matching mutation. `ADD` and `DEL` are the obvious pair; `CHECK`, `STATUS`, and `GC` are there because real systems drift and the cache is not always right.

The verbs are sent in `CNI_COMMAND`:

Operation	Purpose
`ADD`	Attach the namespace to the network. Creates interfaces, addresses, routes, firewall rules.
`DEL`	Detach. Removes whatever `ADD` created — including the IPAM allocation.
`CHECK`	Verify the attachment described by the cached result still exists.
`STATUS`	Report whether the plugin is currently able to service requests.
`VERSION`	Report supported CNI versions.
`GC`	Drop attachments that the runtime no longer considers valid.

`ADD` is the easy path to understand because it creates visible state. `DEL` matters just as much: a host veth, a masquerade rule, and an IPAM allocation outlive the process that asked for them unless something removes them, and the runtime has no way to know what the plugin created beyond what came back in the result. The IPAM allocation is the one that bites first — chapter 14's `host-local` plugin writes a file per address, and a missed `DEL` leaves that file on disk forever.

`CHECK` exists because the kernel state can drift. A daemon restart, a manual `ip link del`, a node reboot — any of these can leave a cached attachment that no longer matches reality. `GC` is the broader form: libcni reads cached attachments, compares them against a runtime-supplied list of attachments that *should* still exist, calls `DEL` on the stragglers, and (for spec `1.1.0` and later) issues a plugin-level `GC` so plugins can clean state the per-attachment cache does not name.

Chains And Reverse-Order Delete

A configuration list is a pipeline. The first plugin creates an attachment; each later plugin reads the cumulative result so far, mutates whatever it intends to mutate, and returns an updated result. By the end of the chain the result describes the union of every plugin's work, and the kernel state matches. The pipeline is the protocol's answer to "how do unrelated plugins compose without knowing about each other" — they communicate by passing a result object down the chain, and the runtime never has to know what any individual plugin does.

Order matters in *both directions*. Creation has to go front-to-back so decorators see something to decorate: a port-forwarding rule needs an allocated IP to point at, and a traffic shaper needs an interface to attach to. Deletion has to go back-to-front so decorators clean up before the thing they decorated disappears — otherwise you have iptables rules pointing at an IP that has already been re-allocated to a different pod.

On `ADD`, libcni walks the chain in order, passing each plugin's result into the next:

```
result, err = c.addNetwork(ctx, list.Name, list.CNIVersion, net, result, rt)
```

The first plugin attaches the namespace and returns a result describing what it created. The second plugin reads that result through the `prevResult` field of its own stdin config, decorates it, and returns a new result. The third does the same. By the end of the chain the result describes the union of every plugin's contribution.

On `DEL`, libcni walks the same list in reverse:

```
for i := len(list.Plugins) - 1; i >= 0; i-- {
    net := list.Plugins[i]
```

Reverse-order delete makes ownership the protocol's responsibility rather than the plugin author's. A decorator does not have to defensively check whether the upstream attachment still exists — it can trust that it is being called first.

From spec `1.1.0` onward, libcni passes the cached `ADD` result into the `DEL` call, so a plugin tearing down its own state has the same view it had during creation. Older plugins that ran `DEL` blind — knowing only the container ID — had to recompute their state from whatever they could probe on the host, which is exactly the kind of thing that goes wrong on a partial failure.

The Bridge Plugin Is Chapter 14 In A Binary

The `bridge` plugin is the canonical main plugin and the one whose source is worth reading first, because every other main plugin follows the same shape. Its `ADD` performs the same `ip link` / `ip addr` / `ip route` / `iptables` sequence chapter 14 wrote out by hand, packaged as a binary that consumes JSON instead of taking shell arguments: create or reuse a Linux bridge, create a veth pair with one end in the namespace given by `CNI_NETNS`, call IPAM, configure the address on the namespaced end, set a default route through the bridge gateway, and — if `ipMasq` is set — install a POSTROUTING masquerade rule for the allocated subnet.

Two lines in the source show the split:

```
hostInterface, containerInterface, err := setupVeth(...)
r, err := ipam.ExecAdd(n.IPAM.Type, args.StdinData)
```

`setupVeth` does the namespace work. It opens the network namespace from the path in `CNI_NETNS`, creates the veth pair *inside* the namespace (so the container end never appears in the host namespace, even briefly), moves the host end back out by name, and attaches it as a port on the configured bridge. The host end keeps the name the plugin chose; the namespaced end is renamed to whatever `CNI_IFNAME` said — `eth0`, for pods.

`ipam.ExecAdd` is the second half, and it is the protocol's defining trick: a plugin can be a CNI runtime to another plugin. The bridge plugin does not allocate addresses. It treats the `type` field inside its `ipam` block as another plugin binary name and re-invokes the CNI protocol — same environment variables, same stdin/stdout shape — against that binary, passing the IPAM sub-config as stdin. The IPAM plugin has no idea it is nested; it sees the same call shape a top-level runtime would have made. The IPs and routes come back through stdout, and the bridge plugin applies them to the namespaced interface before returning the merged result up to libcni.

Delegation is recursion, not a separate concept. That is how CNI keeps the protocol surface small: every problem that looks like "ask another component to do part of this" is solved by another CNI invocation.

IPAM Is A Separate Binary

IP address management is its own problem, and the spec keeps it at arm's length from the main plugin for two reasons. The address-allocation logic — pick from a range, persist the assignment, release on teardown — has nothing to do with bridges, overlays, or any data path; bundling it into every main plugin would mean re-implementing the same allocator. And different

deployments need different allocators: a static range on a developer host, a coordinated DHCP server on a bare-metal network, a cloud provider's IPAM API in a managed environment. The recursion-as-delegation pattern lets all three share the same main plugins.

The `host-local` IPAM plugin is the simplest one shipped. It reads a range from its config, picks the next free address, writes a file per allocation under `/var/lib/cni/networks/<network>/`, and returns the address and any routes the config asked for.

```
ipConf, err := allocator.Get(args.ContainerID, args.IfName, requestedIP)
```

The on-disk state is why `DEL` matters. `host-local` releases an allocation by deleting the file named after the container ID. Skip the `DEL` — because the runtime crashed, because the plugin returned an error, because the user `rm -rf`'d the wrong directory — and the file stays. Later pods then fail to allocate from a range that the file system says is full, even after every visible process has exited. Production failures from "IPAM exhausted" are almost always state files for containers that no longer exist.

The `dhcp` IPAM plugin is the other shape worth knowing about. It runs as a long-lived daemon, holds DHCP leases on behalf of CNI invocations, and answers `ADD` / `DEL` from a Unix socket. Lease renewal happens out of band; the plugin lifecycle exists to keep the daemon's state coherent with the runtime's attachment set.

Decorators: portmap And Chained Plugins

Decorators install kernel state that is only meaningful in the presence of state from an earlier plugin: a port-forwarding rule that targets an allocated IP, a traffic shaper that targets a created interface, an iptables rule that names an interface the main plugin produced. They read the upstream plugin's result through `prevResult` on stdin, optionally combine it with capability data the runtime supplied out of band, and install additional kernel state. The main plugin upstream knows nothing about the decorator; the decorator's contract is with the runtime, not with the plugin it follows. That is what lets one bridge plugin be paired with any combination of portmap, bandwidth, tuning, or third-party decorators without modification.

`portmap` is the textbook decorator. It expects a previous plugin to have produced an interface and an IP, reads `portMappings` from the runtime's capability data, and installs host port forwarding rules through an iptables or nftables backend that target the IP it read out of the previous result.

Its guard is blunt:

```
if netConf.PrevResult == nil {
    return fmt.Errorf("must be called as chained plugin")
}
```

Two things follow from that one check. CNI plugins are not equal peers — they have positional roles. The plugin that creates the interface has to come first, decorators come after, and a config that gets the order wrong is a configuration error rather than a runtime error. And `prevResult` is part of the protocol surface, not an internal detail: a third-party plugin that wants to act on the same attachment reads it from stdin and uses the IPs the upstream plugin reported.

The capability handshake is the other half. `portmap`'s config block declares `"capabilities": {"portMappings": true}`, and the runtime is expected to fill in `runtimeConfig.portMappings` from out-of-band data — for Kubernetes, the pod spec. The plugin reads its own static config plus the runtime-supplied capabilities and produces rules. Bandwidth shaping (`bandwidth`), traffic-control sysctls (`tuning`), and source-based routing (`sbr`) work the same way.

What CNI Does Not Promise

CNI is a process protocol, not a network model. It does not promise that every pod can reach every other pod, that pod IPs are routable off the node, that policies are enforced, that addresses survive a node reboot, or that the data path uses any particular technology. Kubernetes defines the *pod networking model*, plugins implement it with different data paths, and the operator picks a plugin whose promises match the workload.

CNI also does not make plugin execution safe to run casually on a developer host. A real `ADD` mutates kernel interfaces, routes, firewall state, and on-disk IPAM. The previous chapter's hand-rolled topology is reproducible because every command was visible; running an unknown plugin against `/var/run/netns/foo` is not. Part VI puts plugin invocation into a disposable VM, which is where it belongs.

Where This Goes

The next chapter walks the runtime side: how kubelet, containerd CRI, and `go-cni` cooperate to produce the namespace path that this chapter assumed already existed, and how the workload containers in a pod join the namespace the sandbox owns.

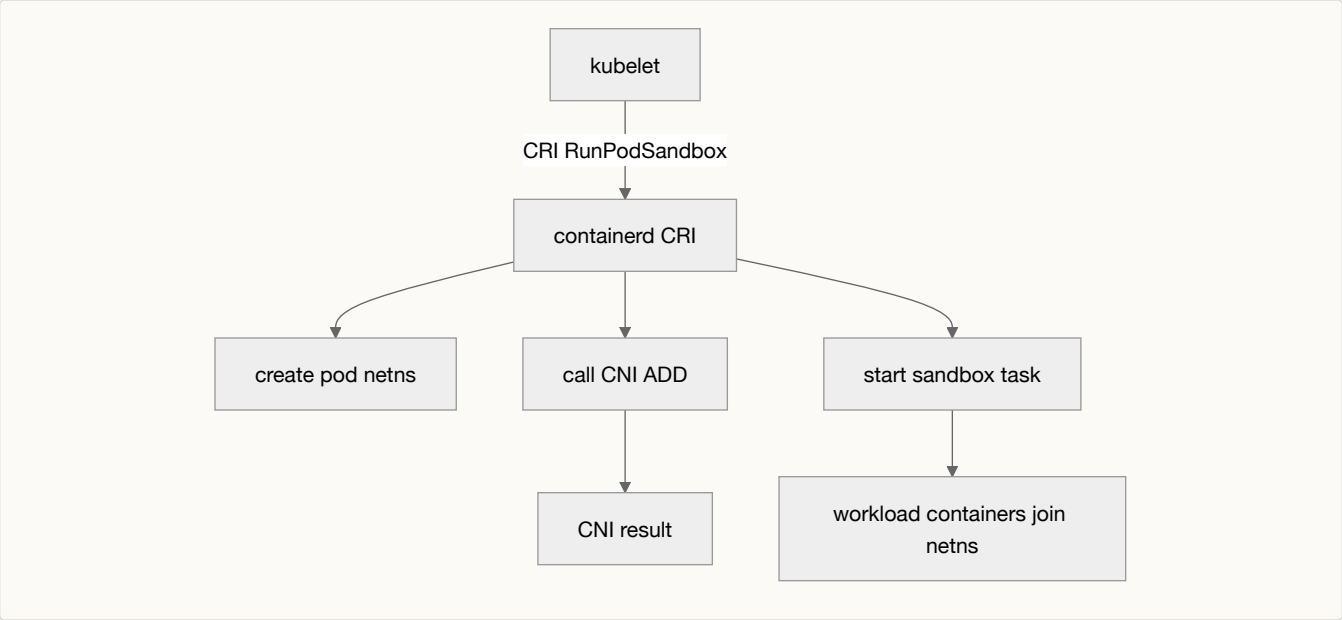
Sources And Further Reading

- CNI specification: https://github.com/containernetworking/cni/blob/v1.3.0/SPEC.md
- CNI docs site: https://www.cni.dev/docs/spec/
- libcni API: https://github.com/containernetworking/cni/blob/v1.3.0/libcni/api.go
- libcni invoke args: https://github.com/containernetworking/cni/blob/v1.3.0/pkg/invoke/args.go
- libcni plugin execution: https://github.com/containernetworking/cni/blob/v1.3.0/pkg/invoke/exec.go
- CNI bridge plugin: https://github.com/containernetworking/plugins/blob/v1.9.1/plugins/main/bridge/bridge.go
- host-local IPAM plugin: https://github.com/containernetworking/plugins/blob/v1.9.1/plugins/ipam/host-local/main.go
- dhcp IPAM plugin: https://github.com/containernetworking/plugins/blob/v1.9.1/plugins/ipam/dhcp/main.go
- portmap plugin: https://github.com/containernetworking/plugins/blob/v1.9.1/plugins/meta/portmap/main.go
- containerd `go.mod`: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/go.mod
- containerd `go-cni`: https://github.com/containerd/go-cni/tree/v1.1.13

Chapter 16: Pod Networking Model

Kubernetes promises pod networking, not "a CNI network." Each pod gets an IP address. Containers in the same pod share the pod's network namespace and port space. Pods can communicate with pods on other nodes without NAT at the Kubernetes layer, and node agents can communicate with pods on their node.

A plugin can satisfy that model with bridges and routes, overlays, eBPF, cloud provider routes, direct device attachment, or a mix of those techniques. In the containerd path, kubelet does not run the plugin itself. kubelet calls CRI, containerd CRI creates or receives the pod sandbox network namespace, and containerd invokes CNI for that namespace.



The pod IP belongs to the shared pod network namespace. It is not assigned independently to each workload container.

The Kubernetes Contract

The Kubernetes networking model has three details that shape runtime behavior. Pods on a node can communicate with all pods on all nodes without NAT at the Kubernetes layer. Agents on a node, such as kubelet or system daemons, can communicate with pods on that node. Containers in one pod share the pod IP and port space because they share one network namespace.

NetworkPolicy sits beside that model rather than inside CNI core. Kubernetes defines the policy API, but enforcement is plugin-specific. A bridge-only local setup, an eBPF plugin, and a cloud CNI can all attach namespaces through CNI while providing very different policy behavior.

RunPodSandbox Creates The Namespace

In containerd `v2.3.0`, the CRI path handles networking inside `RunPodSandbox`. If the pod requests host networking, CRI skips pod network namespace creation. Otherwise it creates a namespace mount, stores the path in sandbox metadata, and passes that path into network setup.

The source path is:

```
sandbox.NetNS, err = netns.NewNetNS(netnsMountDir)
sandbox.NetNSPath = sandbox.NetNS.GetPath()
```

When pod-level user namespaces are enabled, containerd has to create the network namespace after entering the user namespace context. The Linux helper path uses `CLONE_NEWNET` and then mounts the namespace from the helper process PID:

```
syscall.CLONE_NEWNET,
netns.NewNetNSFromPID(netnsMountDir, uint32(pid))
```

User namespaces change ownership and capability rules around namespace creation, so the runtime has to create the network namespace inside the right user-namespace context before CNI runs against it.

CRI Calls CNI

After namespace creation, containerd CRI calls `setupPodNetwork`. That function chooses the CNI plugin set for the runtime handler, prepares Kubernetes labels and runtime capabilities, calls the selected network plugin, and stores the result on the sandbox:

```
result, err = netPlugin.Setup(ctx, id, path, opts...)
sandbox.CNIResult = result
```

The `id` is the sandbox ID. The `path` is the pod network namespace path. The options carry Kubernetes metadata and runtime data that plugins may need. Labels include pod namespace, pod name, pod UID, and the sandbox container ID:

```
"K8S_POD_NAMESPACE": config.GetMetadata().GetNamespace(),
"K8S_POD_INFRA_CONTAINER_ID": id,
```

Capabilities can include annotations, port mappings, bandwidth, DNS, and cgroup path. A plugin can ignore unsupported fields, but a chained plugin such as `portmap` depends on runtime-provided capability data to install host-port rules.

containerd can also select CNI configuration by runtime handler. During Linux service initialization, it builds `go-cni` instances with plugin configuration directories and binary directories:

```
cni.WithPluginConfDir(dir),
cni.WithPluginDir(c.config.NetworkPluginBinDirs)
```

That gives operators a way to pair a Kubernetes runtime class or handler with a particular network configuration.

The Sandbox Still Starts

CNI setup does not replace the pod sandbox task. After networking is configured, the default pod sandbox controller still prepares a sandbox container from the pause image. It builds an OCI spec, prepares a snapshot, creates a containerd container, creates a task with null IO, starts it, records the PID, and marks the sandbox ready.

The sandbox process is the stable namespace anchor for the pod: the network namespace was created before CNI ran, and the sandbox task keeps the pod's namespaces alive for workload containers that start later.

The pause process is one piece of the sandbox. The rest is CRI metadata, the network namespace path, the CNI result, labels, runtime endpoint data, and monitor state, all of which containerd needs to answer kubelet later.

Workload Containers Join The Namespace

When kubelet asks CRI to create a workload container, the request names a pod sandbox. containerd looks up that sandbox, reads the sandbox PID and network namespace path, and builds the workload's OCI spec so it joins the pod namespaces.

The spec option that does the work is `WithPodNamespaces`. For the network namespace, it writes an OCI Linux namespace entry that points at the sandbox process namespace:

```
oci.WithLinuxNamespace(runtimespec.LinuxNamespace{
    Type: runtimespec.NetworkNamespace,
    Path: GetNetworkNamespace(sandboxPid),
})
```

The same option joins IPC and UTS namespaces and handles pod-level user namespace settings. The workload process does not get a new network stack: it joins the pod sandbox's network namespace, sees the pod interfaces and routes, and shares the port space with the other containers in the pod.

That is why two containers in one pod can collide on a TCP port even when they have different root filesystems and processes. Their network namespace is the same object.

DNS And Pod Files

Pod DNS is configured around the network setup, not by it. Kubernetes defines DNS behavior for Services and Pods, and containerd mounts sandbox `/etc/hosts`, hostname, and `/etc/resolv.conf` files into workload containers when those files exist or are delegated to a sandbox controller.

CNI can return DNS fields, and plugins can participate in resolver configuration. But the resolver file a process reads, the search domains Kubernetes chooses, and the records served by the cluster DNS add-on are not created by `CLONE_NEWNET`. A working pod network needs both sides: an attached namespace and the pod files that make names resolve the way Kubernetes promises.

Cleanup

Teardown follows the ownership chain in reverse. CRI owns sandbox lifecycle state. CNI `DEL` removes the network attachment. libcni deletes chained plugins in reverse order, which lets decorators such as port mapping clean their rules before the base interface disappears. The runtime can then remove the sandbox network namespace after network teardown has run.

Cleanup is where partial failures matter. A failed `ADD` can leave an IPAM allocation, a host-side veth, or a firewall rule. A failed `DEL` can make the next pod fail for reasons that look unrelated.

Where This Goes

Part VI turns these relationships into experiments inside a disposable VM.

Sources And Further Reading

- Kubernetes networking model: https://kubernetes.io/docs/concepts/services-networking/
- Kubernetes Pods: https://kubernetes.io/docs/concepts/workloads/pods/
- Kubernetes DNS for Services and Pods: https://kubernetes.io/docs/concepts/services-networking/dns-pod-service/
- containerd CRI sandbox run path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/sandbox_r
- containerd CRI Linux sandbox network namespace helper: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/sandbox_r
- containerd CRI CNI initialization: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/service_lin
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- containerd CRI container create path: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/server/container_
- containerd CRI pod namespace spec opts: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/internal/cri/opts/spec_opts.go

- containerd `go-cni` : https://github.com/containerd/go-cni/tree/v1.1.13

PART VI — EXPERIMENTS

Chapter 17: Lab Safety And Shape

A command that creates a namespace, writes a cgroup file, adds a veth pair, or starts `containerd-shim-runc-v2` mutates host state. Part VI runs every mutating experiment inside a disposable Linux VM.

Mounts can leak through shared propagation. cgroup files can affect real processes. A veth pair and route can change packet flow. CNI plugins can write IPAM state and firewall rules. runc and containerd create runtime directories, cgroups, namespaces, mounts, and processes.

Safety Classes

The experiments use three safety classes.

Class	Meaning	Examples
Inspect-only	Reads state without changing it.	`readlink /proc/self/ns/pid`, `findmnt`, `ctr -n lab containers ls`.
User-namespace scoped	Uses a user namespace to reduce host privilege.	`unshare --user --map-root-user` labs.
VM-only mutation	Changes kernel or runtime state.	Mounts, cgroups, veth, bridges, CNI, runc, containerd tasks.

Root inside a user namespace is not root on the host: distribution policy, kernel configuration, subordinate ID mappings, and capability rules all affect what works. Lab steps that depend on predictable behavior call out a VM.

The Lab Shape

Every mutating experiment follows the same shape:

1. State the question.
2. Name the scope.
3. Inspect the starting state.
4. Make the smallest change.
5. Inspect the changed state.
6. Clean up.
7. Verify cleanup.

An experiment that creates a namespace but never looks at `/proc/<pid>/ns` teaches an incantation. An experiment that starts a containerd task but never reads `pgrep containerd-shim-runc-v2` hides the runtime boundary.

Namespace Tools

`unshare(1)` creates new namespaces for a program. `nsenter(1)` enters namespaces that already exist. In util-linux, both tools map command-line choices to kernel namespace flags.

`unshare` carries the namespace table:

```
{ .type = CLONE_NEWNET,   .name = "ns/net"  },
{ .type = CLONE_NEWPID,   .name = "ns/pid_for_children" },
{ .type = CLONE_NEWNS,    .name = "ns/mnt"  },
```

`nsenter` carries the same idea for target namespace files:

```
{ .nstype = CLONE_NEWNET,   .name = "ns/net",  .fd = -1 },
{ .nstype = CLONE_NEWPID,   .name = "ns/pid",  .fd = -1 },
{ .nstype = CLONE_NEWNS,    .name = "ns/mnt",  .fd = -1 },
```

The header comment states the purpose:

```
 * nsenter(1) - command-line interface for setns(2)
```

`unshare(1)` and `nsenter(1)` are lab handles for the same `setns(2)` and `clone(2)` flags that runtimes use.

Persistent References

A namespace can outlive the process that first created it if something still holds a reference. A bind mount of a namespace file is one way to keep that reference. That is useful when an experiment needs two shells to inspect one namespace, but it also creates a cleanup obligation.

The cleanup step should not stop at "exit the shell." It should verify that namespace bind mounts, processes, links, routes, cgroup directories, CNI cache entries, runc state, and containerd tasks are gone.

For Part VI, the shortest useful cleanup rule is:

```
If the setup step names an object, the cleanup step names the same object.
```

Every lab object in Part VI carries a `cdb-` prefix: `cdb-net-a`, `cdb-br0`, `cdb-runc`, `cdb-task`, `cdb-lab.slice`. The prefix is what lets one `find`, `grep`, or `ip link` filter the lab's residue out of the host's existing state.

The First Check

Every lab VM should start with one inspect-only check that records the environment. The exact commands can vary by distribution, but the state being checked does not:

```
uname -a
readlink /proc/self/ns/{mnt,pid,net,user,cgroup}
findmnt -no TARGET,FSTYPE,OPTIONS /sys/fs/cgroup
ip -br link
```

That gives the reader the kernel, current namespace identities, cgroup mount type, and starting link list. If a later cleanup step fails, the lab has a baseline to compare against.

Sources And Further Reading

- `unshare(1)`: https://man7.org/linux/man-pages/man1/unshare.1.html
- `nsenter(1)`: https://man7.org/linux/man-pages/man1/nsenter.1.html
- `setns(2)`: https://man7.org/linux/man-pages/man2/setns.2.html
- `/proc/<pid>/ns`: https://man7.org/linux/man-pages/man5/proc_pid_ns.5.html
- util-linux `unshare.c`: https://github.com/util-linux/util-linux/blob/2308d4c07f74d3149d9bb127afb85ce617ecad88/sys-utils/unshare.c
- util-linux `nsenter.c`: https://github.com/util-linux/util-linux/blob/2308d4c07f74d3149d9bb127afb85ce617ecad88/sys-utils/nsenter.c

Chapter 18: Linux Primitive Experiments

These labs look at kernel objects directly: namespace links, mount table rows, cgroup files, process IDs — before any runtime appears.

These commands are sketches for a disposable Linux VM. Do not run the mutating sections on a normal workstation.

Namespace Membership

Question: what changes when a process enters new namespaces?

Scope: VM-only mutation, with an optional user-namespace variant later.

Start by recording the current namespace links:

```
readlink /proc/self/ns/{mnt,pid,uts,ipc,net,user,cgroup}
```

Then run a shell in new PID, mount, UTS, and IPC namespaces:

```
sudo unshare --fork --pid --mount --mount-proc --uts --ipc bash
```

Inside that shell, inspect the same links:

```
echo "inside pid: $$"
readlink /proc/self/ns/{mnt,pid,uts,ipc,net,user,cgroup}
ps -ef
exit
```

The PID namespace needs `--fork` because the new PID namespace applies to children. `--mount-proc` mounts a procfs view for that PID namespace, which is why `ps` becomes meaningful inside the lab shell. The network and user namespace links should not change in this exact command; the point is to see that namespaces are independent choices.

Cleanup is the shell exit. Verification is another read of the original shell's namespace links.

Entering A Target Namespace

Question: how does another process enter an existing namespace?

Scope: VM-only mutation.

In one shell, keep a namespaced process alive:

```
sudo unshare --fork --pid --mount --mount-proc --uts bash -c 'hostname cdb-lab; sleep 300'
```

In another shell, find that process and inspect its namespace links:

```
pid=$(pgrep -f "sleep 300" | head -n 1)
sudo readlink /proc/"$pid"/ns/{pid,mnt,uts}
sudo nsenter --target "$pid" --pid --mount --uts hostname
```

`nsenter(1)` is the user-space wrapper for `setns(2)`. The test is whether `/proc/$pid/ns/uts` matches the link the parent shell read; the `hostname` output is only a sanity check.

Cleanup the sleeping process:

```
sudo kill "$pid"
```

Mount Namespace

Question: does a mount namespace give a process its own mount table?

Scope: VM-only mutation.

Run a shell with a new mount namespace, then make propagation private before creating test mounts:

```
sudo unshare --mount bash
mount --make-rprivate /
mkdir -p /tmp/cdb-mnt/source /tmp/cdb-mnt/target
touch /tmp/cdb-mnt/source/inside-source
mount --bind /tmp/cdb-mnt/source /tmp/cdb-mnt/target
findmnt /tmp/cdb-mnt/target
grep /tmp/cdb-mnt /proc/self/mountinfo
umount /tmp/cdb-mnt/target
exit
```

The bind mount exists in the new mount namespace. `mount --make-rprivate /` is there because shared mount propagation can make mount experiments surprise the host.

Verify cleanup from the original shell:

```
findmnt /tmp/cdb-mnt/target || true
rm -rf /tmp/cdb-mnt
```

Root Filesystem Boundary

Question: what does a root filesystem need before a process can run inside it?

Scope: VM-only mutation.

A directory is not automatically runnable: a dynamic binary needs its loader and shared libraries, `/proc` does not exist unless mounted, device nodes do not appear unless created or mounted, and a shell does not exist unless it is in the tree.

Whichever rootfs the lab uses — a static `busybox` tarball, an exported image, an extracted layer — the inspection checkpoints are the same:

```
find rootfs -maxdepth 2 -type f -o -type l | sort
file rootfs/bin/sh
ldd rootfs/bin/sh || true
```

`rootfs/` is a directory tree, not an image or a snapshot; it can become `/` for a process once the mount namespace and root switch are set up. `pivot_root(2)` is the runtime's call (chapter 20 uses it inside an OCI bundle); `chroot(2)` is enough to demonstrate pathname resolution but does not produce container filesystem setup.

cgroup v2

Question: how does cgroup v2 attach a process to resource-control files?

Scope: VM-only mutation. On a systemd VM, prefer a delegated subtree. Do not write arbitrary cgroup files under host-managed services.

Start with inspection:

```
findmnt -no TARGET,FSTYPE,OPTIONS /sys/fs/cgroup
cat /sys/fs/cgroup/cgroup.controllers
cat /proc/self/cgroup
```

The mutating lab should create a named lab cgroup only under a subtree the lab owns. The smallest useful controller experiment is `pids.max`, because it can be observed without a benchmark:

```
sudo mkdir /sys/fs/cgroup/cdb-lab
echo $$ | sudo tee /sys/fs/cgroup/cdb-lab/cgroup.procs
cat /sys/fs/cgroup/cdb-lab/cgroup.procs
echo 20 | sudo tee /sys/fs/cgroup/cdb-lab/pids.max
cat /sys/fs/cgroup/cdb-lab/pids.current
```

Cleanup requires moving the shell back out before removing the cgroup:

```
echo $$ | sudo tee /sys/fs/cgroup/cgroup.procs
sudo rmdir /sys/fs/cgroup/cdb-lab
```

If `rmdir` fails, something still belongs to the cgroup or the hierarchy does not allow the lab to remove it.

Sources And Further Reading

- `namespaces(7)`: https://man7.org/linux/man-pages/man7/namespaces.7.html
- `unshare(1)`: https://man7.org/linux/man-pages/man1/unshare.1.html
- `nsenter(1)`: https://man7.org/linux/man-pages/man1/nsenter.1.html
- `mount_namespaces(7)`: https://man7.org/linux/man-pages/man7/mount_namespaces.7.html
- `mount(2)`: https://man7.org/linux/man-pages/man2/mount.2.html
- `pivot_root(2)`: https://man7.org/linux/man-pages/man2/pivot_root.2.html
- Linux cgroup v2 docs: https://www.kernel.org/doc/html/latest/admin-guide/cgroup-v2.html
- Linux shared subtree docs: https://github.com/torvalds/linux/blob/57b8e2d666a31fa201432d58f5fe3469a0dd83ba/Documentation/filesystems/sharedsub

Chapter 19: Networking And CNI Experiments

These labs build the Linux pieces by hand — namespaces, veth, bridges — before invoking a CNI plugin against the result.

Every command in this chapter is for a disposable Linux VM. These labs create network namespaces, veth devices, bridges, routes, and possibly firewall or CNI state.

Manual Network Namespace

Question: what does a new network namespace contain before a plugin touches it?

Scope: VM-only mutation.

Create a namespace and inspect its starting state:

```
sudo ip netns add cdb-a
sudo ip -n cdb-a -br link
sudo ip -n cdb-a route
```

Bring up loopback explicitly:

```
sudo ip -n cdb-a link set lo up
sudo ip -n cdb-a -br link
```

A new network namespace has its own link list and route table. Loopback exists, but it is not useful until it is up.

Cleanup:

```
sudo ip netns del cdb-a
ip netns list
```

veth Pair

Question: how does a namespace get a link to the outside?

Scope: VM-only mutation.

Create a namespace, create a veth pair, move one end into the namespace, and assign addresses:

```
sudo ip netns add cdb-a
sudo ip link add cdb-host type veth peer name cdb-eth0
sudo ip link set cdb-eth0 netns cdb-a
sudo ip addr add 10.200.0.1/24 dev cdb-host
sudo ip link set cdb-host up
sudo ip -n cdb-a addr add 10.200.0.2/24 dev cdb-eth0
sudo ip -n cdb-a link set cdb-eth0 up
sudo ip -n cdb-a link set lo up
```

Inspect both sides:

```
ip -br addr show cdb-host
sudo ip -n cdb-a -br addr
sudo ip -n cdb-a route
ping -c 2 10.200.0.2
sudo ip netns exec cdb-a ping -c 2 10.200.0.1
```

The veth driver stores peer pointers in both directions:

```
rcu_assign_pointer(priv->peer, peer);
rcu_assign_pointer(priv->peer, dev);
```

One kernel network device transmits to its peer.

Cleanup:

```
sudo ip netns del cdb-a
sudo ip link del cdb-host 2>/dev/null || true
```

Deleting the namespace should remove the namespace-owned veth end. The explicit `ip link del` is there so cleanup is idempotent if the host end still exists.

Bridge

Question: what changes when the host-side veth is attached to a bridge?

Scope: VM-only mutation.

Create a bridge and attach a veth host end:

```
sudo ip netns add cdb-a
sudo ip link add cdb-br0 type bridge
sudo ip addr add 10.201.0.1/24 dev cdb-br0
sudo ip link set cdb-br0 up

sudo ip link add cdb-vetha type veth peer name cdb-eth0
sudo ip link set cdb-vetha master cdb-br0
sudo ip link set cdb-vetha up
sudo ip link set cdb-eth0 netns cdb-a
sudo ip -n cdb-a addr add 10.201.0.2/24 dev cdb-eth0
sudo ip -n cdb-a link set cdb-eth0 up
sudo ip -n cdb-a link set lo up
```

Inspect the bridge relationship:

```
bridge link show
ip -br addr show cdb-br0
sudo ip -n cdb-a route
sudo ip netns exec cdb-a ping -c 2 10.201.0.1
```

Forwarding and NAT can collide with the VM's default network setup, so this lab stops at bridge attachment.

Cleanup:

```
sudo ip netns del cdb-a
sudo ip link del cdb-br0
```

CNI With cnitool

Question: what does CNI add above manual namespace wiring?

Scope: VM-only mutation.

`cnitool` runs a CNI configuration against an existing network namespace; the namespace is created by the lab first, then the plugin chain mutates it.

Use a local config and plugin directory, not the host defaults:

```
sudo mkdir -p /tmp/cdb-cni/net.d /tmp/cdb-cni/bin
sudo ip netns add cdb-cni
```

Whichever plugin the lab uses (a small `bridge` or `ptp` config), the runtime variables passed to `cnitool` are the same:

```
sudo NETCONFPATH=/tmp/cdb-cni/net.d CNI_PATH=/tmp/cdb-cni/bin cnitool add cdb-net /var/run/netns/cdb-cni
sudo NETCONFPATH=/tmp/cdb-cni/net.d CNI_PATH=/tmp/cdb-cni/bin cnitool check cdb-net /var/run/netns/cdb-cni
sudo NETCONFPATH=/tmp/cdb-cni/net.d CNI_PATH=/tmp/cdb-cni/bin cnitool del cdb-net /var/run/netns/cdb-cni
```

The experiment should inspect three things after `ADD`: the target namespace links and routes, the host-side link or bridge state, and the IPAM/cache files the plugin wrote. After `DEL`, inspect the same three places again.

Cleanup:

```
sudo ip netns del cdb-cni 2>/dev/null || true
sudo rm -rf /tmp/cdb-cni
```

DNS Boundary

Question: why can a namespace have working packets but broken names?

Scope: inspect-only or VM-only, depending on how the namespace was created.

DNS is not created by `CLONE_NEWNET`. Resolver behavior comes from files and orchestration policy. In a VM namespace lab, inspect route reachability separately from resolver configuration:

```
sudo ip -n cdb-a route
sudo ip netns exec cdb-a cat /etc/resolv.conf
```

If a lab later adds a custom resolver file, it should say exactly how the process sees that file: bind mount, chroot/rootfs content, runtime-generated pod file, or host file inherited by `ip netns exec`.

Sources And Further Reading

- `network_namespaces(7)`: https://man7.org/linux/man-pages/man7/network_namespaces.7.html
- `ip-netns(8)`: https://man7.org/linux/man-pages/man8/ip-netns.8.html
- `ip-link(8)`: https://man7.org/linux/man-pages/man8/ip-link.8.html
- `ip-address(8)`: https://man7.org/linux/man-pages/man8/ip-address.8.html
- `ip-route(8)`: https://man7.org/linux/man-pages/man8/ip-route.8.html
- `veth(4)`: https://man7.org/linux/man-pages/man4/veth.4.html
- Linux veth driver: https://github.com/torvalds/linux/blob/57b8e2d666a31fa201432d58f5fe3469a0dd83ba/drivers/net/veth.c
- Linux bridge interface source: https://github.com/torvalds/linux/blob/57b8e2d666a31fa201432d58f5fe3469a0dd83ba/net/bridge/br_if.c
- CNI `cnitool`: https://www.cni.dev/docs/cnitool/
- CNI specification: https://github.com/containernetworking/cni/blob/v1.3.0/SPEC.md

Chapter 20: runc And containerd Experiments

The final lab group connects the raw Linux experiments to the runtime stack. runc consumes an OCI bundle and drives the kernel setup. containerd prepares image, snapshot, container, and task state, then talks to a runtime v2 shim.

Run these only in a disposable Linux VM. runc and containerd create real processes, mounts, cgroups, runtime directories, snapshots, and shim processes.

OCI Bundle

Question: what does runc need before it can create a container?

Scope: VM-only mutation.

runc expects an OCI bundle: a directory with `config.json` and a root filesystem. The README's basic flow is still the right mental model: populate `rootfs/`, generate a starter spec with `runc spec`, edit the spec, then run lifecycle commands.

The `spec` command source generates a starter spec and writes it as `config.json`:

```
spec := specconv.Example()
data, err := json.MarshalIndent(spec, "", "\t")
return os.WriteFile(specConfig, data, 0o666)
```

The lab should inspect these fields before running anything:

```
find bundle -maxdepth 2 -type f -o -type d | sort
sed -n '1,160p' bundle/config.json
grep -n '"path"\|"args"\|"namespaces"\|"mounts"' bundle/config.json
```

The rootfs source is a choice with consequences. A prepared static rootfs (a busybox tarball, for example) keeps the lab self-contained. Exporting an image with `docker create` and `docker export` matches the runc README but pulls Docker into the dependency list. Pick one and document it in the lab notes; a floating choice makes cleanup unreliable.

runc Lifecycle

Question: what is the difference between create and start?

Scope: VM-only mutation.

The runc commands name the split:

```
Name:  "run",
Usage: "create and run a container",
```

```
Name:  "create",
Usage: "create a container",
```

`runc run` is convenience. It creates, starts, waits, and cleans up depending on flags. The lifecycle lab should use `create`, `state`, `start`, `kill`, and `delete` so the state transitions are visible:

```
cd bundle
sudo runc create cdb-runc
sudo runc state cdb-runc
sudo runc start cdb-runc
sudo runc state cdb-runc
pid=$(sudo runc state cdb-runc | sed -n 's/.*"pid": *\([0-9][0-9]*\).*/\1/p')
sudo readlink /proc/"$pid"/ns/{mnt,pid,net}
sudo cat /proc/"$pid"/cgroup
sudo runc kill cdb-runc KILL
sudo runc delete cdb-runc
```

The process needs to stay alive long enough to inspect it, so set `process.args` in `config.json` to `["sleep", "300"]` and `process.terminal` to `false` before running `runc create`.

Cleanup verification:

```
sudo runc state cdb-runc || true   # nonzero = clean
```

containerd Task

Question: where does the shim appear when containerd starts a task?

Scope: VM-only mutation.

containerd's own docs say `ctr` is for debugging containerd. That is why this lab uses `ctr` instead of a friendlier container CLI.

Use a dedicated containerd namespace:

```
sudo ctr namespaces create cdb-lab 2>/dev/null || true
sudo ctr -n cdb-lab images pull docker.io/library/busybox:latest
sudo ctr -n cdb-lab containers create docker.io/library/busybox:latest cdb-task sleep 300
sudo ctr -n cdb-lab containers ls
sudo ctr -n cdb-lab tasks start -d cdb-task
sudo ctr -n cdb-lab tasks ls
```

Now inspect the runtime boundary:

```
ps -ef | grep -E 'containerd-shim-runc-v2|sleep 300' | grep -v grep
sudo ctr -n cdb-lab tasks ps cdb-task
```

The runtime v2 docs make the ownership clear:

```
containerd, the daemon, does not directly launch containers.
```

The shim invokes the OCI runtime, usually `runc`, and holds the task's control socket while containerd is restart-cycled.

Cleanup:

```
sudo ctr -n cdb-lab tasks kill cdb-task
sudo ctr -n cdb-lab tasks delete cdb-task
sudo ctr -n cdb-lab containers delete cdb-task
sudo ctr namespaces remove cdb-lab
```

If task deletion fails, inspect `ctr -n cdb-lab tasks ls` before forcing anything.

Bundle From containerd

Question: how does containerd's generated runtime bundle relate to the hand-built runc bundle?

Scope: VM-only mutation, mostly inspection after a task exists.

After creating a task, inspect containerd's runtime state directory for the lab namespace and task. The exact path depends on the containerd build and configuration, but the object to find is stable: a runtime v2 bundle containing an OCI `config.json` for the task.

The inspection target should include:

```
sudo find /run/containerd -path '*cdb-lab*' -o -path '*cdb-task*'
```

Once the bundle is found, compare its `config.json` to the runc bundle from the earlier lab. The generated spec should show where image config, snapshot mounts, runtime options, namespaces, cgroups, and task arguments ended up.

Events And Logs

Question: what can containerd tell us while the task is running?

Scope: inspect-only after the VM-only task setup.

`ctr events` can show lifecycle events while another shell creates and starts a task:

```
sudo ctr -n cdb-lab events
```

Run after the task lab; the events stream is empty without an active task. Debug logs and `strace` follow the same rule.

Sources And Further Reading

- runc README: https://github.com/opencontainers/runc
- runc `spec` command: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/spec.go
- runc `run` command: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/run.go
- runc `create` command: https://github.com/opencontainers/runc/blob/eb7eaf19b6eec5d1143b257057899e4a7b738c81/create.go
- OCI Runtime Specification bundle docs: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/bundle.md
- OCI runtime lifecycle: https://github.com/opencontainers/runtime-spec/blob/6999a89a76a0329f440d5740497bedb9dd431297/runtime.md
- containerd getting started: https://containerd.io/docs/getting-started/
- containerd runtime v2 docs: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/docs/runtime-v2.md
- containerd runtime v2 bundle handling: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/core/runtime/v2/bundle.go
- containerd runc v2 shim task service: https://github.com/containerd/containerd/blob/2976f38ccbfcda5ef1364d63d60b0a304e4bf94a/cmd/containerd-shim-runc-v2/task/service.go