

Principles of Distributed Systems

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Section 3: Processes, Threads and Virtualization

This content is based on the following public resources: <https://www.distributed-systems.net/index.php/books/ds4/>

Processes, Threads and Virtualization

Introduction to Processes and Threads

- **Definition:** A process is an independent program in execution with its own memory space, while a thread is a lightweight unit of execution within a process, sharing the process's memory.
- **Memory:** A process has its own isolated memory space (address space), whereas threads within the same process share the same memory space, including code, data, and resources.
- **Overhead:** Processes are heavier, requiring more system resources and time for creation and context switching, while threads are lighter, with lower overhead for creation and switching.
- **Communication:** Inter-process communication (IPC) is complex and slower (e.g., pipes, sockets), while threads communicate faster via shared memory but require synchronization (e.g., locks).

Context switching

Observations

- ① Threads share the same address space. Thread context switching is much faster than process context switching:
 - ① only registers and program counter need to be saved and restored
- ② Process context switching is more expensive (in time and space) as
 - ① TLB needs to be flushed
 - ② page table is reloaded
 - ③ address space changes
- ③ Creating and destroying threads is much cheaper than doing so for processes.

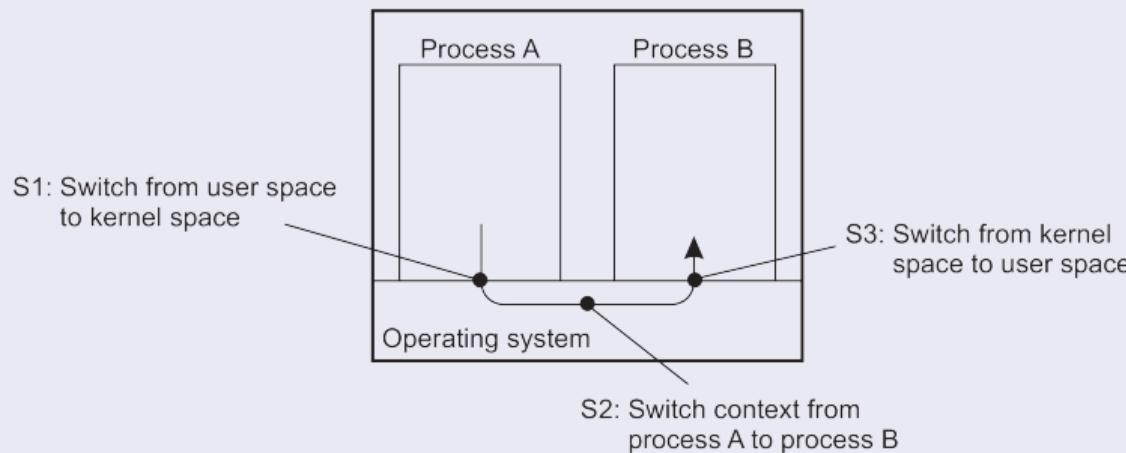
Why use threads

Some simple reasons

- **Avoid needless blocking:** a single-threaded process will **block** when doing I/O; in a multithreaded process, the operating system can switch the CPU to another thread in that process.
- **Exploit parallelism:** the threads in a multithreaded process can be scheduled to run in parallel on a multiprocessor or multicore processor.
- **Avoid process switching:** structure large applications not as a collection of processes, but through multiple threads.

Avoid process switching

Avoid expensive context switching



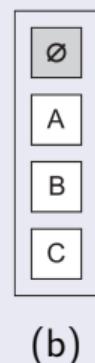
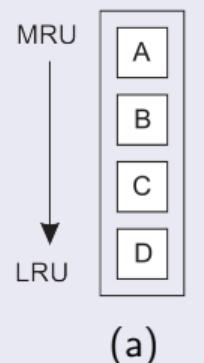
Trade-offs

- Threads use the same address space: more prone to errors
- No support from OS/HW to protect threads using each other's memory
- Thread context switching may be faster than process context switching

The cost of a context switch

Suppose we have a page cache on the CPU with 4 slots. Each slot can accommodate one 4k page, associated with the instructions for a process (below, A,B,C,D)

What a context switch may cause: indirect costs



(a) before the context switch

(b) after the context switch

(c) after accessing block D.

Cache Perturbation Hypothesis

Ref: "The Context-Switch Overhead Inflicted by Hardware Interrupts (and the Enigma of Do-Nothing Loops)" by Dan Tsafrir (IBM T.J. Watson Research Center), presented at the ACM Workshop on Experimental Computer Science (ExpCS '07)."

Experiment

- A trivial 1 ms loop is repeatedly executed.
- Time measurements show perturbations due to interrupts.
- Some implementations showed overheads an order of magnitude larger than expected.

Hardware counters were insufficient to isolate cause. Some effects might involve:

- Instruction cache
- Data cache
- TLB
- Branch predictors

Thread Switch vs Process Context Switch

Thread Switch

- Switch between threads of the *same process*
- Address space remains unchanged
- Page tables and memory mappings are reused
- Faster than process switches
- Typically used for concurrency within applications

Overhead:

- Save/restore registers
- Update stack pointer and program counter

Process Context Switch

- Switch between threads of *different processes*
- Address space changes
- Page tables must be switched
- TLB often flushed or invalidated
- Slower than thread switches

Overhead:

- Save/restore registers
- Switch address space
- Update memory management state

Threads and operating systems

Main issue

Should an OS kernel provide threads, or should they be implemented as user-level packages?

User-space solution

- All operations can be completely handled **within a single process** ⇒ implementations can be extremely efficient.
- **All services provided by the kernel are done on behalf of the process in which a thread resides** ⇒ if the kernel decides to block a thread, the entire process will be blocked.
- Threads are used when there are many external events: **threads block on a per-event basis** ⇒ if the kernel can't distinguish threads, how can it support signaling events to them?

Linux Kernel Threads

- **Task Struct Representation:** In the Linux kernel, threads are implemented as lightweight processes, each represented by a `task_struct` (defined in `include/linux/sched.h`), sharing memory but maintaining separate execution contexts for scheduling.
- **Scheduling with CFS:** The Completely Fair Scheduler (CFS) in `kernel/sched/fair.c` manages kernel threads, treating them as virtual processors and allocating CPU time fairly using a red-black tree.
- **POSIX Threads Integration:** User-space threads (e.g., via `pthread_create`) map to kernel threads, enabling Java's 1:1 threading model to leverage Linux's scheduling for efficient concurrency.

Using threads at the client side

Multithreaded web client

Hiding network latencies:

- Web browser scans an incoming HTML page, and finds that **more files need to be fetched**.
- **Each file is fetched by a separate thread**, each doing a (blocking) HTTP request.
- As files come in, the browser displays them.

Multiple request-response calls to other machines (RPC)

- A client does several calls at the same time, each one by a different thread.
- It then waits until all results have been returned.
- Note: if calls are to different servers, we may have a **linear speed-up**.

Multithreaded clients: does it help?

Thread-level parallelism: TLP

Let c_i denote the fraction of time that exactly i threads are being executed simultaneously.

$$TLP = \frac{\sum_{i=1}^N i \cdot c_i}{1 - c_0}$$

with N the maximum number of threads that (can) execute at the same time.

Practical measurements

A typical Web browser has a TLP value between 1.5 and 2.5 \Rightarrow threads are primarily used for **logically organizing** browsers.

Using threads at the server side

Improve performance

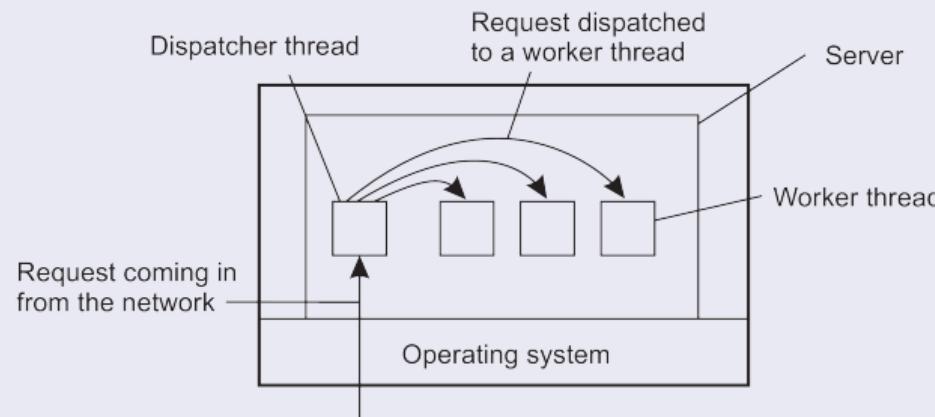
- Starting a thread is cheaper than starting a new process.
- Having a single-threaded server prohibits simple scale-up to a **multiprocessor system**.
- As with clients: **hide network latency** by reacting to next request while previous one is being replied.

Better structure

- Most servers have high I/O demands. Using simple, **well-understood blocking calls** simplifies the structure.
- Multithreaded programs tend to be **smaller and easier to understand** due to **simplified flow of control**.

Why multithreading is popular: organization

Dispatcher/worker model



Overview

Multithreading	Parallelism, blocking system calls
Single-threaded process	No parallelism, blocking system calls

Virtualization

Scope and Terminology

- **System virtualization:** presents a virtual hardware platform capable of running an OS
- **Process virtualization:** presents a virtual execution environment for a single program (e.g., a managed runtime)
- **Emulation:** reproduces an ISA and/or device behavior in software
- **Hypervisor / VMM:** software layer(s) that create and isolate system VMs

Goal

Provide isolation and controllable sharing of CPU, memory, and I/O while preserving expected software semantics.

Execution Virtualization Spectrum

- **Emulation** (ISA/device reproduction): maximizes compatibility across architectures, typically higher overhead
- **Process VM** (language bytecode runtime): portability and safety for applications, not a full OS boundary
- **System VM** (hypervisor-based): strong isolation and full OS virtualization

Key distinction

Process VMs virtualize a *program execution model*; hypervisors virtualize a *machine interface*.

Diagram: Taxonomy of Virtualization Approaches

Emulation

- Virtualizes an ISA and/or devices in software
- Primary benefit: cross-architecture compatibility

Process Virtual Machine (e.g., JVM)

- Virtualizes an application execution model (bytecode + runtime services)
- Primary benefit: portability, safety properties, managed services

program boundary

System Virtual Machine (Hypervisor / VMM)

- Virtualizes CPU, memory, and devices to run an unmodified OS
- Primary benefit: strong isolation and resource control at machine granularity

OS boundary

Figure: Conceptual taxonomy. Emulation targets compatibility, process VMs target portable execution for programs, and system VMs target full OS virtualization and isolation.

System VMs: Type 1 and Type 2 Hypervisors

- **Type 1 (bare-metal):** hypervisor runs directly on hardware, commonly with a privileged management domain
- **Type 2 (hosted):** hypervisor/VMM runs atop a general-purpose host OS and leverages host drivers/services

Engineering focus

The practical security boundary is determined by the **trusted computing base (TCB)**: what must be trusted for isolation.

Diagram: Type 1 vs Type 2 Stack Organization

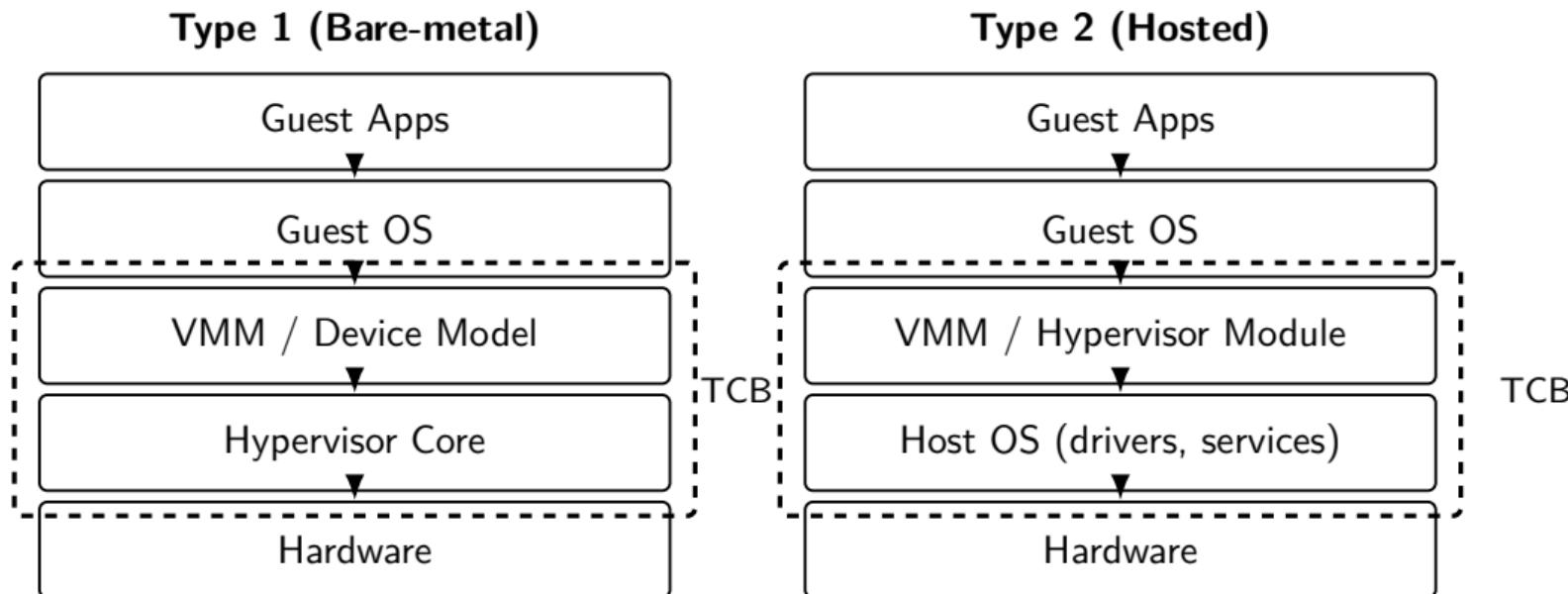


Figure: Representative stack organizations. In Type 2 systems, the host OS becomes part of the trusted base for isolation.

Emulation vs Hypervisor-Based Virtualization

- **Emulation:** can execute software for a different ISA; overhead arises from instruction translation and device modeling
- **System VM with hardware assist:** guest code runs largely natively; overhead concentrates in traps/exits and I/O paths
- **Process VM (e.g., JVM):** does not virtualize devices or privileged CPU state; relies on the host OS for isolation

Implication

ISA portability and OS-level isolation are different objectives; they are frequently conflated but have different mechanisms and costs.

Resource Control: CPU and Memory

CPU control concepts

- **Capacity:** number of vCPUs and their mapping to physical CPUs
- **Shares/weights:** proportional allocation under contention
- **Limits/caps:** enforce maximum CPU usage (often expressed as a percentage of a core set)
- **Reservations:** minimum guaranteed CPU capacity (where supported)

Memory control concepts

- **Static limit:** maximum assigned memory for a VM
- **Ballooning:** cooperative reclamation from guests to enable overcommit
- **Swapping/reclamation:** provider-side memory pressure mechanisms (risk of latency inflation)

Diagram: Resource Allocation and Enforcement Points

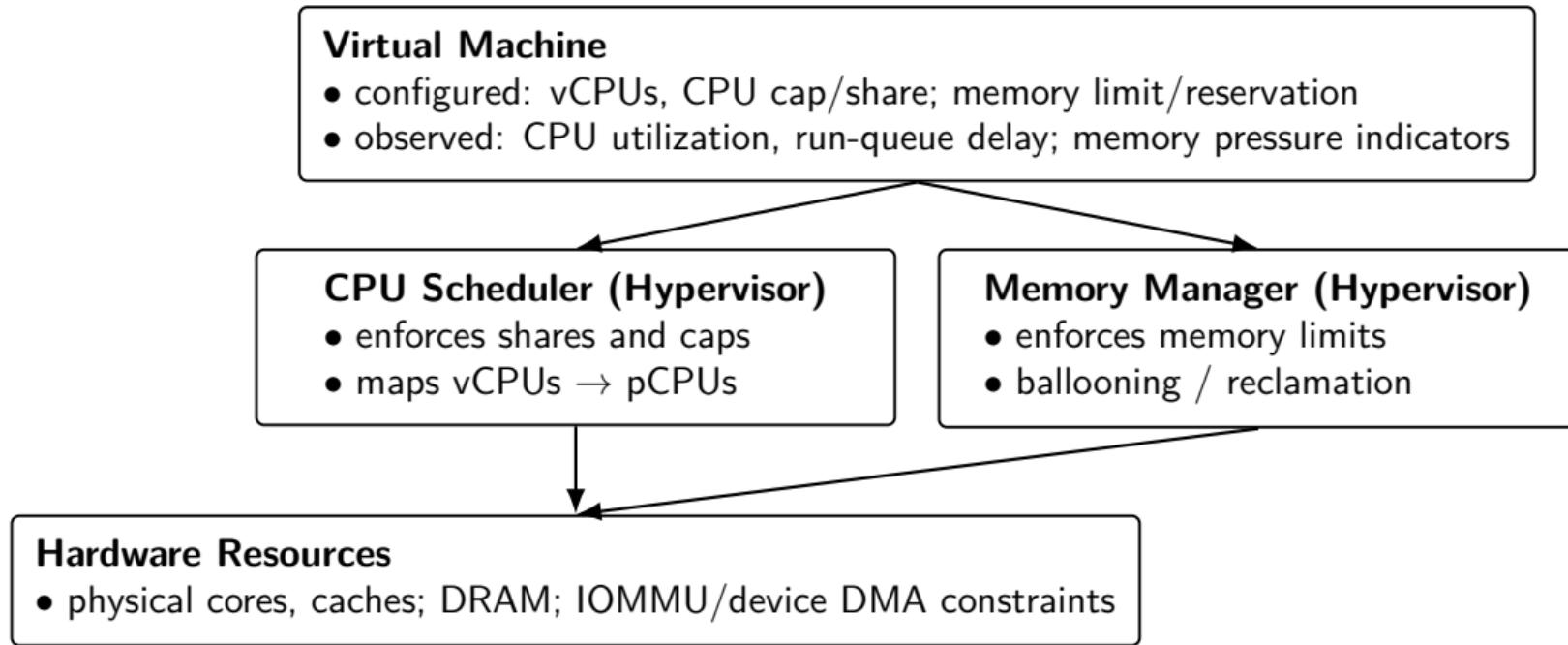


Figure: Enforcement points for CPU and memory control. Allocation policies are implemented by the hypervisor scheduler and memory manager, which multiplex physical resources across VMs.

Concrete Control Examples (CPU % and Memory %)

CPU

- **CPU cap (percentage):** limit a VM to (e.g.) 60% of one core or 240% of a 4-core entitlement
- **Shares/weights:** if two VMs have weights 2:1, they receive that proportion under contention
- **Pinning/affinity:** restrict vCPUs to selected cores to control interference and improve predictability

Memory

- **Memory limit:** hard upper bound on guest-usable memory
- **Reservation:** minimum memory intended to remain available (platform-dependent)
- **Overcommit with ballooning:** reclaim unused guest pages before swapping at the host

Summary

- Emulation, process VMs, and hypervisors address different requirements and expose different boundaries
- Type 1 and Type 2 hypervisors differ mainly in where the trusted base resides and how drivers are obtained
- Modern platforms treat CPU and memory as first-class, policy-controlled resources: shares, caps, reservations, and limits

Virtualization and Containers

Virtualization is about running workloads as if they had their own machine.

In Linux container-style virtualization, two kernel features provide most of the illusion:

- **Namespaces** → *isolation*: “what you can see”
- **Control groups (cgroups)** → *control*: “what you can use”

A **container** is typically: *namespaces + cgroups* (plus filesystem + tooling).

If multiple applications share one OS kernel, we want:

- Strong **separation of views** (processes, network, mounts, hostnames, users)
- Predictable **resource sharing** (CPU, memory, I/O) without one app starving others

Linux containers achieve this without a hypervisor by virtualizing *interfaces to the kernel*.

Namespaces: isolation of kernel resources

A **namespace** gives a process a private view of a specific kernel resource.

Common namespaces:

- **PID** (process IDs): processes see a different PID tree
- **Mount (MNT)**: separate mount table / filesystem view
- **Network (NET)**: interfaces, routes, ports isolated
- **UTS**: hostname/domainname isolation
- **IPC**: SysV IPC, POSIX message queues, etc.
- **User (USER)**: user/group ID mapping (enables unprivileged containers)
- **Cgroup** namespace: hides cgroup paths

Control groups (cgroups): accounting and limits

cgroups group processes and apply resource *accounting, limits, and prioritization*.

Typical controls:

- **CPU**: shares/quotas; prevent CPU hogging
- **Memory**: limits; OOM behavior per group
- **I/O**: throttle block I/O
- **PIDs**: limit number of processes

Key idea: **namespaces isolate; cgroups constrain**.

How they fit together (container model)

A container runtime typically:

- ① Creates new **namespaces** for the process (isolation)
- ② Places the process into **cgroups** (resource governance)
- ③ Sets up a root filesystem and mounts (often with overlayfs)
- ④ Configures networking (veth pairs, bridges, NAT, etc.)

The result: a process that *looks* like it runs on its own system and can be *limited*.

Diagram: cgroups as a resource governance tree

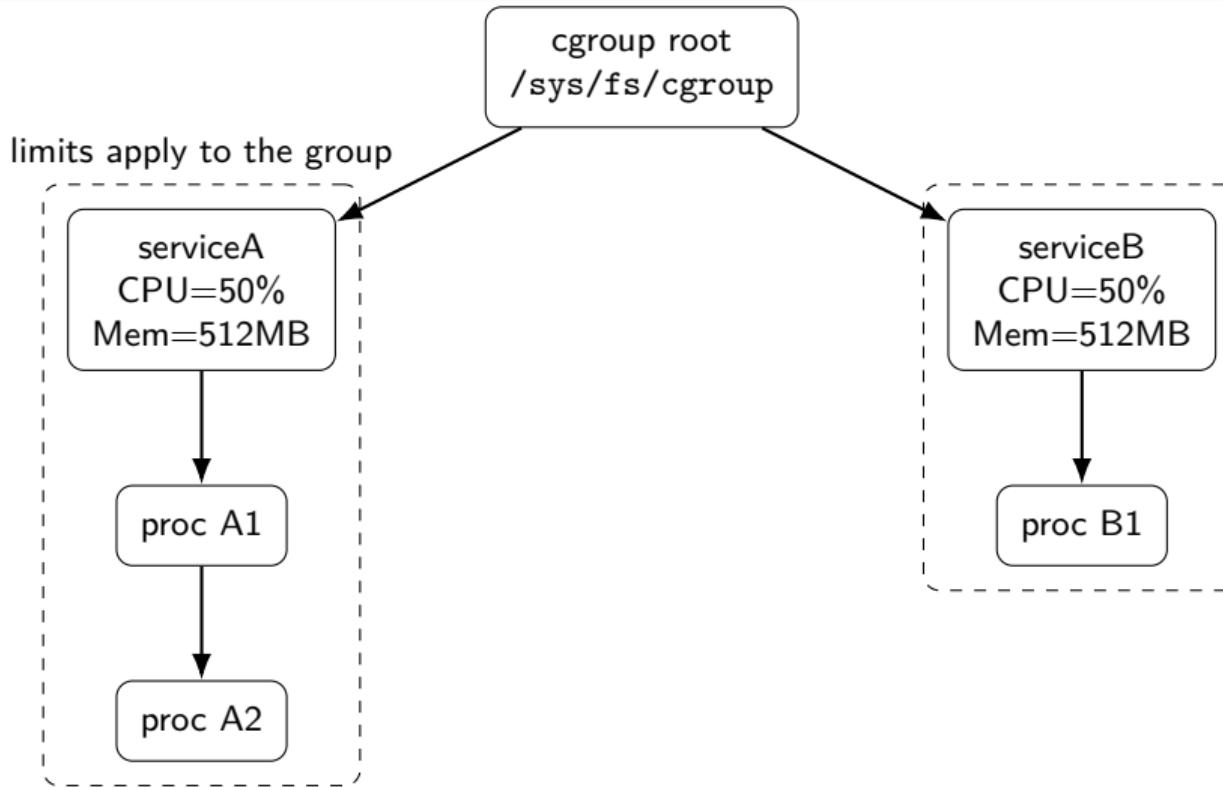


Figure: Cgroups organize processes into a hierarchy and apply resource limits/accounting per group.

Diagram: namespaces provide separate “views”

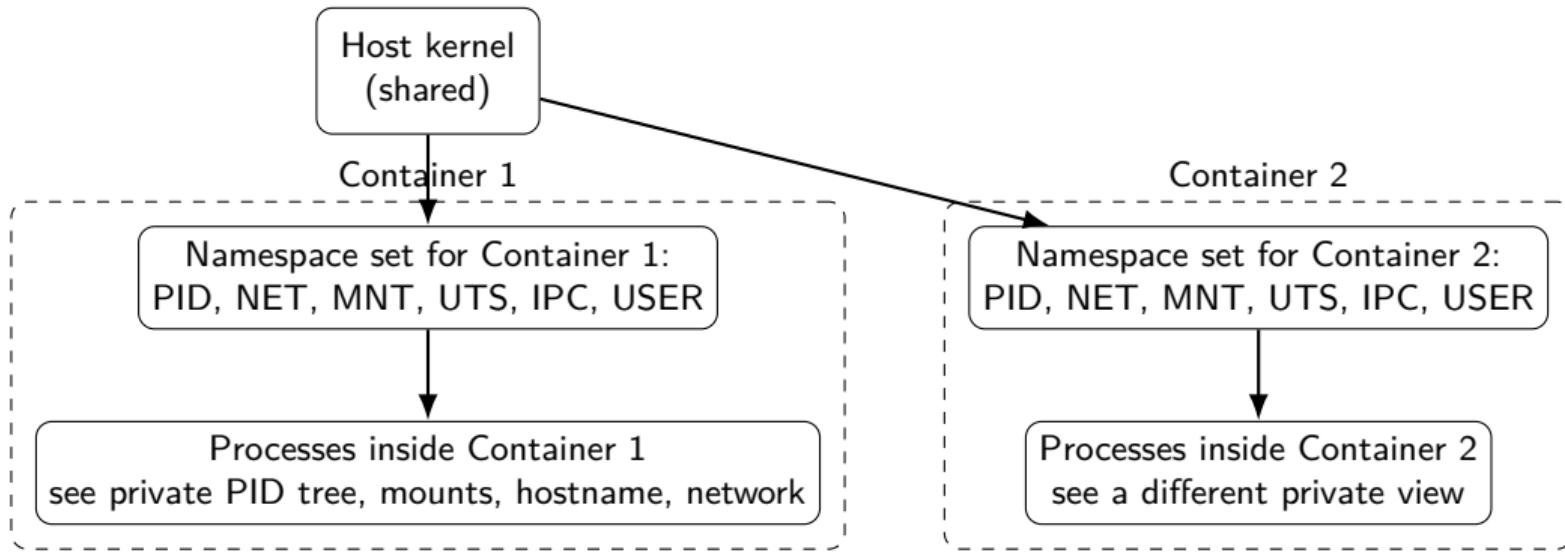


Figure: Namespaces isolate what processes can see; multiple containers can share one kernel while keeping distinct views.

A simple isolation example with unshare

`unshare` creates new namespaces for a process (and its children).

We'll demonstrate isolation by creating:

- a new **UTS namespace** (private hostname)
- a new **PID namespace** (PID 1 inside)
- a new **mount namespace** (private mount table)
- optionally a **user namespace** (run as “root” inside without host root)

Example: unshare for a private hostname + PID tree

```
1 # Create new user, mount, UTS, and PID namespaces.  
2 # --map-root-user maps your user to root inside the user namespace.  
3 unshare --user --map-root-user --mount --uts --pid --fork /bin/bash
```

Inside the new shell:

```
1 # UTS namespace: hostname is private  
2 hostname container-demo  
3  
4 # PID namespace: this shell's child processes start a new PID tree  
5 echo "my pid:" $$  
6  
7 # Compare process listing (you should see a tiny PID universe)  
8 ps -ef
```

Example: mount namespace isolation (private mounts)

In the same unshare shell:

```
1 # Make mount operations "private" to this namespace
2 mount --make-rprivate /
3
4 # Create a temporary mount only visible here
5 mkdir -p /tmp/ns-mnt
6 mount -t tmpfs tmpfs /tmp/ns-mnt
7
8 # Observe it exists here:
9 mount | grep ns-mnt
```

On the host (outside the namespace), that tmpfs mount will not appear in `mount` output.

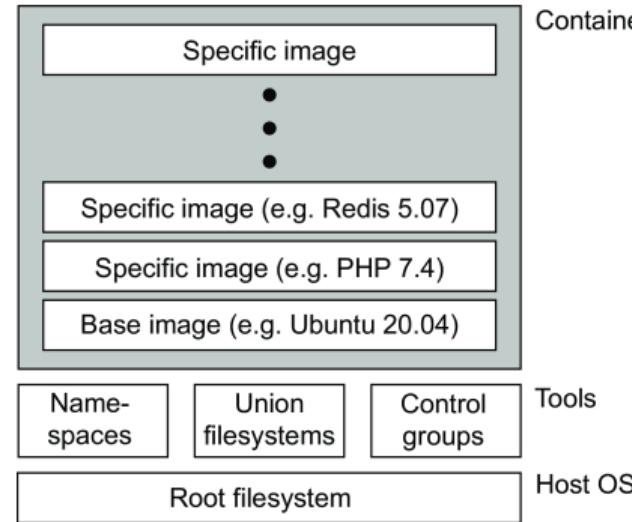
What isolation did we get?

From the example:

- **UTS namespace**: hostname change does not affect the host
- **PID namespace**: processes see a new PID hierarchy (often with PID 1 inside)
- **Mount namespace**: mounts are private to the namespace
- **User namespace**: you can have root-like IDs inside without being host root

This is the core of container isolation, and it ties directly back to virtualization:
virtualize the process's view of the system without virtualizing the hardware.

Containers



- **Namespaces:** a collection of processes in a container is given their own view of identifiers
- **Union file system:** combine several file systems into a layered fashion with only the highest layer allowing for write operations (and the one being part of a container).
- **Control groups:** resource restrictions can be imposed upon a collection of processes.

Summary

- Virtualization can be done at different layers: hardware (VMs) vs. OS interfaces (containers).
- **Namespaces** isolate what processes can see (views of kernel resources).
- **cgroups** govern what processes can use (resource limits/accounting).
- `unshare` is a minimal, direct way to see namespace isolation in action.

Virtualization in Cloud Computing

Virtualization is the foundational technology that enables modern cloud platforms.

In cloud computing, virtualization:

- Allows multiple **virtual machines (VMs)** to run on a single physical server
- Provides strong **isolation** between tenants for security and fault containment
- Enables **elastic resource allocation** (CPU, memory, storage) on demand
- Makes infrastructure **hardware-agnostic**, simplifying scaling and migration

Cloud providers rely on virtualization to offer Infrastructure-as-a-Service (IaaS), where users deploy full operating systems without managing physical hardware.

Containerization in Cloud Computing

Containerization builds on virtualization to improve efficiency and agility.

In cloud environments, containers:

- Package applications with their dependencies for **portable deployment**
- Share the host kernel, enabling **higher density** than VMs
- Start quickly, supporting **rapid scaling** and auto-healing services
- Integrate naturally with orchestration systems (e.g., Kubernetes)

As a result, containerization is central to Platform-as-a-Service (PaaS) and microservice-based architectures, enabling fast iteration and efficient use of cloud resources.

Summary

Summary and Conclusions

We have discussed processes and threads in Distributed Systems, namely:

- Processes and Threads
- Context Switching
- Multithreading
- Virtualization
- Containerization