TensorWorks

Training Session CN001

Containers and container orchestration

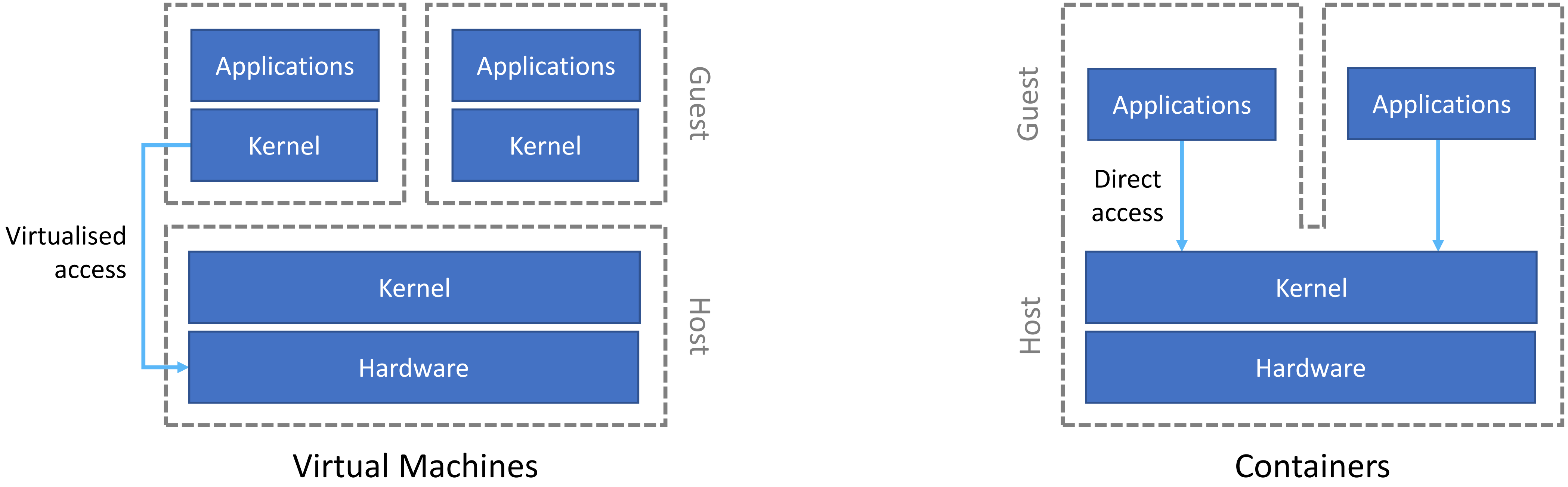
Outline

- Introduction to containers
- Peeking under the hood: process isolation explained
- Differences between Linux containers and Windows containers
- Virtual Machine-based isolation implementations
- Hardware acceleration in containers
- Overview of container orchestration
- Orchestration with Kubernetes

Introduction to containers

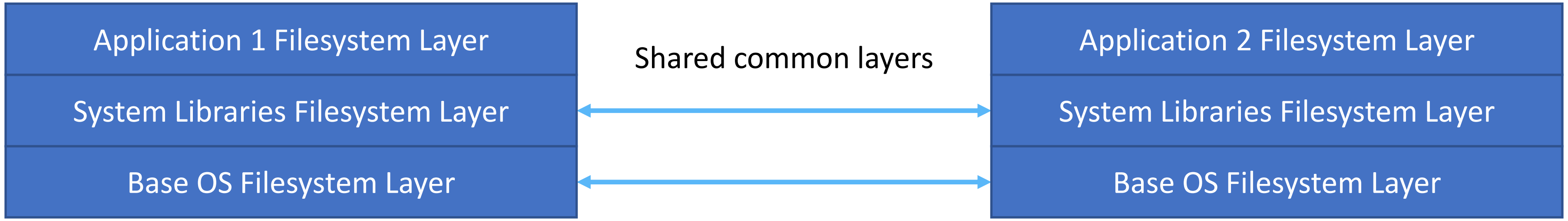
Introduction to containers

Conceptually, containers can be thought of as a lightweight and flexible alternative to Virtual Machines (VMs): (although they're actually much more than that!)



Introduction to containers

- The defining feature of containers is that they **share the kernel** with the host system
- Direct access to the host kernel makes container creation as fast as process creation
- Containers typically utilise union filesystems to facilitate composing images from a set of compact, reusable filesystem layers that are combined at runtime



Introduction to containers

Popular container frontends like Docker pair union filesystems with a configuration-as-code approach to deterministically build images from declarative specifications:

```
# Specifies the base image whose filesystem layers we will build upon
FROM ubuntu:18.04

# Copies files from the host into the image (creates a new filesystem layer)
COPY . /app

# Builds source code inside the image (creates a new filesystem layer)
RUN make /app
```

Introduction to containers

Although popular tools such as Docker and Kubernetes typically act as de-facto standards for building and running containers, the Open Container Initiative was founded in 2015 to provide standard specifications that all container implementations should adhere to:

- OCI Runtime Specification defines how runtimes create and manage containers
- OCI Image Specification defines a standard format for packaging containers

Introduction to containers

In addition to the Open Container Initiative, the Linux Foundation maintains a number of other initiatives with a strong focus on the use of containers:

CLOUD NATIVE COMPUTING FOUNDATION

Oversees the development of key container tools, including Kubernetes and containerd

CD.FOUNDATION

Oversees projects that focus on CI/CD tooling for building and deploying containers

Introduction to containers

Important events in modern container history:

- **2007:** Google contributes cgroups to the Linux kernel
- **2008:** LXC is released by Google and IBM (along with other contributors)
- **2013:** Docker is released, bringing containers to widespread attention
- **2014:** Google releases Kubernetes, the first major container orchestration system
- **2014:** CoreOS rkt is released, providing the first major alternative to Docker

Introduction to containers

Important events in modern container history **(continued)**:

- **2015:** The Open Container Initiative (OCI) is founded
- **2015:** The Cloud Native Computing Foundation (CNCF) is founded
- **2016:** Microsoft adds container support to Windows Server 2016 and Windows 10
- **2019:** The Continuous Delivery Foundation (CDF) is founded
- **2019:** Kubernetes 1.14 introduces production-ready support for Windows containers

Introduction to containers

The following operating systems support containers in one form or another:

- FreeBSD: supported in the form of FreeBSD jails, introduced in 2000
- Solaris: supported in the form of Solaris Zones, introduced in 2005
- Linux: supported since the early 2000s, but popularised by Docker in 2013
- Windows: supported since 2016, with improved orchestration support since 2018
- macOS: not officially supported, but that won't stop us: https://macOScontainers.org

Post-Section Activity:

01 – Building and running Linux containers

Peeking under the hood: process isolation explained

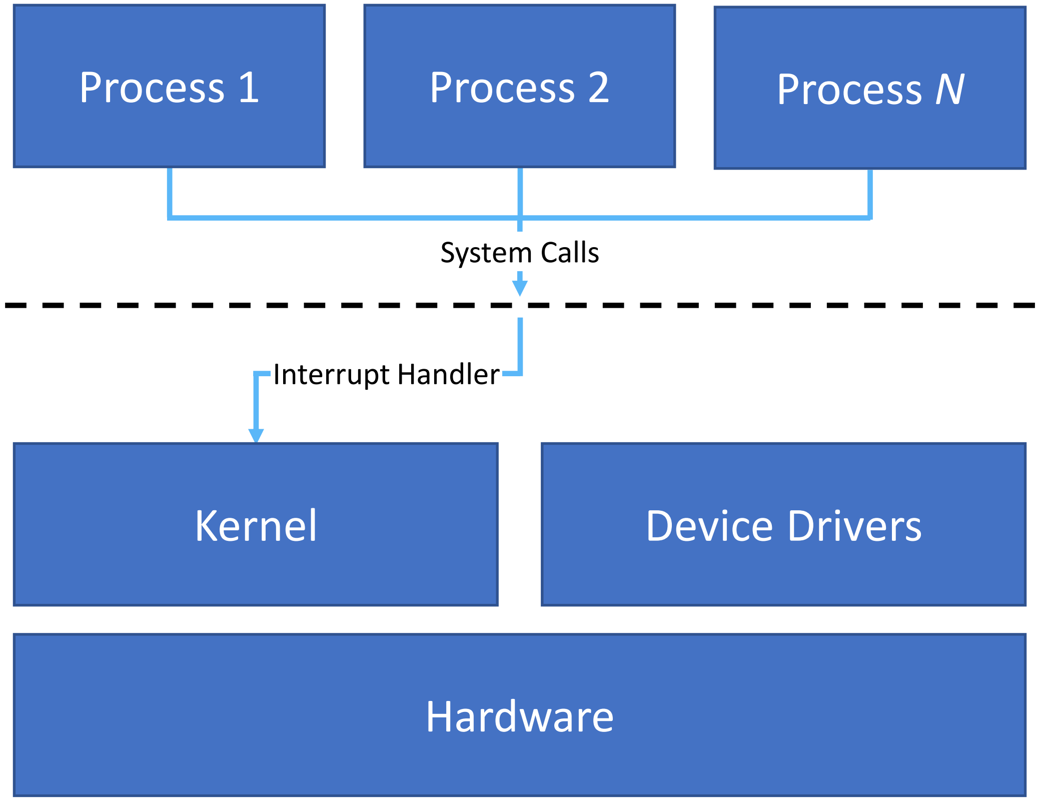
Peeking under the hood: process isolation explained

Note: implementation details in this section refer to the Linux kernel, but the key concepts are the same under other platforms

Peeking under the hood: process isolation explained

User mode

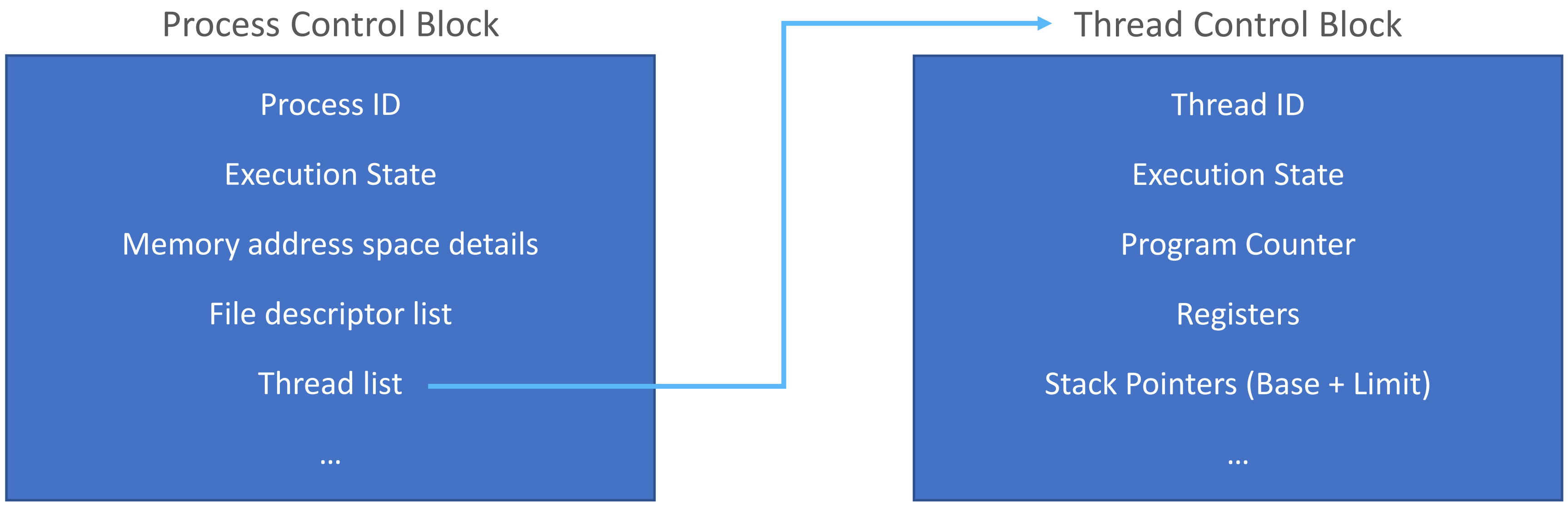
Kernel mode



(Windows abstracts this with RPC calls to system services, but they still trap down into the kernel under the hood)

Peeking under the hood: process isolation explained

Processes are really just Process Control Blocks managed by the kernel:



Peeking under the hood: process isolation explained

Every interaction between processes and their environment is abstracted by the kernel:

- Thread management (including CPU scheduling)
- Memory management (allocation, deallocation, etc.)
- Device access (I/O and filesystems, networking, etc.)
- IPC mechanisms (shared memory, PIDs, signals, etc.)

Peeking under the hood: process isolation explained

This abstraction makes it easy to control what processes see and do:

- Namespaces partition environment visibility into distinct views
- Control groups apply resource accounting & access restrictions to process groups

Peeking under the hood: process isolation explained

The first type of namespace in the Linux kernel was the Mount Namespace:

- This powered an early isolation mechanism known as a chroot jail
- Set the root filesystem directory for a process & its children using the **`chroot`** command
- Only the required files are mounted into the new filesystem

Peeking under the hood: process isolation explained

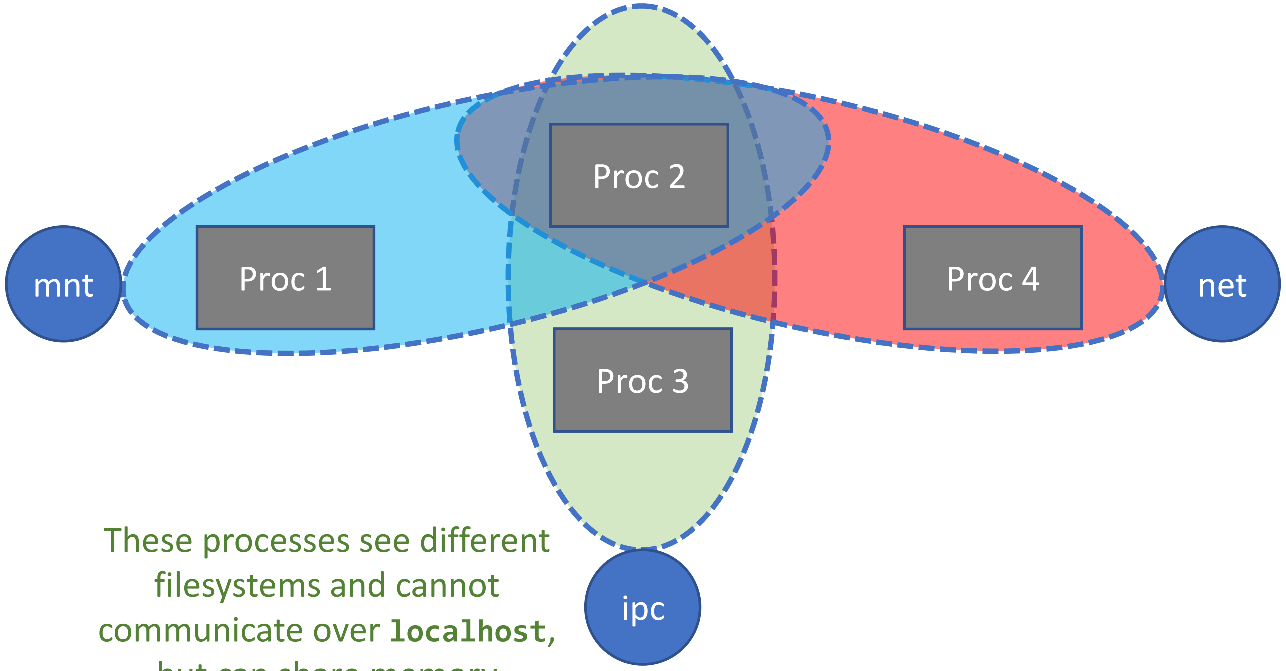
Linux kernel developers soon realised the potential and added more namespaces:

- **pid** — The PID Namespace creates unique sets of PIDs for processes
- **net** — The Network Namespace controls the visibility of network devices
- **ipc** — The IPC Namespace controls the visibility of resources such as shared memory
- **UTS** — The UTS Namespace controls the hostname that processes see
- **user** — The User ID Namespace creates virtual user IDs that map to real user IDs

Peeking under the hood: process isolation explained

Every process belongs to one instance of each namespace, and each namespace instance can contain an arbitrary number of processes:

These processes see the same filesystem, but cannot share memory or communicate over **`localhost`**

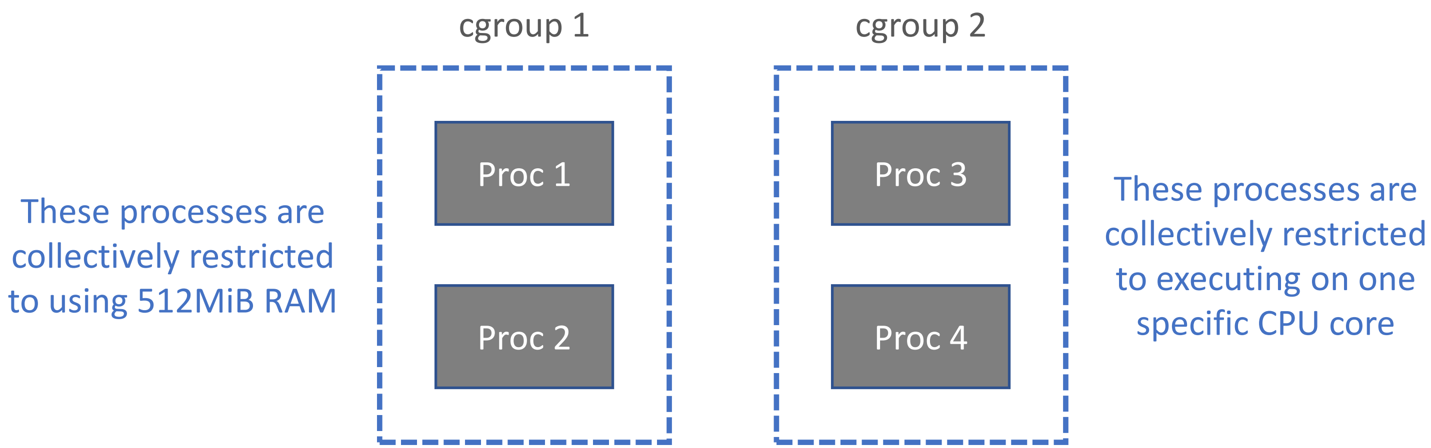


These processes see different filesystems and cannot share memory, but can communicate over **`localhost`**

These processes see different filesystems and cannot communicate over **`localhost`**, but can share memory

Peeking under the hood: process isolation explained

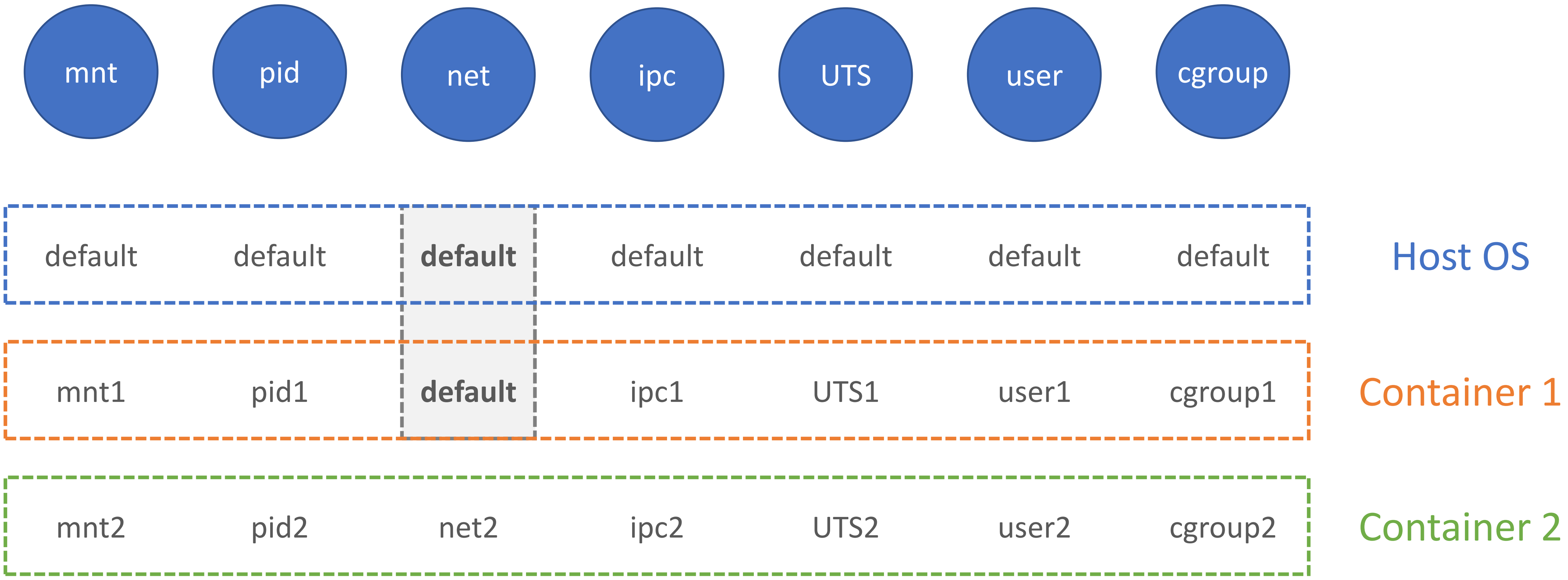
Like namespaces, every process belongs to one cgroup, and each cgroup can contain an arbitrary number of processes:



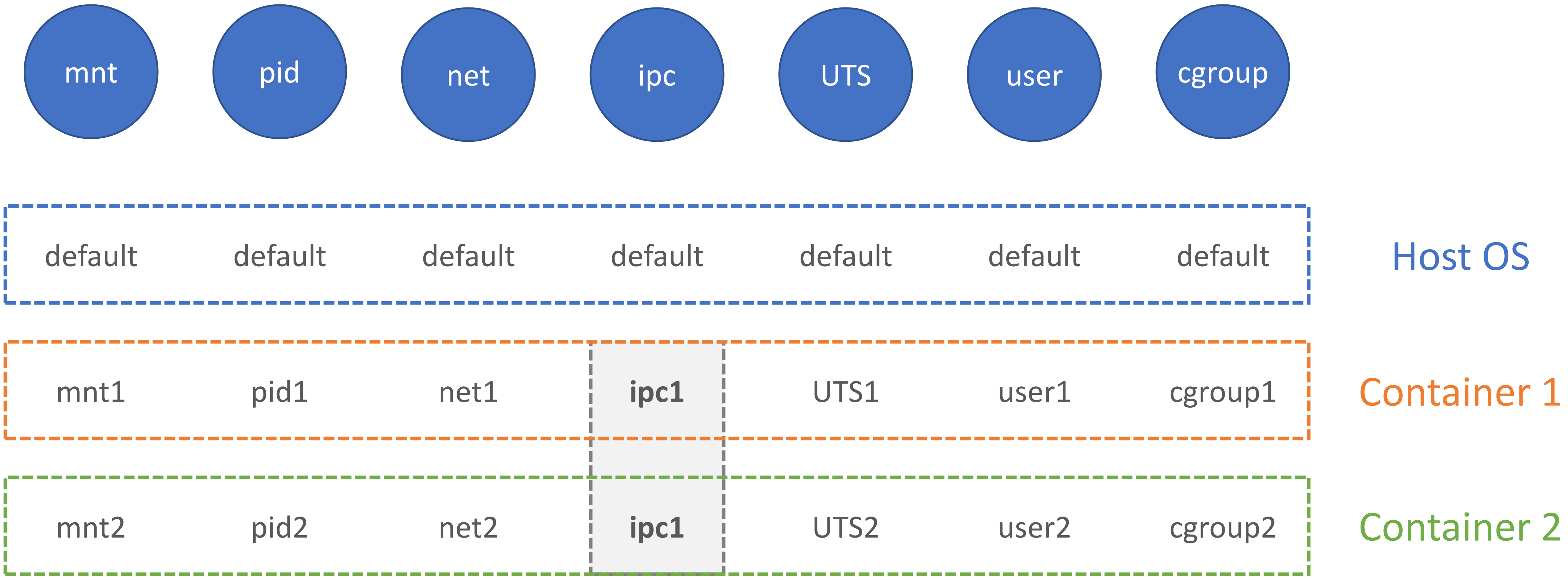
Peeking under the hood: process isolation explained

	mnt	pid	net	ipc	UTS	user	cgroup
Host OS	default	default	default	default	default	default	default
Container 1	mnt1	pid1	net1	ipc1	UTS1	user1	cgroup1
Container 2	mnt2	pid2	net2	ipc2	UTS2	user2	cgroup2

Peeking under the hood: process isolation explained



Peeking under the hood: process isolation explained



Peeking under the hood: process isolation explained

Containers are just an abstraction on top of the isolation features of the kernel:

- Each container commonly has its own **unique** cgroup and set of namespaces
- Containers can **share** a cgroup or any namespace(s) with the host or other containers
- Orchestration systems often group related containers using shared namespaces

Post-Section Activity:

02 – Exploring namespace sharing

Differences between
Linux containers and Windows containers

Differences between Linux containers and Windows containers

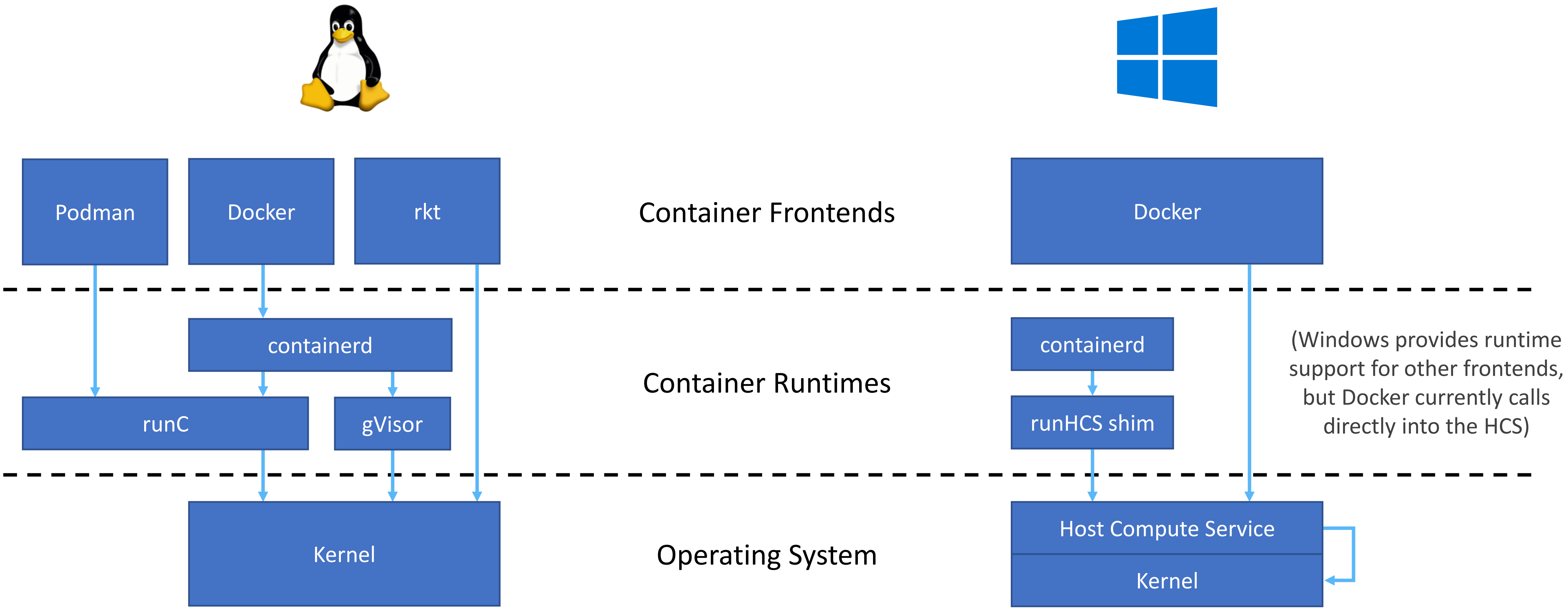
Container support was added to the Windows kernel in Windows Server 2016:

- Extended the existing Windows Job Object functionality that groups processes
- Improved existing resource control mechanisms
- Added chroot support to the system-level Object Namespace (`\DosDevices\C:`, etc.)
- Added a new system service called the Host Compute Service (HCS) to abstract all this

Differences between Linux containers and Windows containers

Interface:	Exposed directly by the kernel	Abstracted by the Host Compute Service
Processes:	Only the entrypoint process & its children	Entrypoint & children + system services
Union Filesystem:	True Union FS for everything	True Union FS for registry, hybrid for NTFS
Kernel Compatibility:	Full backwards compatibility	Containers must match compatible host kernel

Differences between Linux containers and Windows containers



Differences between Linux containers and Windows containers

Unlike Linux containers, Windows containers only support Microsoft-supplied base images:

- Three base image variants exist:
  - Nano Server
  - Server Core
  - Full Windows (version 1809 and newer only)
- New versions of each base image are released for each Windows kernel version
- Base filesystem layers are marked as "foreign layers" to ensure they're always pulled directly from Microsoft's container registry

Differences between Linux containers and Windows containers

Windows supports three types of containers:

HostProcess

a.k.a.

"Not actually a container"

Process-isolated

a.k.a.

"A traditional container"

Hyper V-isolated

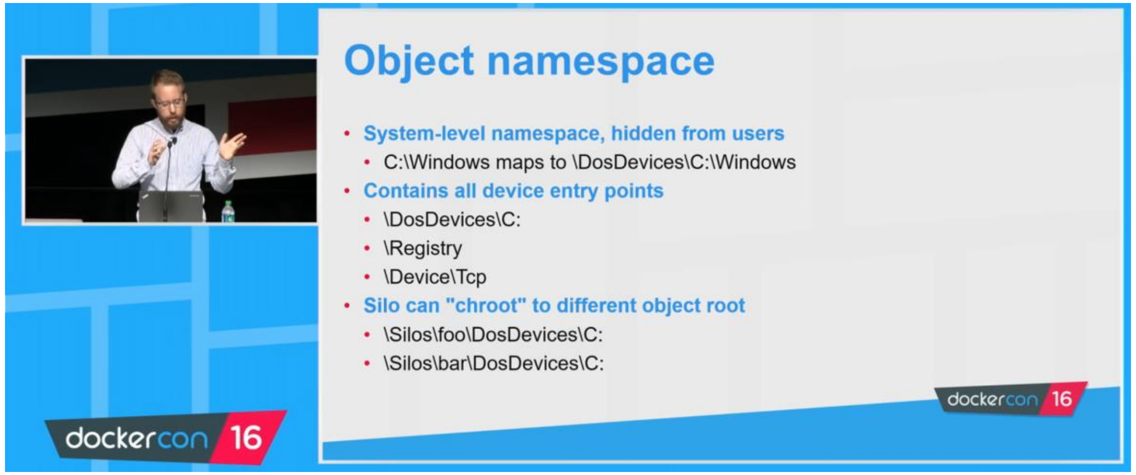
a.k.a.

"A container wrapped in a VM"

(Discussed in the next section)

Differences between Linux containers and Windows containers

Jon Starks' DockerCon 2016 presentation provides all the low-level details:
https://youtu.be/85nCF5S8Qok



Post-Section Activity:

03 – Building and running Windows containers

Virtual Machine-based isolation implementations

Virtual Machine-based isolation implementations

Process isolation is frequently associated with security holes that risk privilege escalation attacks known as container breakouts:

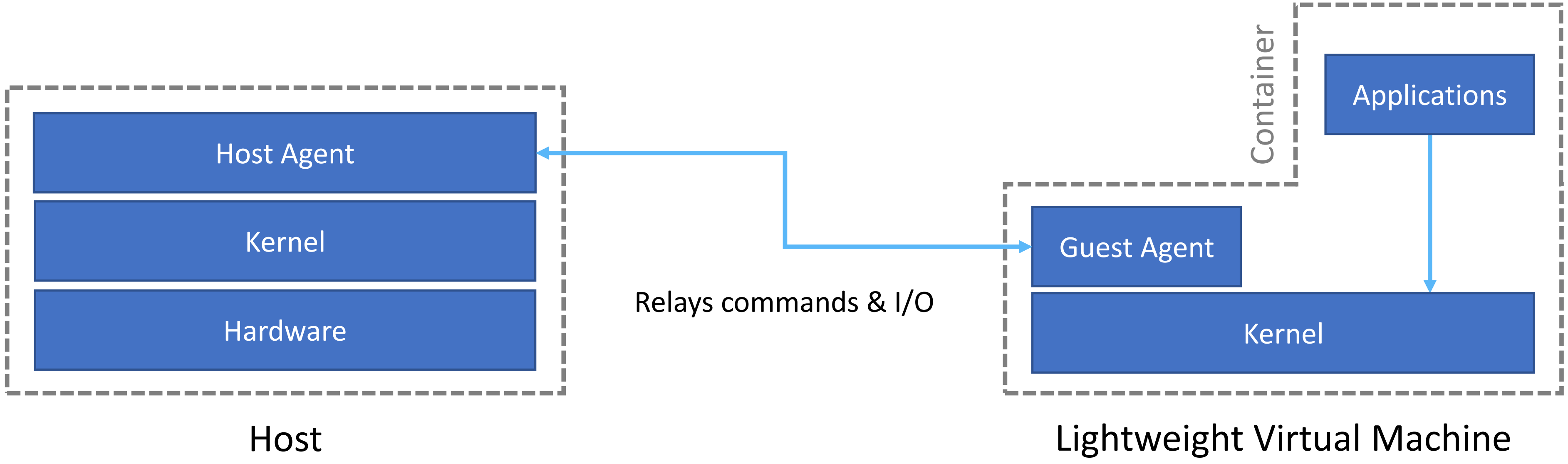
- **December 2014:** CVE-2014-9357 demonstrates the first critical security bug in Docker
- **February 2019:** CVE-2019-5736 demonstrates a critical security bug in runC
- **May 2019:** three major security flaws found in the now-unmaintained rkt runtime
- **July 2020:** first breakout attack documented for process-isolated Windows containers
- **September 2020:** CVE-2020-14386 demonstrates a security bug in the Linux kernel that affects all process isolation-based Linux container runtimes except for gVisor

Virtual Machine-based isolation implementations

VM-based isolation implementations address security concerns by wrapping host kernels in purpose-built lightweight virtual machines:

- Contain only the kernel and an agent to communicate with the host container runtime
- Optimised for faster startup and lower memory overheads than standard VMs
- Typically include platform-specific tweaks to help mitigate performance reductions
- Can run multiple containers within a single VM using process isolation

Virtual Machine-based isolation implementations



Virtual Machine-based isolation implementations

VM isolation provides **improved security** but introduces limitations not present when using process isolation:

- Inability to easily share hardware devices with the host system
- Reliant on nested virtualisation to function when the host is itself a VM
- Communication overheads between the host container runtime and VM guest agent
- Ability to share namespaces between related containers varies by implementation

Virtual Machine-based isolation implementations

Windows

Windows containers support both process isolation mode and Hyper-V isolation mode:

- Runs a Windows Server kernel in a lightweight “utility VM”
- Facilitates running older kernel versions under newer versions of Windows
- The only supported isolation mode under Windows 10 prior to version 1809

Virtual Machine-based isolation implementations

katacontainers

Kata Containers is an open source project that provides VM isolation for Linux containers:

- Drop-in replacement for the standard runC runtime
- Uses lightweight virtual machines similar to Hyper-V utility VMs
- Only supports sharing namespaces between related containers when using Kubernetes

Post-Section Activity:

04 – Running Hyper-V isolated Windows containers

Hardware acceleration in containers

Hardware acceleration in containers

- Access to devices such as GPUs is useful for containerising specialised workloads
- Shared hardware access **only available when using process isolation**
- Exclusive hardware access theoretically possible when using VM isolation, but **not currently implemented** for Linux or Windows containers
- Device support varies by platform and container runtime

Hardware acceleration in containers

Linux containers can access NVIDIA GPUs using the NVIDIA Container Toolkit:

- Adds a prestart hook that works with the standard runC runtime
- Supports CUDA, OpenCL, OpenGL and Vulkan
- Base images with the required runtime libraries provided by NVIDIA on Docker Hub

Hardware acceleration in containers

Linux containers can access AMD GPUs using the Radeon Open Compute (ROCm) platform:

- Kernel modules on the host communicate with runtime libraries inside containers
- Supports APIs that ROCm can run (HIP, OpenCL, CUDA, etc.)
- Base images with the required runtime libraries provided by AMD on Docker Hub

Hardware acceleration in containers

Windows containers can access any GPU with a WDDM 2.5 or newer driver:

- Requires Docker 19.03 and Windows Server 2019 / Windows 10 version 1809 or newer
- Only works with the full-fat Windows base image (1809 or newer)
- Only supports DirectX and APIs built atop it (e.g. DirectML), **no other APIs**

Post-Section Activity:

05 – Running GPU-accelerated Linux containers with the NVIDIA Container Toolkit

Overview of container orchestration

Overview of container orchestration

Tools like Docker provide a way of building and running containers, but we need container orchestration frameworks to effectively deploy containers at scale:

- Manage scaling and scheduling of containers across a dynamic cluster of host nodes
- Manage network configuration and service discovery (both internal and external)
- Monitor container and host node health, automatically replacing crashed instances
- Manage security and provide storage and deployment of runtime secrets

Overview of container orchestration

Concern #1: Scheduling and scaling

- The underlying cluster may change its size and composition dynamically
- The number of replicas for a service's containers may scale based on demand
- Containers need to be scheduled (and often moved) in an efficient manner
- Bin packing allows us to maximise deployment density and minimise wasted resources

Overview of container orchestration

Concern #2: Network configuration and service discovery

- Load balancing routes requests to an ever-changing set of ephemeral containers
- In a microservices architecture, many internal services need to communicate
- An additional infrastructure layer known as a service mesh often provides advanced networking functionality on top of the container orchestration framework itself

Overview of container orchestration

Concern #3: Health monitoring and self-healing

- If a container or host node crashes, it needs to be replaced automatically
- Liveness probes facilitate proactive culling & replacement of unresponsive instances
- Event/status metrics should be collected for improved visibility and traceability of issues
- Health checks can be used to control service migration during canary deployments

Overview of container orchestration

Concern #4: Security and secrets management

- Security policies should be supported to restrict the access that containers have to both internal (on-cluster) and external resources
- Sensitive information (passwords, SSH keys, API keys, etc.) should **never** be stored in plaintext in container images or configuration files
- Secrets should be managed by the orchestration framework, encrypted at rest and securely injected into containers at runtime via files or environment variables

Overview of container orchestration

There are a number of container orchestration frameworks available, including:

- Kubernetes, created by Google
- Docker Swarm, created by Docker, Inc.
- Mesosphere Marathon, created by the Apache Software Foundation

Despite providing competing orchestration implementations, Docker Enterprise Edition and Apache Mesosphere both **support Kubernetes** in addition to their own offerings.

Orchestration with Kubernetes

Orchestration with Kubernetes

kubernetes

Kubernetes is a container orchestration framework created by Google and subsequently adopted as a project of the Cloud Native Computing Foundation (CNCF):

- Kubernetes is a modern successor to Google's internal Borg cluster manager, which has been running containers in production since 2003
- Google contributed Kubernetes to the CNCF as its first project in 2015

Orchestration with Kubernetes

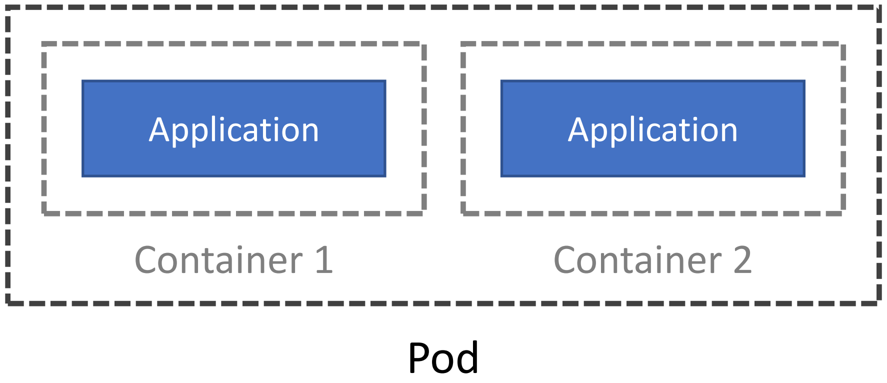
Kubernetes has become the de facto standard for container orchestration and managed Kubernetes services are now offered by all major cloud providers:

- Google Kubernetes Engine (GKE)
- Amazon Elastic Kubernetes Service (EKS)
- Azure Kubernetes Service (AKS)
- Red Hat OpenShift Online
- IBM Cloud Kubernetes Service

Plus dozens of others…

Orchestration with Kubernetes

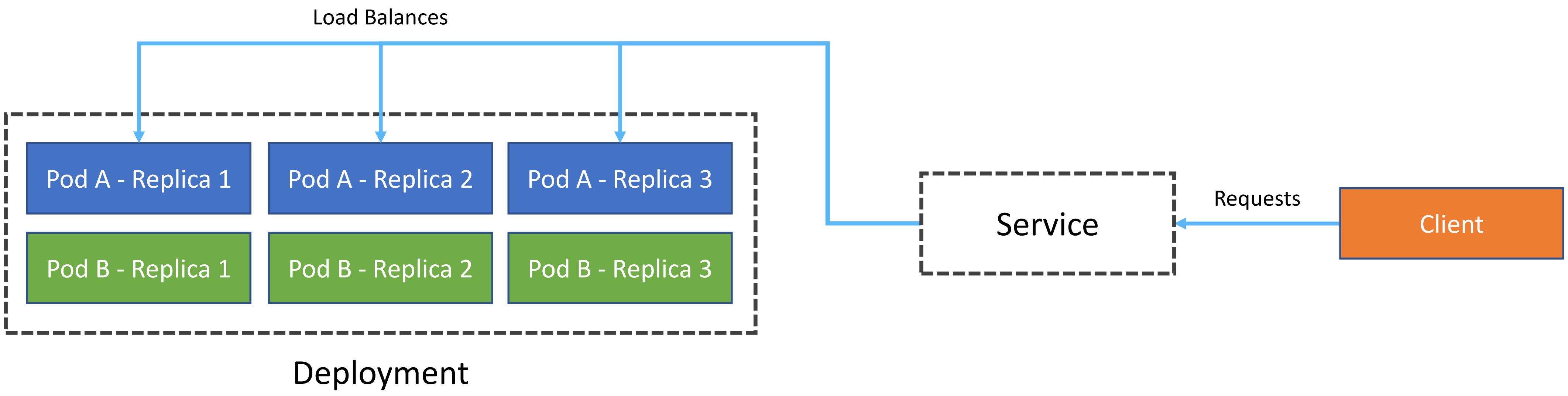
The primitive unit of computation in Kubernetes is a Pod, which consists of a set of one or more tightly-coupled containers that share the net, ipc and UTS namespaces:



The processes in the containers see different filesystems / user IDs / PIDs / etc., but can share memory and communicate over `localhost`, and can also bind-mount common shared volumes

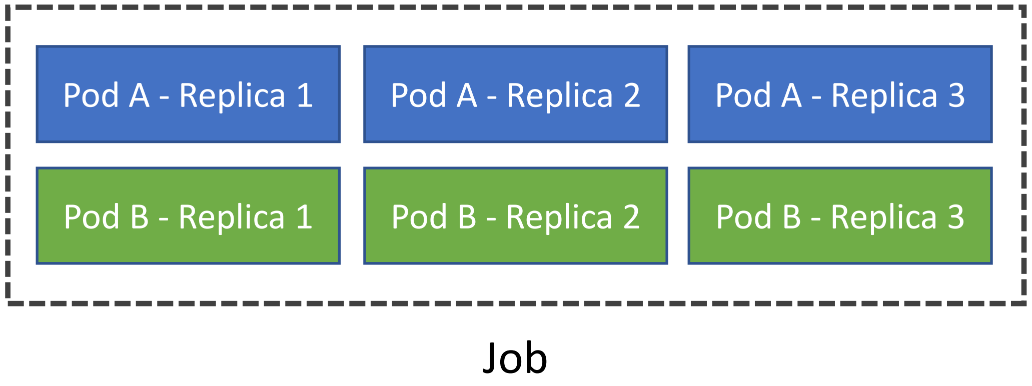
Orchestration with Kubernetes

Pods can be deployed and exposed using Deployments and Services for always-available applications that service requests:



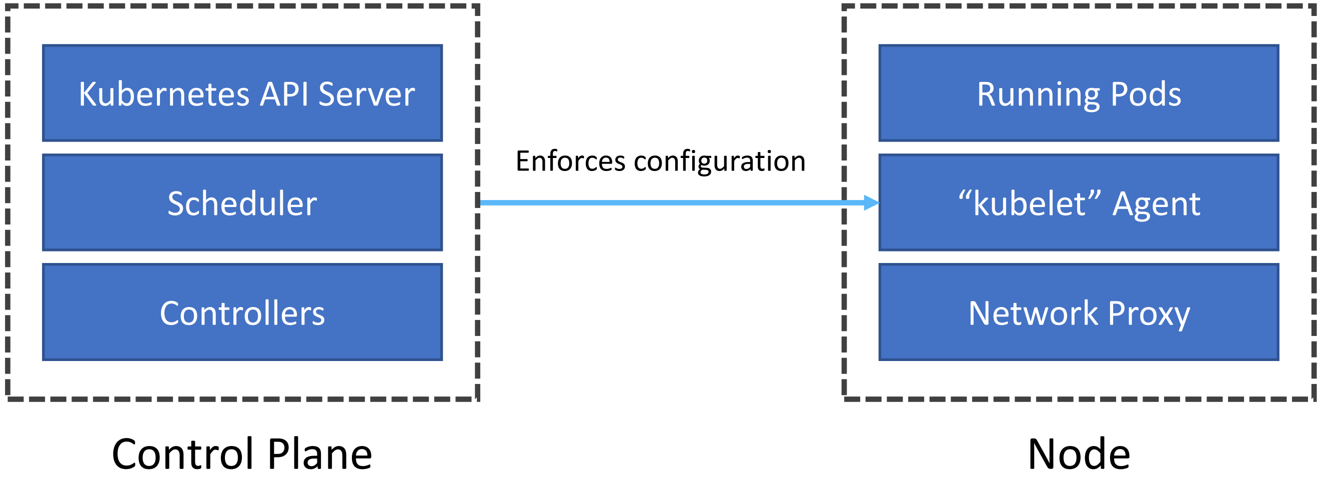
Orchestration with Kubernetes

Pods can be also deployed using Jobs for batch processing tasks that run to completion and stop, which can use replicas for batching data if desired:



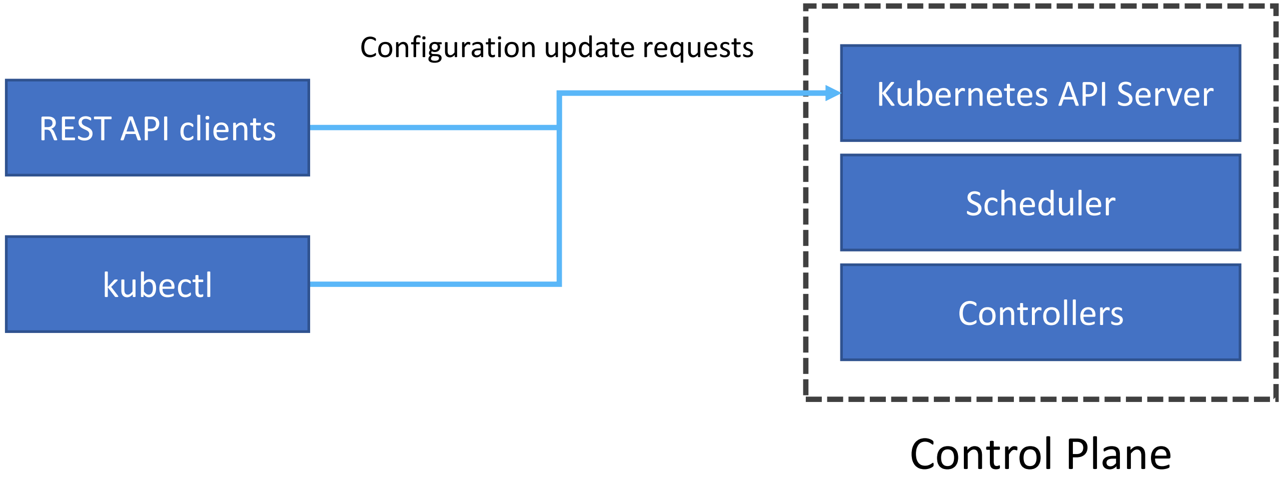
Orchestration with Kubernetes

Kubernetes architecture is split into the control plane and cluster nodes. The control plane contains the Kubernetes master components, which control the cluster nodes:



Orchestration with Kubernetes

The Kubernetes API Server services requests to modify cluster configuration via the Kubernetes REST API or frontends such as the kubectl command-line tool:



Orchestration with Kubernetes

Desired configuration states are specified declaratively using the JSON or YAML markup languages (using **YAML is recommended** as a best practice):

```yaml
apiVersion: apps/v1
kind: Deployment                # Creates a Deployment (for running always-available services)
metadata:
  name: nginx-deployment
  labels:
    app: nginx
spec:
  replicas: 3                   # Creates 3 replicas of our nginx pod
  selector:
    matchLabels:
      app: nginx                # Label matching is how the Deployment recognises the Pods it owns
  template:
    metadata:
      labels:                   # These labels are used to identify the Pods that get created
        app: nginx
    spec:
      containers:               # The pod consists of a single container running nginx
      - name: nginx
        image: nginx:1.7.9
        ports:
        - containerPort: 80     # nginx will be servicing HTTP requests on TCP port 80
```

Post-Section Activity:

06 – Deploying a simple Kubernetes service

Related Resources

Introduction to containers:

- Red Hat knowledgebase article discussing the mechanics and history of Linux containers:
  https://www.redhat.com/en/topics/containers/whats-a-linux-container

- Red Hat knowledgebase article discussing how containers fit into the context of cloud native apps:
  https://www.redhat.com/en/topics/cloud-native-apps

- Official definition of cloud native computing from the CNCF (which lists containers as a key component):
  https://github.com/cncf/toc/blob/master/DEFINITION.md

- Overview of Docker storage drivers, which discusses union filesystems:
  https://docs.docker.com/storage/storagedriver/

Related Resources

Process isolation:

- Linux manpage for namespaces:
  http://man7.org/linux/man-pages/man7/namespaces.7.html
- *Linux Journal* article discussing cgroups:
  https://www.linuxjournal.com/content/everything-you-need-know-about-linux-containers-part-i-linux-control-groups-and-process

Related Resources

Windows containers:

- Jon Starks' DockerCon presentation with all the low-level details about how Windows containers work: https://youtu.be/85nCF5S8Qok
- Microsoft documentation for Windows containers: https://docs.microsoft.com/en-us/virtualization/windowscontainers/

Related Resources

VM isolation:

- Documentation for process-isolated Windows container breakout vulnerability:
  https://unit42.paloaltonetworks.com/windows-server-containers-vulnerabilities/
- Microsoft documentation for Hyper-V isolation mode:
  https://docs.microsoft.com/en-us/virtualization/windowscontainers/manage-containers/hyperv-container
- Microsoft documentation for LCOW:
  https://docs.microsoft.com/en-us/virtualization/windowscontainers/deploy-containers/linux-containers
- Kata Containers architecture documentation:
  https://github.com/kata-containers/documentation/blob/master/design/architecture.md

Related Resources

Hardware acceleration in containers:

- NVIDIA blog post introducing NVIDIA Docker and discussing how it works:
  https://devblogs.nvidia.com/nvidia-docker-gpu-server-application-deployment-made-easy/

- AMD blog post discussing using ROCm with Docker containers:
  https://community.amd.com/community/radeon-instinct-accelerators/blog/2018/11/13/the-amd-deep-learning-stack-using-docker

- Microsoft documentation for hardware device support in Windows containers:
  https://docs.microsoft.com/en-us/virtualization/windowscontainers/deploy-containers/hardware-devices-in-containers

- Microsoft documentation for GPU acceleration in Windows containers:
  https://docs.microsoft.com/en-us/virtualization/windowscontainers/deploy-containers/gpu-acceleration

Related Resources

Container orchestration:

- Google publication describing the design of their internal scheduler, Borg (the predecessor of Kubernetes) with an empirical evaluation of its performance:
  https://ai.google/research/pubs/pub43438

- *Wired* article (from shortly before Kubernetes was released) discussing how Apache Mesos aimed to replicate Google's "secret weapon" (Borg):
  https://www.wired.com/2013/03/google-borg-twitter-mesos/

- Red Hat knowledgebase article discussing service meshes:
  https://www.redhat.com/en/topics/microservices/what-is-a-service-mesh

Related Resources

Kubernetes:

- Google blog post discussing the origins of Kubernetes and how it evolved from Borg:
  https://cloud.google.com/blog/products/gcp/from-google-to-the-world-the-kubernetes-origin-story

- Official Kubernetes documentation, providing comprehensive details on every aspect of the framework:
  https://kubernetes.io/docs/

TensorWorks

Prepared for TensorWorks by Dr Adam Rehn. Copyright © 2019 - 2021, TensorWorks Pty Ltd.

Licensed under a Creative Commons Attribution 4.0 International License.

All logos are the copyright, trademark or registered trademark of their respective owners.