(An Overview of) The Basic Building Blocks of Cloud Computing

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M2 MoSIG

October 2025

Outline

- General-purpose computing
- Networking (very brief overview)
- Storage (will be studied in a separate lecture)

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- **General-purpose computing**
  - Virtual machines
  - Containers
  - Physical machines
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- Storage (will be studied in a separate lecture)

Infrastructure building blocks for general-purpose computing tasks

- **Goals**: **Deploying, running, managing:**
  - *… arbitrary tasks*
  - *… made of arbitrary code*
  - *… in a flexible, convenient, secure, and efficient way (on a cloud platform).*

- Such an infrastructure relies on two major software building blocks:
  - Virtual machines
  - Containers

- Vocabulary: the above tasks are called **"guest code"** and are managed by the **"host" environment**.

Why virtual machines and containers in the Cloud?

- In a Cloud computing context, virtual machines and containers are **mainly used to support server consolidation while providing isolation guarantees**.

- **Server consolidation & multi-tenancy:**
  - **Main goals:** Improve resource usage and amortize costs by running (concurrent) workloads on the same physical machine.
  - Server consolidation **fosters multi-tenancy**, i.e., sharing hardware resources between workloads/applications deployed by distinct users/customers (“tenants”).

- Consolidation brings **several kinds of isolation requirements** (see details later):
  - Software configuration and dependency management
  - Performance and Quality of Service (QoS)
  - Safety/security/confidentiality of physical and logical resources

Virtual machines (1/6)

- *A (system-level) virtual machine is an **efficient & isolated duplicate** of a real (physical) machine*
- Often abbreviated as “VMs” or “Guest VMs” or “Guests”
- Machine **resources** include CPU(s), main memory (RAM), I/O devices (disks, NICs, peripherals …)
- Goals:
  - **“Duplicate”:** code running in a VM cannot distinguish between real or virtual hardware
  - **“Isolated”:** Several VMs execute concurrently on the same machine without interfering with each other (at least w.r.t. safety and security considerations)
  - **“Efficient”:** VMs should execute at a speed close to that of real hardware

Virtual machines (2/6)

The resources exported by a virtual machine may or may not correspond to the ones of the underlying physical hardware.

Typically, in practice, on a Cloud server:

- **Regarding the functional interface:**
  - The VM exports the same CPU model as the one of the physical machine (*same ISA: Instruction Set Architecture – such as Intel/AMD x86-64*).
  - The VM may or may not export the same types of I/O devices as the one of the physical machine.
- **Regarding the amount of available resources:**
  - A VM typically exports fewer resources than the total of physical resources.
  - Two main reasons:
    - Concurrent execution of multiple VMs (with decent performance)
    - Virtualization overhead

Virtual machines (3/6)

- The software layer in charge of supporting (system-level) virtual machines is called a **"Hypervisor"** or a **"Virtual Machine Monitor" (VMM)**.
  - **Warning:** These two expressions are often use interchangeably. However, in some designs/documents, they correspond to different parts of the virtualization system.

- In order to achieve better virtualization performance (i.e., lower overhead), nowadays **most hypervisors partially rely on support from the physical hardware**.
  - For virtualizing the CPU and main memory
  - Also possibly for some types of I/O devices (e.g., high-speed network interfaces)

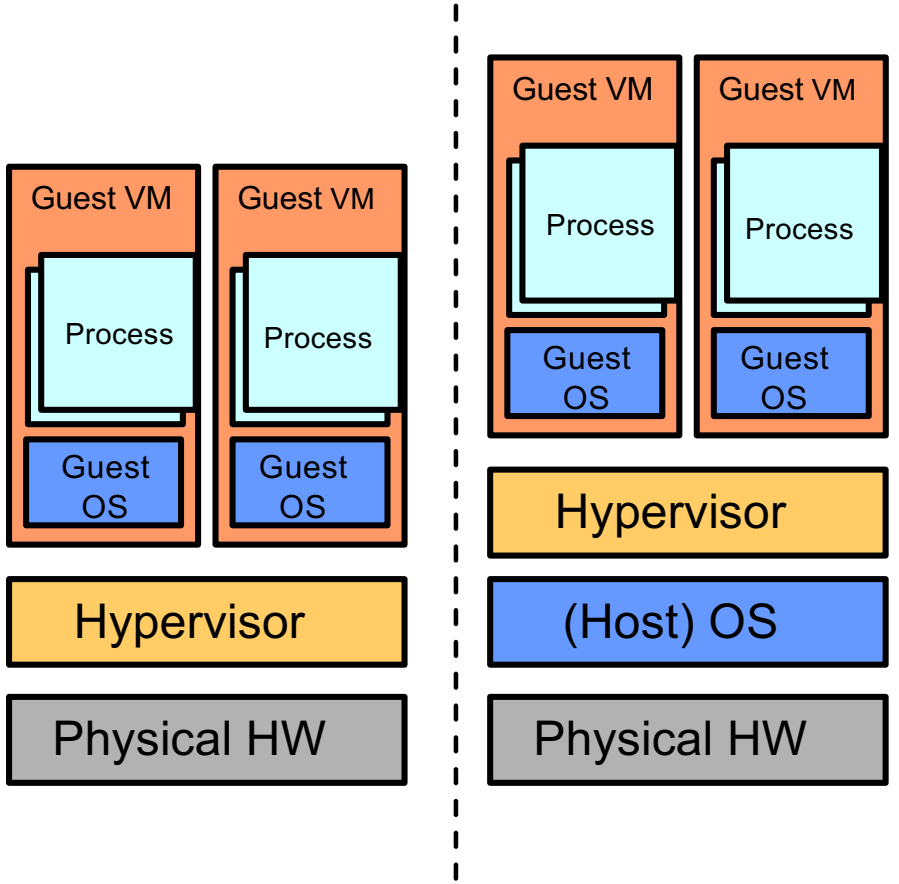
Virtual machines (4/6)

Where is the hypervisor in the software stack?

- There are several possibilities.
- On server systems, for performance reasons, the hypervisor is typically the lowest software layer (which directly controls the hardware).

In any case:

- Each guest VM has it own (guest) OS instance.
- Different VMs may have similar or different guest OSes.
- The expression “host software” corresponds to the layer(s) below the guests.



Virtual machines (5/6)

Warning: Beware of confusions between the concept of “hypervisor” and the other types of software layers listed below.

- **Language-level virtual machines:**
  - Examples: Java Virtual Machine (JVM), Python VM
  - Provide higher-level abstractions, at the scale of individual processes
  - Generally rely on a standard OS interface
- **Emulators:**
  - Conceptually closer to hypervisors
  - But with significant differences between the physical and virtual hardware (e.g., different ISA)
  - Mostly used for backwards compatibility or cross-development/testing
- **Hardware simulators:**
  - Aimed at precisely modelling the internal behavior of computer hardware (CPUs and/or devices)
  - Very different trade-off in terms of speed vs. accuracy
  - In contrast, hypervisors are only focused on externally-visible behavior of the hardware resources.

Virtual machines (6/6)

Most hypervisors rely on one or several forms of optimizations in order to improve the performance of the guest VMs.

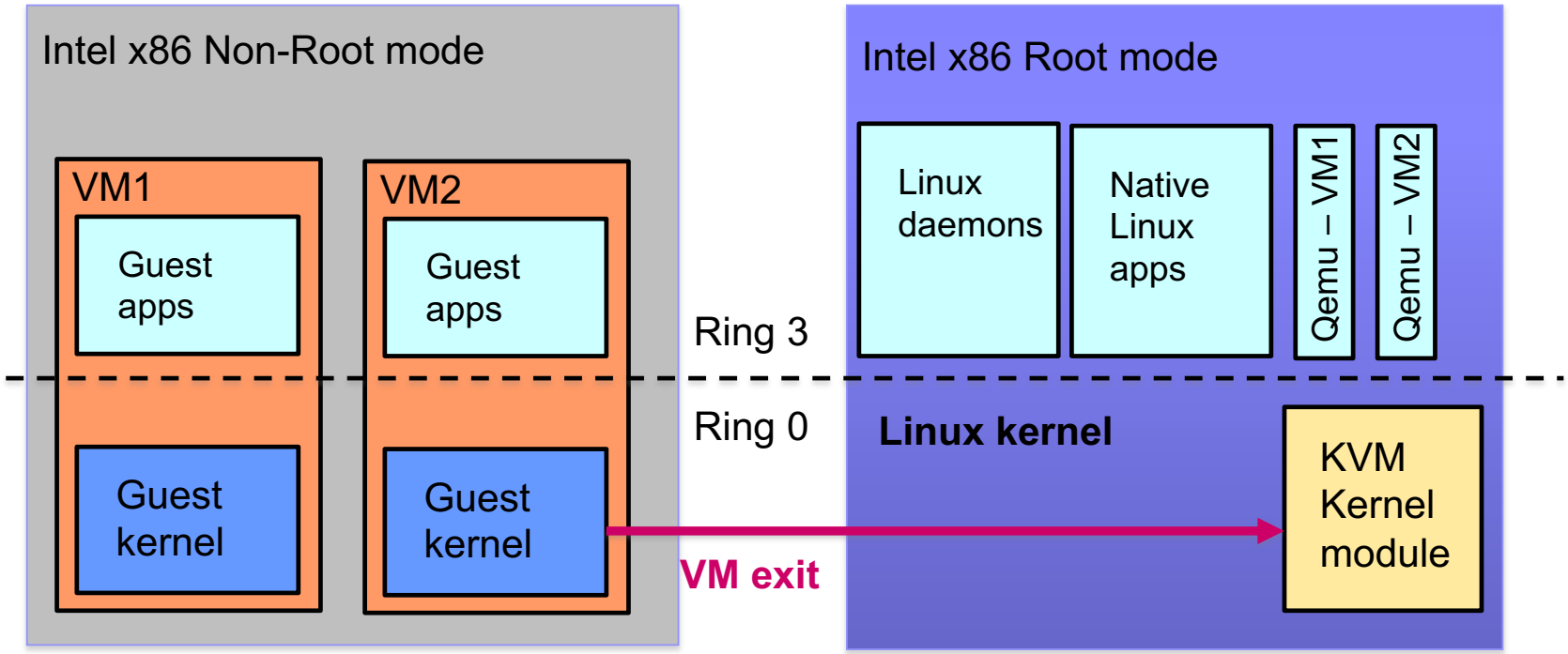
- **Paravirtualization:**
  - Principle: *Make the guest software "aware" of the fact that it is running in a virtualized platform.*
  - Involves various degrees of modifications in the guest OS:
    - At least, installation of specific device drivers
    - Also possibly deeper modifications of the guest kernel
  - Guest applications generally not modified
- **Direct device assignment:**
  - Principle: *Hypervisor gives full/direct control of a given physical device to a given guest.*
  - In practice, this usually relies on self-virtualizable hardware devices.

Hypervisor design

- There exists various hypervisor designs for server machines.
- Each design has **different characteristics and trade-offs regarding different dimensions**:
  - Virtualization performance
  - Resource footprint
  - Security and attack surface
  - Code maintainability and reuse
- Next, we will study **two mainstream open-source hypervisors**: Xen and Linux KVM,
  - In our illustration, we will focus on the versions designed for the Intel x86 architecture.
- **Some general trends:**
  - Hypervisor **code bases have become very large and feature-rich**. The attack surface and the number of security vulnerabilities is significant.
  - **More and more virtualization operations are offloaded to the hardware**, for performance and security reasons.

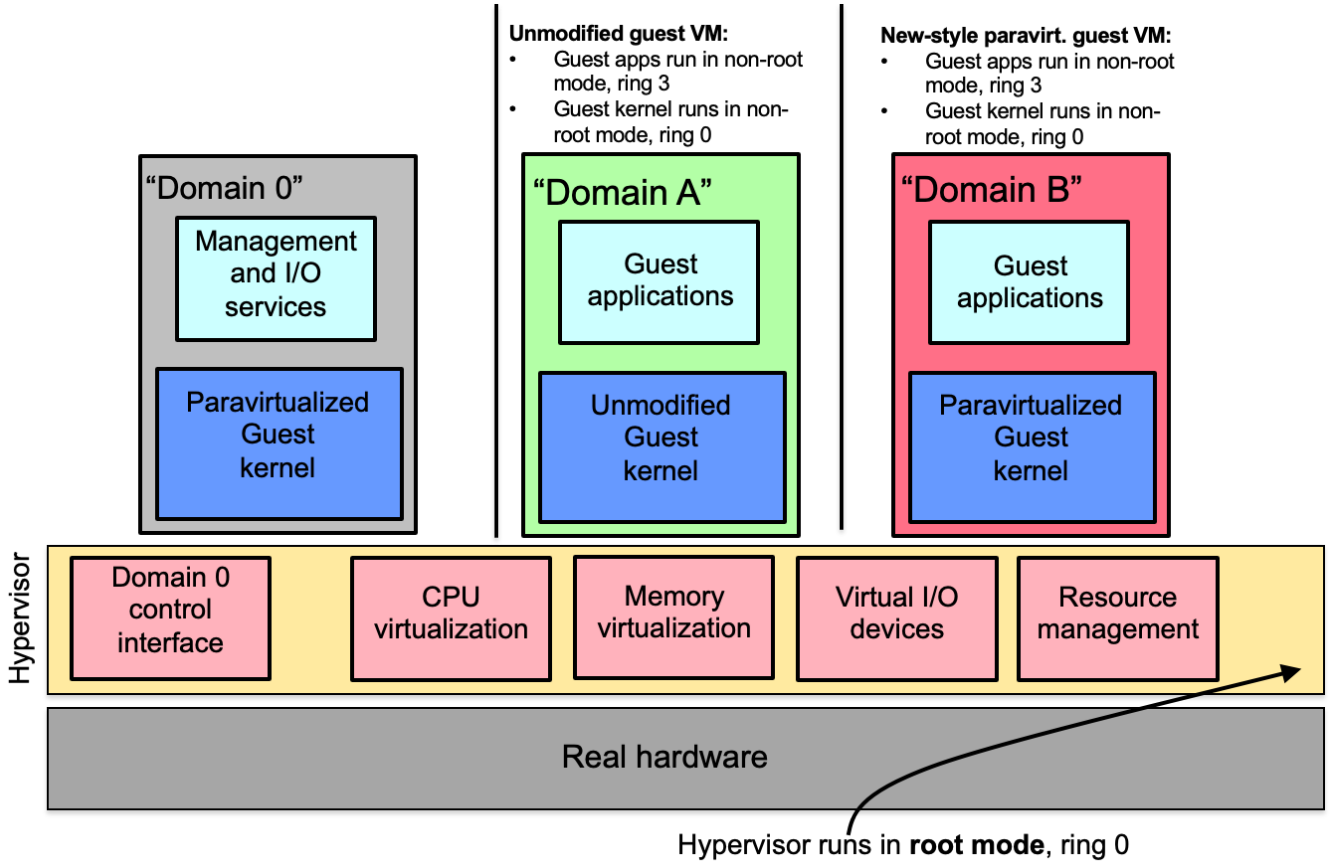
Hypervisor design – Example #1: Linux/KVM (Intel x86-64 version)

- KVM consists in a Linux kernel module + other software components allowing the Linux kernel to become a hypervisor.



Hypervisor design – Example #2: Xen (Intel x86-64 version)

- Xen consist in a native hypervisor + a specific VM (Linux-based, named “domain 0”) in charge of provide control and I/O services.

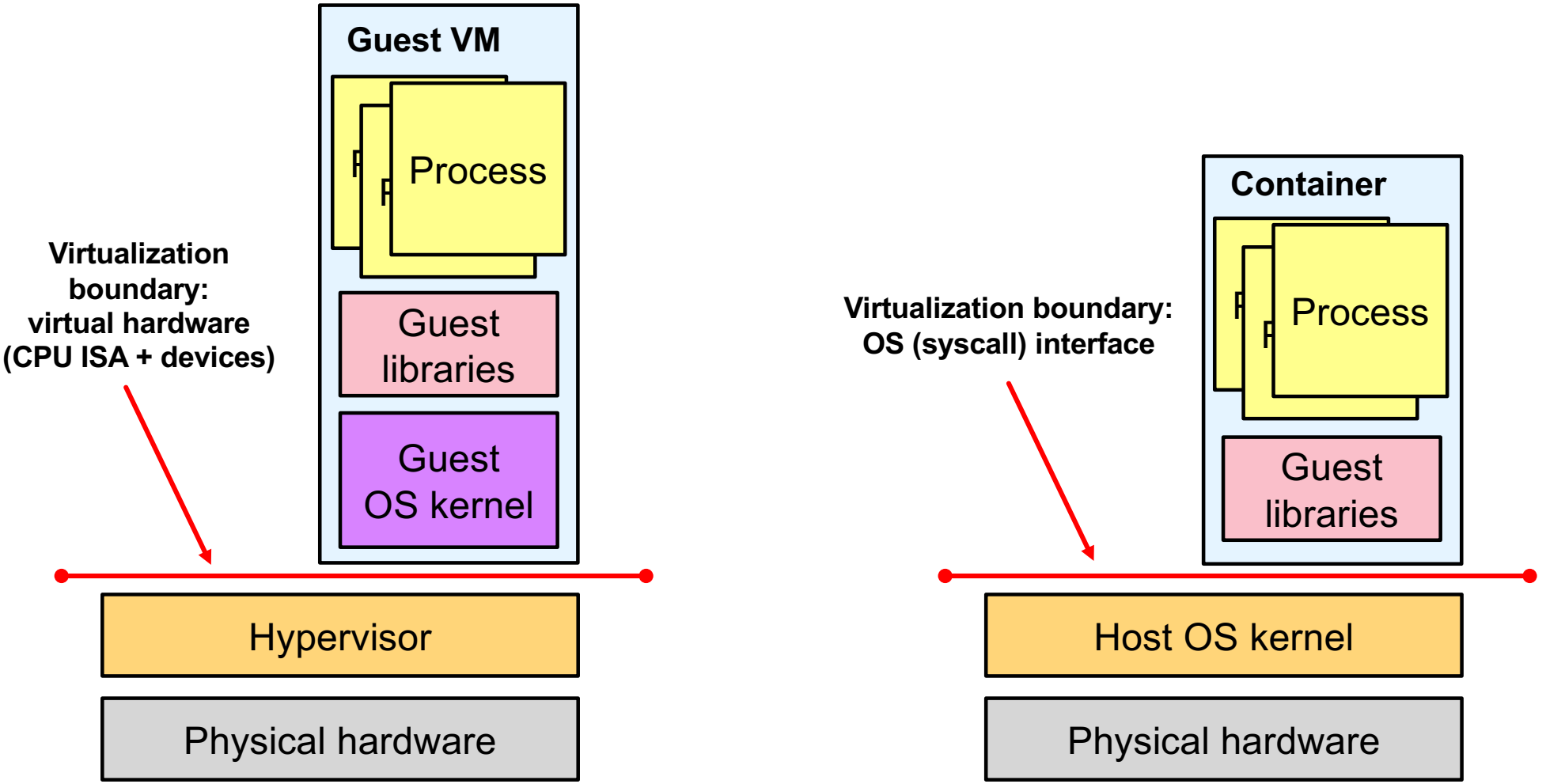


Containers (1/5)

- *Unlike (system-level) virtual machines,* ***containers support virtualization at the level of the OS interface*** *(rather than at the hardware interface).*
- Hence, they are also known as **"OS-level containers"** or **"OS-level virtualization"**.

- Roughly speaking, a container is akin to a "process group" in a traditional OS … yet with more isolation guarantees regarding security, performance and software configuration.
- Different containers running on the same machine **share the same underlying host kernel**. There are no guest kernels.

Containers (2/5)



Containers (3/5)

On Linux, the concept of containers is not a unified facility provided by the operating system.

Rather, *the management of containers is achieved by* ***combining a set of independent facilities*** provided by distinct Linux kernel subsystems and tools, among which:

- **Namespaces**: for configuring the system resources that are visible by a given process (network interfaces/ports, users, PIDs, …)
- **Control groups ("cgroups"):** for enforcing resource allocation limits
- **Capabilities:** for controlling the operations that a given process/user is allowed to perform on various kinds of resources
- **Seccomp:** for filtering the legitimate system calls that a process can make

Containers (4/5)

The containers ecosystem also includes **tools and facilities to simplify the management of container images** (i.e., the files to be included in the file system within a container).

- **Application packaging**
  - Management of executables, libraries, and configuration files
  - Management of version numbers and dependencies
  - Layered file system, allowing to define new images based on existing ones, in a simple and space-efficient way
- **Distribution and sharing of images**
  - Repository (“hub”) of existing images
  - Facilitated by the fact that most container images are lightweight (and layered)

Containers (5/5)

In practice, the management of containers is addressed via a set of software tools, which encompass **different needs**:

- Building **container images**, managing images, sharing and downloading images
- Managing **container instances**, running containers

There exists several tools with roughly similar features, like Docker and Podman.

The above-mentioned tools are themselves based on several modular building blocks, among which:

- **"Low-level runtimes"** focused on the machinery for running containers. Example: *runc* (used by Docker).
- **"High-level runtimes"** focused on support for download/managing container images and running a container from an image. Example: *containerd* (used by Docker).

OCI: Open Container Initiative (1/2)

- The OCI is (since 2015) "*an open governance structure for the express purpose of creating open industry standards around container formats and runtimes"*.
- So far, 3 main specifications have been produced (image, runtime, distribution).
- **Image format specification**:
  - "Defines the requirements for an OCI Image (container image), which consists of a manifest, an optional image index, a set of filesystem layers, and a configuration."
- **Runtime specification**:
  - "Specifies the configuration, execution environment, and lifecycle of a container." In particular, "defines how to properly run a container *"filesystem bundle"* which fully adheres to the OCI Image Format Specification."
- **Distribution specification**:
  - "Defines an API protocol to facilitate and standardize the distribution of content. It was launched in April 2018 to standardize container image distribution around the specification for the Docker Registry HTTP API V2 protocol, which supports the pushing and pulling of container images."

OCI: Open Container Initiative (2/2)

- For more details:
  - I. Velichko. What Is a Standard Container (2021 edition). https://iximiuz.com/en/posts/oci-containers/
  - B. Chen. Open Container Initiative (OCI) Specifications. 2019. https://alibaba-cloud.medium.com/open-container-initiative-oci-specifications-375b96658f55
  - A. Krajewska. Container image formats under the hood. 2020. https://snyk.io/blog/container-image-formats/
  - J. Webb. Docker and the OCI container ecosystem. LWN. 2022. https://lwn.net/Articles/902049/

  - OCI image spec: https://github.com/opencontainers/image-spec/
  - OCI runtime spec: https://github.com/opencontainers/runtime-spec
  - OCI distribution spec: https://github.com/opencontainers/distribution-spec

Virtual machines and Containers (1/3)

Virtual machines and containers **share a set of common design goals**:

- **Deployment:**
  - Notion of “virtual appliance”: Encapsulating code (applications, libraries, …) & configuration information to make software components more portable across machines and hosting environments.

- **Security isolation (a.k.a. “sandboxing”):**
  - Preventing “guest” code from performing unauthorized actions and accessing unauthorized data
  - In particular, preventing unwanted interactions with:
    - The (code and data of the) host and the other guests
    - The hardware resources of the machine (including the I/O devices)

- **Performance isolation:**
  - Precisely controlling the amount of low-level resources granted to each guest.
    - Avoiding/mitigating interferences between guests
    - Avoiding resource exhaustion/saturation (denial of service)
    - Possibly differentiating QoS between guests

Virtual machines and Containers (2/3)

However, virtual machines and containers also **have significantly different characteristics regarding some aspects:**

- **Dependencies for portability:** Hardware interface vs. OS interface (ABI)
- **Memory and disk footprint:** Containers are more lightweight.
- **Startup and shutdown latency:** Containers are faster.
- **I/O performance:** Depending on the chosen setups, VMs and/or containers may have non-negligible overheads for network- or disk-sensitive workloads. (There is no clear performance hierarchy between the two).
- **Syscall performance:** Same remark as above for syscall-intensive workloads.
- **Security:** VMs are arguably more secure. However, VM and container technologies both have a large attack surface.
- **Live migration (across physical hosts):** VMs have more mature/robust support.
- **Support for stateful (vs. stateless) workloads:** VMs have more mature/robust support.

Virtual machines and Containers (3/3)

These two technologies are not necessarily antagonist and mutually exclusive.

- In public clouds, containers are often/typically deployed within virtual machines.

- Modern “container orchestration” systems are agnostic regarding the actual container implementation and can use VMs as a replacement.
  - For example, in the Kubernetes orchestrator, the CRI (*container runtime interface*) specification is also compatible with virtual machines.

- Many recent facilities integrated in host operating systems can be leveraged by both technologies.
  - For example, on Linux, the seccomp and eBPF subsystems available for secure and efficient sandboxing & monitoring of guest code.

For more details on the principles and origins of virtual machines & containers

- **On virtual machines:**
  - A. Tanenbaum & H. Bos. Modern operating systems (4th edition). Pearson education. 2014. Chapter 7: "Virtualization and the cloud".
  - E. Bugnion, J. Nieh, D. Tsafrir. Hardware and Software Support for Virtualization. Morgan & Claypool. 2017.
- **On containers:**
  - A. El Amri. The missing introduction to containerization. 2019. https://medium.com/faun/the-missing-introduction-to-containerization-de1fbb73efc5
  - I. Lewis. Container runtime series (parts 1-4). 2017. https://www.ianlewis.org/en/container-runtimes-part-1-introduction-container-r
  - I. Velichko. What Is a Standard Container (2021 edition). https://iximiuz.com/en/posts/oci-containers/
  - E. Baker. A comprehensive container runtime comparison. 2020. https://www.capitalone.com/tech/cloud/container-runtime/
  - J. Webb. Docker and the OCI container ecosystem. 2022. https://lwn.net/Articles/902049/
  - A.Suda. The internals and the latest trends of container runtimes. 2023. https://medium.com/nttlabs/the-internals-and-the-latest-trends-of-container-runtimes-2023-22aa111d7a93
- **On both kinds of resources:**
  - Allison Randal. The Ideal Versus the Real: Revisiting the History of Virtual Machines and Containers. ACM Computing Surveys. May 2020. https://dl.acm.org/doi/abs/10.1145/3365199

“Lightweight” virtual machines (1/3)

- Containers have thrived because they are lightweight … but they are more difficult to run securely than virtual machines.

- Recently, new virtualization software has emerged with the following goals:
  - Reaching resource footprints ~ similar to those of containers
  - Reaching startup/shutdown times ~ similar to those of containers
  - Providing good I/O performance (without per-VM dedicated I/O devices)
  - Retaining the stronger isolation properties of virtual machines

"Lightweight" virtual machines (2/3)

Such "lightweight" virtual machines can use either:

- A stripped-down version of **a traditional guest OS** like Linux
- A **"unikernel"** (a.k.a. **"library OS"**)
  - A specialized guest OS that is tightly linked with the application (single binary)
  - There is no run-time boundary between the app and the guest OS
  - Provides better performance and lower resource footprint
  - May complicate some other aspects: administration, debugging, compatibility with multiprocess applications, …

"Lightweight" virtual machines (3/3)

Examples (open-source projects):

- **Firecracker VMM** by Amazon Web Services
  - Used by AWS for secure and efficient execution of lightweight/ephemeral services (e.g., AWS Lambda and AWS Fargate)
  - Based on a modified version of the KVM hypervisor + a replacement of the QEMU emulator + restricted/simplified device set/model + implementation in a safe language (Rust) + container technologies
  - https://firecracker-microvm.github.io
  - A. Agache et al. Firecracker: Lightweight virtualization for serverless applications. In Proceedings of NSDI 2020. https://www.usenix.org/conference/nsdi20/presentation/agache
- **Kata containers** by Intel
  - https://katacontainers.io
- **LightVM project** (research prototype)
  - http://sysml.neclab.eu/projects/lightvm/
  - Research article: F. Manco et al. "My VM is faster (and safer) than your container". In Proceedings on the 2017 ACM Symposium on Operating System Principles.

Unikernels

For more details, see the following references:

- http://unikernel.org
- A. Madhavapeddy and D. Scott. Unikernels: The rise of the virtual library operating system. Communications of the ACM. January 2014.
- A. Kivity et al. OSv—Optimizing the Operating System for Virtual Machines. In Proceedings of the 2014 USENIX Annual Technical Conference.
- Bryan Cantrill. Unikernels are unfit for production. January 2016. https://www.joyent.com/blog/unikernels-are-unfit-for-production
- S. Kuenzer. Unikraft: Fast, Specialized Unikernels the Easy Way. In Proceedings of EuroSys 2021. https://unikraft.org
- A. Raza et al. Unikernel Linux (UKL). Proceedings of EuroSys 2023. https://dspace.mit.edu/bitstream/handle/1721.1/150839/3552326.3587458.pdf

Physical machines (1/2)

- Also known as “**bare-metal instances**” or “**hardware as a service (HaaS)**”
- **Interface:**
  - a raw, dedicated physical machine, on which a user can freely deployed the host OS of his choice
  - … through remote management software interacting with the machine’s firmware and BMC (baseboard management controller)
- **Popular in various contexts:**
  - Private clouds
  - High-Performance Computing (HPC) centers
  - Research & teaching testbeds
  - Also, more recently, in public clouds. For example:
    - AWS EC2 bare metal instances
    - Packet.com (specialized provider for bare metal cloud resources)

Physical machines (2/2)

- **Allow full machine reservation and reinstallation at small time scales.**
  - OS image installation/deployment time ~ a few minutes
  - Flexible reservations times (from minutes to days)
  - Public clouds support per-second billing
- **Useful for various needs:**
  - Benefits stemming from the **physical isolation of the machine** (removing potential interferences caused by multi-tenancy):
    - Improved security
    - Improved performance
    - Improved predictability (e.g., important for research and real-time workloads)
  - Also, benefits due to the **removal of virtualization**:
    - May have significant positive impact on some workloads (e.g., HPC, network intensive)
    - May enable/accelerate guest-level virtualization (removing the need for nested virtualization)
    - May enable support for non-virtualized hardware accelerators (e.g., GPUs)

Virtual & physical machines – Offerings in the public clouds

- **A large & growing diversity of hardware configurations**
  - Several main categories (with sub-categories and sub-parameters in each)
    - General purpose
    - Compute optimized
    - Memory optimized
    - Storage optimized
    - Accelerated computing
    - Custom configurations
  - Fixed CPU resources vs. burstable

- **Different pricing/reservation models**
  - On demand instances
  - Reserved instances
  - Spot/preemptible instances

Outline

- General-purpose computing
- **Networking** (very brief overview)
- Storage (will be studied in a separate lecture)

Networking

Typical features/services include:

- Virtual Private Cloud (VPC):
  - IP subnet topology/setup
  - Virtual LANs (VLANs)
  - Network Address Translation (NAT) Gateways
  - Virtual Private Networks (VPNs)
  - Firewalls
  - Routers
- Domain Name System (DNS)
- Content delivery networks (CDNs)
- Application-level load balancers
- API gateways