15-440 Distributed Systems

Scaling Techniques

Virtualization

Lecture #19, Tuesday Nov 9th 2021

Announcements

- HW4: Released 11/17 Due 11/29, ***No Late Days***
  - ***Note,*** *question on BFT will not be graded so you can technically finish HW4 in a week (by 11/24) before thanksgiving starts!*
- P3 (Tribbler): Released 11/14
  - *Checkpoint: 11/23, P3 Final (12/3). Team Matching survey @Piazza*
- Thanksgiving: No class Tues (11/23) or Thurs (11/25)!
  - Modified TA and instructor OHs that week, To be Announced
- Midterm-2 - In Class, During Class Time
  - Thursday, December 2nd, 10:10 – 11:30
  - Please try and arrive early, 10:00-10:05am, get settled.
  - Topics: Focus on the 2nd half of class (links to 1st half also possible)

What is “Scalability”?

Ability to easily and rapidly grow the system

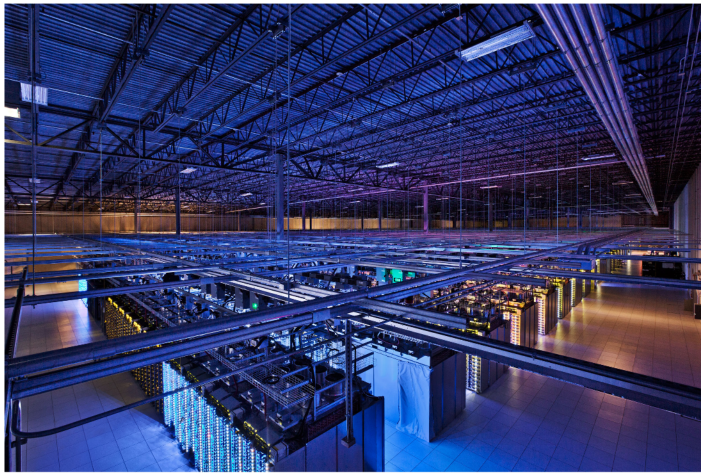
Many aspects:

1. load scalability (How easy to add more concurrent users?)
2. content scalability (How easy to add content? aka “data scalability”)
3. geographic scalability (Tolerance for high-latency WANs?)
4. functional scalability (How easy to add new capabilities?)
5. evolutionary scalability (How easy to add new hardware/software?)
6. administrative scalability (How hard to manage?)

Load Scalability

Characteristic of good design for distributed systems

- small marginal load due to each additional client
- maximum # of clients with fixed # servers



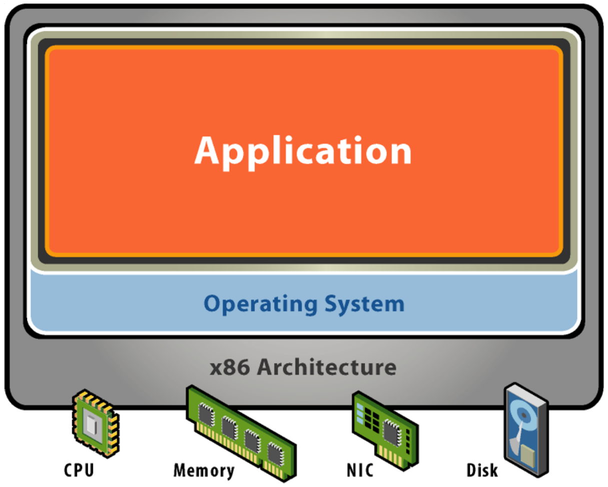
Need: ability to dynamically grow resources

- hard to do with real resources
  - → purchase of new servers, storage, networks, etc.
  - → growing/shrinking over small timeframes/quanta not feasible
- made possible by **virtualization**
  - → primarily Virtual Machines (VMs), but extends to other resources as well
  - → e.g "software-defined networking" virtualizes network components
  - → e.g. "software-defined storage"virtualizes storage components

Virtual Machine

Virtual machine = perfect software abstraction of
OS-visible hardware

Starting Point: Physical Machine



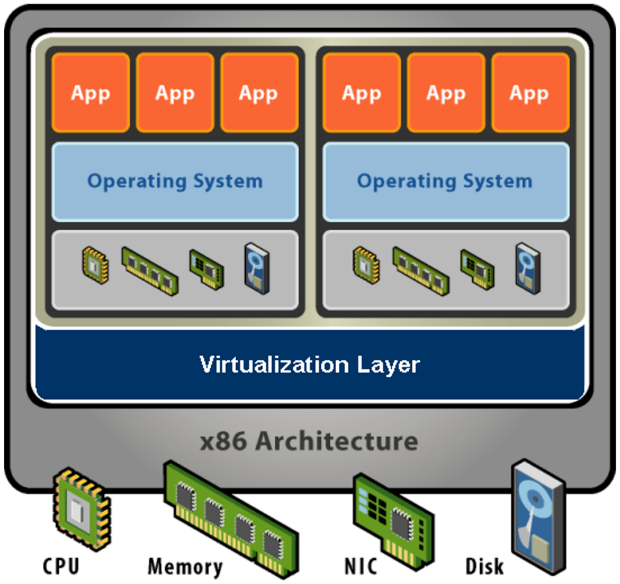
- Physical Hardware
  - Processors, memory, I/O devices,…
- Software
  - Single active OS instance
  - OS controls hardware

Figure adapted from: Eyal DeLara

Virtual Machine

Virtual machine = perfect software abstraction of
OS-visible hardware

Virtual machines on a physical machine

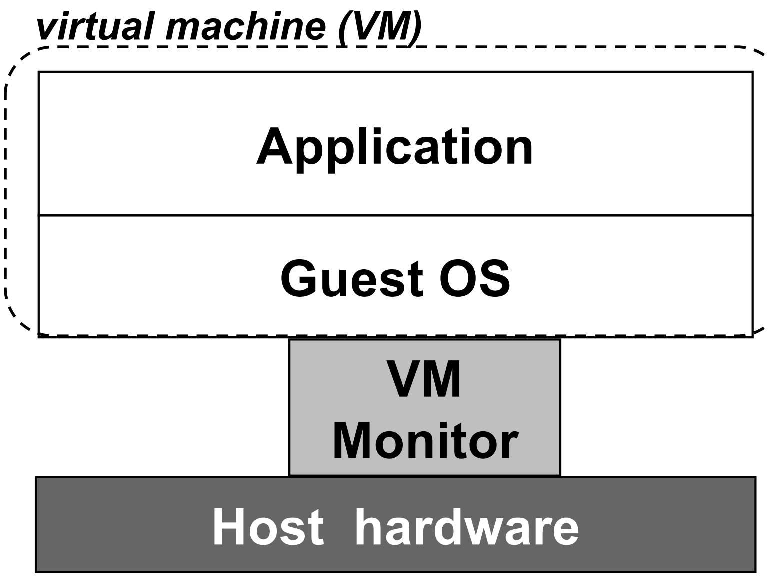


- Software Abstraction
  - Behaves just like hardware
  - Allows multiple OSes

Figure adapted from: Eyal DeLara

Virtual Machines

- A virtual machine monitor (VMM) aka "hypervisor" implements the VM abstraction
  - software layer between OS and hardware
  - functionally invisible to OS and apps
  - able to multiplex hardware among multiple VMs



Reasons for Virtualization

Virtualization can transform CAPEX into OPEX

- CAPEX → "capital expenses"
- OPEX → "operational expenses"

  → smaller incremental investments, different accounting rules

  → great boon for startups and small mature companies

- Cloud computing/storage:
  - cloud owner (e.g. Amazon) incurs CAPEX
  - cloud users (e.g. startup) incurs only OPEX

    → cloud owner makes a profit from OPEX pricing
  - Flexible allocation of resources in cloud **→ "elasticity"**
    - "EC2" in "Amazon EC2" stands for "elastic cloud computing"

Reasons for Virtualization

Improve Resource Utilization

CAPEX→ OPEX;
Elasticity: Adapt to changing resource requirements

Resource & Failure Isolation

Monitor and limit resource usage (e.g., CPU) , Contain failures locally

Mixed-OSEnvironment

Support multiple operating systems on a single hardware platform

Security Isolation

“Sandboxing”: fully control any resource access and possible actions of tenant

Roots of VM Technology

Roots of today’s VMs reach back to 1960s

M44/44X (IBM), CTSS (MIT), {CP-40, CP-67, CP/CMS} (IBM) VM/370 (IBM product, 1972)

What was the driving force?

- Hardware very expensive (mainframes) → few machines
- Explosion of effort in low-level system software
- Pain point: need real hardware for testing
  → “nearly identical” not good enough

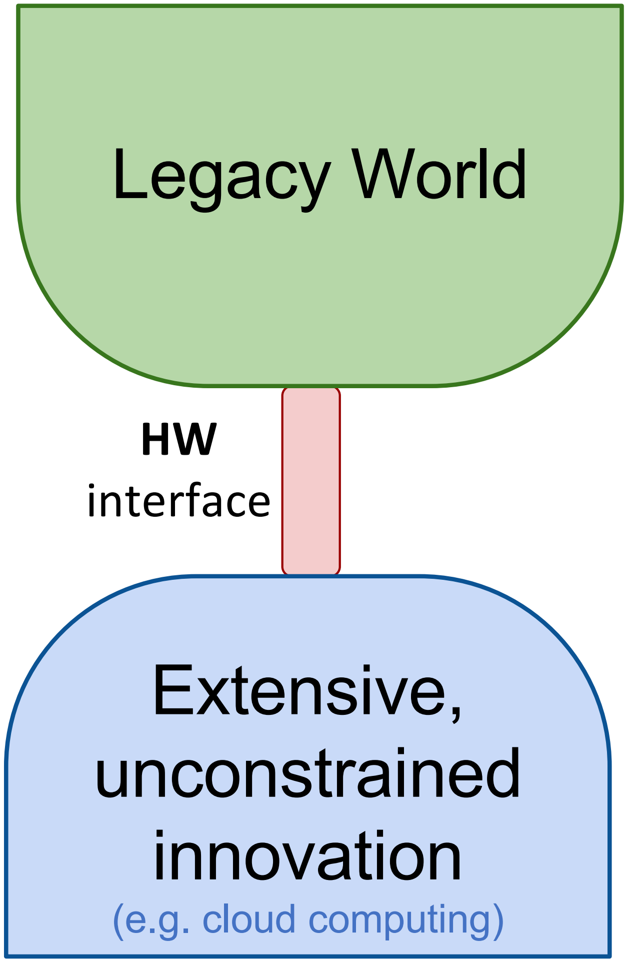
Hardware virtualization wins big

- enhances productivity of system software development
- new software runs concurrently with older versions
- Multiple developers can share a single physical machine

The Strange History of VMs

mid-1960s to early 1970s	birth and emergence
early 1970s to late 1970s	extensive commercial use (VM/CMS)
late 1970s to early 1980s	emergence of personal computers (IBM PC)
late 1980s to late 1990s	“demise” of VMs
late 1990s	rebirth of VMs (VMware)
early 2000s	resurgence of research interest in VMs
late 2000s to present	explosion of commercial interest (cloud computing)

Why is HW Virtualization special?



Narrow & stable waistline critical

- narrow → freer innovation
- narrow → vendor neutrality
- stable → longevity / ubiquity

Software too malleable and too wide!

Wide interfaces → brittle abstractions

- Hard to deploy, hard to sustain, hard to scale
- E.g., software interface: processes

Virtual Machine Monitor

- A virtual machine monitor (VMM) aka “hypervisor” implements the VM abstraction
  - software layer between OS and hardware
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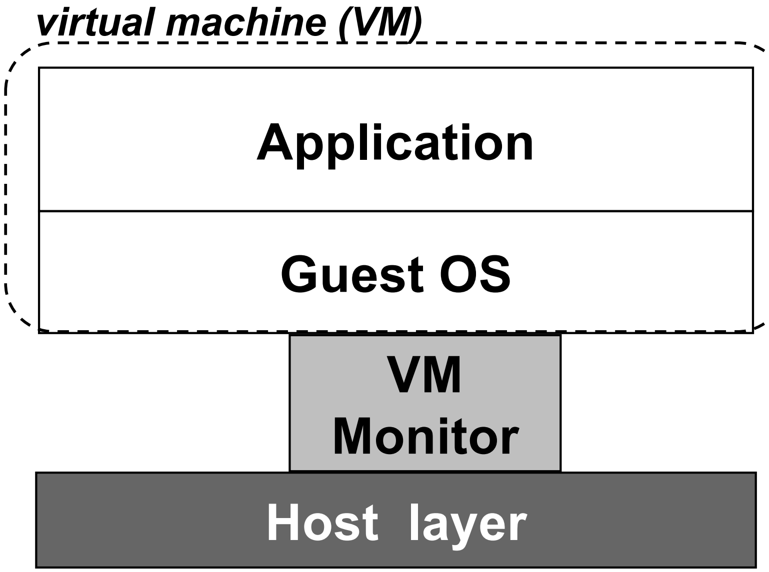


Virtual Machine Monitor

- Classic Definition (Popek and Goldberg ’74)

A virtual machine is … an efficient, isolated duplicate of the real machine.
… the VMM provides an environment for programs which is essentially identical with the original machine;
second, programs run in this environment show at worst only minor decreases in speed;
and last, the VMM is in complete control of system resources.

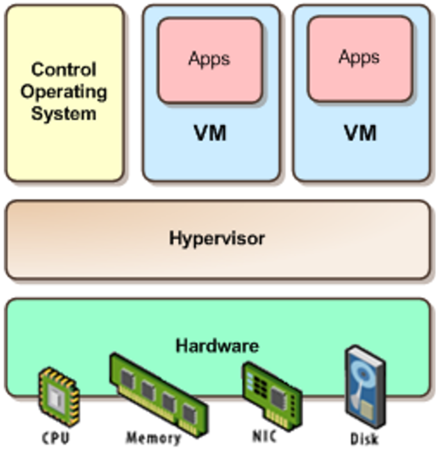
Virtual Machine Monitor

Desired properties for VMM (aka “hypervisor”)

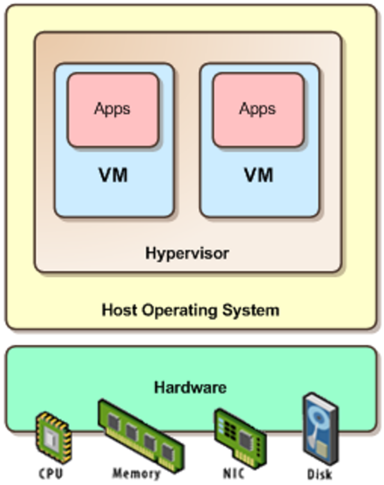
- **Fidelity**: Programs running in the virtualized environment run identically to running natively.
- **Performance**: A statistically dominant subset of the instructions must be executed directly on the CPU.
- **Safety and isolation**: The VMM must completely control access to system resources.

Types of System Virtualization

- Type 1: Native/Bare metal
  - Higher performance
  - E.g., VMWare ESX, KVM, Xen, Hyper-V



- Type 2: Hosted
  - Easier to install and use, cheaper
  - Leverage host's device drivers
  - Aka "client hypervisors"
  - E.g., VMware Workstation, Parallels



- Guest OS'es unaware of the type of hypervisor

Picture from: https://itechthoughts.wordpress.com/tag/full-virtualization/

Properties of VMs

- Isolation

  Resource & Failure Isolation

  Mixed-OS Environment

  - Fault isolation, performance isolation, software isolation
- Encapsulation and portability

  Improved Resource Utilization

  - Cleanly capture all VM state
    - Enables VM snapshots, clones
  - Independent of physical hardware
  - Enables migration of live, running VMs
- Interposition

  Security Isolation

  - Transformations on **instructions, memory, I/O**
  - Enables encryption, compression, …

Adapted from: Eyal DeLara

CPU Virtualization

Privileged instructions

Non-Privileged instructions

- **Privileged instructions** (e.g., IO requests, Update CPU state, Manipulate page table)

- **Non-privileged instructions** (e.g., Load from mem)

CPU Virtualization

Privileged instructions

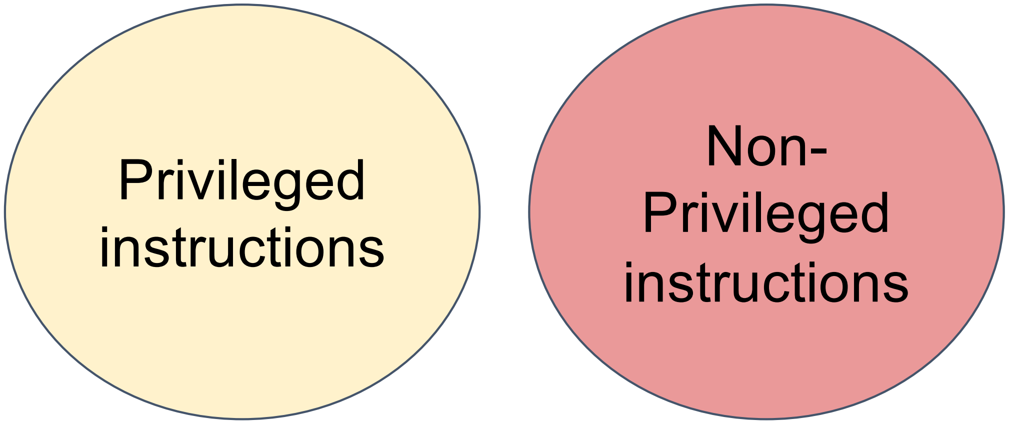
Non-Privileged instructions

OS (even without any virtualization) also needs to handle these differently: kernel mode vs user mode

- **Privileged instructions from user mode:**
“Trap to OS” and executed from kernel mode

- **Non-privileged instructions:** Run directly from user mode

CPU Virtualization

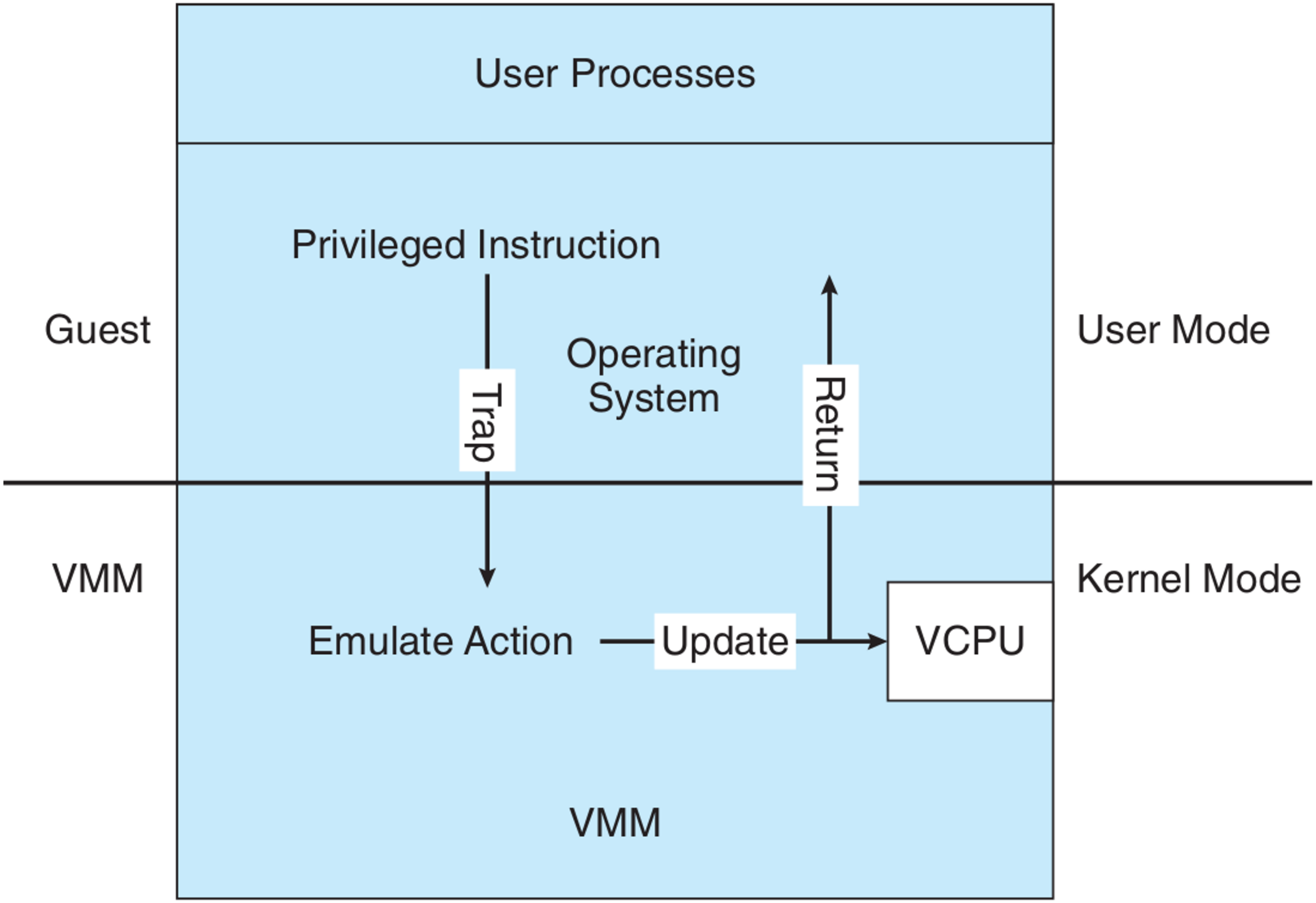


For virtualization:

- **Privileged instructions from user mode:** **"Trap to VMM"**

- **Non-privileged instructions:** Run directly on native CPU

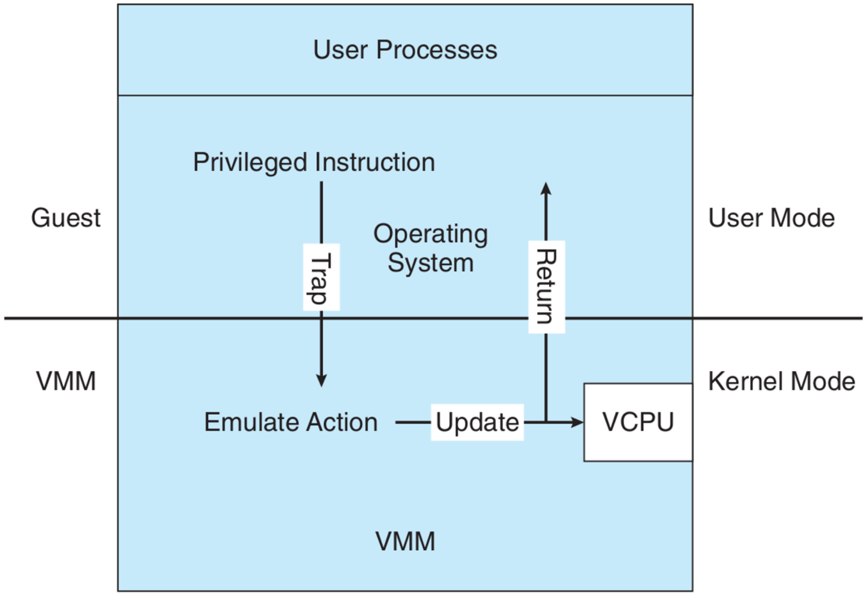
CPU Virtualization



CPU Virtualization

Privileged instructions

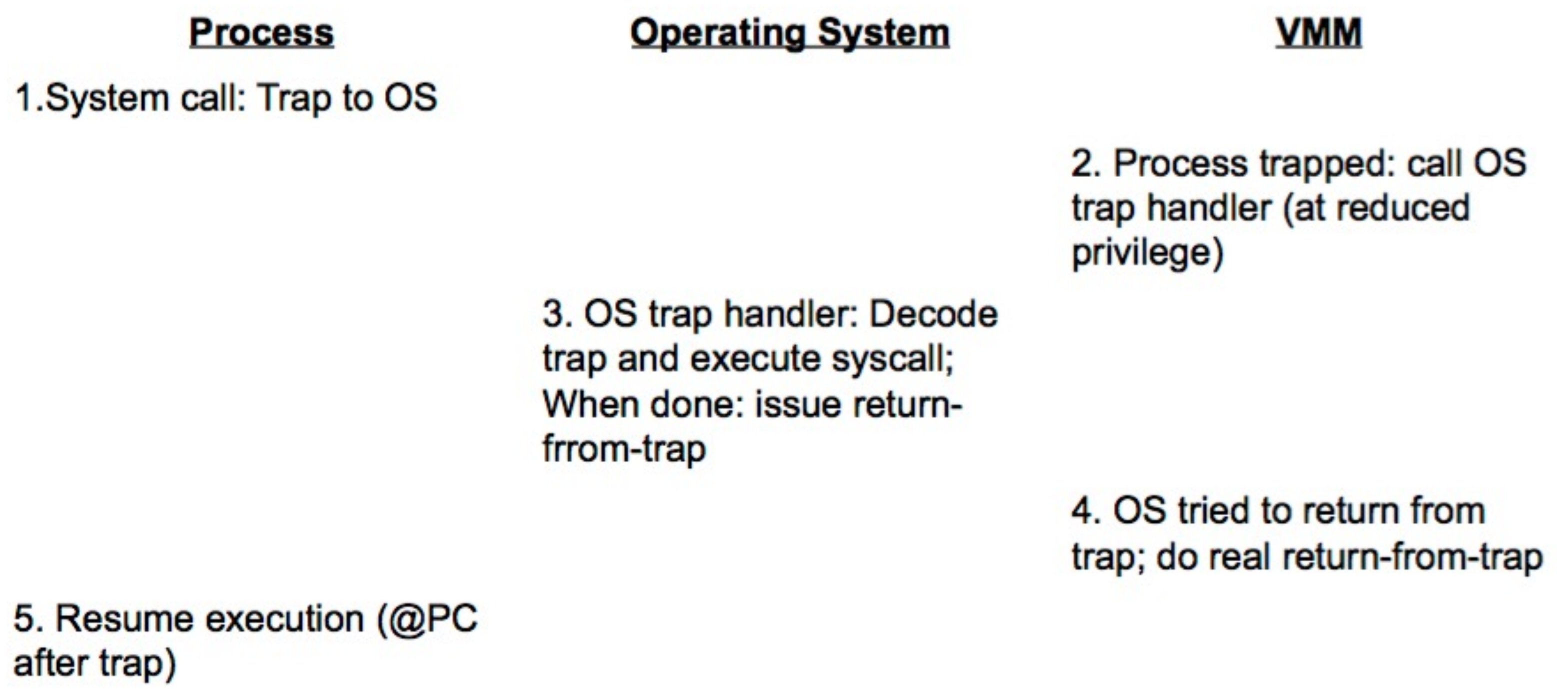
Non-Privileged instructions



This is called Trap and Emulate
→ Full Control for VMM

More complex in reality (no clear separation)
→ Processor support Intel VT-x, AMD-V

System Call Example



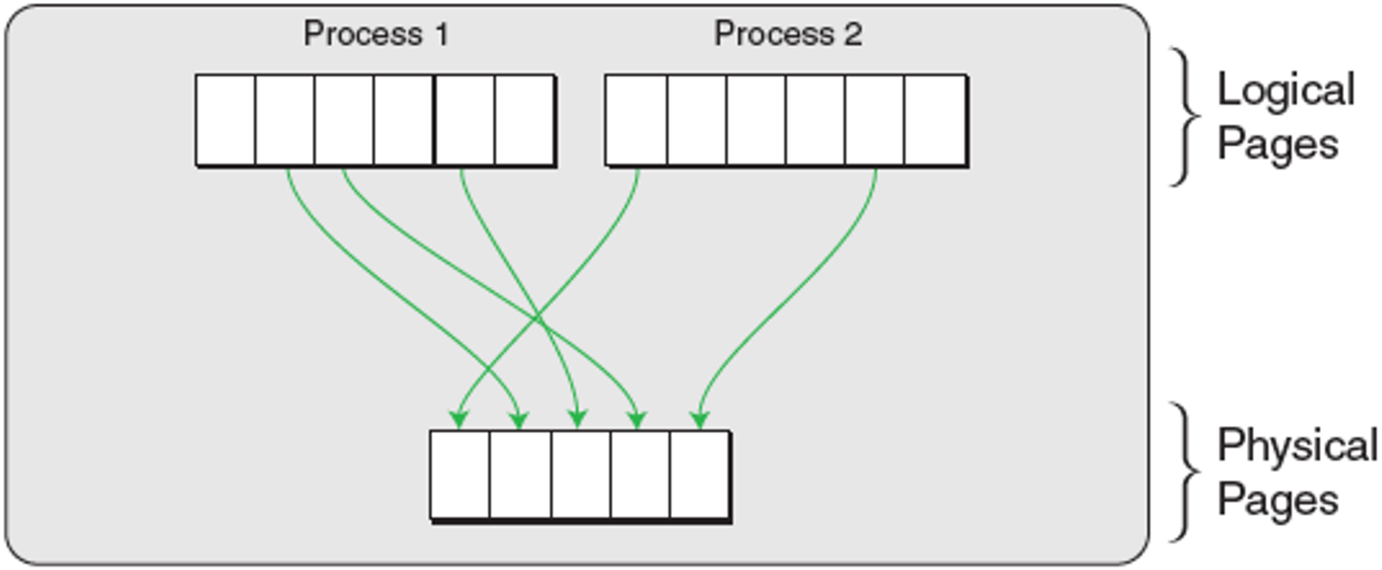
Process	Operating System	VMM
1.System call: Trap to OS		
		2. Process trapped: call OS trap handler (at reduced privilege)
	3. OS trap handler: Decode trap and execute syscall; When done: issue return-frrom-trap	
		4. OS tried to return from trap; do real return-from-trap
5. Resume execution (@PC after trap)		

- *Run guest operating system deprivileged*
- *All privileged instructions trap into VMM*
- *VMM emulates instructions against virtual state*
  e.g. disable virtual interrupts, not physical interrupts
- *Resume direct execution from next guest instruction*

Adapted from: JP Singh @ Princeton

Memory Virtualization

- OS assumes that it has full control over memory
    - Management: Assumes it owns it all
    - Mapping: Assumes it can map any Virtual→ Physical



Native machine

Adapted from: Alex Snoeren

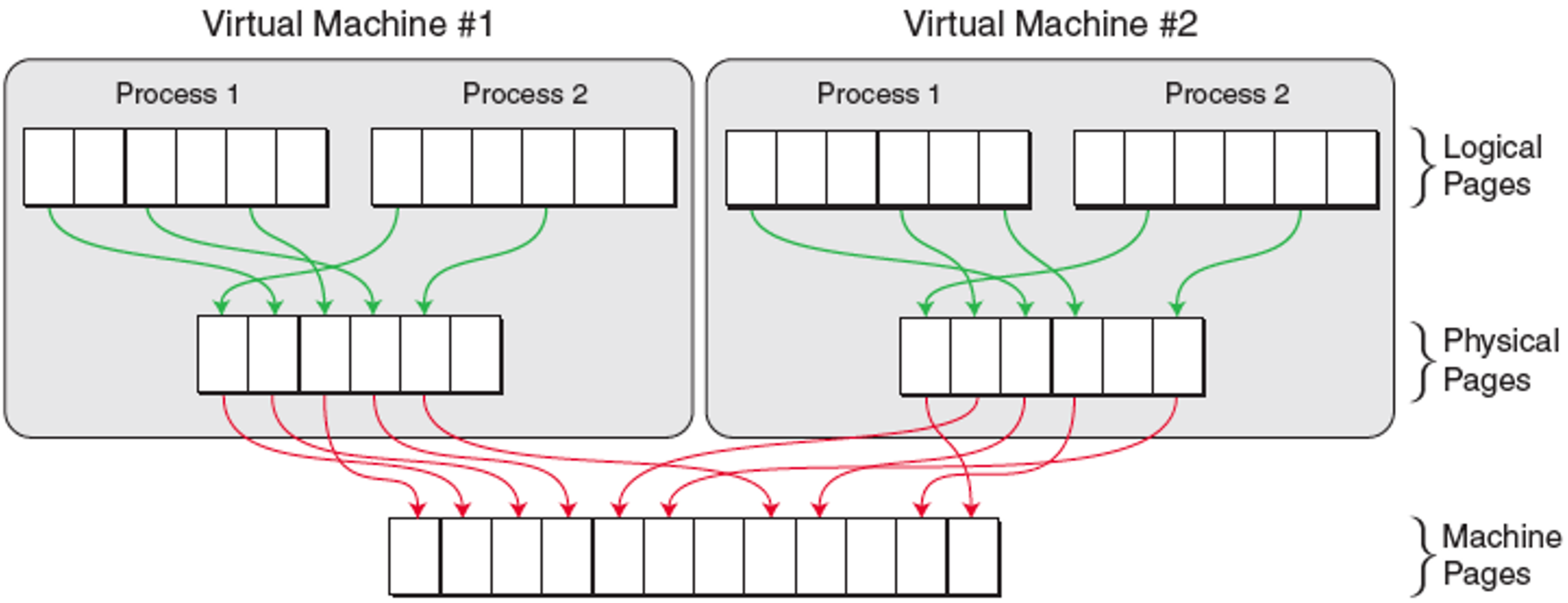
Memory Virtualization

- OS assumes that it has full control over memory
  - Management: Assumes it owns it all
  - Mapping: Assumes it can map any Virtual→ Physical

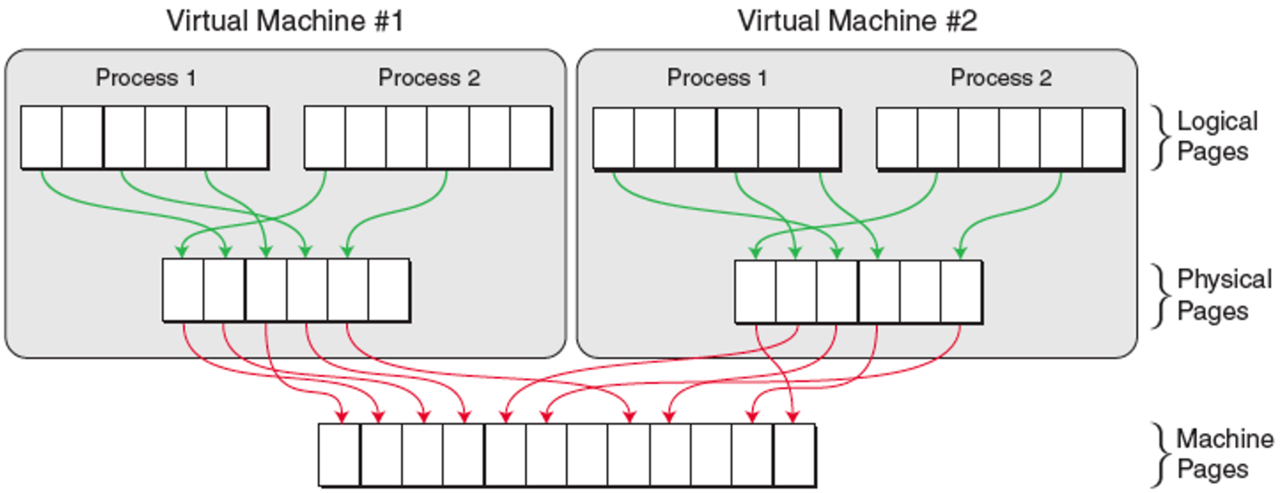
- However, VMM partitions memory among VMs
  - VMM needs to assign hardware pages to VMs
  - VMM needs to control mapping for isolation
    - Cannot allow OS to map any Virtual ⇒ hardware page

Adapted from: Alex Snoeren

Virtualized Memory: Three Levels of Abstraction



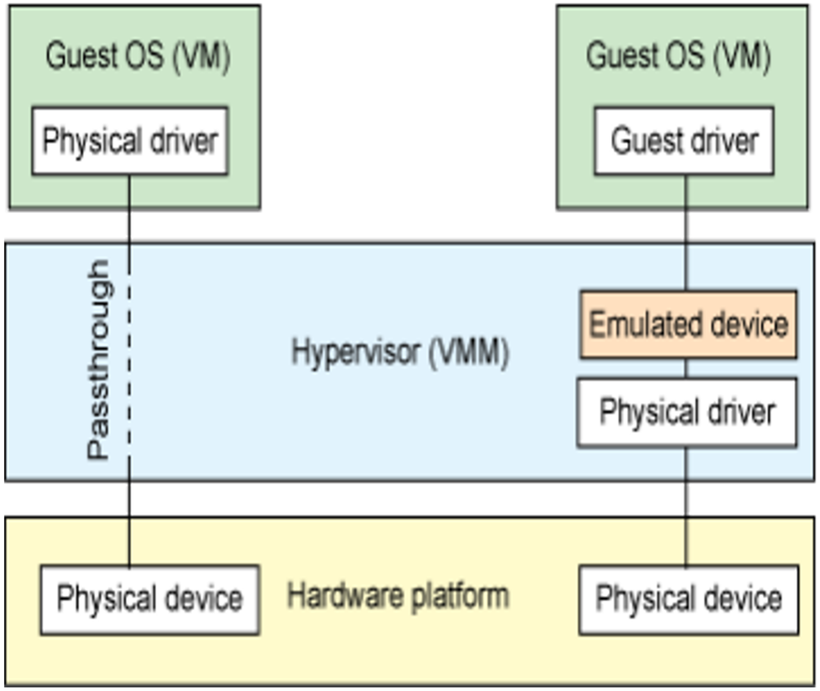
Virtualized Memory: Three Levels of Abstraction



- **Logical**: process address space in a VM
- **Physical**: abstraction of hardware memory. Managed by guest OS
- **Machine**: actual hardware memory (e.g. 2GB of DRAM). Managed by VMM

I/O Virtualization

- Direct access: VMs can directly access devices
    - Requires H/W support (e.g., DMA passthrough, SR-IOV)
- Shared access: VMM provides an emulated device and routes I/O data to and from the device and VMs

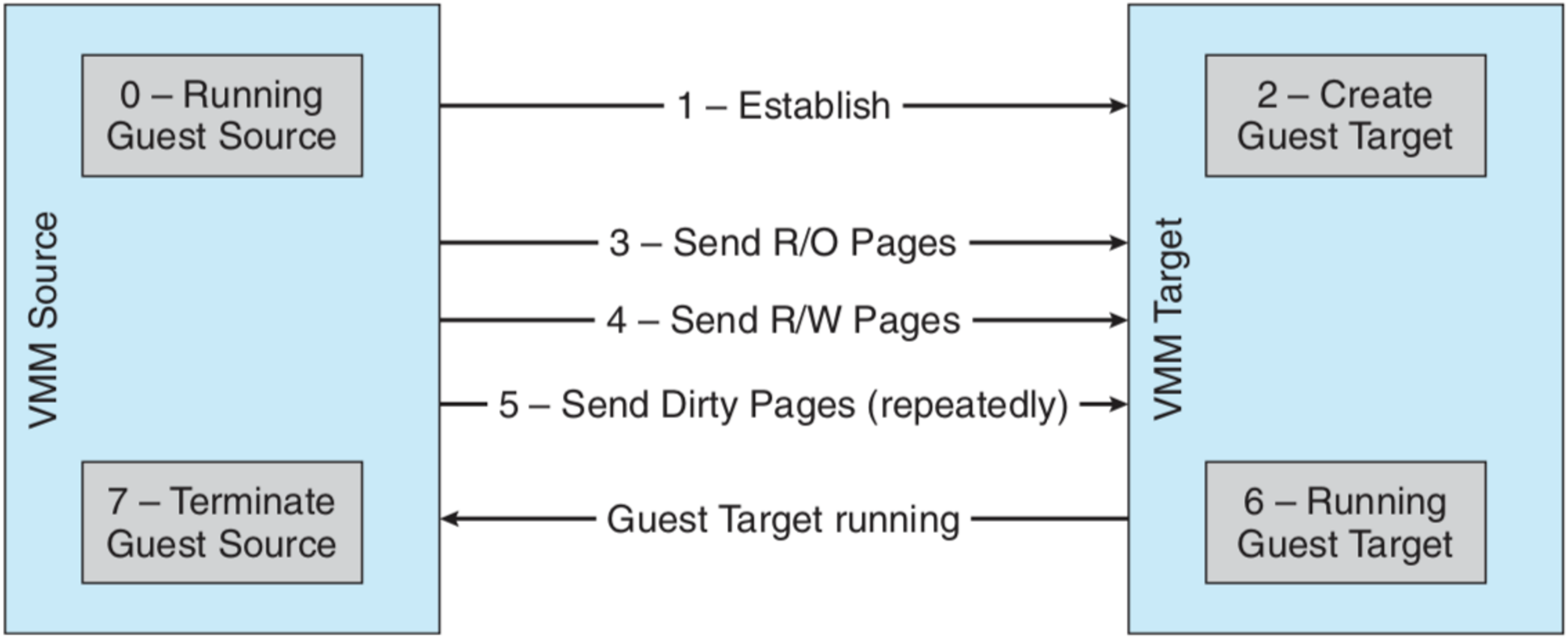


- VMM provides "virtual disks"
    - Type 1 VMM – store guest root disks and config information within file system provided by VMM as a disk image
    - Type 2 VMM – store the same info as files in the host OS' file system

Live migration

- Running guest OS can be moved between systems, without interrupting user access to the guest or its apps
- Supported by type 1 and type 2 hypervisors
- Very useful for resource management, no downtime for upgrades/maintenance, etc.

Live migration: How does it work?



When cycle of steps 4 and 5 become very short, source VMM freezes guest, sends VCPU’s final state, sends final dirty pages, and tells target to start running the guest

Topics Today

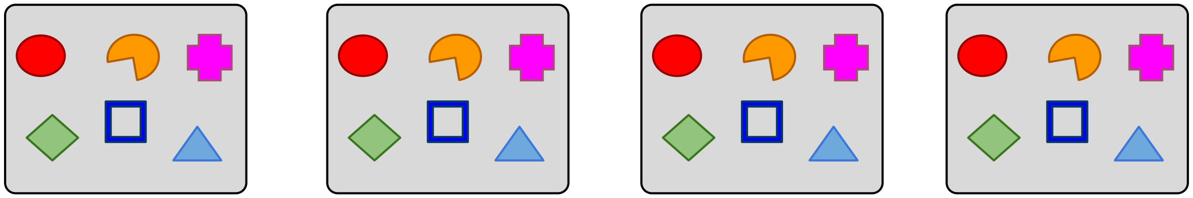
- Motivation
- System Virtualization (VMs)
- Container Virtualization
  - Motivation for Containers
  - Implementation in Linux
  - Practical Implications

Motivation for Containers

Architecture of web applications is changing

Classical architecture

Monolithic application
100 engineers
Release / month
Horizontal scale out



Components
- ● Login
- ◔ Personification
- ◆ Renderer
- □ Ads
- ✚ Suggestions
- ▲ Encoders

Potential limitations of this architecture?

.WAR too big for IDE?

Async release of updates?

Change tech of a component?

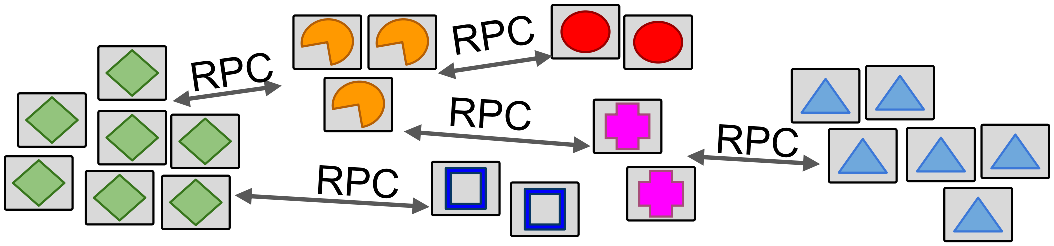
Failure Isolation?

Motivation for Containers

Changing architecture of web applications

New architecture: components → “micro services”

Define API between components
10-20 engineers / component
Components release and scale independently



Components

- 🔴 Login
- ◔ Personification
- ◇ Renderer
- ☐ Ads
- ✚ Suggestions
- △ Encoders

Potential limitations of this new architecture?

Per-component overhead?

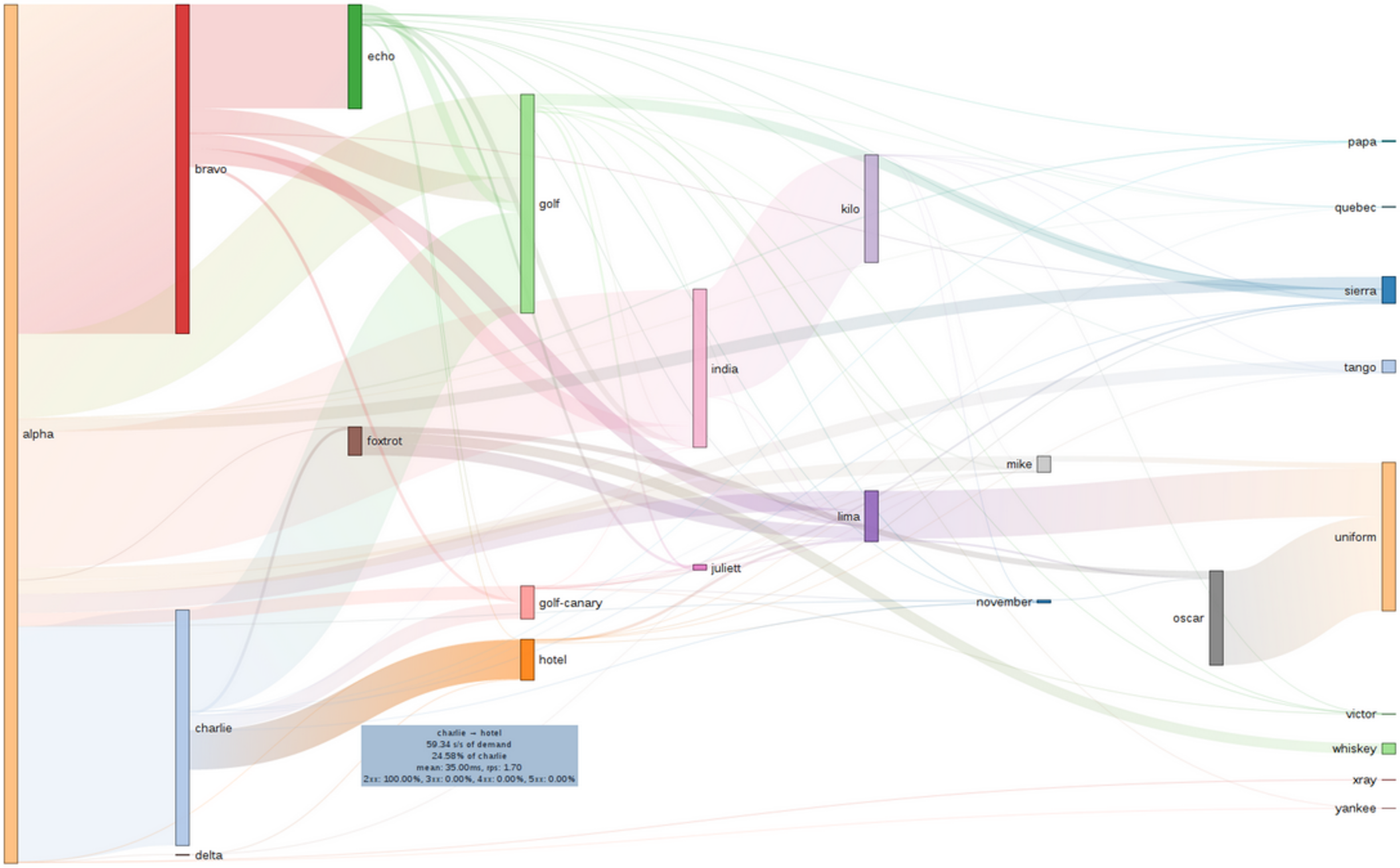
How to define services?

API/Communication latency?

Prominent Example: Netflix

Migration to micro services: 2008-2016

Hundreds of services, complex dependencies



Why Container Virtualization?

Overhead associated with deploying on VMs

- I/O overhead
- OS-startup overhead per VM
- Memory/Disk overhead (duplicate data)

Overhead becomes dominant at scale: thousands of VMs / server

Perception: VM have too much overhead!

New idea:

- Multiple isolated instances of programs
- Running in user-space (shared kernel)
- Instances see only resources (files, devices) assigned to their container

Other names: OS-level virtualization, partitions, jails (FreeBSD jail, chroot jail)

Requirements on Containers

- Isolation and encapsulation
  - Fault and performance isolation
  - Encapsulation of environment, libraries, etc.

Resource & Failure Isolation

- Low overhead
  - Fast instantiation / startup
  - Small per-operation overhead (I/O, ..)

Improved Resource Utilization

- Reduced Portability

Mixed-OS Environment

- ~~Interposition~~ (no hypervisor)

Security Isolation

Implementation

Key problems:

- Isolating which resources containers see
- Isolating resource usage
- Efficient per-container filesystems

Resource View Isolation

Problem: containers should only see “their” resources, and are the only users of their resource

(e.g., process IDs (PIDs), hostnames, users IDs (UIDs), interprocess communication (IPC))

Solution: each process is assigned a “namespace”

- Syscalls only show resources within own namespace
- Subprocesses inherit namespace

Current implementation: namespace implementation per resource type (PIDs, UIDs, networks, IPC), in Linux since 2006

Practical implication:

- Containers feel like VMs, can get root
- Security relies on kernel, containers make direct syscalls

Resource Usage Isolation

Problem: meter resource usage and enforce hard limits per container

(e.g., limit memory usage, priorities for CPU and I/O usage)

Solution: usage counters for groups of processes (cgroups)

- Compressible resources (CPU, I/O bandwidth): rate limiting
- Non-compressible resources (Memory/disk space): require terminating containers (e,g., OOM killer per cgroup)

Current implementation: cgroups/kernfs, in Linux since 2013/2014

Practical implication:

- Efficiency: 1000s of containers on a single host
- Small overhead per memory allocation, and in CPU scheduler

Filesystem Isolation

Problem: per-container filesystems without overhead of a “virtual disk” for each container

Solution: layering of filesystems (copy on write):

- Read-write (“upper”) layer that keeps per-container file changes
- Read-only (“lower”) layer for original files

Current implementation: OverlayFS, in Linux since 2014

Practical implication:

- Instant container startup
- “Upper” layer is ephemeral

Upper: /index.html /photo/cat.jpg

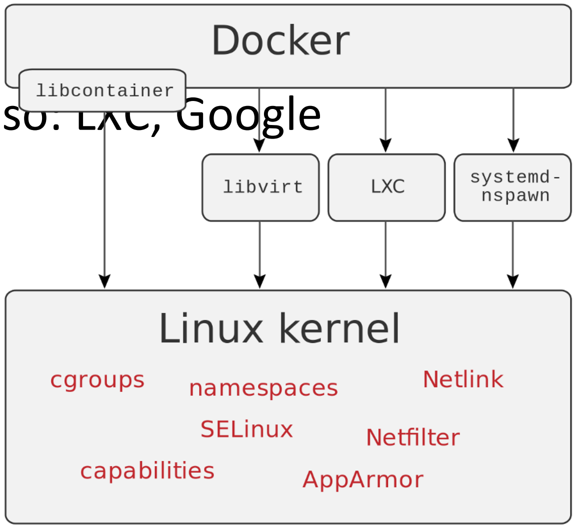
Lower: /index.html

The Container Ecosystem

Docker (also: LXC, Google lmctfy)

Libcontainer (written in GO)

- Automates using kernel features (namespaces, cgroups, OverlayFS)
- Container-image configuration language



Docker

libcontainer

libvirt

LXC

systemd-nspawn

Linux kernel

cgroups

namespaces

Netlink

SELinux

Netfilter

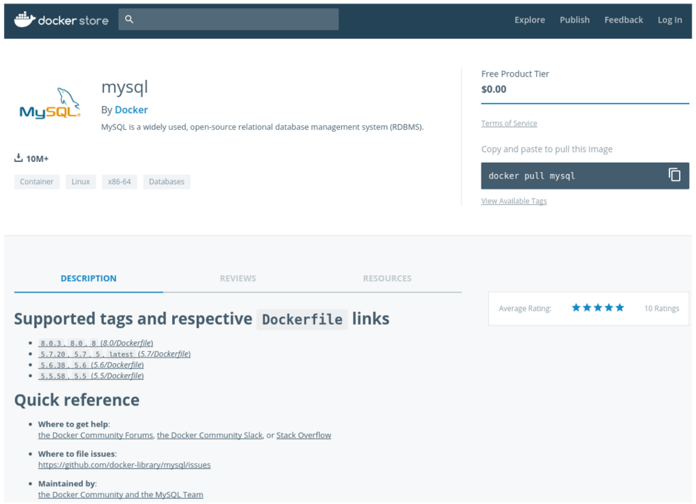
capabilities

AppArmor

```
FROM golang

WORKDIR /go/src
COPY ./src .
RUN go-wrapper install monitor

CMD ./start.sh
```



mysql

By Docker

MySQL is a widely used, open-source relational database management system (RDBMS).

10M+

Container Linux x86-64 Databases

Free Product Tier

$0.00

Terms of Service

Copy and paste to pull this image

```
docker pull mysql
```

View Available Tags

Average Rating: ★★★★★ 10 Ratings

Supported tags and respective `Dockerfile` links

- `8.0.3`, `8.0`, `8` (*8.0/Dockerfile*)
- `5.7.20`, `5.7`, `5`, `latest` (*5.7/Dockerfile*)
- `5.6.38`, `5.6` (*5.6/Dockerfile*)
- `5.5.58`, `5.5` (*5.5/Dockerfile*)

Quick reference

- **Where to get help**:
  the Docker Community Forums, the Docker Community Slack, or Stack Overflow
- **Where to file issues**:
  https://github.com/docker-library/mysql/issues
- **Maintained by**:
  the Docker Community and the MySQL Team

Advantages of Containers

Fast boot times:

    100s of milliseconds

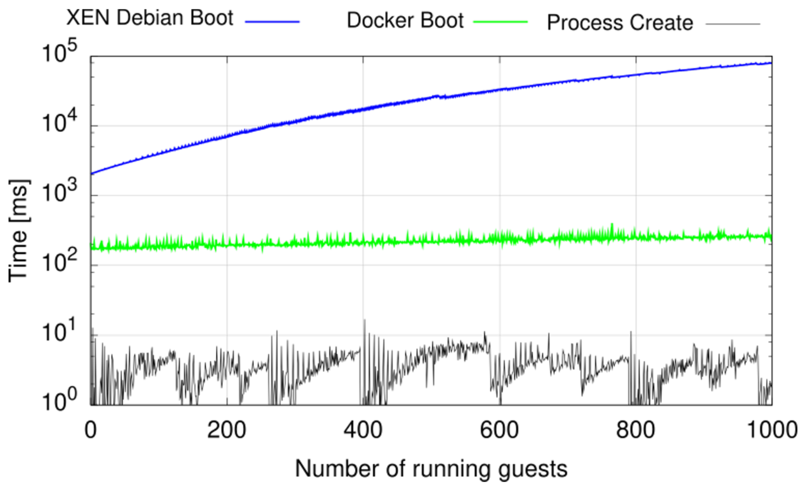
    (10s-100s of seconds for VMs)

High density:

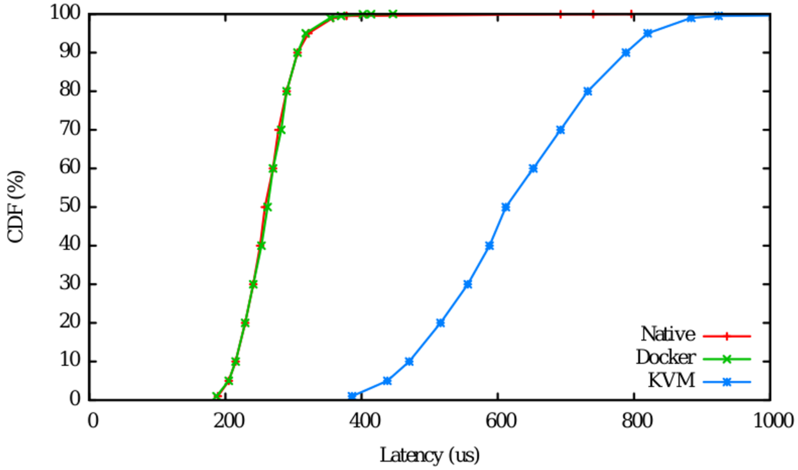
    1000s of containers per machine

Very small I/O overhead

Require no CPU support



Manco, Filipe, et al. "My VM is Lighter (and Safer) than your Container." SOSP 2017.



Felter, et al. An Updated Performance Comparison of Virtual Machines and Linux Containers, IBM Report 2014.

Limitations of Containers

Implementation Complexity

- Much more complex (“wider”) interface for processes
- Need to configure namespace, cgroup, overlayfs (and more)

Less general than VMs

- Can only run the same Operation System (shared OS)

Harder to migrate than VMs

- State of containers is not fully encapsulated, state leaks into host OS
- In practice: no container migration. Instead: containers are ephemeral - just terminate old one and start new one

Large attack surface under adversarial behavior

- Containers typically have access to all syscalls
  - Linux offers 400 syscalls (10 new syscalls / year)
- One approach: syscall filtering (very complicated)

Summary

VMs

Strengths: strong isolation guarantees, can run different OSs

VM migration practical

Weaknesses: OS startup, disk,memory, and hypervisor overhead

Containers

Strength: fast startup times, negligible I/O overheads, very high density

Weaknesses: weak security isolation

In practice: techniques complement each other

Use VMs to isolate between different users, and containers to isolate different applications/services of a single user