Virtualization Support

Advanced Operating Systems and Virtualization

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System Virtualization

- Virtualization allows to show resources different from the physical ones
- More operating systems can be run on the same hardware
- A Virtual Machine is a mixure of software- and hardware-based facilities
- The software component is the Hypervisor or VMM (Virtual Machine Monitor).

- Advantages:
  - Isolation of different execution environments (on the same hardware)
  - Reduction of hardware and administration costs

Hypervisor

- *Host system*: the real system where (software implemented) virtual machines run
- *Guest system*: the system that runs on top of a (software implemented) virtual machine

- Hypervisor:
  - It manages hardware resources provided by the *host system*
  - It makes virtualized resources available to the *guest system* in a correct and secure way

  - *Native Hypervisor:* runs with full capabilities on bare metal. It resembles a lightweight virtualization kernel operating on top of the harware.
  - *Hosted Hypervisor:* it runs as an applicaiton, which accesses host services via system calls

Software-based Virtualization

- Instructions are executed by the native physical CPU in the host platform
- A subset of the instruction set must be emulated
- No particular hardware component playes a role in virtualiztion

- *The main problems:*
  - What if ring 0 is required for guest activities?
  - Risk to bypass the VMM resource management policy in case of actual ring 0 access

- *The solution:* ring deprivileging

Ring Deprivileging

- A technique to let the guest kernel run at a privilege level that "simulates" 0
- Two main strategies:
  1. 0 / 1 / 3 Model:
     - VMM runs at ring 0
     - Kernel guest runs at ring 1 (not typically used by native kernels)
     - Applications still run at ring 3
     - This is the most used approach
  2. 0 / 3 / 3 Model :
     - VMM runs at ring 0.
     - Kernel guest and applications run at ring 3.
     - Too close to *emulation*, too high costs

0/1/3 Model

- Applications (running at ring 3) cannot alter the state of the guest operating system (running at ring 1).
- The guest operating system cannot access privileged instructions and data structures of the host operating system
  - we guarantee the isolation of guest systems
- Any exception must be trapped by the VMM (at ring 0) and must be properly handled (e.g. by reflecting it into ring 1 tasks)

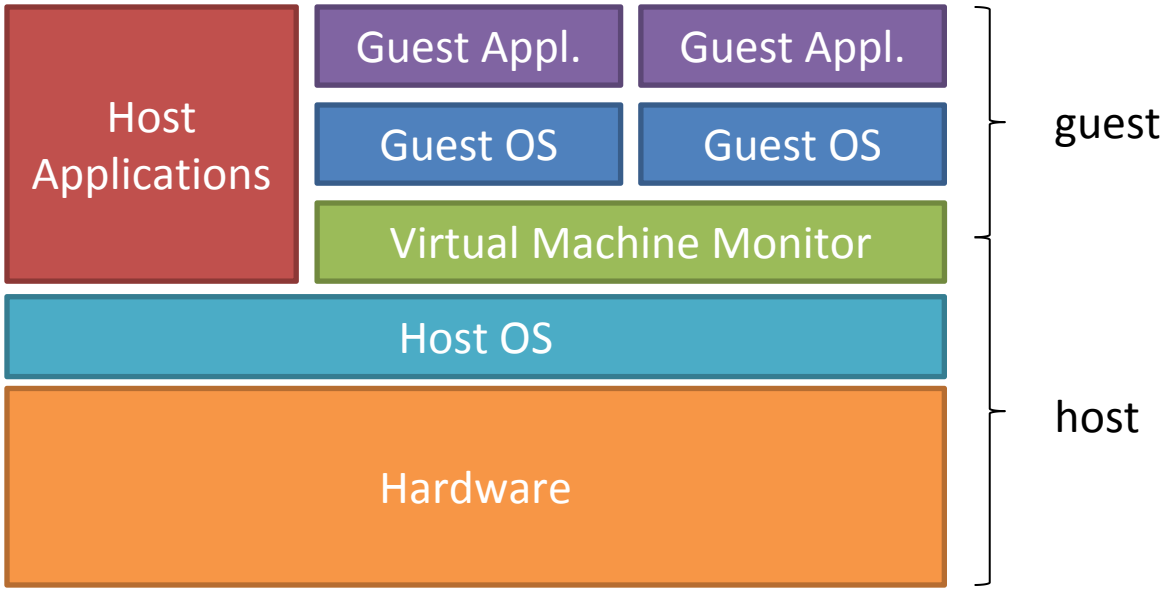
- Issues to cope with:
  - Ring aliasing
  - Virtualization of the interrupts
  - Frequent access to privileged resources

Ring Aliasing

- An OS kernel is designed to run at ring 0, while it is actually being run at ring 1 for guest systems
- Privileged instructions generate an exception if not run at CPL 0:
  - Some examples: `hlt`, `lidt`, `lgdt`, `invd`, `mov %crx`
- *I/0 sensistive instructions*: they generate a trap if executed when CPL > IOPL (I/O Privilege Level). Classical examples are:
  - `cli`, `sti`
- The generated trap (*general protection fault*) must be handled by the VMM, so as to finally determine how to handle it (emulation vs interpretation)

The VirtualBox Example

- Based on hosted hypervisor with ad-hoc kernel facilities, via classical special devices (0/1/3 model)



- Pure software virtualization is supported for x86
  - Fast Binary Translation (code patching): the kernel code is analysed and modified before being executed
  - Privileged instructions replaced with semantically equivalent blocks of code

Execution Modes and Context

- Guest context (GC): execution context for the *guest system*. It is based on two modes:
  - Raw mode: native guest code runs at ring 3 or 1
  - Hypervisor: VirtualBox runs at ring 0

- Host context (HC): execution context for userspace portions of VirtualBox (ring 3):
  - The running thread implementing the VM lives in this context upon a mode change
  - Critical/privileged instructions are emulated upon a GPF

VBOXGDT

- Introduction of gate descriptors for kernel code/data segments with DPL=1. These segments are accessible with CPL=1
- New TSSD pointing to the TSS wrapper which keeps info on stack positioning at ring 1 (ss1,esp1) and ring 0 (ss0,esp0).
- 2 new segments for the Hypervisor are addedd with DPL=0

DESCRIPTION	OFFSET	DPL	BASE
Entry 0	$(0000)_H$	-	null
...	...	...	...
KERNEL CODE SEGMENT	$(0060)_H$	1	
KERNEL DATA SEGMENT	$(0068)_H$	1	
...	...	...	...
VIRTUALBOX TSSD	$(FFE0)_H$	0	
...	...	...	...
HYPERVISOR DATA SEGMENT	$(FFF0)_H$	0	
HYPERVISOR CODE SEGMENT	$(FFF8)_H$	0	

ORIGINAL TSS

...	...
esp0	...
ss0	$(0068)_H$
esp1	unused
ss1	unused
...	

VBOXTSS

...	...
esp0	$(FE557000)_H$
Ss0	**$(FFF0)_H$**
esp1	$(F70D3FF8)_H$
ss1	$(0069)_H$
...	

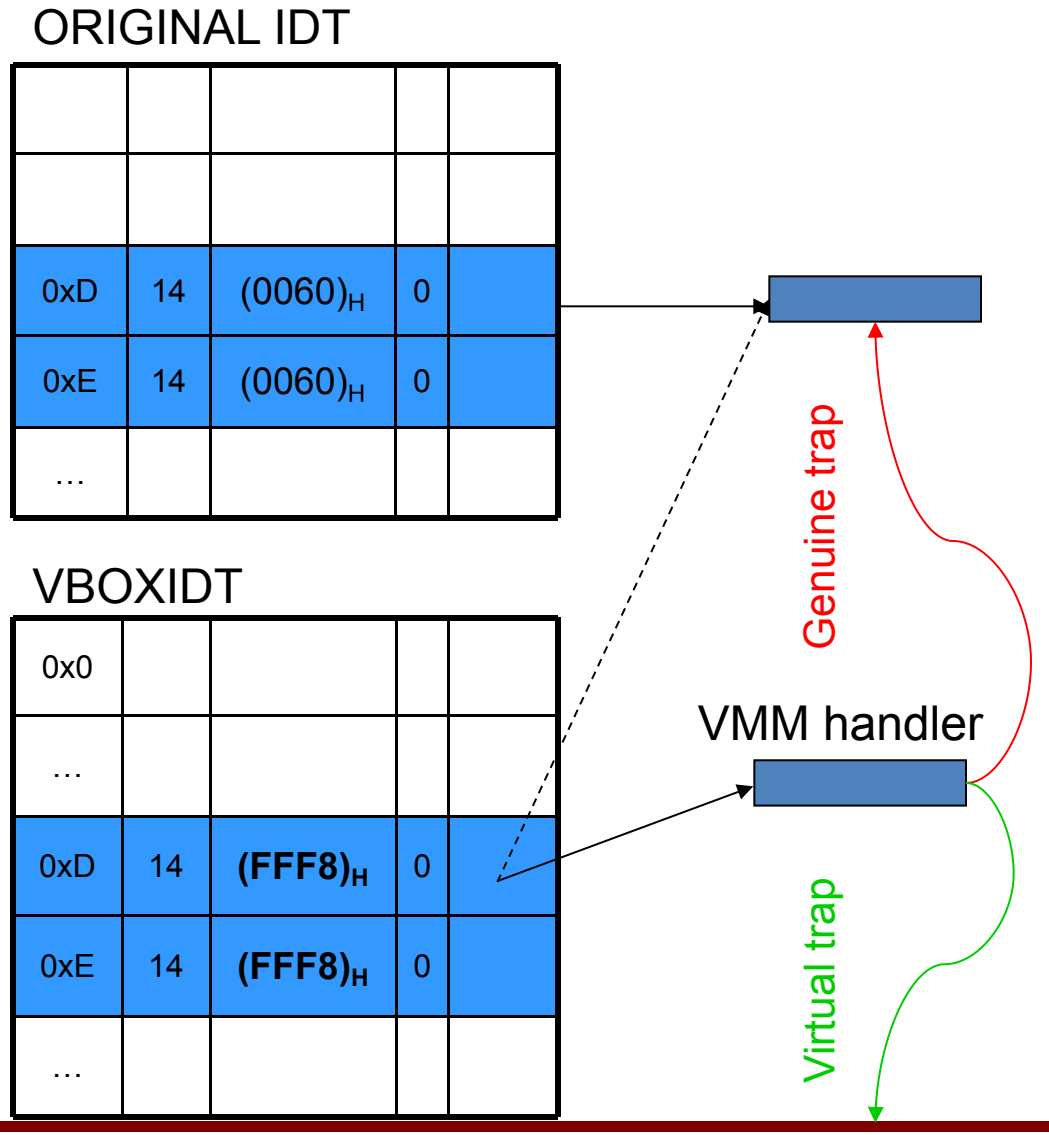
ss1=ss0 | 1

CPL = Current Privilege Level

DPL = Descriptor Privilege Level

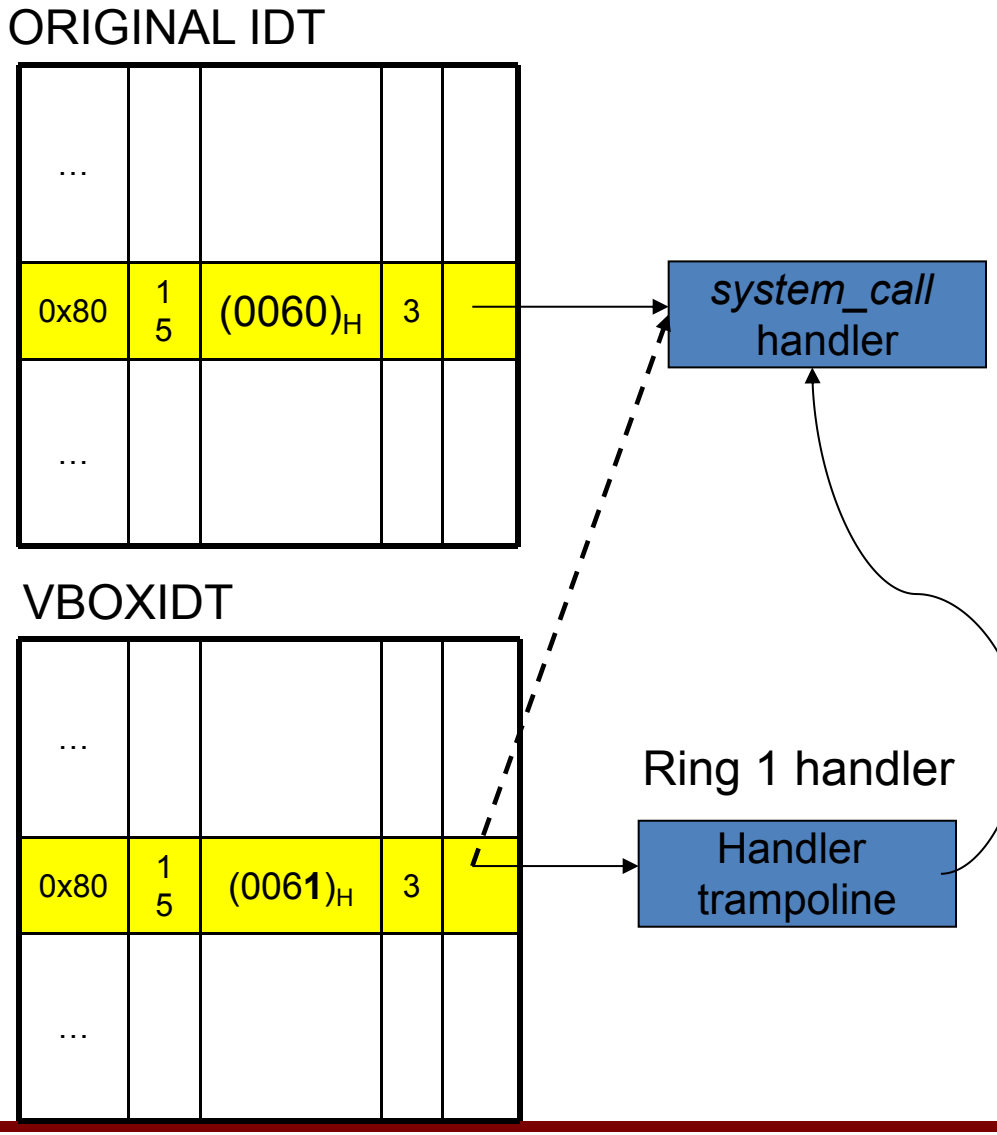
VBOXIDT: interrupt gate

- Interrupt must be managed by the VMM.
- To this end, a wrapper for the IDT is generated
- Proper handlers are instantiated, which get executed by the Hypervisor upon traps. VMM can take control thanks to the ad-hoc segment selector (at the GDT offset for the *hypervisor code segment*).
- In case of a "genuine" trap, the control goes to the native kernel, otherwise the virtual handler is executed



VBOXIDT: gate 0x80

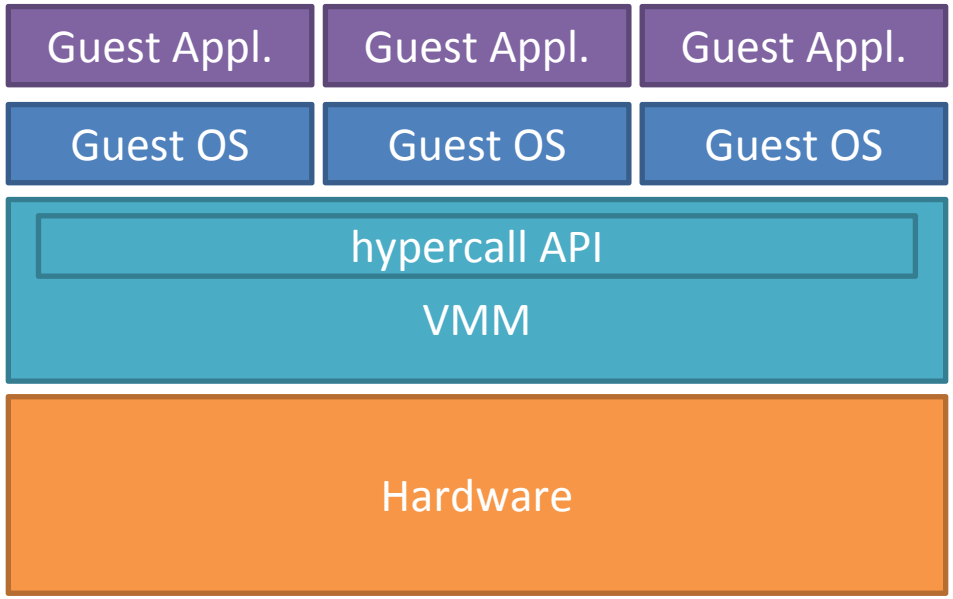
- INT 0x80 has an ad-hoc management
- The syscall gate is modified so as to provide a segment selector with RPL = 1
- It indicates the GDT offset for the code segment (at ring 1).
- Hence calling a system call does not require interaction with the Hypervisor
- The trampoline handler is then used to launch the actual syscall handler



Paravirtualization

- The VMM offers a virtual interface (*hypercall API*) used by guest OS to access resources
  - To run privileged instructions, hypercalls are executed
  - There is a need to modify the code of the guest OS
  - VMM is simplified: no need to account for traps generated by virtualized OS
- An example: Xen

Paravirtualization



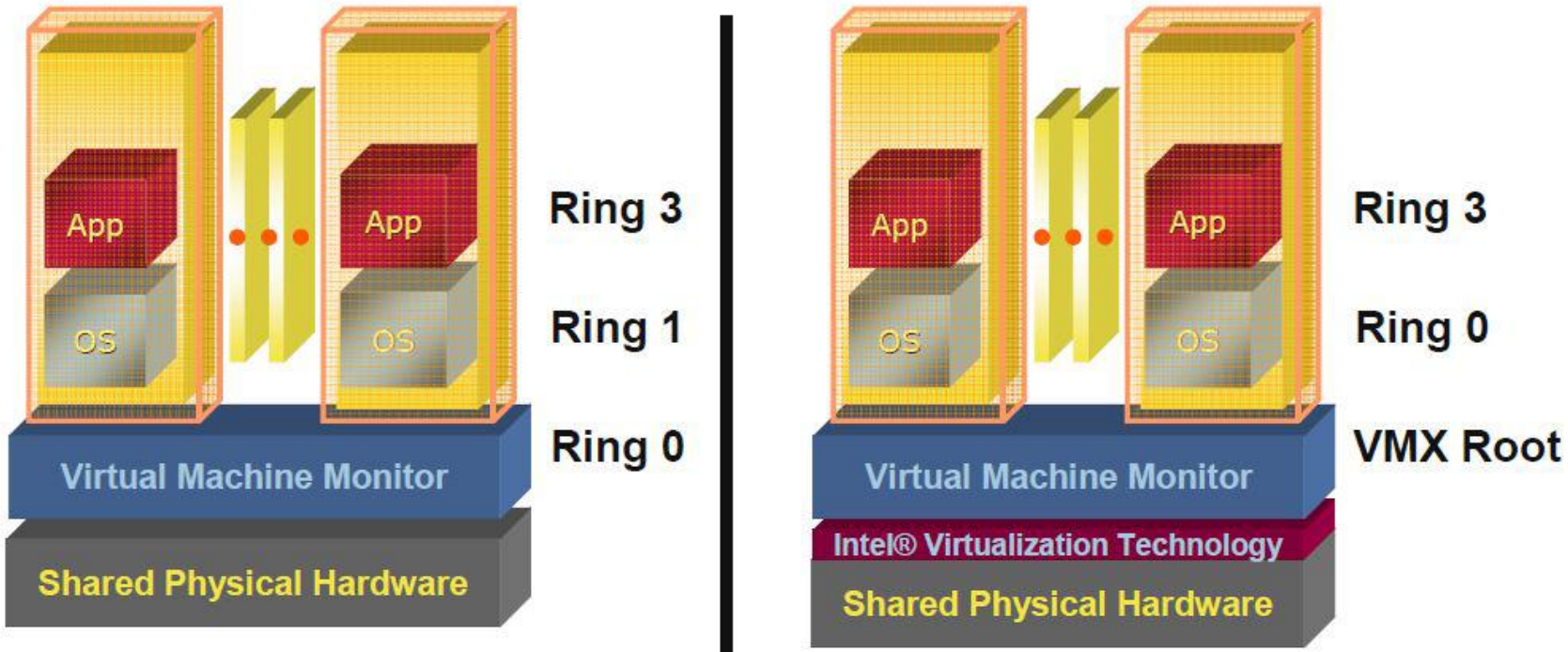
Hardware-Assisted Virtualization: VT-x

- Intel *Vanderpool Technology*, referred to as VT-x, represents Intel's virtualization technology on the x86 platform.
- Its goal: simplify VMM software by closing virtualization holes by design.
  - Ring Compression (lack of OS/Applications separations if only 2 rings are used)
  - Non-trapping instructions (some instructions at ring 1 are not trapped, for example `popf`)
  - Excessive trapping
- Eliminate need for software virtualization (i.e paravirtualization, binary translation).

Virtual Machine Extension (VMX)

- Virtual Machine Extensions define CPU support for VMs on x86 by a new form of operation called *VMX operation*
- Kinds of VMX operation:
  - **root:** VMM runs in VMX root operation
  - **non-root:** Guest runs in VMX non-root operation
- Eliminate ring deprivileging for guest OS
- VMX Transitions between VMX root operation and VMX non-root operation:
  - **VM Entry:** Transitions into VMX non-root operation.
  - **VM Exit:** Transitions from VMX non-root operation to VMX root operation.
  - Registers and address space swapped in one atomic operation.

Virtual Machine Extension (VMX)



Pre VT-x | **Post VT-x**

VMM ring deprivileging of guest OS	VMM executes in VMX root-mode
Guest OS aware its not at Ring 0	Guest OS deprivileging eliminated
	Guest OS runs directly on hardware

VMCS: VM Control Structure

- Data structure to manage VMX non-root operation and VMX transitions
  - Specifies guest OS state
  - Configured by VMM
  - Controls when VM exits occur

The VMCS consists of six logical groups:

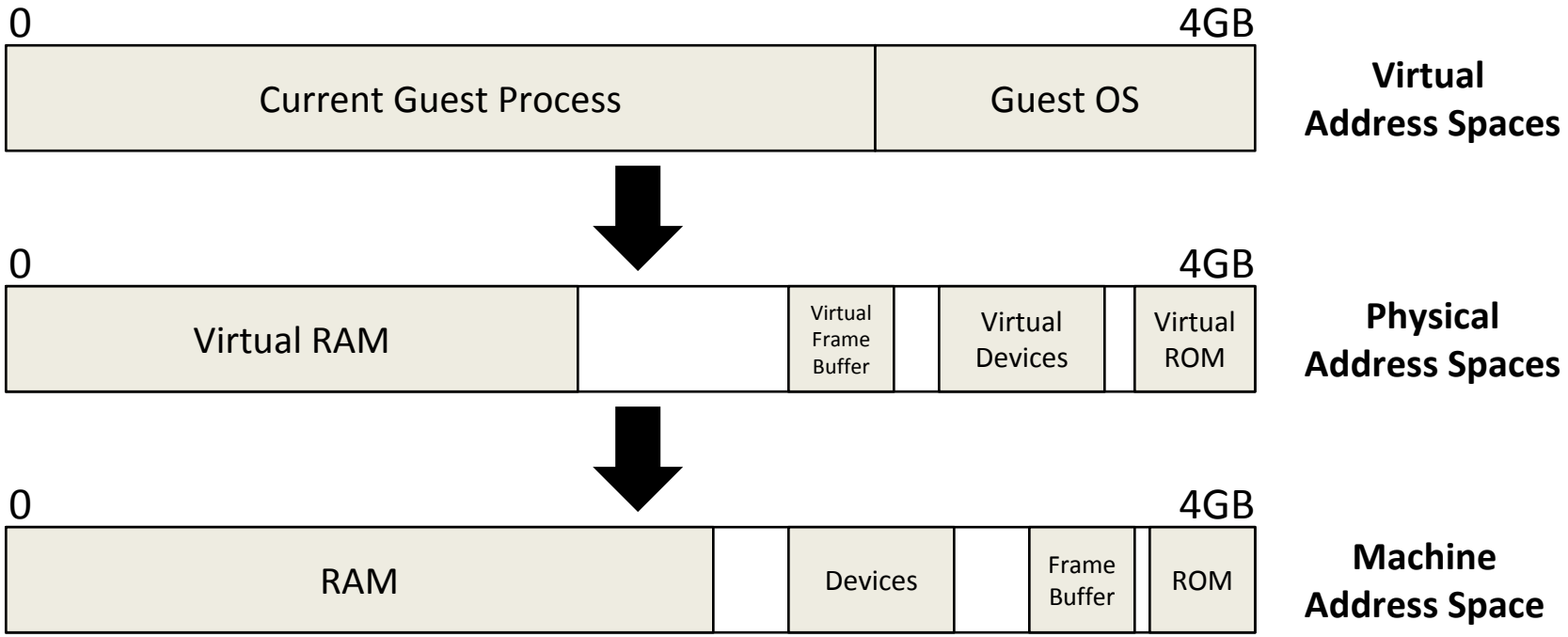
- **Guest-state area:** processor state saved into the guest-state area on VM exits and loaded on VM entries.
- **Host-state area:** processor state loaded from the host-state area on VM exits.
- **VM-execution control fields:** fields controlling processor operation in VMX non-root operation.
- **VM-exit control fields:** fields that control VM exits.
- **VM-entry control fields:** fields that control VM entries.
- **VM-exit information fields:** read-only fields to receive information on VM exits describing the cause and the nature of the VM exit.

MMU Virtualization with VT-x: VPIDs

- First generation VT-x forces TLB flush on each VMX transition
- Performance loss on all VM exits
- Performance loss on most VM entries
  - Guest page tables not modified always
- Better VMM software control of TLB flushes is beneficial
- VPID:
  - 16-bit virtual-processor-ID field in the VMCS
  - Cached linear translations tagged with VPID value
  - No flush of TLBs on VM entry or VM exit if VPID active
  - TLB entries of different virtual machines can all co-exist in the TLB

Virtualizing Memory in Software

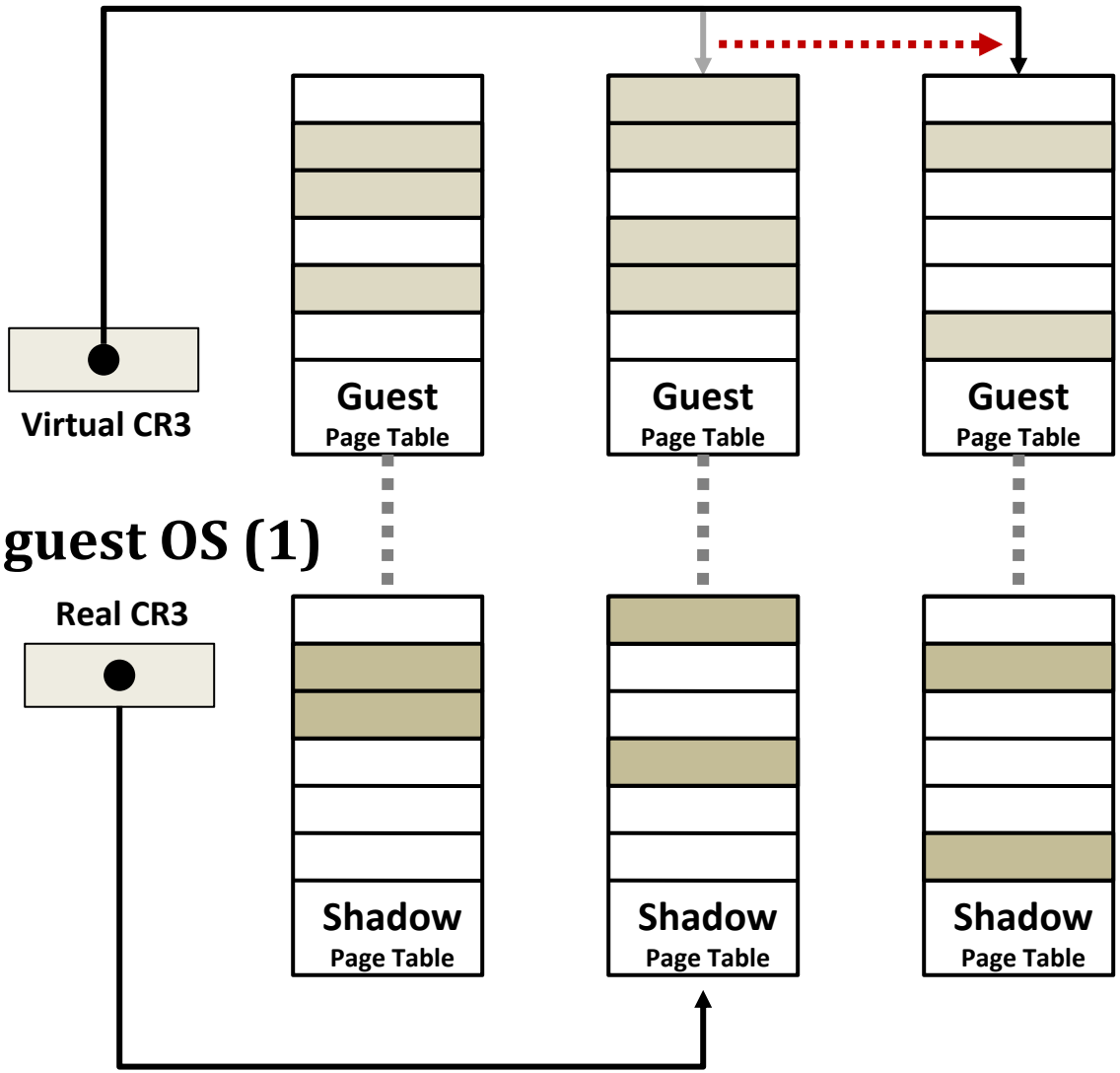
- Three abstractions of memory:



Shadow Page Tables

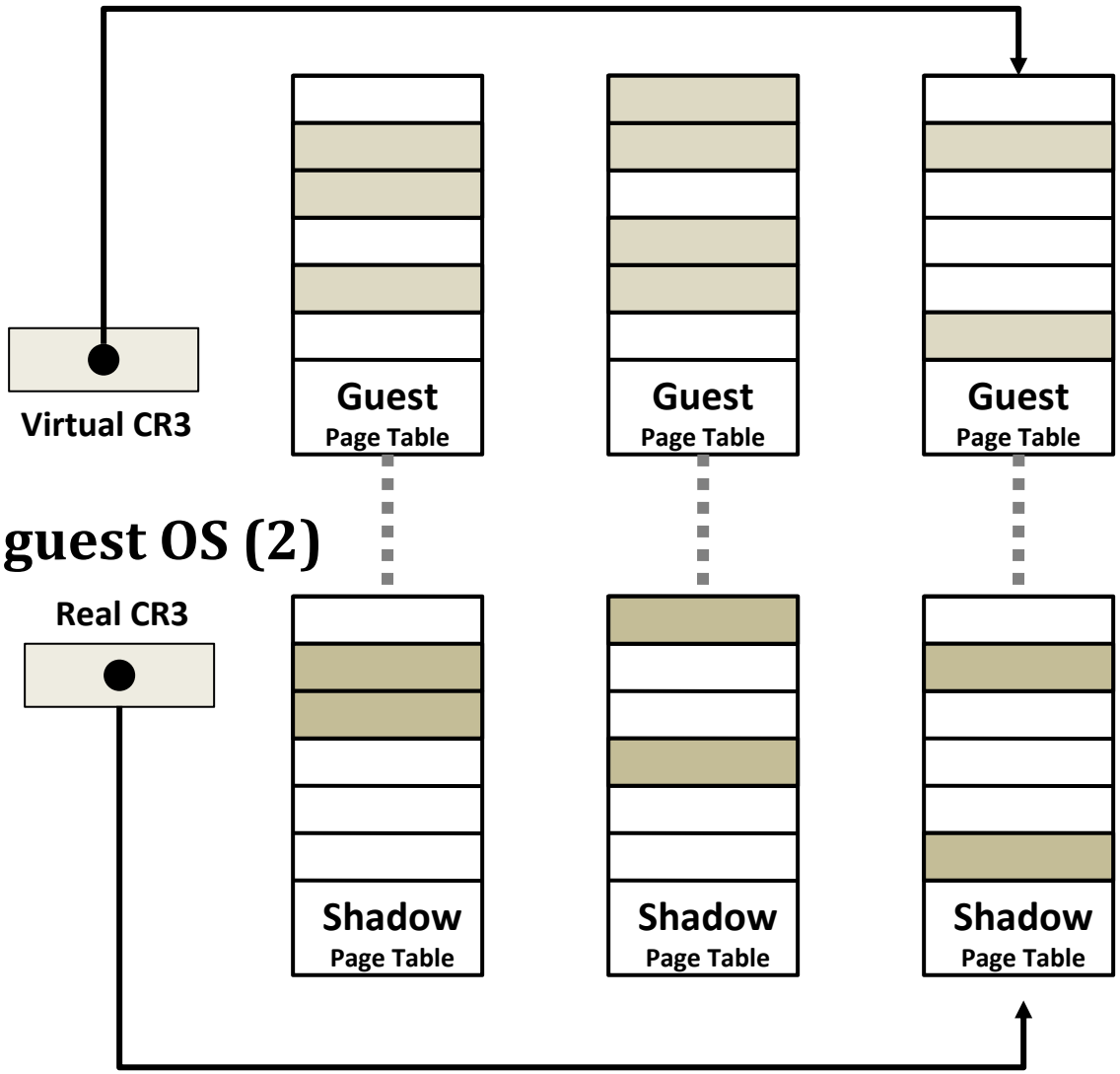
- VMM maintains shadow page tables that map guest-virtual pages directly to machine pages
- Guest modifications to V→P tables synced to VMM V→M shadow page tables
  - Guest OS page tables marked as read-only
  - Modifications of page tables by guest OS → trapped to VMM
  - Shadow page tables synced to the guest OS tables

Shadow Page Tables



Set CR3 by guest OS (1)

Shadow Page Tables



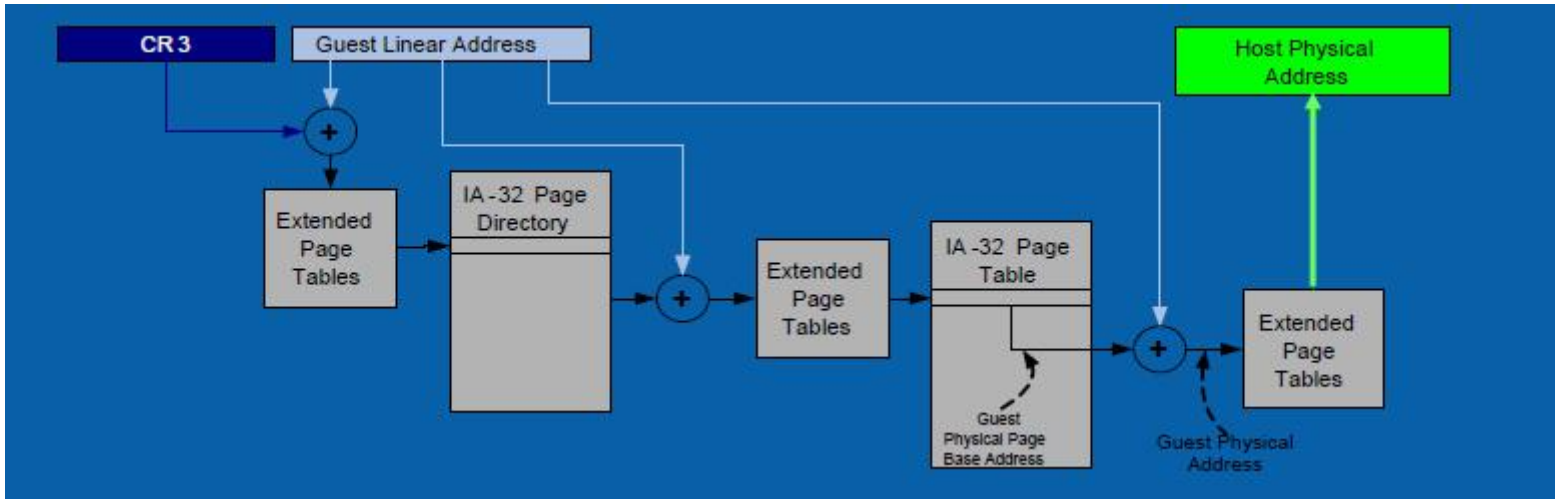
Set CR3 by guest OS (2)

Shadow Page Tables: Drawbacks

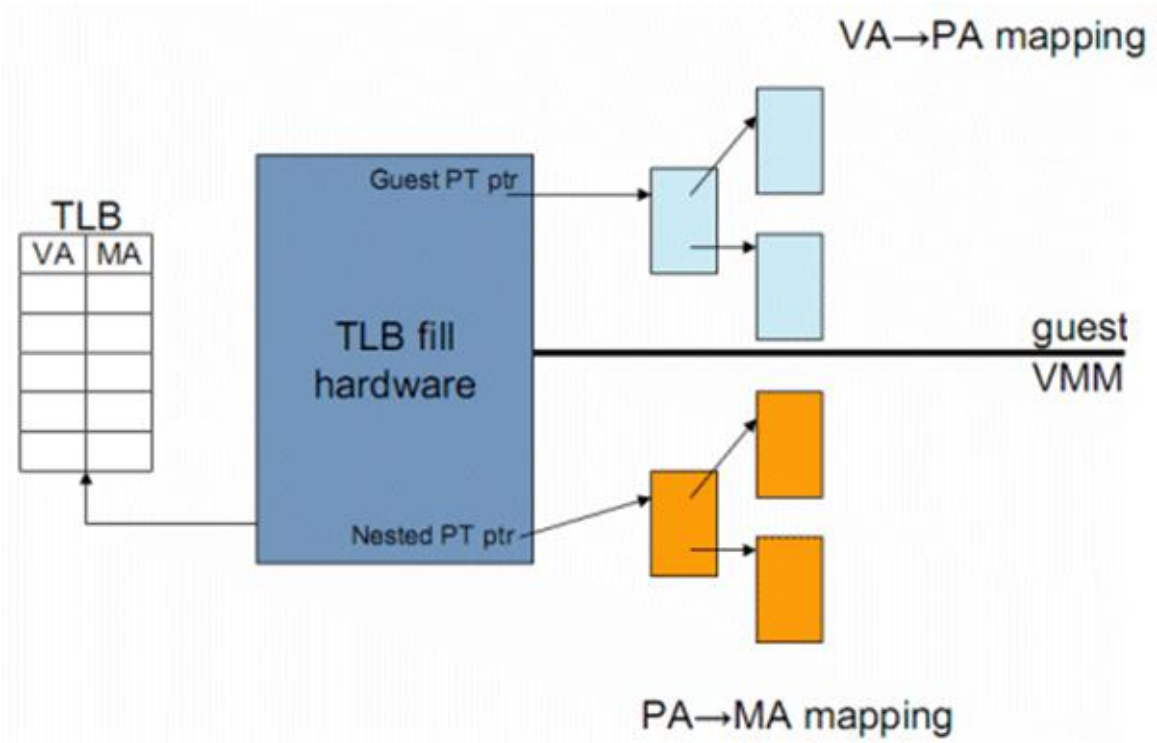
- Maintaining consistency between guest page tables and shadow page tables leads to an overhead: VMM traps
- Loss of performance due to TLB flush on every “world-switch”
- Memory overhead due to shadow copying of guest page tables

Nested / Extended Page Tables

- The Extended Page-Table mechanism (EPT) is used to support the virtualization of physical memory
- Translates the guest-physical addresses used in VMX non-root operation
- Guest-physical addresses are translated by traversing a set of EPT paging structures to produce physical addresses that are used to access memory



Nested / Extended Page Tables



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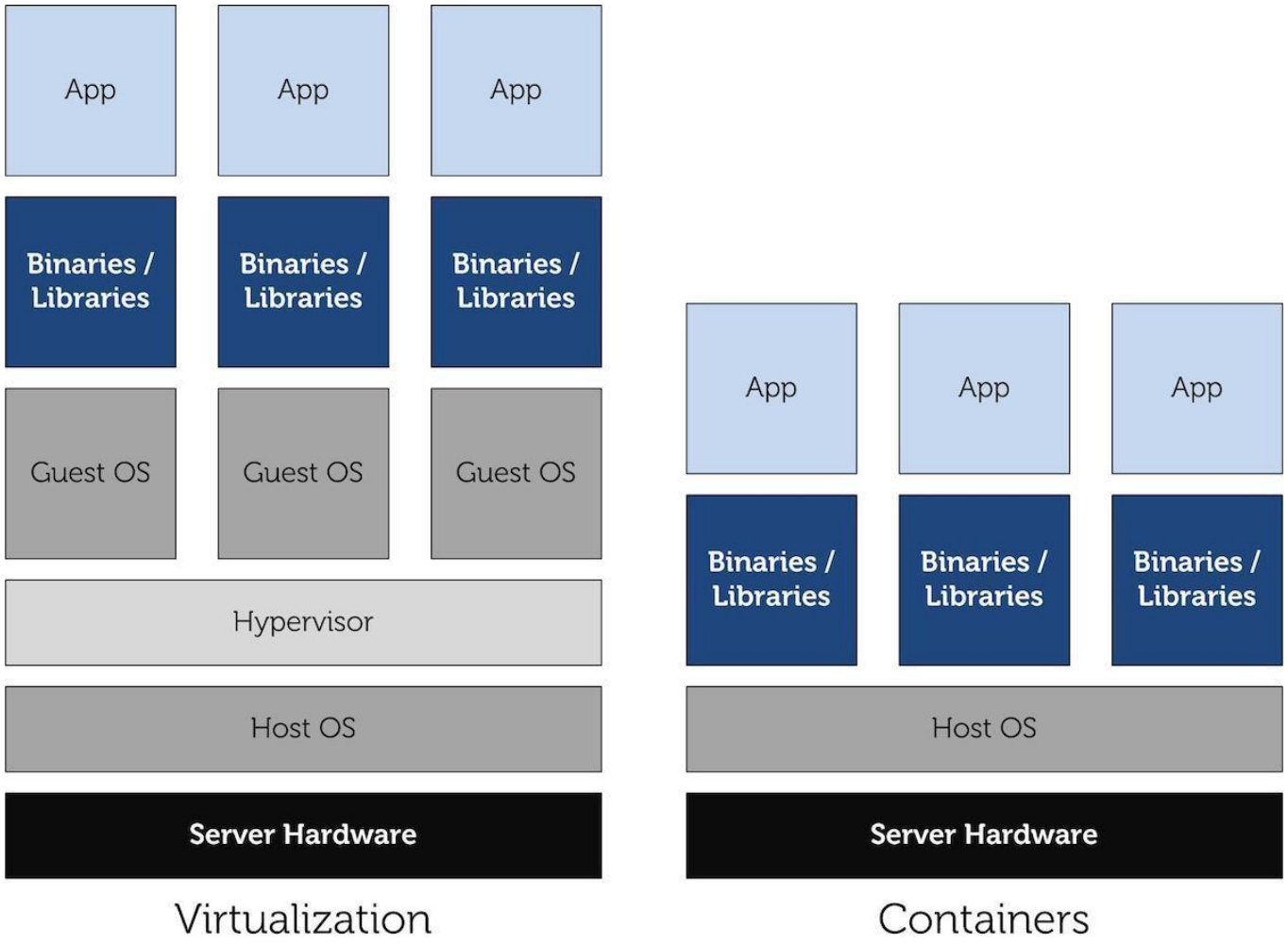
Considerations on EPT

- Advantages:
  - Simplified VMM design
  - Guest page table modifications need not to be trapped, hence VM exits reduced
  - Reduced memory footprint compared to shadow page table algorithms
- Disadvantages:
  - TLB miss is very costly since guest-physical address to machine address needs an extra EPT walk for each stage of guest-virtual address translation

Linux Containers



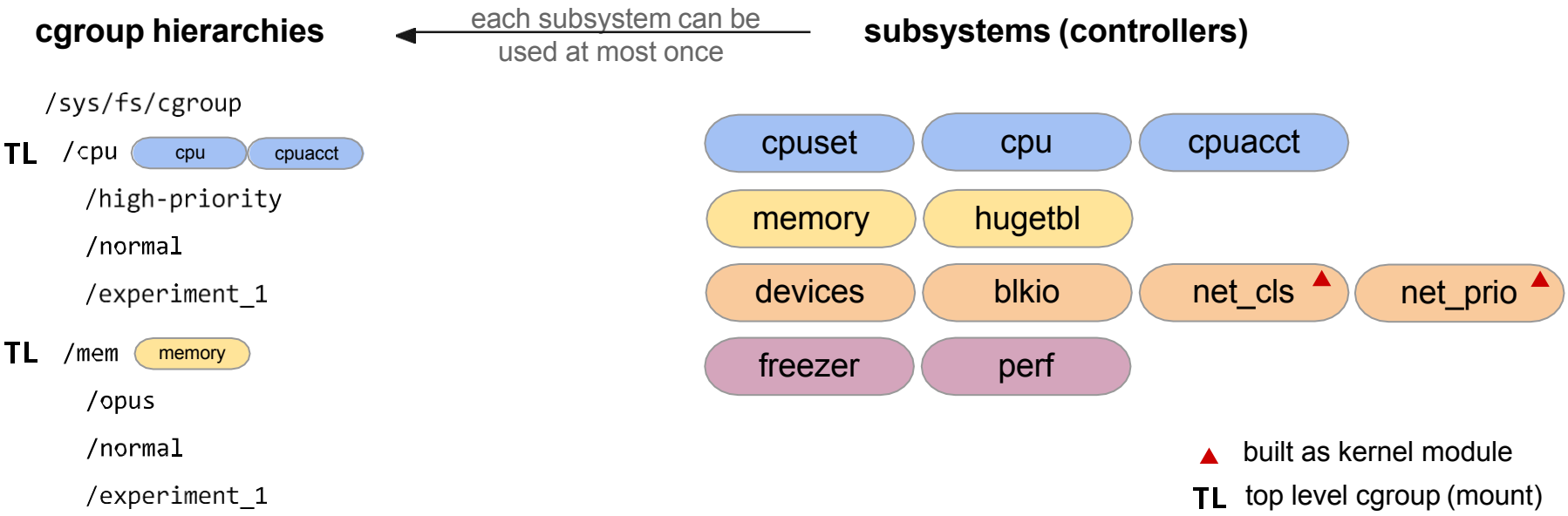
Underlying Kernel Mechanisms

- cgroups: *manage resources for groups of processes*
- namespaces: *per-process resource isolation*

- seccomp*: limit the possible syscalls to be executed to* `exit()`, `sigreturn()`, `read()` *and* `write()`, *the last two only to already-opened file descriptors*
- capabilities: *privileges available to processes*

cgroups (as seen from userspace)

- low-level filesystem interface similar to sysfs and procfs
- new filesystem type “cgroup”, default location in /sys/fs/cgroup



cgroups (as seen from userspace)

cgroup hierarchies

```
/sys/fs/cgroup
TL  /cpu   [cpu] [cpuacct]
      /high-priority
      /normal
      /experiment_1
TL  /mem   [memory]
      /opus
      /normal
      /experiment_1
```

common

tasks
cgroup.procs
release_agent TL
notify_on_release
cgroup.clone_children
cgroup.sane_behavior

cpuacct

cpuacct.stat
cpuacct.usage
cpuacct.usage_percpu

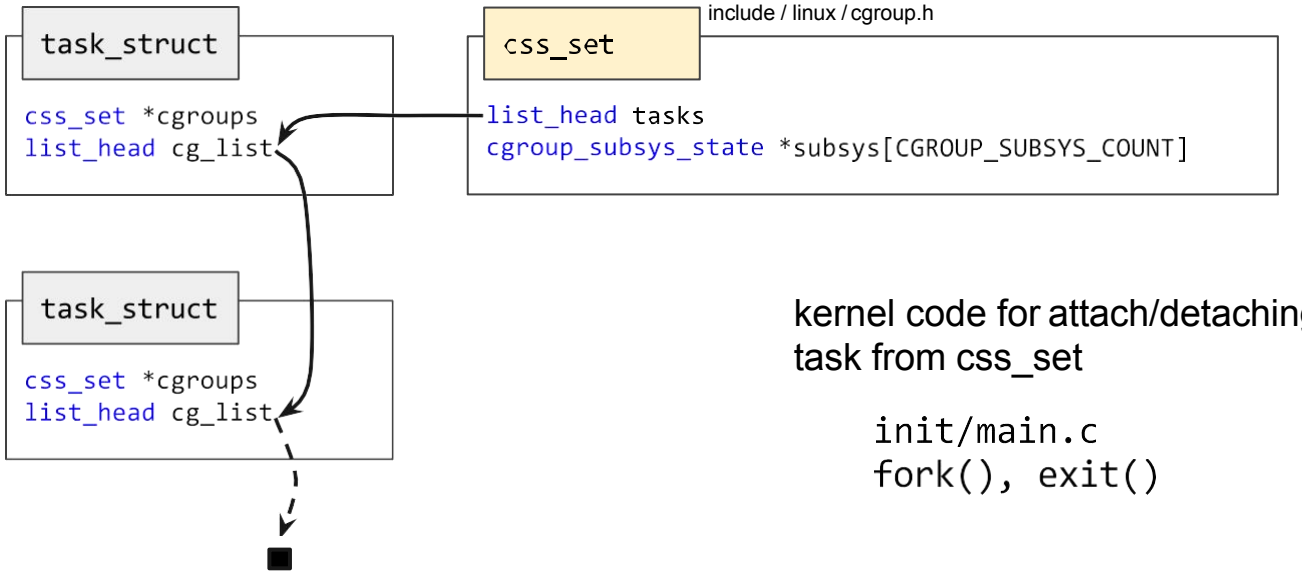
cpu

cpu.stat
cpu.shares
cpu.cfs_period_us
cpu.cfs_quota_us
cpu.rt_period_us
cpu.rt_runtime_us

cpuset | memory | hugetbl | devices | blkio

net_cls ▲ | net_prio ▲ | freezer | perf

cgroups (as managed by kernel)

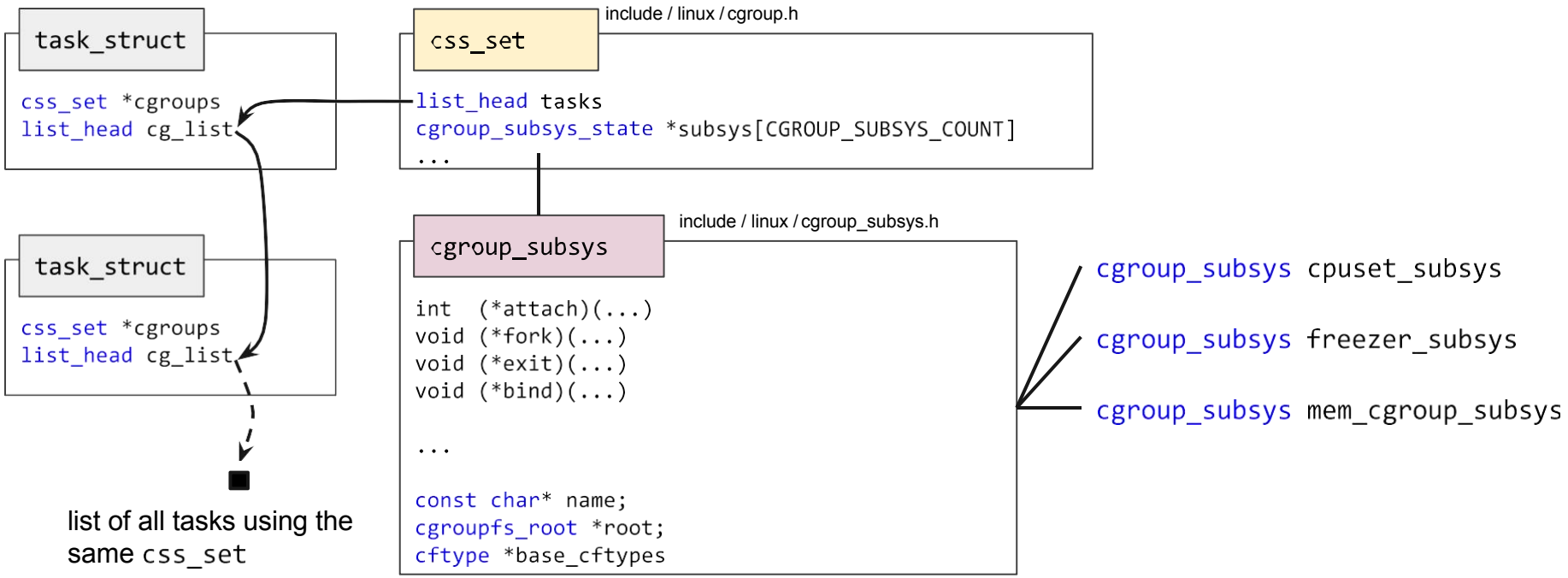


list of all tasks using the same `css_set`

kernel code for attach/detaching task from css_set

```
init/main.c
fork(), exit()
```

cgroups (as managed by kernel)



cgroups (as managed by kernel)

include / linux / cgroup_subsys.h

cgroup_subsys

```
int  (*attach)(...)
void (*fork)(...)
void (*exit)(...)
void (*bind)(...)

...

const char* name;
cgroupfs_root *root;
cftype *base_cftypes
```

```
cgroup_subsys cpuset_subsys
                .base_cftypes = files
```

```
1819 static struct cftype files[] = {
1820 ▸-{
1821 ▸-▸-.name = "cpus",
1822 ▸-▸-.seq_show = cpuset_common_seq_show,
1823 ▸-▸-.write_string = cpuset_write_resmask,
1824 ▸-▸-.max_write_len = (100U + 6 * NR_CPUS),
1825 ▸-▸-.private = FILE_CPULIST,
1826 ▸-},
1827
1828 ▸-{
1829 ▸-▸-.name = "mems",
1830 ▸-▸-.seq_show = cpuset_common_seq_show,
1831 ▸-▸-.write_string = cpuset_write_resmask,
1832 ▸-▸-.max_write_len = (100U + 6 * MAX_NUMNODES),
1833 ▸-▸-.private = FILE_MEMLIST,
1834 ▸-},
1835
1836 ▸-{
1837 ▸-▸-.name = "cpu_exclusive",
1838 ▸-▸-.read_u64 = cpuset_read_u64,
1839 ▸-▸-.write_u64 = cpuset_write_u64,
1840 ▸-▸-.private = FILE_CPU_EXCLUSIVE,
1841 ▸-},
1842
1843 ▸-{
1844 ▸-▸-.name = "mem_exclusive",
1845 ▸-▸-.read_u64 = cpuset_read_u64,
1846 ▸-▸-.write_u64 = cpuset_write_u64,
1847 ▸-▸-.private = FILE_MEM_EXCLUSIVE,
1848 ▸-},
```

namespaces (as seen from userspace)

- namespaces limit the scope of kernel-level *names* and *data structures* at process granularity
- Some examples:
  - mnt (mount points, file systems) `CLONE_NEWNS`
  - pid (processes) `CLONE_NEWPID`
  - net (network stack) `CLONE_NEWNET`
  - ipc (System V IPC) `CLONE_NEWIPC`
  - uts (unix timesharing) `CLONE_NEWUTS`
  - user (UIDs) `CLONE_NEWUSER`

namespaces (as seen from userspace)

- There are three system calls for management:
  - `clone()`: create new process, new namespace, attach to namespace
  - `unshare()`: create new namespace, attach current process to it
  - `setns(int fd, int nstype)`: join an existing namespace
- Each namespace is identified by a unique inode
  - symbolic links in /proc/<pid>/ns

namespaces (as managed by kernel)

- For each namespace type, a default namespace exists (the global namespace)
- `struct nsproxy` is shared by all tasks with the same *set* of namespaces

task_struct

```
struct nsproxy *nsproxy
struct cred *cred
```

include / linux / nsproxy.h

nsproxy

```
atomic_t count
struct uts_namespace *uts_ns
struct ipc_namespace *ipc_ns
struct mnt_namespace *mnt_ns
struct pid_namespace *pid_ns_for_children
struct net           *net_ns
```

include / linux / cred.h

cred

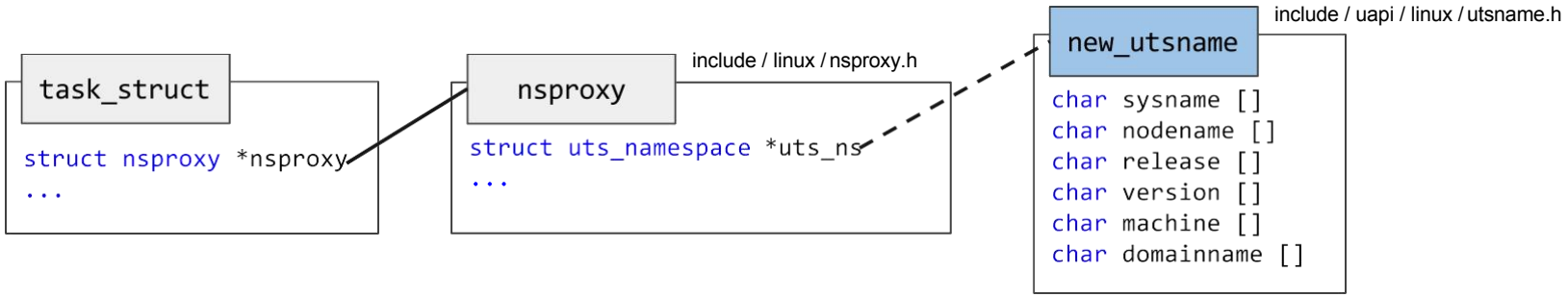
```
...
struct user_namespace *user_ns
```

include / linux / nsproxy.h

```
nsproxy* task_nsproxy(struct task_struct *tsk)
```

namespaces (as managed by kernel)

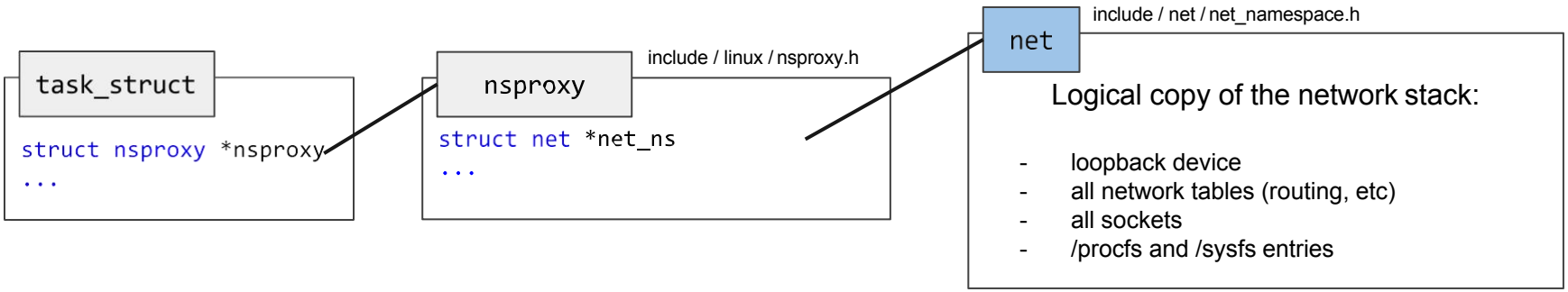
- Example for the UTS namespace



- Global access to hostname: `system_utsname.nodename`
- Namespace-aware access to hostname: `&current->nsproxy->uts_ns->name->nodename`

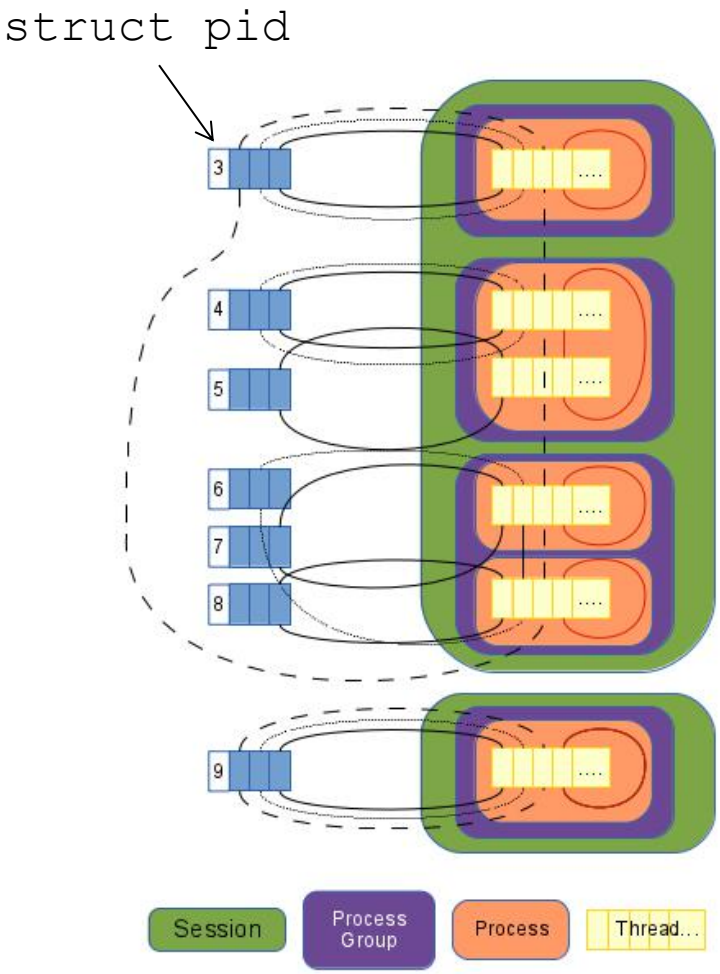
namespaces (as managed by kernel)

- Example for the `net` namespace



- A network device belongs to exactly one namespace
- A socket belongs to exactly one namespace
- A new namespace only includes the loopback device
- Communications between namespaces are handled via veth or unix sockets

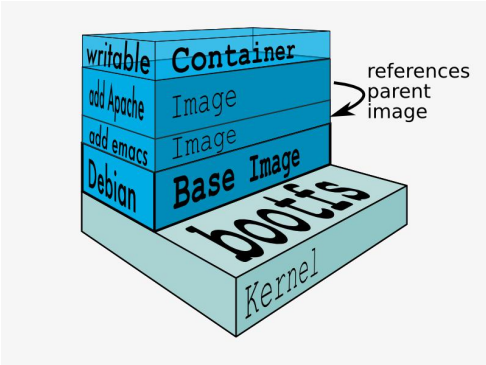
pids and namespaces



- `struct pid` links together pids in the namespace world

Containers

- A light form of resource virtualization based on kernel mechanisms
- A container is a *user-space* construct
- Multiple containers run on top of the same kernel
  - illusion that they are the only one using resources (cpu, memory, disk, network)
- some implementations offer support for:
  - container templates
  - deployment / migration
  - union filesystems

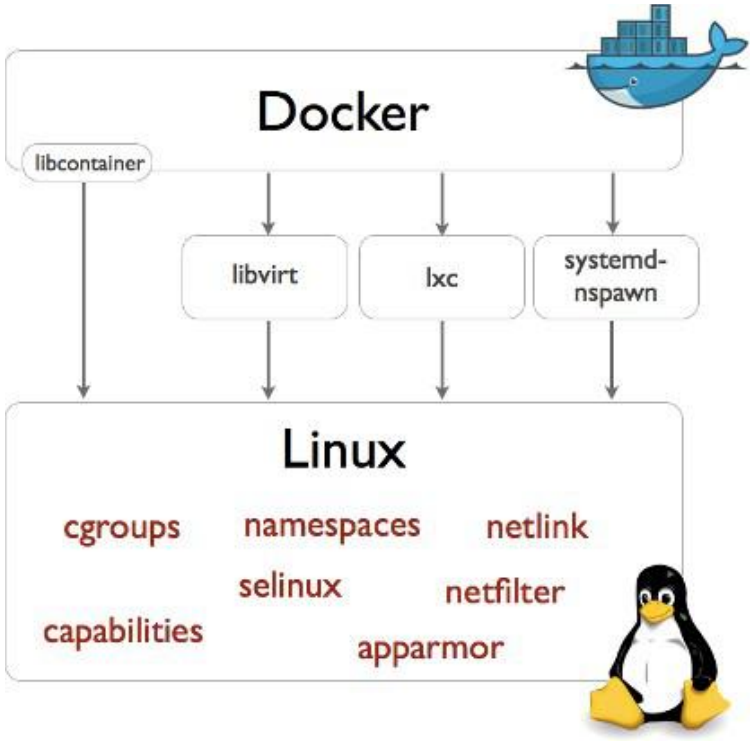


Container Solutions: LXC

- An LXC container is a userspace process created with the `clone()` syscall:
  - with its own pid namespace
  - with its own mnt namespace
  - net namespace is configurable
- Container templates can be found in /usr/share/lxc/templates
- Shell scripts:
  - lxc-create -t ubuntu -n containerName

Container Solutions: Docker

- A Linux container engine
- Multiple backend drivers
- Application-centric
- Diff-based deployment of updates (AUFS)
- Links (tunnels) between containers



Kernel Samepage Merging

- COW is used by the kernel to share physical frames with different virtual mappings
- If the kernel has no knowledge on the usage of memory, a similar behaviour is difficult to put in place
- KSM exposes the `/dev/ksm` pseudofile
- By means of `ioctl()` calls, programs can register portions of their address spaces
- An additional `ioctl()` call enables the page sharing mechanism, and the kernel starts looking for pages to share

Kernel Samepage Merging

- The KSM driver (in a kernel thread) picks one registered region and starts scanning it
  - A SHA1 hash is used to compare frames
  - If a similarity is found, all processes "sharing" the page will point to the same frame (in COW mode)
- A host running several guest Windows machines can overcommit its memory 300% without affecting performance
  - Windows zeroes all free'd memory