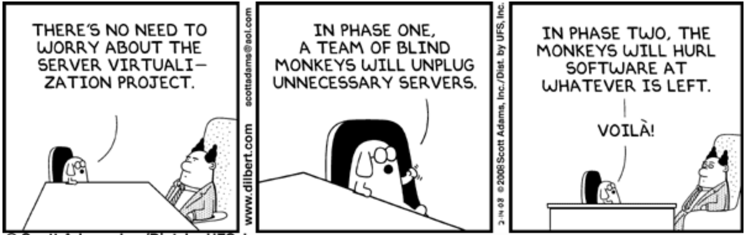
THERE'S NO NEED TO WORRY ABOUT THE SERVER VIRTUALI- ZATION PROJECT.
scottadams@aol.com
www.dilbert.com
IN PHASE ONE, A TEAM OF BLIND MONKEYS WILL UNPLUG UNNECESSARY SERVERS.
© 2008 Scott Adams, Inc./Dist. by UFS, Inc.
IN PHASE TWO, THE MONKEYS WILL HURL SOFTWARE AT WHATEVER IS LEFT.
VOILÀ!

Microkernel-based Operating Systems
— Virtualisation —

Jan Bierbaum

Hannes Weisbach
Julian Stecklina

2024-12-17

Goals

Give you an overview about:

- Virtualisation and virtual machines in general
- Hardware-assisted virtualisation on x86

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We will *not* discuss:

- Lots and lots of details
- Language runtimes
- How to use Xen/KVM/...

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Gave rise to IBM's VM line of operating systems:

- First release: 1972
- Latest release: z/VM 7.4 (20 September 2024)

Virtualisation is Great

- Consolidation: improve server utilization
- Isolation: isolate services for security reasons or because of incompatibility
- Reuse: run legacy software
- Development

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. . . but was confined to the mainframe world for a very long time.

Starting Point

You want to write a new operating system that is

- secure
- trustworthy
- small
- fast
- fancy

but . . .

Commodity Applications

Users expect to run all the software they are used to ("legacy support"):

- Browsers
- MS Word
- iTunes
- certified business applications
- new (Windows/DirectX) and ancient (DOS) games

Porting or rewriting all applications is infeasible!

Commodity Hardware

Users expect to run an (x86) OS on any PC which requires support for:

- input devices (USB, PS2, keyboards, mice, tablets, ...)
- graphics adapters (AMD, Intel, nVidia, ...)
- disks (SATA, SAS, USB, Thunderbolt, ...)
- network (Ethernet, Wifi, ...)
- printer, scanner, webcams, ...

Porting or rewriting all drivers is infeasible!

One Solution: Virtualisation

"By virtualizing a commodity OS [. . .] we gain support for legacy applications, and devices we don't want to write drivers for."

"All this allows the research community to finally escape the straitjacket of POSIX or Windows compatibility [. . .]"

— Roscoe, Elphinstone, Heiser: "Hype and virtue" (2007)

Virtualisation

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—Butler Lampson, 1972

“...except for the problem of too many layers of indirection.”

—David Wheeler

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Suppose you develop on your x86 workstation (**H**ost) an operating system that is to run on an ARM-based mobile device (**G**uest).

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- CPU
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An emulator for G running on H precisely emulates G's:

- CPU
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- I/O devices

Ideally, programs running on the emulated G exhibit the same behaviour as when running on a real G (except for timing).

Emulation

The emulator

- simulates every instruction in software as it is executed,
- prevents G from directly accessing to H's resources,
- maps G's devices onto H's devices, and
- may run multiple times on H.

Mapping G to H

G and H may have considerably different

- instructions sets
- hardware devices

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making emulation slow and complex (depending on emulation fidelity).

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Virtualisation

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- near-native execution speed should be possible.

This is (easily) possible, if the architecture is *virtualisable*.

Idea: Executing the guest as a user process

Run the guest operating system as a normal user process on the host.

[1] Often used synonymously with “hypervisor”. We’ll come back to tht later.

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Idea: Executing the guest as a user process

Run the guest operating system as a normal user process on the host.

But this is not just about executing instructions!

We need to emulate virtual hardware. The software providing the illusion of a real machine is the Virtual Machine Monitor (VMM)[1].

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A hypothetical instruction: `OUT`

Suppose our system has an instruction `OUT` that writes to a device register in kernel mode.

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Otherwise device access cannot be (easily) virtualized.

Virtualizability

. . . is a property of the *Instruction Set Architecture* (ISA).

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Instructions are divided into two classes:

Sensitive

A sensitive instruction changes or depends in its behavior on the processor's configuration or mode.

Privileged

A privileged instruction causes a trap when executed in user mode.

Trap & Emulate

An ISA is virtualizable, i.e. a VMM can be written, if all sensitive instructions are privileged.

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An ISA is virtualizable, i.e. a VMM can be written, if all sensitive instructions are privileged.

Approach:

- Execute guest in unprivileged mode
- Emulate all instructions that cause traps

Popek, Goldberg: "Formal Requirements for Virtualizable Third-Generation Architectures", 1973

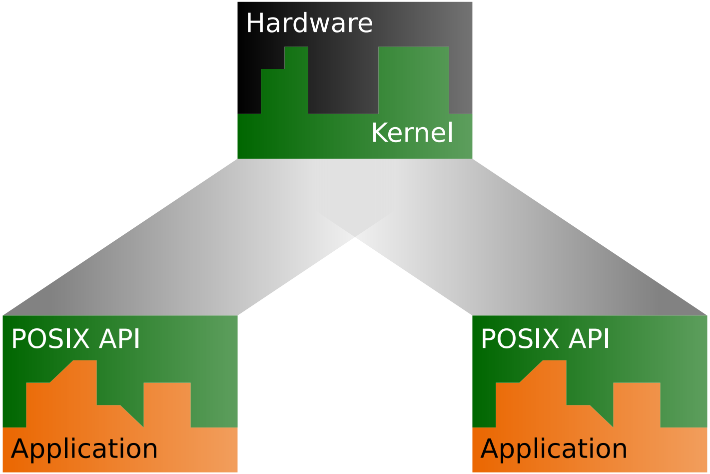
VMM

The Virtual Machine Monitor (VMM) needs to handle:

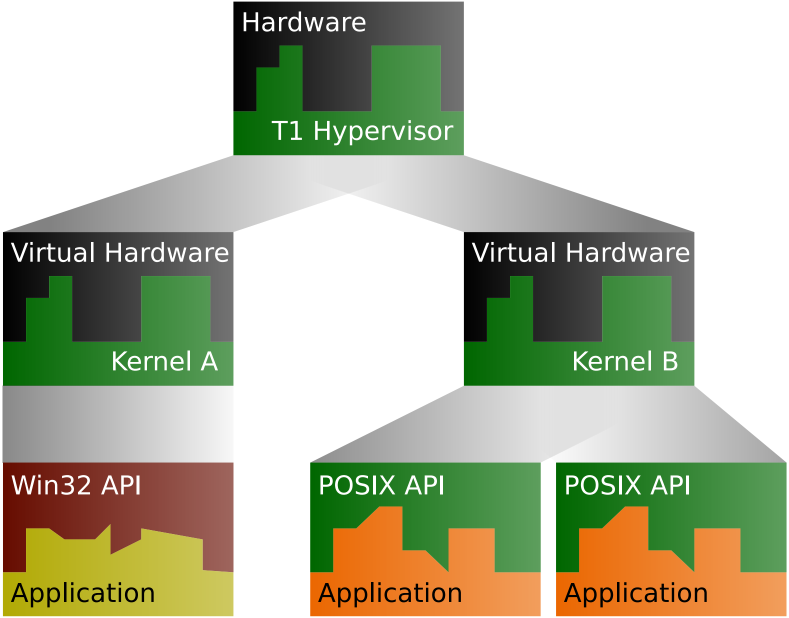
- address space changes
- device accesses
- system calls
- ...

Most of these are not problematic, because they trap to the host kernel.

Where to put the VMM?



Type-1/Bare-Metal/Native Hypervisor



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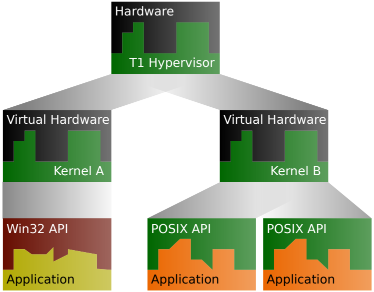
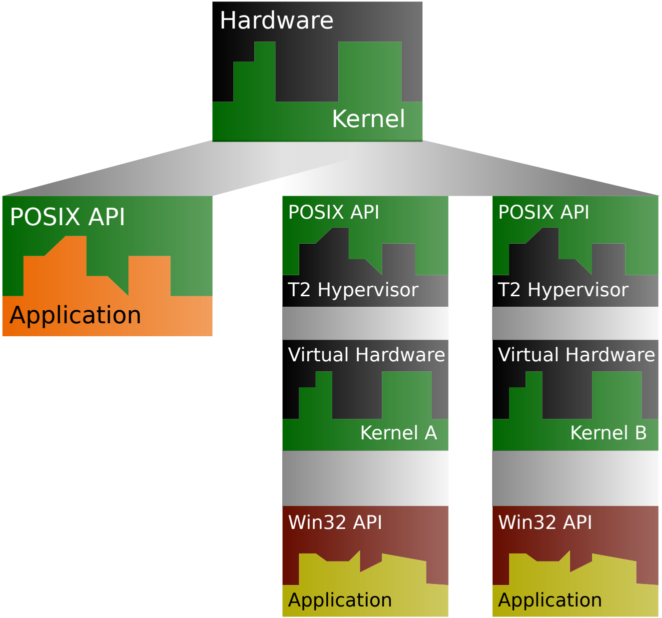


- Implemented directly on hardware
- No OS overhead
- Complete control over host resources
- High maintainance effort

Popular examples:

- Xen
- Hyper-V
- VMware ESXi

Type-2/Hosted Hypervisor



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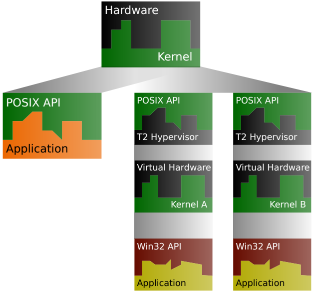

- Implemented as normal process on top of an OS
- Doesn't reinvent the wheel
- Performance may suffer
- Requires Host-OS support for CPU's virtualisation features

Popular examples:

- KVM,
- VMware Server/Workstation,
- VirtualBox,
- ...

Paravirtualisation

Why all the trouble?
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Compromise: Paravirtualized drivers for I/O performance (KVM virtio, VMware)

Examples: Usermode Linux, L^4Linux, Xen/XenoLinux, DragonFlyBSD VKERNEL, ...

Virtualised ABI

Why deal with the OS kernel at all? Just reimplement its interface!

Example: Wine

- Reimplements (virtualizes) Windows ABI
- Run unmodified Windows binaries
- Windows API calls are mapped to host OS's (Linux/MacOS/*BSD/...) equivalents
- Huge moving target/maintainance effort

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Also: API "virtualisation": Recompile Windows applications as native applications linking to `winelib`

Recap — Virtualisation

- Classification criteria:
  - Target? Hardware, OS ABI, OS API, . . .
  - Modified guest? Paravirtualisation
  - Emulation vs. Virtualisation (Interpret all or only some instructions?)

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  - Emulation vs. Virtualisation (Interpret all or only some instructions?)
- Popek, Goldberg: "*A virtual machine is an efficient, isolated duplicate of a real machine.*" implemented by a Virtual Machine Monitor (hypervisor).
  - Type 1/bare-metal hypervisors run as kernel
  - Type 2/hosted hypervisors run as applications on a conventional OS

Is x86 Virtualizable?

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- Other examples: KQemu, Virtual Box, Valgrind

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- Typically, VMs have very few (if any) VM-exits for CPU/memory virtualisation

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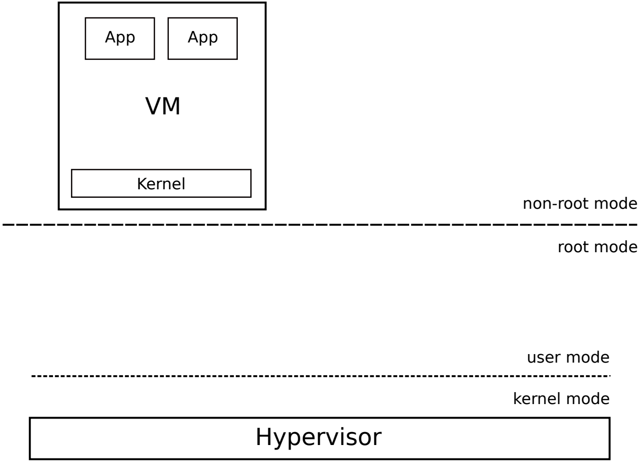

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- Reduced software complexity

Supported by all major virtualisation solutions today.

Instruction Emulation

Intel VT and AMD-V still require an instruction emulator, e.g. for

- Running 16-bit code (not in AMD-V, current Intel VT)
  - BIOS
  - Boot loaders
- Handling memory-mapped I/O
  - Realized as non-present page
  - Page fault on access
  - Emulate offending instruction
- ...

MMU Virtualisation

Early versions of Intel VT do not completely virtualize the MMU. The VMM has to handle guest virtual memory.

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Four different types of memory addresses:

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- **hVA** Host virtual address
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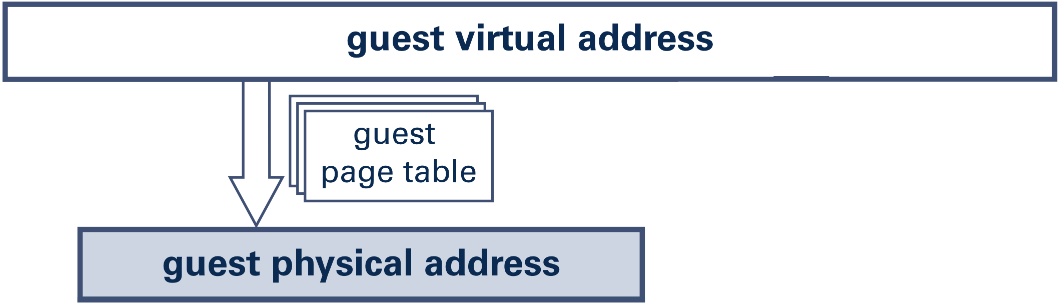
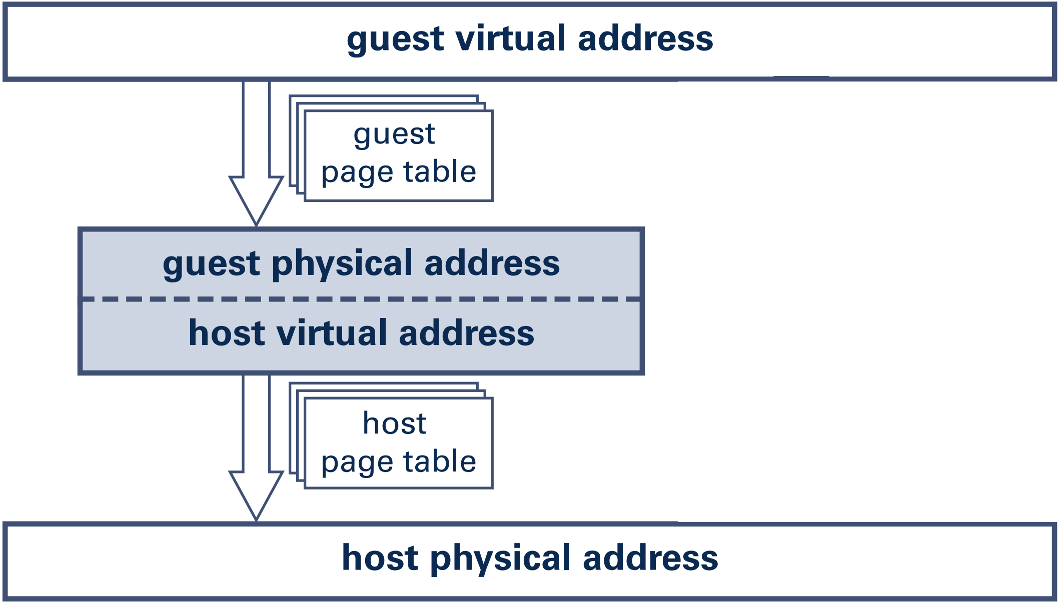
Usually GPA == HVA or other simple mapping (e.g. constant offset).


guest virtual address
guest
page table
guest physical address

MMU Virtualisation

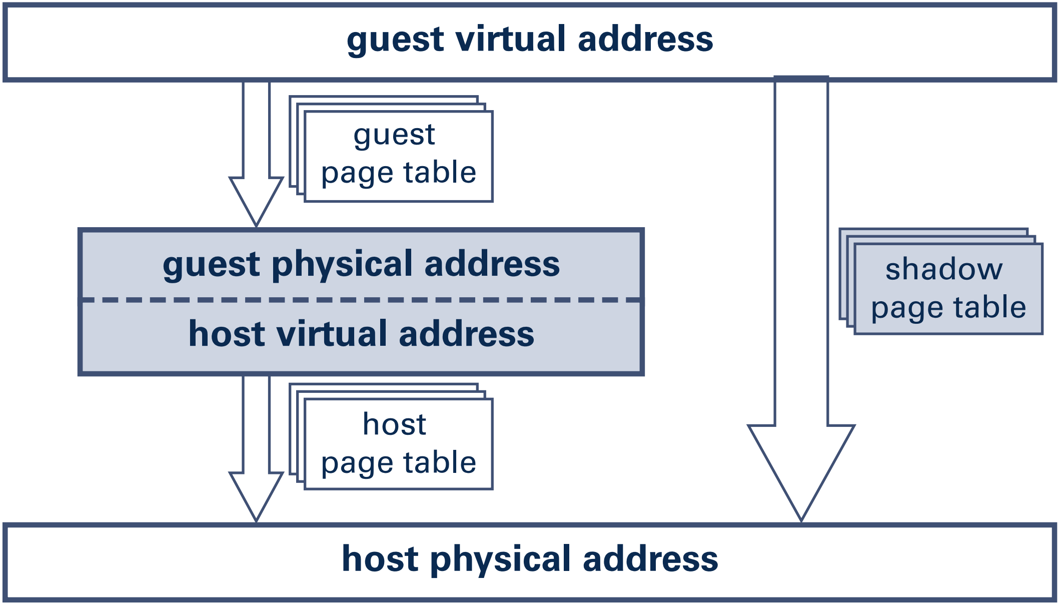


Shadow Page Tables

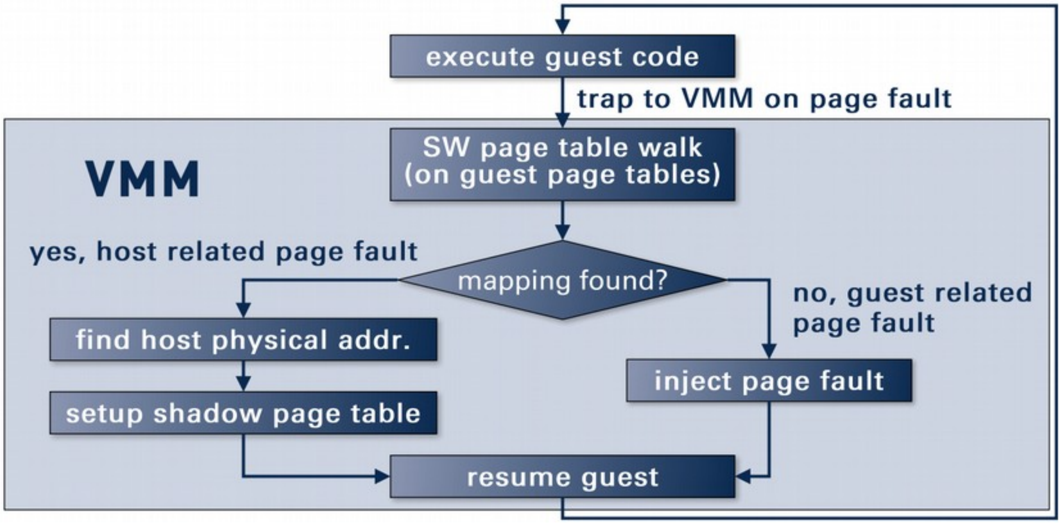
If the hardware can handle only one page table, the hypervisor must maintain a shadow page table that

- maps from GVA to HPA ("merging" guest and host page table),
- must be adapted on changes to virtual memory layout.

MMU Virtualisation



Shadow Paging in a Nutshell



Drawbacks of Shadow Paging

Maintaining shadow page tables causes significant overhead, because they need to be updated or recreated on

- guest page table modification,
- guest address space switch.

Certain workloads are penalized.

Second Level Address Translation (SLAT)

Intel *Nehalem* (Extended Page Table, EPT) and AMD *Barcelona* (Nested Paging) microarchitectures introduced hardware support for MMU virtualisation.

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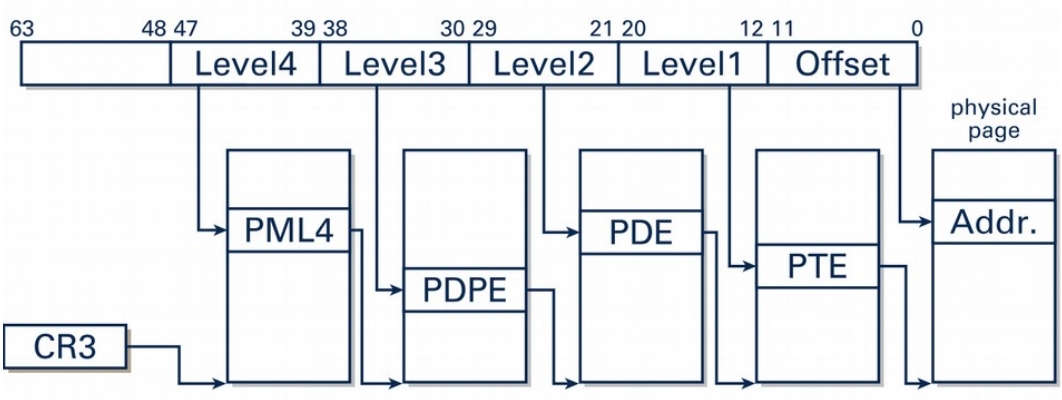
This feature introduces a measurable constant overhead ($< 1\%$).

Guest Address Translation



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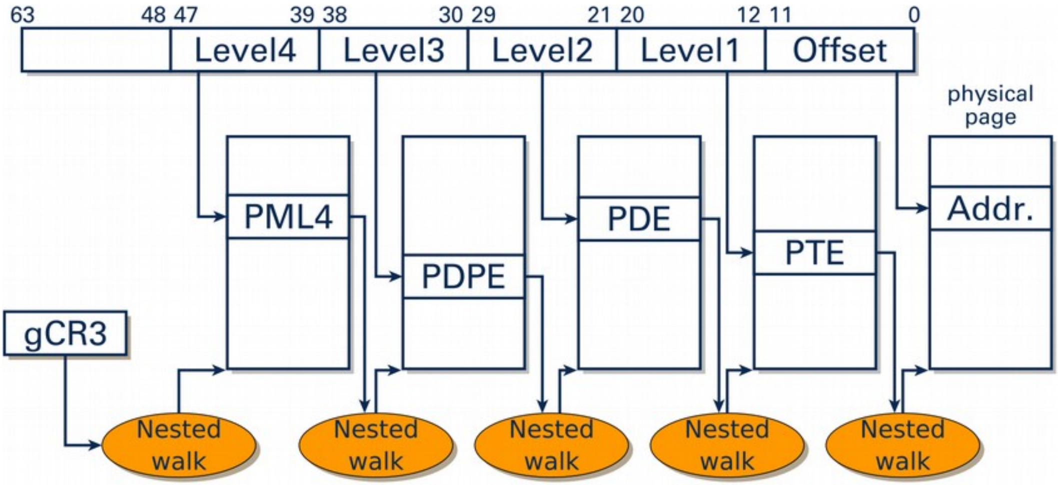
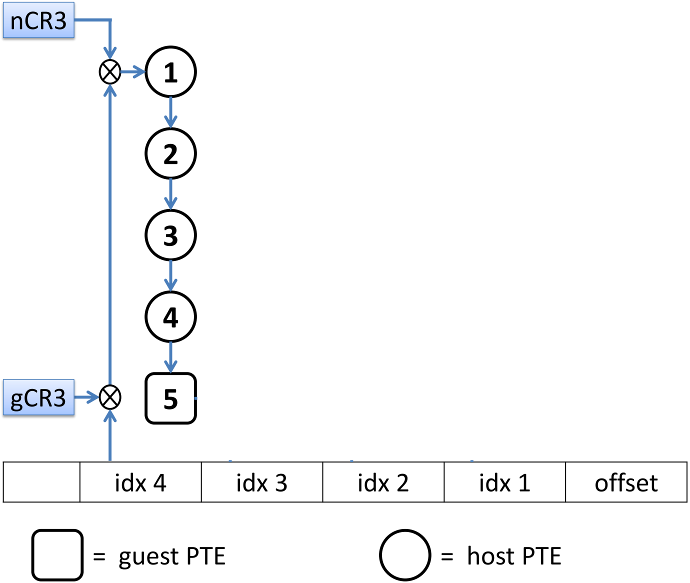


2D Page Table Walk



"Hash, Don't Cache (the Page Table)", 2016
— Yaniv, Tsafrir

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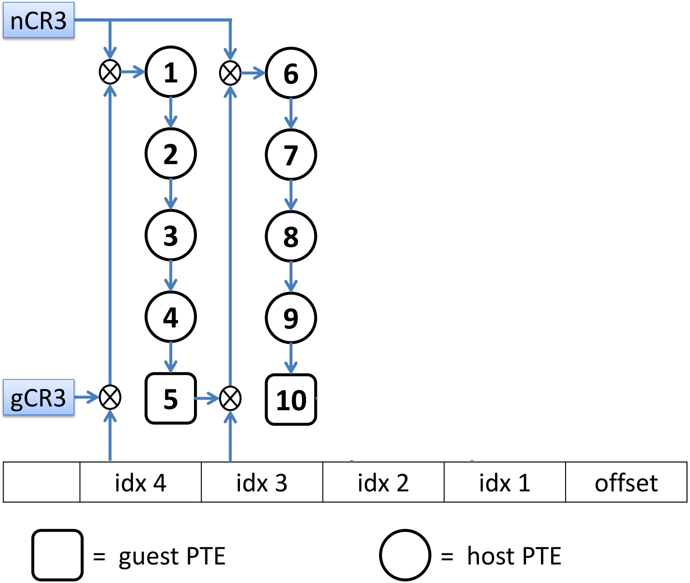

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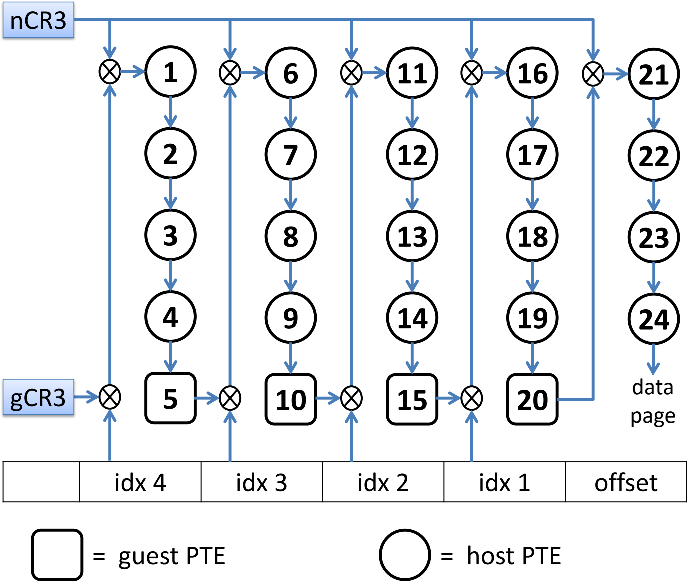

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Shadow Paging vs. SLAT

Event	Shadow Paging	EPT
vTLB Fill	181,966,391	
Guest Page Fault	13,987,802	
CR Read/Write	3,000,321	
vTLB Flush	2,328,044	
Port I/O	723,274	610,589
INVLPG	537,270	
Hardware Interrupts	239,142	174,558
Memory-Mapped I/O	75,151	76,285
HLT	4,027	3,738
Interrupt Window	3,371	2,171
Sum	202,864,793	867,341
Runtime (sec)	645	470
Exit/sec	314,519	1,845

—Linux kernel compilation, from Steinberg, Kauer
"NOVA: A Microhypervisor-Based Secure Virtualization Architecture", 2010

Arm

- Virtualisation Support since Cortex A15 (2010)
- New processor mode “HYP” (PL2/EL2) — different from x86
- Nested paging from the start
- No processor-defined state layout (VMCS/VMCB) ⇒ Hypervisor saves/restores all registers
- Interrupt controller (GIC) and generic timer have built-in virtualisation support
- Hardware support for nested virtualisation

TCB of Virtual Machines

The *Trusted Computing Base* of a Virtual Machine is the hardware and software components you have to trust to guarantee this VM's security.

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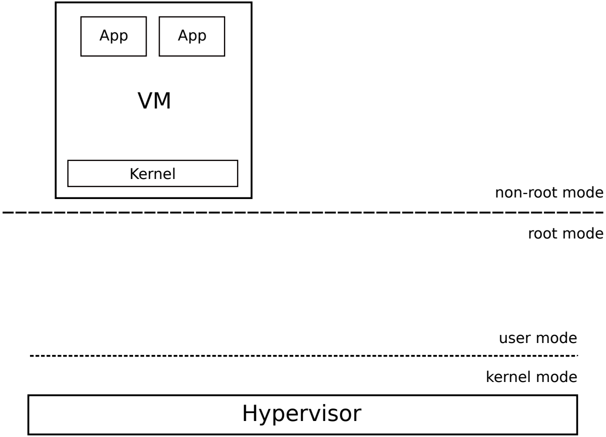

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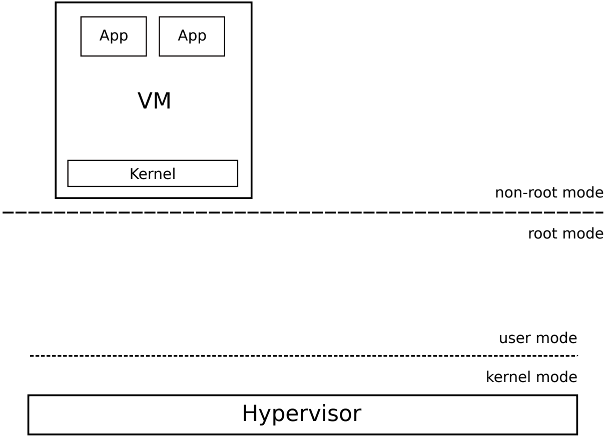

For e.g. KVM this (conservatively) includes the Linux kernel and Qemu.

Recap: Microkernels & L4Re

- Small is beautiful: small TCB; security & safety, application-specific TCBs

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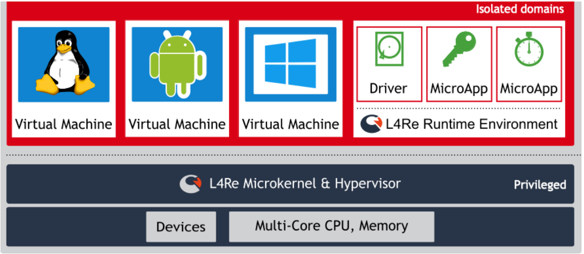
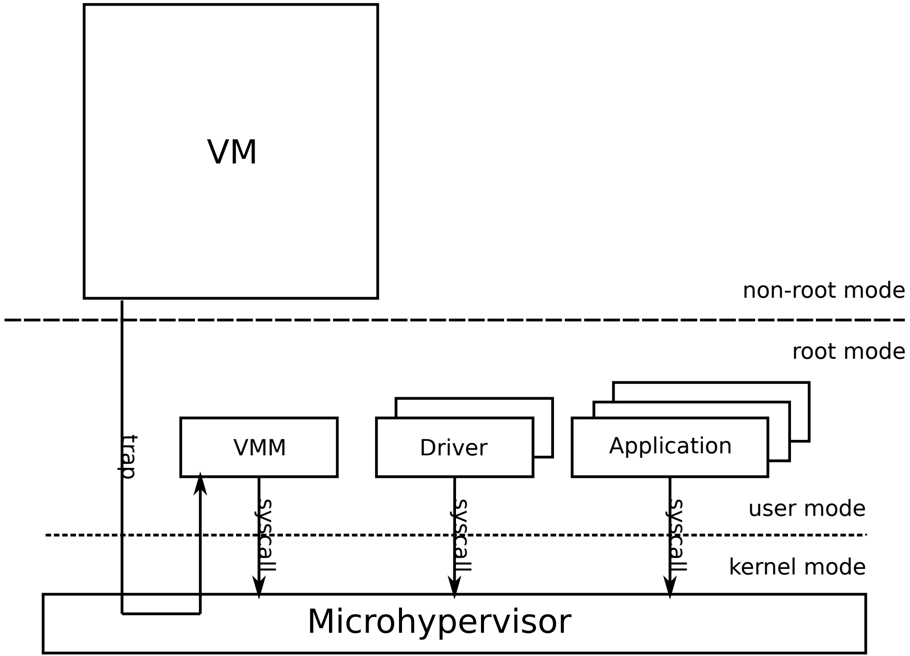
L4Re: OS Framework

- Fiasco/L4Re Microkernel
- L4Re user-level infrastructure
- ...supports virtualisation



Shrinking the Hypervisor



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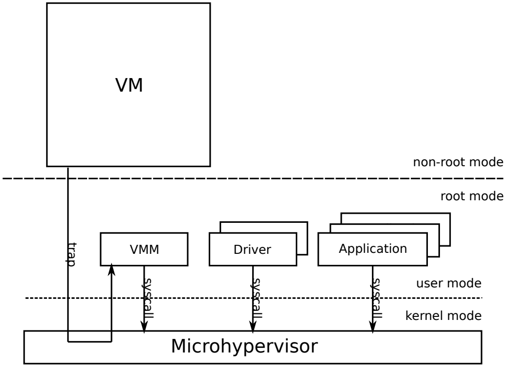


What needs to be in the Microhypervisor? Ideally nothing, but

- VT-x instructions are privileged
- Hypervisor has to validate guest state to enforce isolation

Microhypervisor vs. VMM

"Hypervisor" and "VMM" do not need to be synonymous...

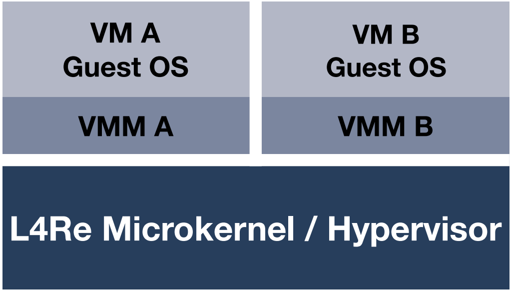
Microhypervisor

- "Kernel part"
- Provides & ensures isolation
- Enables safe access to virtualisation features to userspace
- Mechanisms, no policies!

VMM

- "User-space part"
- Platform & device emulation
- Design options!

VMM Design Options



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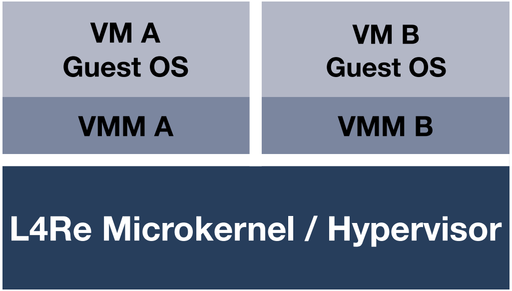

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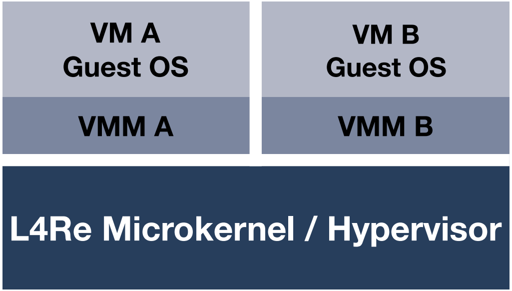

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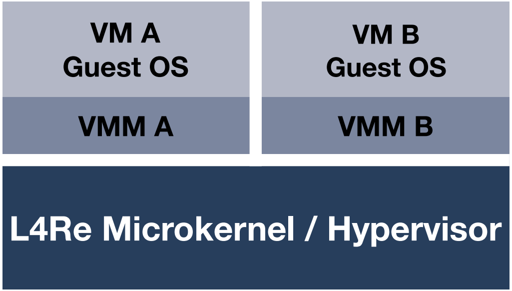

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- Application-specific: simple vs. feature-rich
- VMM is an untrusted user application
- Border between guest and VMM is not the only one

L4Re: uvmm

- VMM for Arm, MIPS, RISC V, and x86

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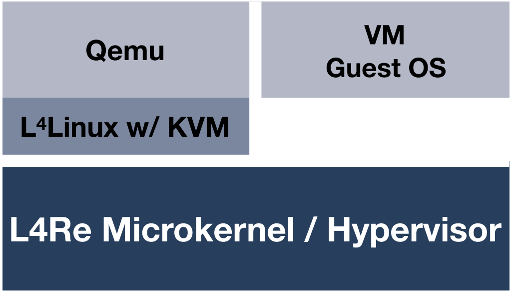
- Small
- Uses virtio for guests
- Mainly (unmodified) Linux as guest OS, but others on request

- x86
- Complex and feature-rich VMM
- Uses L4Linux to run KVM + Qemu
- Runs Windows
- Used in production



L4Re: KVM/L4

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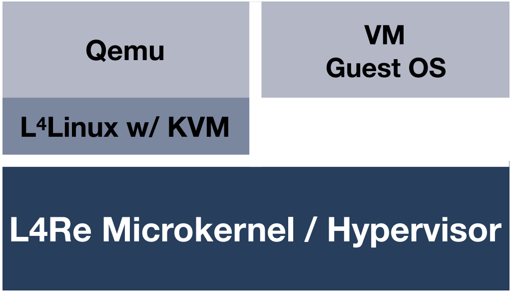

Shows flexibility of L4Re architecture:
integration of existing virtualization solutions, e.g. KVM

L^4Linux

. . . is a paravirtualized Linux running as a user-level application on top of L4Re; first presented at SOSP'97

- Regard "L4Re" as new *hardware* platform in Linux and implement
  - Syscall interface: kernel entry, signal delivery, copy from/ to userspace
  - Hardware access: CPU state/features, MMU, interrupts, MMIO & port I/O

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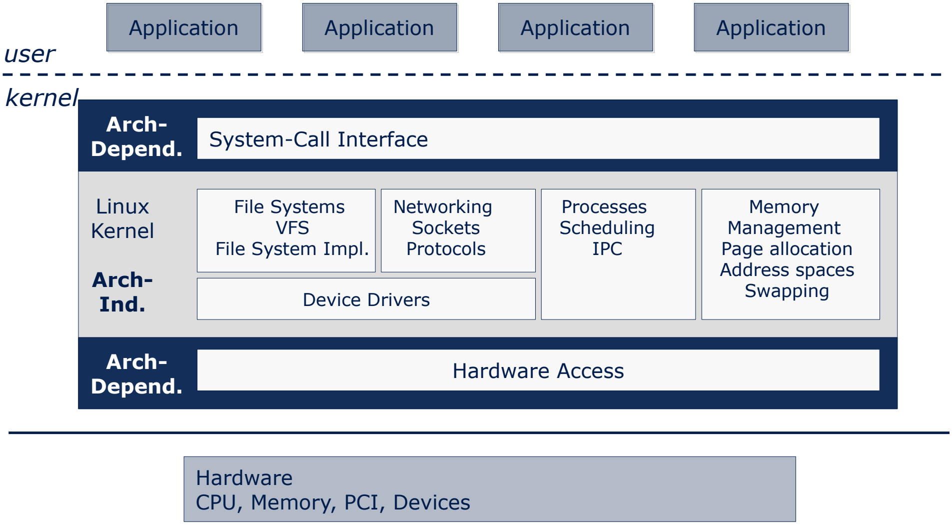
L^4Linux Architecture



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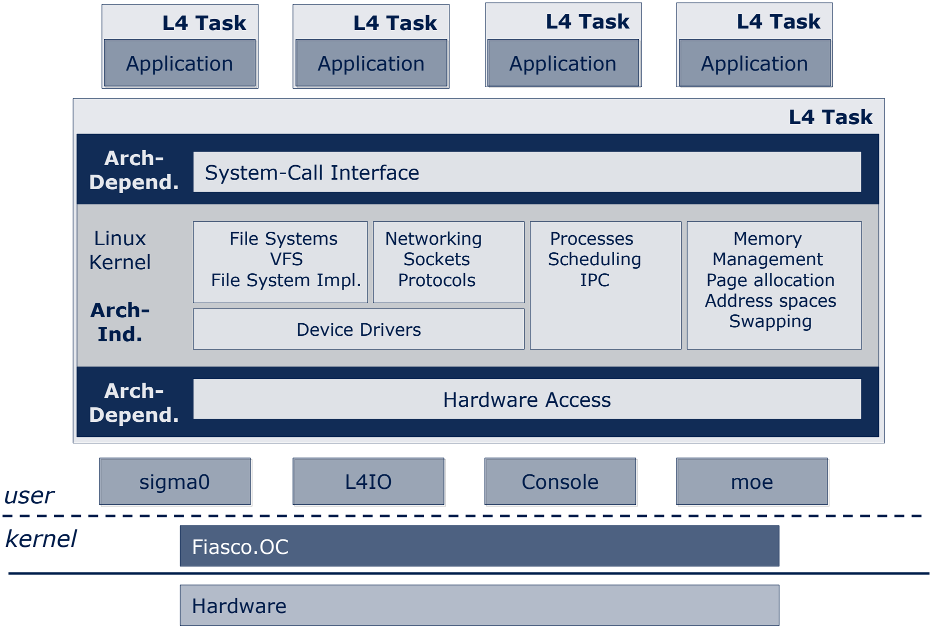

Software Abstractions

Interface between kernel/microhypervisor and user-level/VMM

Requirements:

- Asynchronous execution model of OS kernels (IRQs)
- Paravirtualization + hardware-assisted virtualisation
- Smooth integration into system

Challenges

Fundamental problem: How to map three logical levels of privilege (Linux application, Linux kernel, L4Re microkernel/hypervisor) onto the two privilege levels the platform provides (user/kernel mode)?

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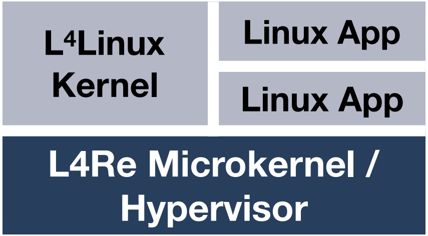
CPU: Run Linux kernel & applications in microkernel user land

Memory: Linux kernel manages memory for Linux applications



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Regular/“Legacy” L4 Thread

- Executes XOR waits (for event, messages, IRQs)
- Hard to map OS kernel onto

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- State save area: Memory area to hold CPU & message state

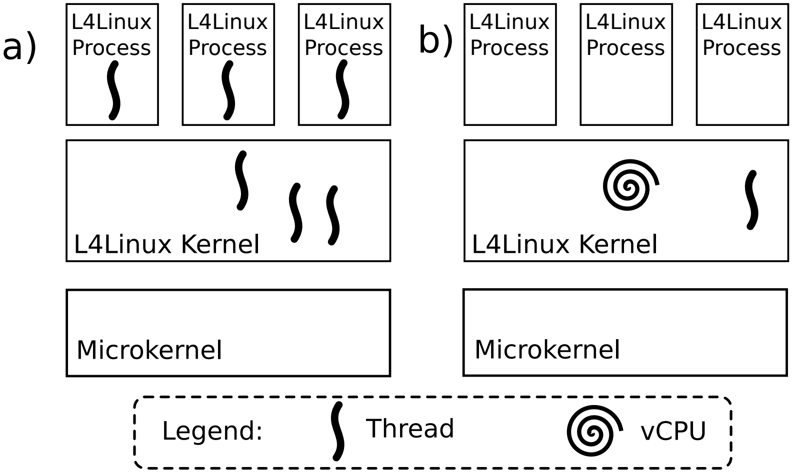
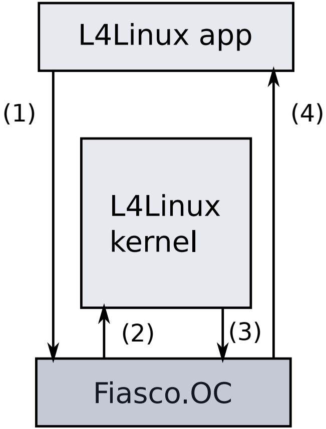


FIGURE 3: *(a) L4Linux implemented with threads and (b) L4Linux implemented with vCPUs.*

—from Lackorzynski, Warg, Peter "Virtual Processors as Kernel Interface", 2010

Event Processing, e.g. Syscalls

- Linux syscall interface (`int 0x80`) causes trap



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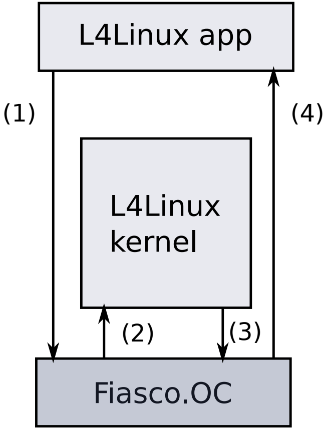

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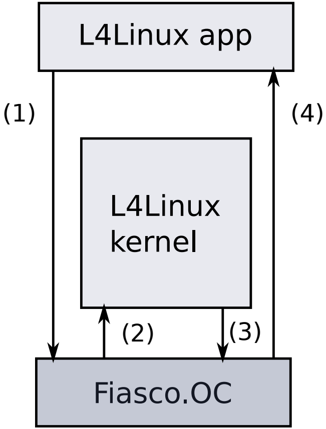

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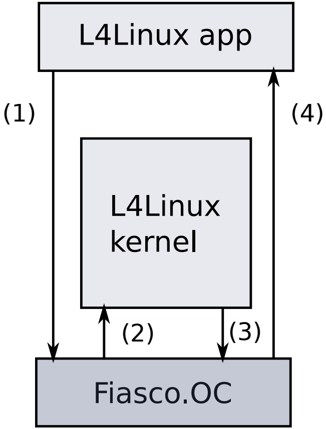
⇒ Hardware-assisted virtualisation
  - Nicely integrates into vCPU abstraction
  - Nested paging by `L4::Task`/`L4::VM`



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- Options:
  - Exclusive: Pass-through
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- Pass through resources:
  - MMIO (direct mapping)
  - Interrupts via Microkernel/Hypervisor
  - Interrupts delivered directly to guest on recent hardware

VirtIO

- Standard for virtual devices
- Defines common data structures
- Widely supported (Linux, *BSD, Windows, QNX, . . .)
- Optimised for virtualisation, but also usable for hardware devices

IOMMU

- Important hardware building block
- MMU for devices
- Indirection & Protection
  - Limit device access to memory → prevents DMA attacks by guests, devices/firmware, . . .
  - Guest can use gPA (instead of hPA) to program DMA
- Programmed by assigning `L4::Task` to device

L^4Linux as a Toolbox

Reuse large parts of code from Linux:

- Filesystems
- Network stack
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Hybrid applications can provide these services to native L4 applications.

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  - Use VM to provide comon runtime, then *decouple* critical applications