UNSW
THE UNIVERSITY OF NEW SOUTH WALES

COMP9242
Advanced Operating Systems

S2/2012 Week 4:
Virtualization

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Virtual Machine (VM)

"A VM is an efficient, isolated duplicate of a real machine"

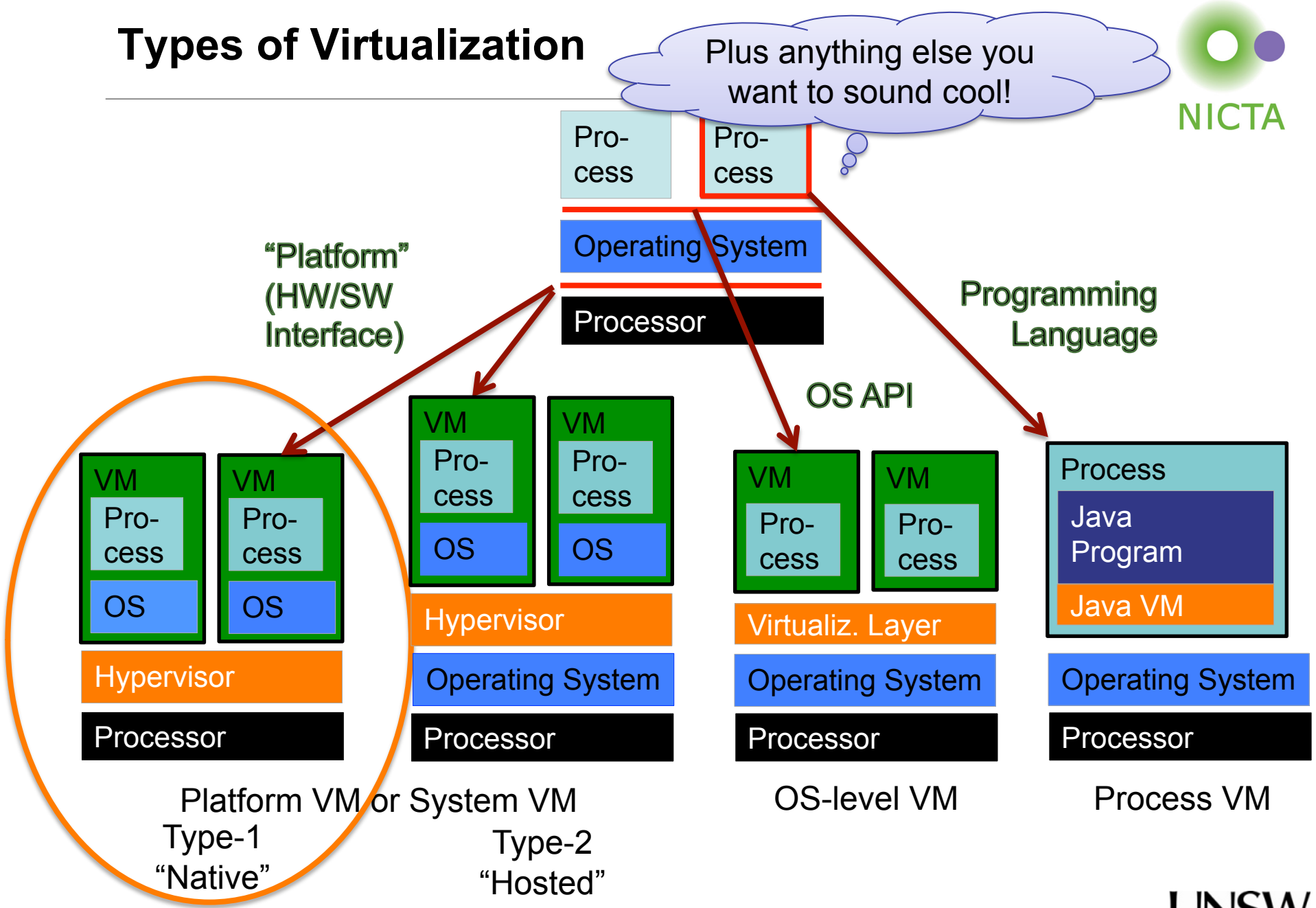
→ Duplicate: VM should behave identically to the real machine
- Programs cannot distinguish between execution on real or virtual hardware
- Except for:
  - Fewer resources available (and potentially different between executions)
  - Some timing differences (when dealing with devices)

→ Isolated: Several VMs execute without interfering with each other

→ Efficient: VM should execute at speed close to that of real hardware
- Requires that most instruction are executed directly by real hardware

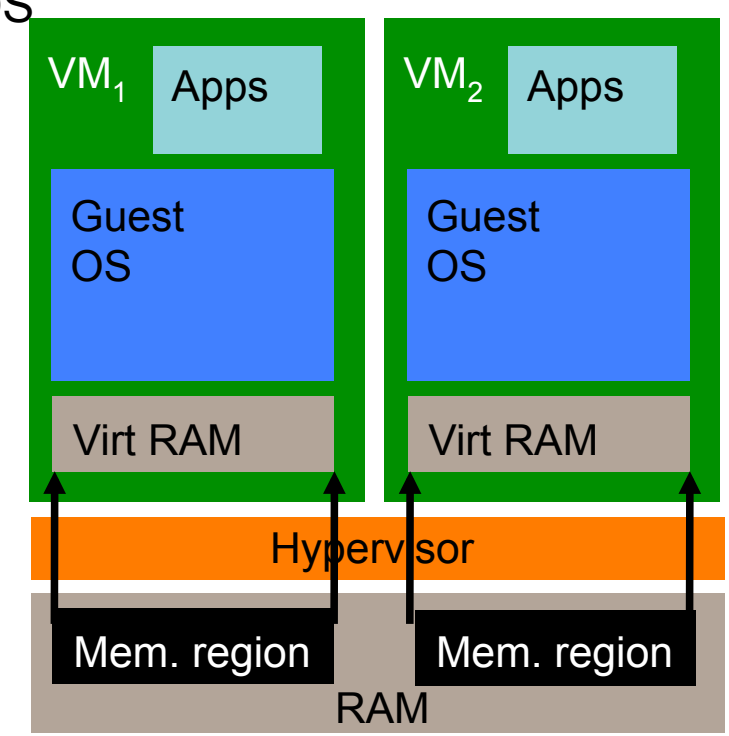
Hypervisor aka *virtual-machine monitor*: Software implementing the VM

Types of Virtualization



Why Virtual Machines?

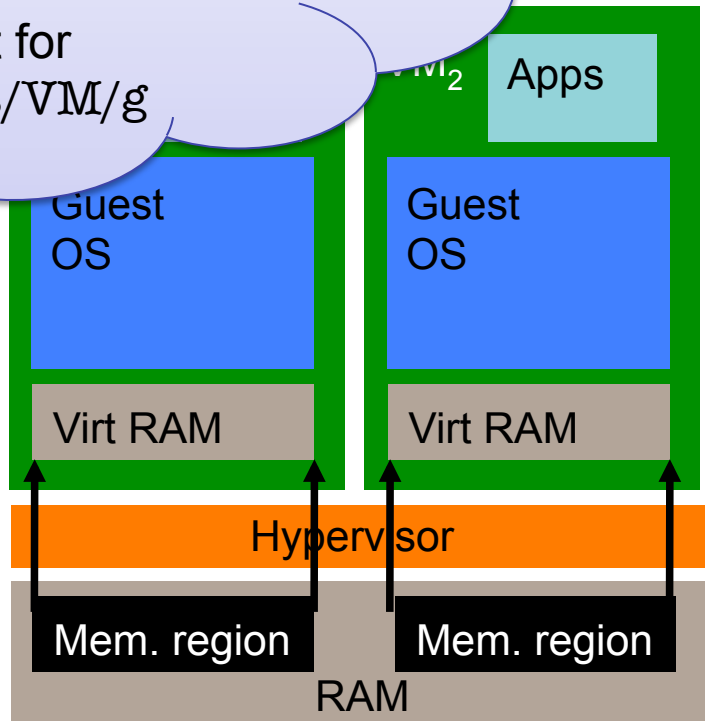
- Historically used for easier sharing of expensive mainframes
  - Run several (even different) OSes on same machine
    - called *guest operating system*
  - Each on a subset of physical resources
  - Can run single-user single-tasked OS in time-sharing mode
    - legacy support
- Gone out of fashion in 80's
  - Time-sharing OSes common-place
  - Hardware too cheap to worry...



Why Virtual Machines?

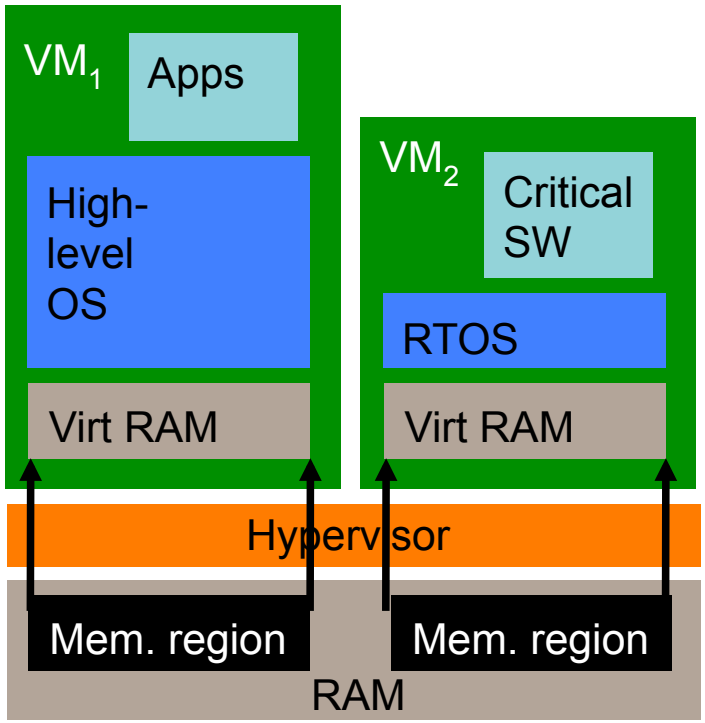
- Renaissance in recent years for improved isolation
- Server/desktop virtual machines
  - Improved QoS and
  - Uniform view of
  - Complete en
    - replication
    - migration
    - checkpointing
    - debugging
  - Different concurrent OSes
    - eg Linux + Windows
  - Total mediation
- Would be mostly unnecessary
  - … if OSes were doing their job!

Gernot prediction of 2004:
2014 OS textbooks will be
identical to 2004 version
except for
s/process/VM/g



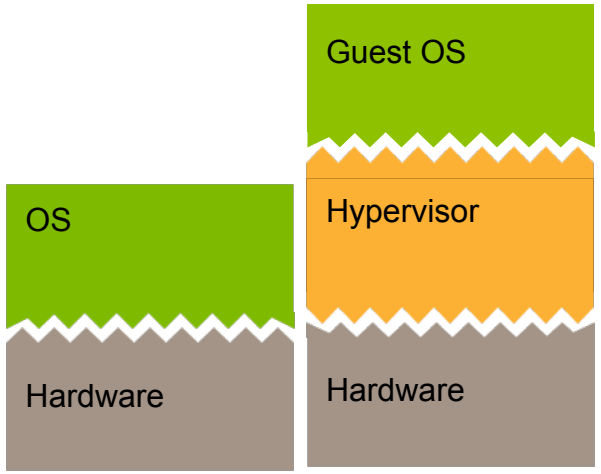
Why Virtual Machines?

- Embedded systems: integration of heterogenous environments
  - RTOS for critical real-time functionality
  - Standard OS for GUIs, networking etc
- Alternative to physical separation
  - low-overhead communication
  - cost reduction



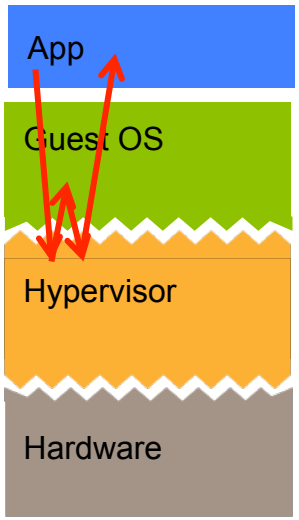
Hypervisor

- Program that runs on real hardware to implement the virtual machine
- Controls resources
  - Partitions hardware
  - Schedules guests
    - "*world switch*"
  - Mediates access to shared resources
    - e.g. console
- Implications
  - Hypervisor executes in *privileged* mode
  - Guest software executes in *unprivileged* mode
  - *Privileged instructions* in guest cause a trap into hypervisor
  - Hypervisor interprets/emulates them
  - Can have extra instructions for *hypercalls*

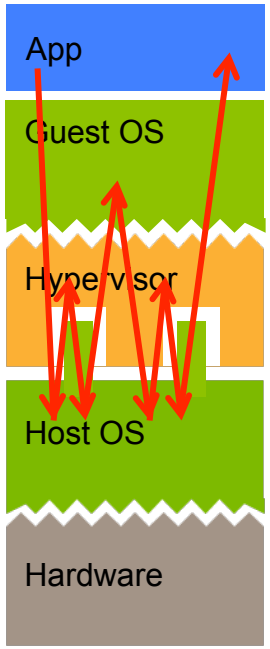


Native vs. Hosted VMM

Native/Classic/ Bare-metal/Type-I



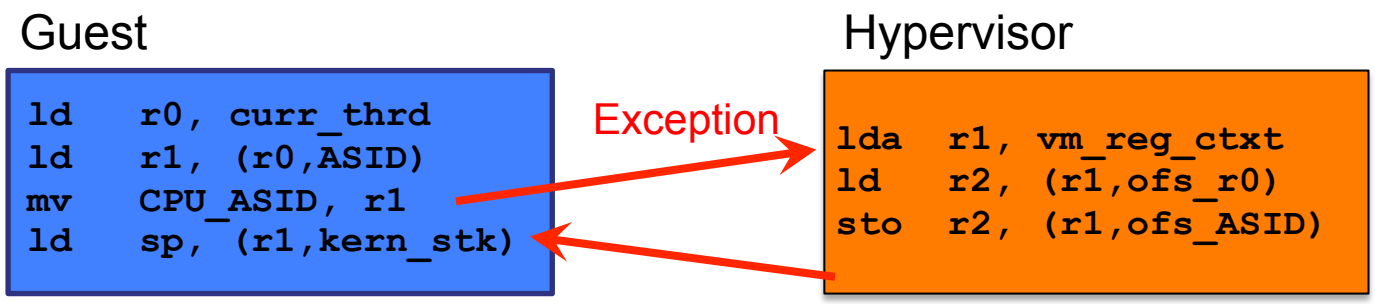
Hosted/Type-II



- → Hosted VMM can run besides native apps
  - Sandbox untrusted apps
  - Convenient for running alternative OS on desktop
- → Less efficient
  - Twice number of mode switches
  - Twice number of context switches
  - Host not optimised for exception forwarding

Virtualization Mechanics: Instruction Emulation

- Traditional "*trap and emulate*" approach:
  - guest attempts to access physical resource
  - hardware raises exception (trap), invoking hypervisor's exception handler
  - hypervisor emulates result, based on access to virtual resource
- Most instructions do not trap
  - makes efficient virtualization possible
  - requires that VM ISA is (almost) same as physical processor ISA



Trap-and-Emulate Requirements

Definitions:

- **Privileged instruction**: executes in privileged mode, *traps in user mode*
  - Note: trap is required, NO-OP is insufficient!
- **Privileged state**: determines resource allocation
  - Includes privilege mode, addressing context, exception vectors, …
- **Sensitive instruction**: control-sensitive or behaviour-sensitive
  - **control sensitive**: *changes* privileged state
  - **behaviour sensitive**: *exposes* privileged state
    - includes instructions which are NO-OPs in user but not privileged mode
- **Innocuous instruction**: not sensitive

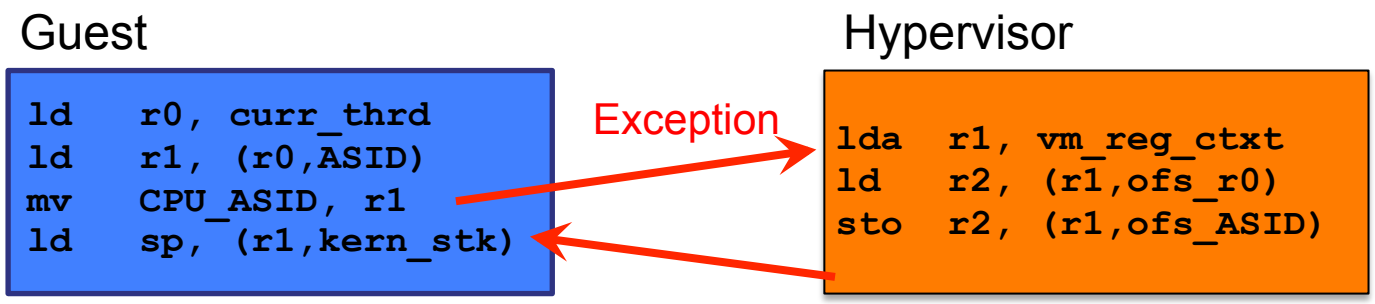
Note:

- Some instructions are inherently sensitive
  - e.g. TLB load
- Others are sensitive in some context
  - e.g. store to page table

Trap-and-Emulate Architectural Requirements

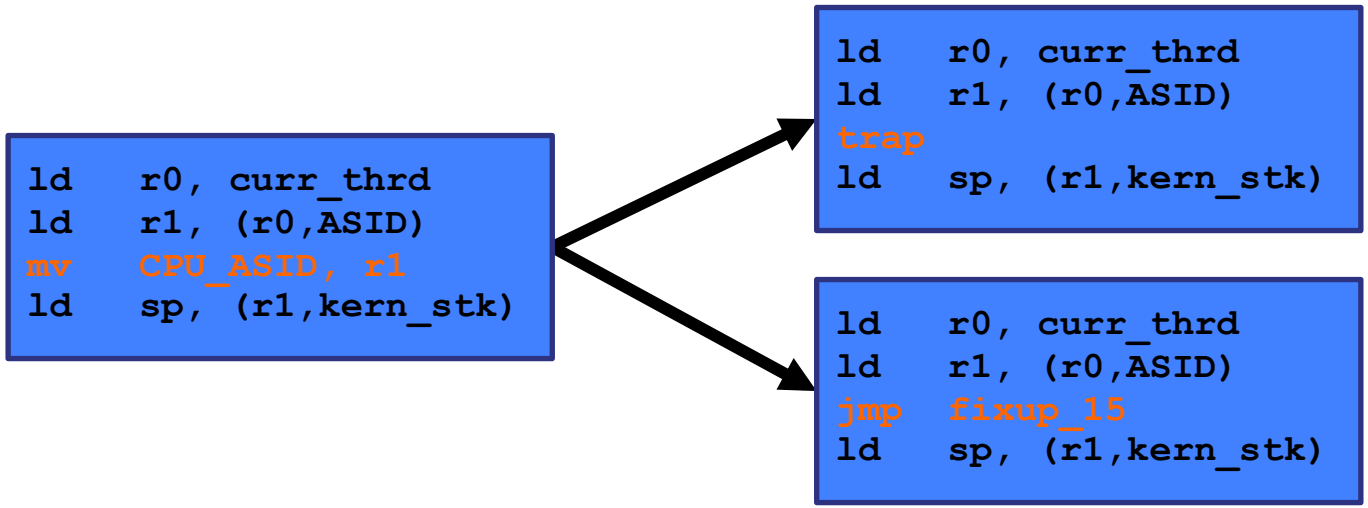
Trap-and-emulate *virtualizable* if all *sensitive* instructions are *privileged*

- → Can then achieve accurate, efficient guest execution
  - by simply running guest binary on hypervisor
- → VMM controls resources
- → Virtualized execution is indistinguishable from native, except:
  - Resources more limited (running on smaller machine)
  - Timing is different (if there is an observable time source)
- → Recursively virtualizable machine:
  - VMM can be built without any timing dependence



Impure Virtualization

- Used for two reasons:
  - Architecture not trap-and-emulate virtualizable
  - Reduce virtualization overheads
- Change the guest OS, replacing sensitive instructions
  - by trapping code (hypercalls)
  - by in-line emulation code
- Two standard approaches:
  - binary translation: modifies binary
  - para-virtualization: changes ISA

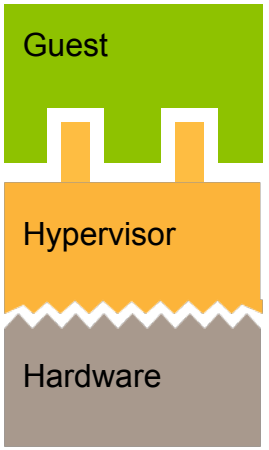


Binary Translation

- Locate sensitive instructions in guest binary and replace on-the-fly by emulation code or hypercall
  - pioneered by VMware
  - can also detect combinations of sensitive instructions and replace by single emulation
  - doesn't require source, uses unmodified native binary
    - in this respect appears like pure virtualization!
  - very tricky to get right (especially on x86!)
    - "heroic effort" [Orran Krieger, then IBM later VMware ;-)]
  - needs to make some assumptions on sane behaviour of guest

Para-Virtualization

- New name, old technique
  - Mach Unix server [Golub et al, 90], L^{4}Linux [Härtig et al, 97], Disco [Bugnion et al, 97]
  - Name coined by Denali [Whitaker et al, 02], popularised by Xen [Barham et al, 03]
- Idea: manually port the guest OS to modified ISA
  - Augment by explicit hypervisor calls (*hypercalls*)
    - -Use more high-level API to reduce the number of traps
    - -Remove un-virtualizable instructions
    - -Remove “messy” ISA features which complicate virtualization
  - Generally out-performs pure virtualization and binary-rewriting
- Drawbacks:
  - Significant engineering effort
  - Needs to be repeated for each guest-ISA-hypervisor combination
  - Para-virtualized guest needs to be kept in sync with native guest
  - Requires source

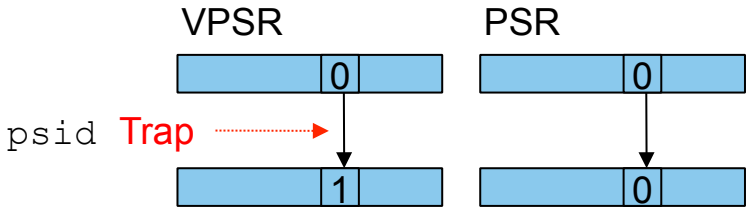


Virtualization Overheads

- VMM needs to maintain virtualized privileged machine state
  - processor status
  - addressing context
  - device state...
- VMM needs to emulate privileged instructions
  - translate between virtual and real privileged state
  - e.g. guest ↔ real page tables
- Virtualization traps are be expensive on modern hardware
  - can be 100s of cycles (1150 cycles round-trip on latest Intel x86 processors)
- Some OS operations involve frequent traps
  - STI/CLI for mutual exclusion
  - frequent page table updates during fork()...
  - MIPS KSEG address used for physical addressing in kernel

Virtualization Techniques

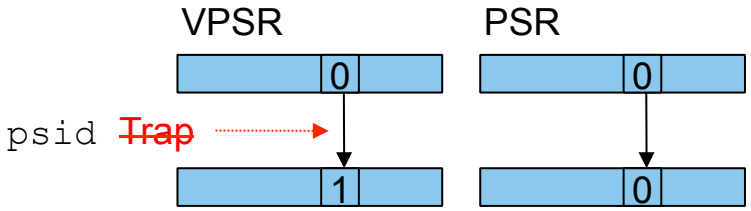
- Impure virtualization methods enable new optimisations
  - due to the ability to control the ISA
- E.g. maintain some virtual machine state inside VMM:
  - e.g. interrupt-enable bit (in virtual PSR)
  - requires changing guest's idea of where this bit lives
  - hypervisor knows about VMM-local virtual state and can act accordingly
    - e.g. queue virtual interrupt until guest enables in virtual PSR




```
mov   r1,#VPSR
ldr   r0,[r1]
orr   r0,r0,#VPSR_ID
sto   r0,[r1]
```

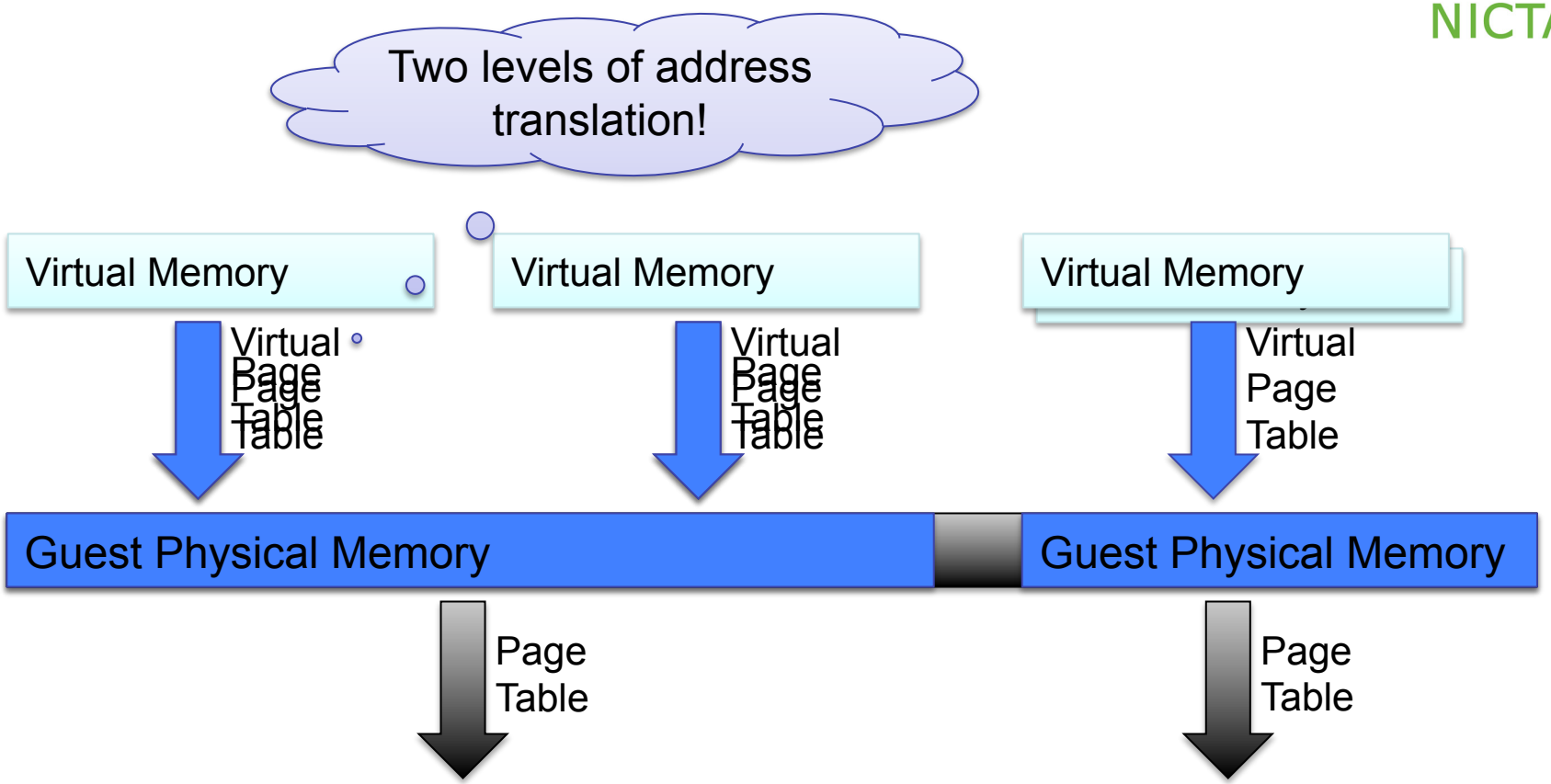
Virtualization Techniques

- E.g. lazy update of virtual machine state
  - virtual state is kept inside hypervisor
  - keep copy of virtual state inside VM
  - allow temporary inconsistency between local copy and real VM state
  - synchronise state on next forced hypervisor invocation
    - -actual trap
    - -explicit hypercall when physical state must be updated
  - Example:guest enables FPU
    - -no need to invoke hypervisor at this point
    - -hypervsior syncs state on virtual kernel exit



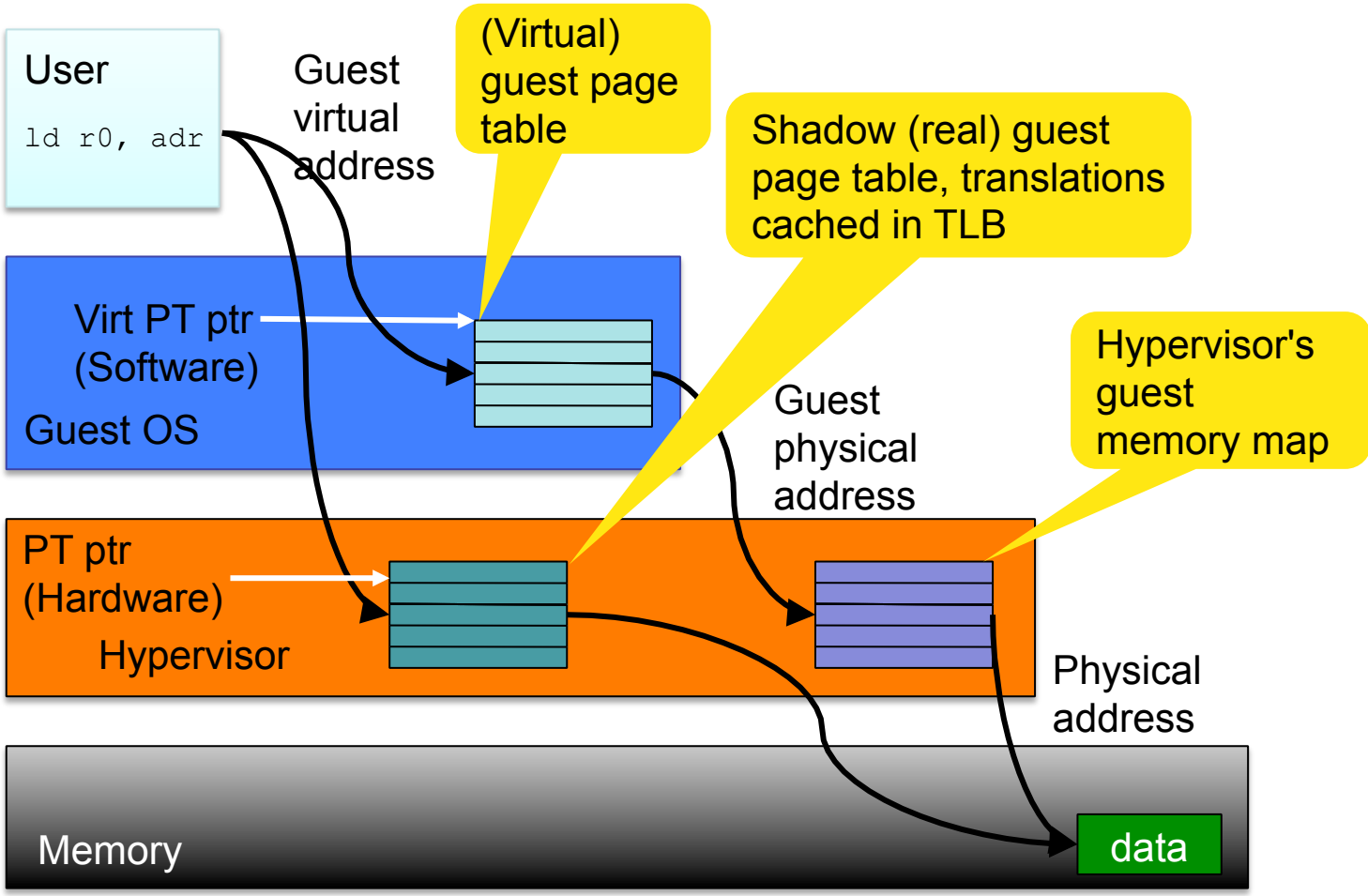

```
mov   r1,#VPSR
ldr   r0,[r1]
orr   r0,r0,#VPSR_ID
sto   r0,[r1]
```

Virtualization and Address Translation

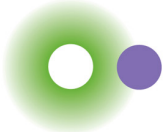


Must implement with single MMU translation!

Virtualization Mechanics: Shadow Page Table



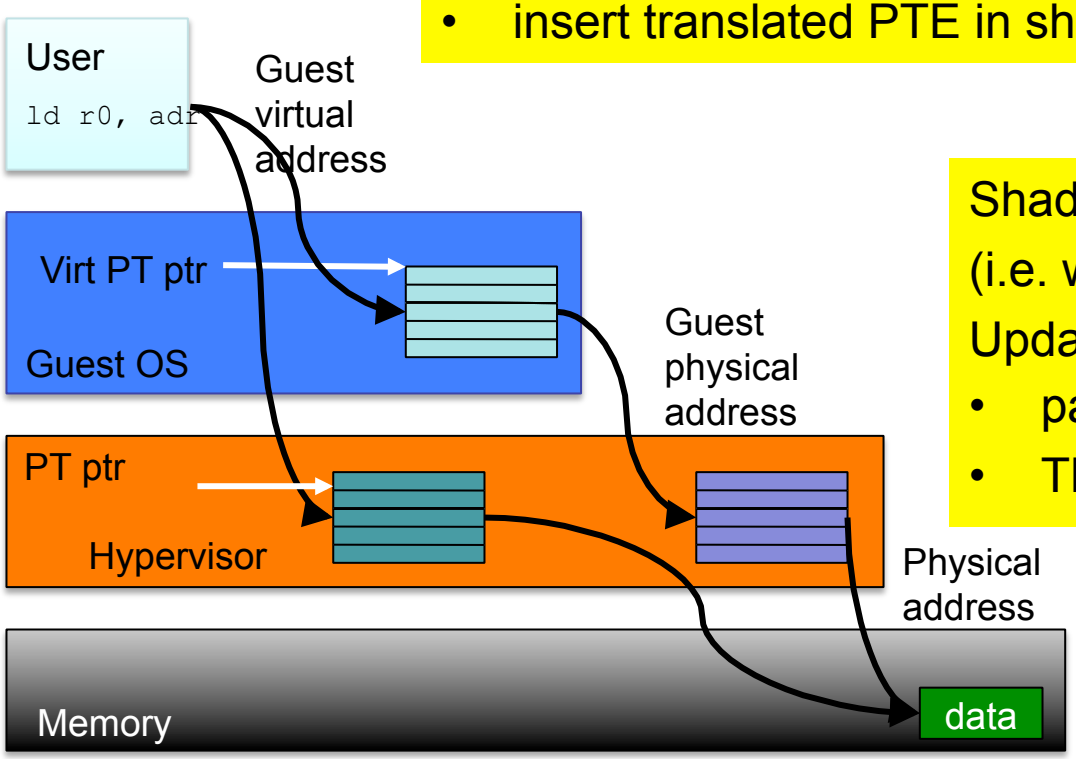
Virtualization Mechanics: Shadow Page Table



Hypervisor must shadow (virtualize) all PT updates by guest:

- trap guest writes to guest PT
- translate guest PA in guest (virtual) PTE using guest memory map
- insert translated PTE in shadow PT

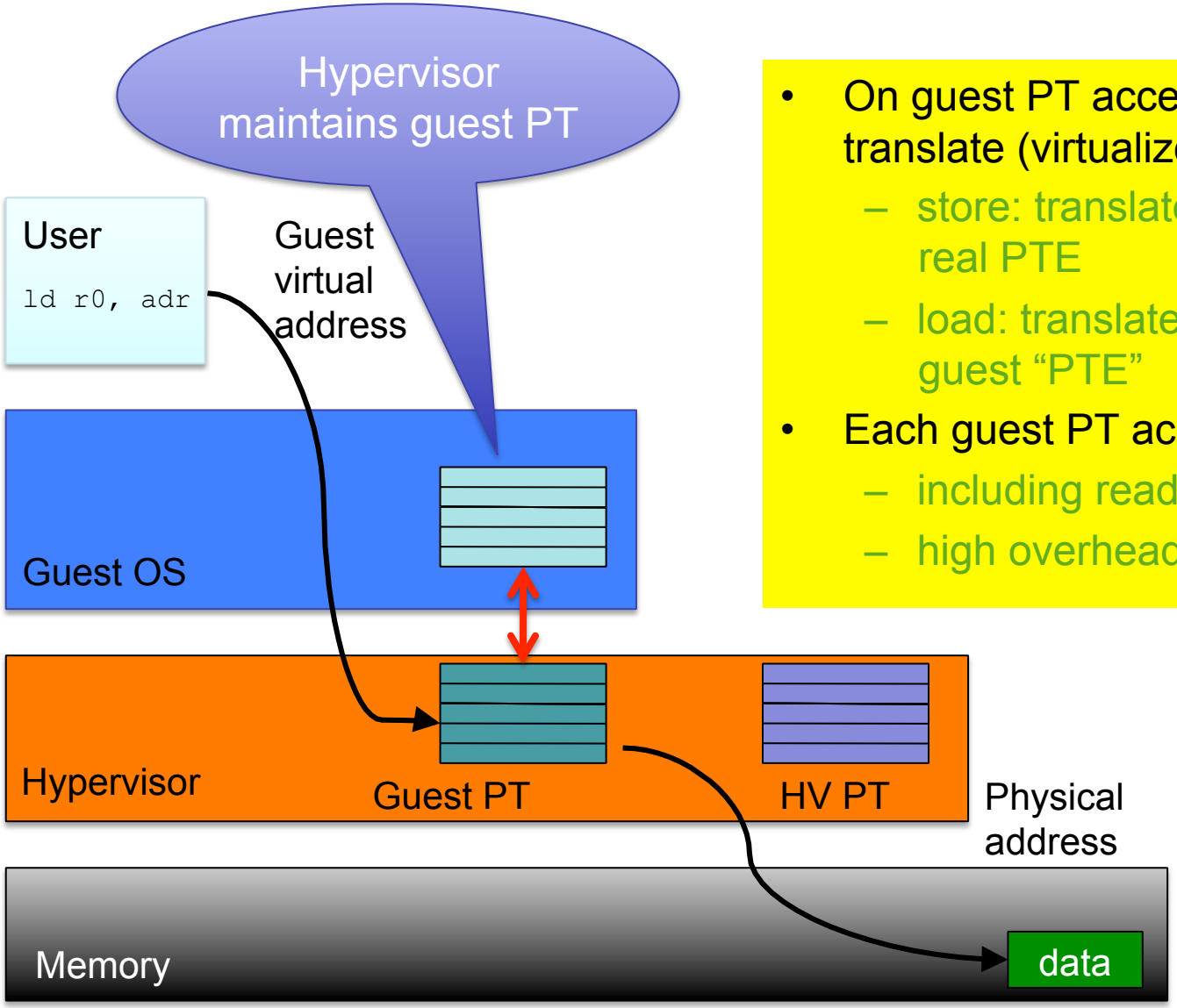
Used by VMware



Shadow PT has TLB semantics (i.e. weak consistency) ⇒ Update at synchronisation points:

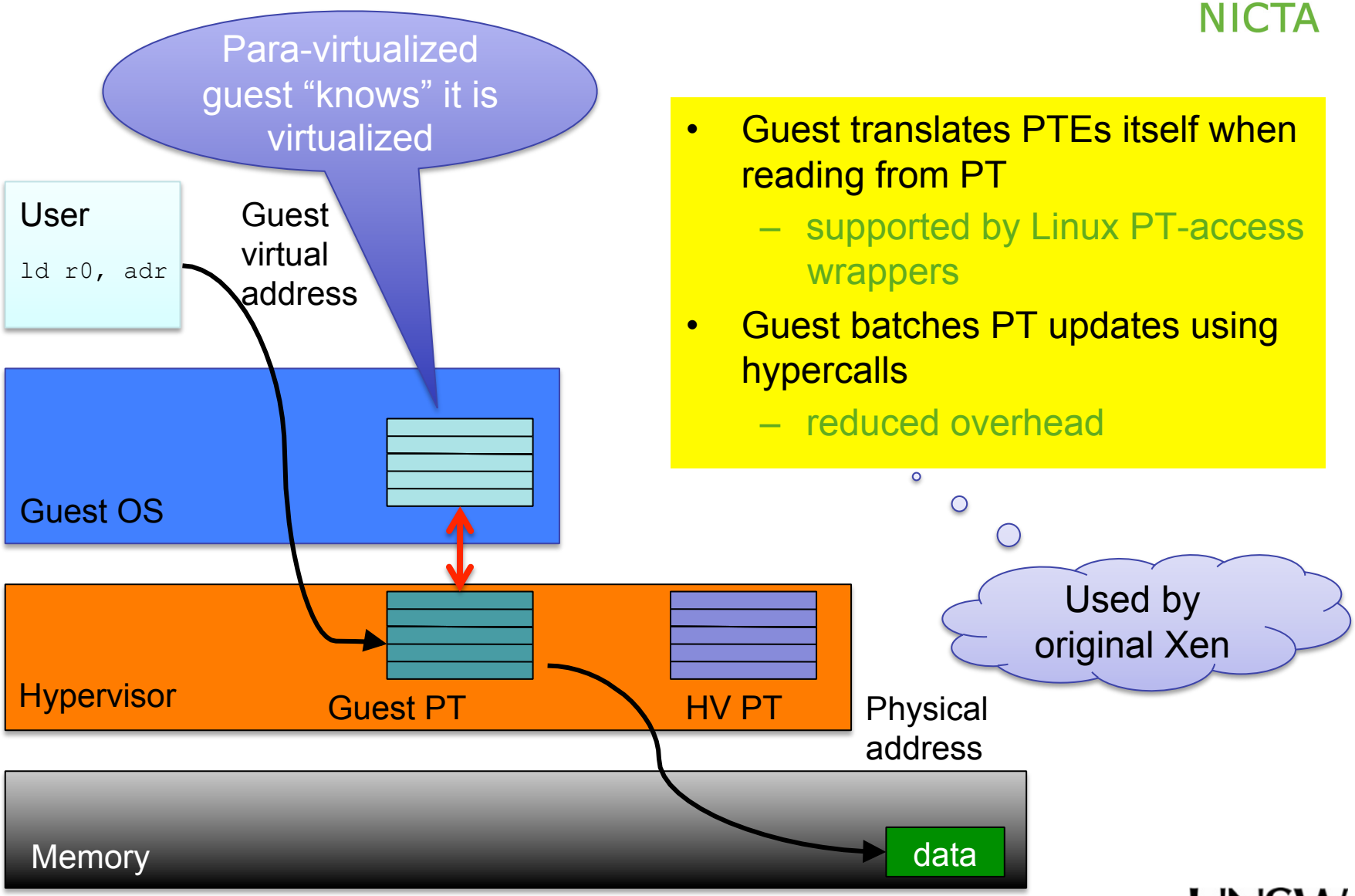
- page faults
- TLB flushes

Virtualization Mechanics: Real Guest PT



- On guest PT access must translate (virtualize) PTEs
  - store: translate guest "PTE" to real PTE
  - load: translate real PTE to guest "PTE"
- Each guest PT access traps!
  - including reads
  - high overhead

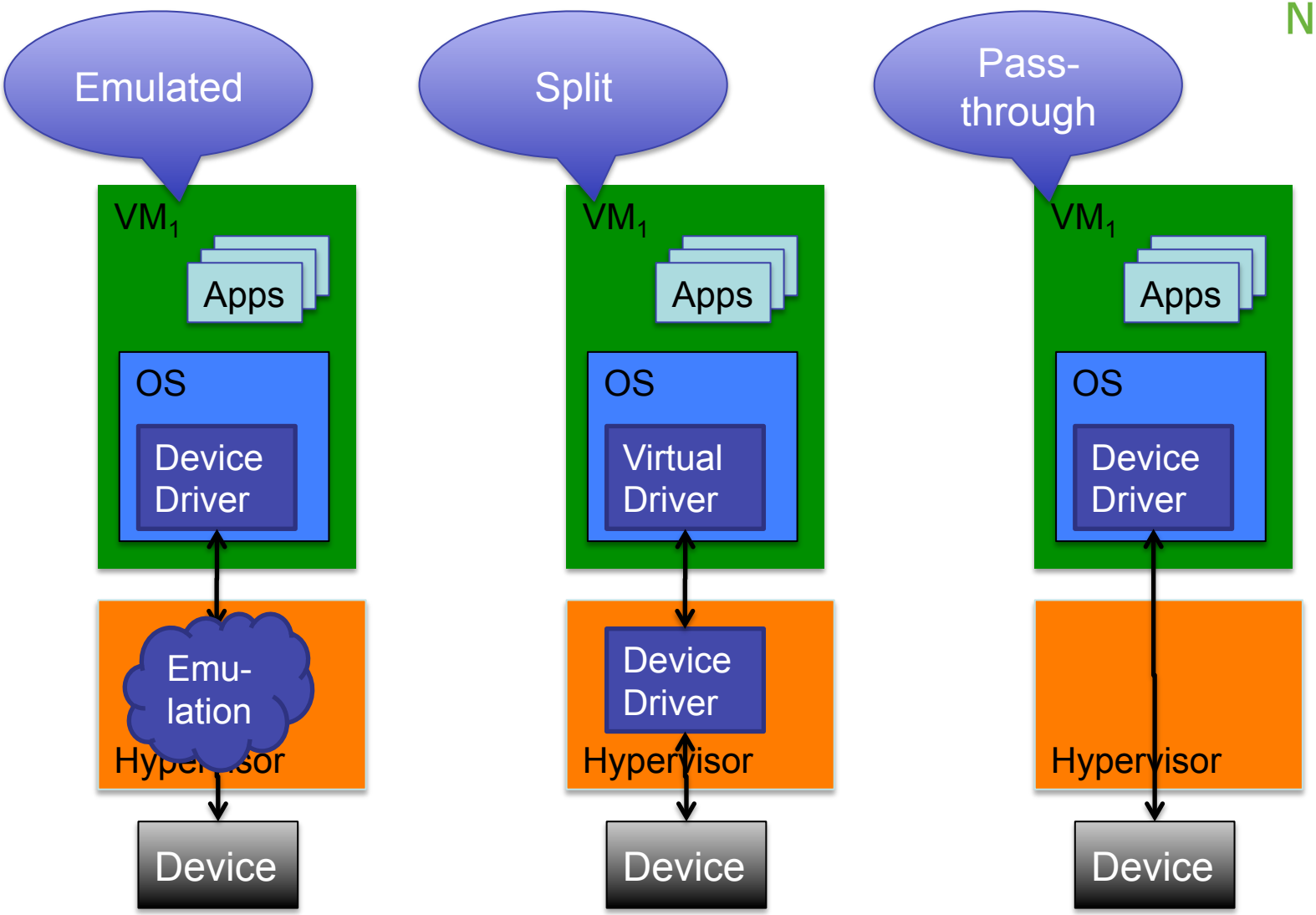
Virtualization Mechanics: Optimised Guest PT



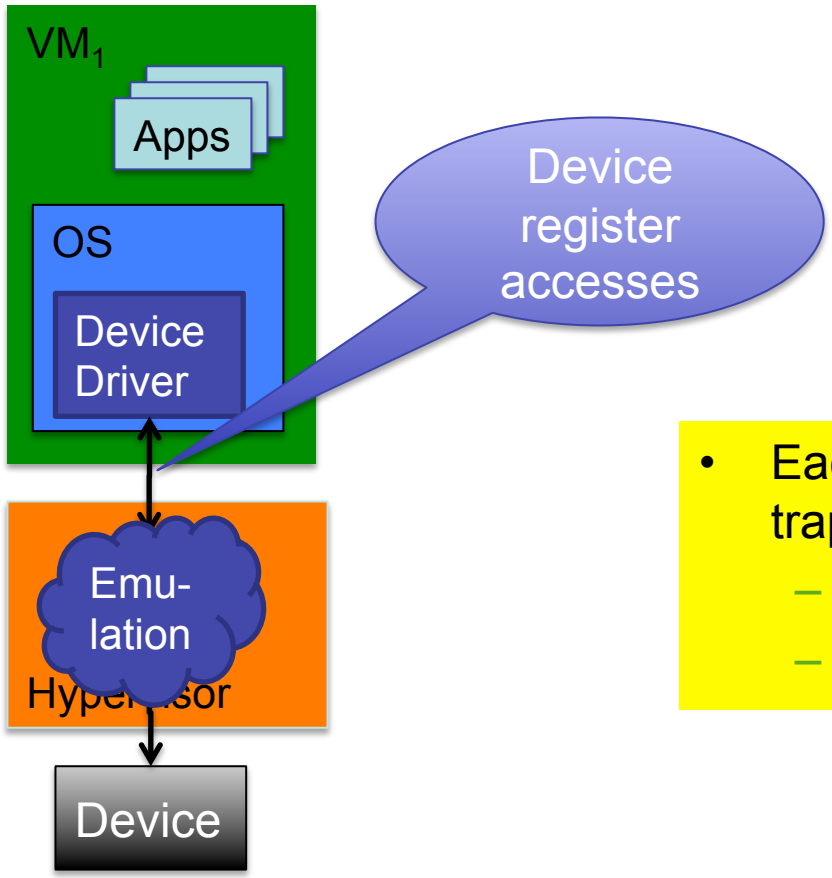
- Guest translates PTEs itself when reading from PT
  - supported by Linux PT-access wrappers
- Guest batches PT updates using hypercalls
  - reduced overhead

Used by original Xen

Virtualization Mechanics: 3 Device Models

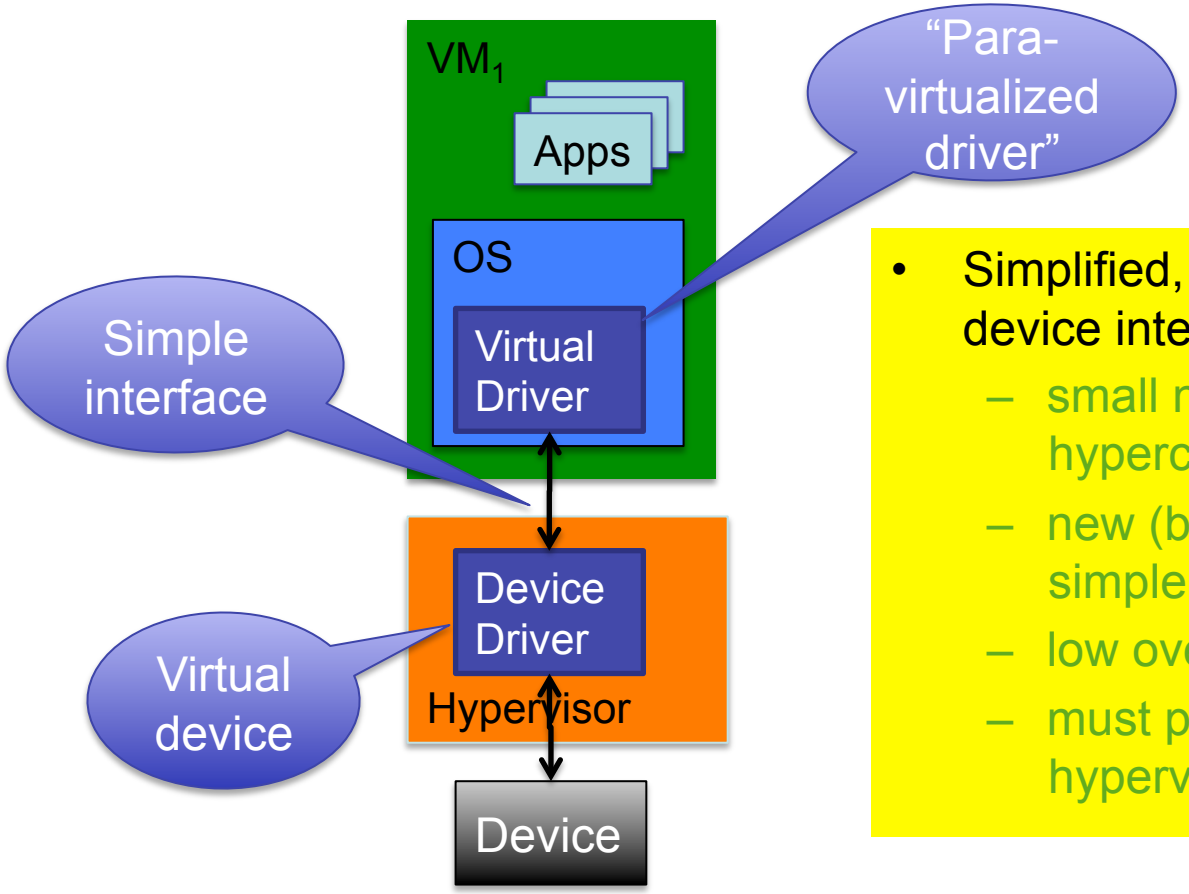


Virtualization Mechanics: Emulated Device



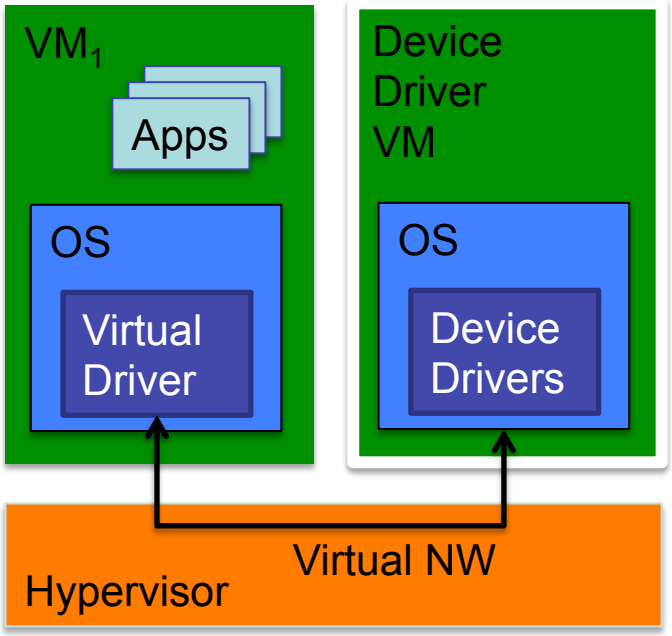
- Each device access must be trapped and emulated
  - unmodified native driver
  - high overhead!

Virtualization Mechanics: Split Driver (Xen speak)



- Simplified, high-level device interface
  - small number of hypercalls
  - new (but very simple) driver
  - low overhead
  - must port drivers to hypervisor

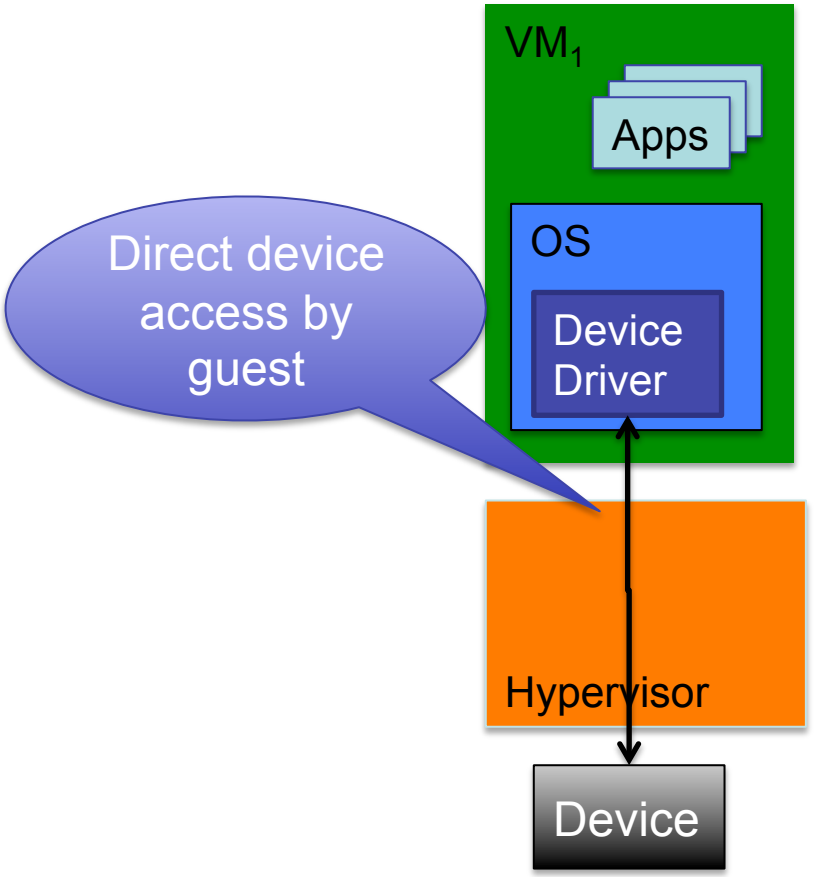
Virtualization Mechanics: Driver OS (Xen Dom0)



- Leverage Driver-OS native drivers
  - no driver porting
  - must trust complete Driver OS guest!

Virtualization Mechanics: Pass-Through Driver

- Unmodified native driver
- Must trust driver (and guest)
  - unless have hardware support (IO MMU)

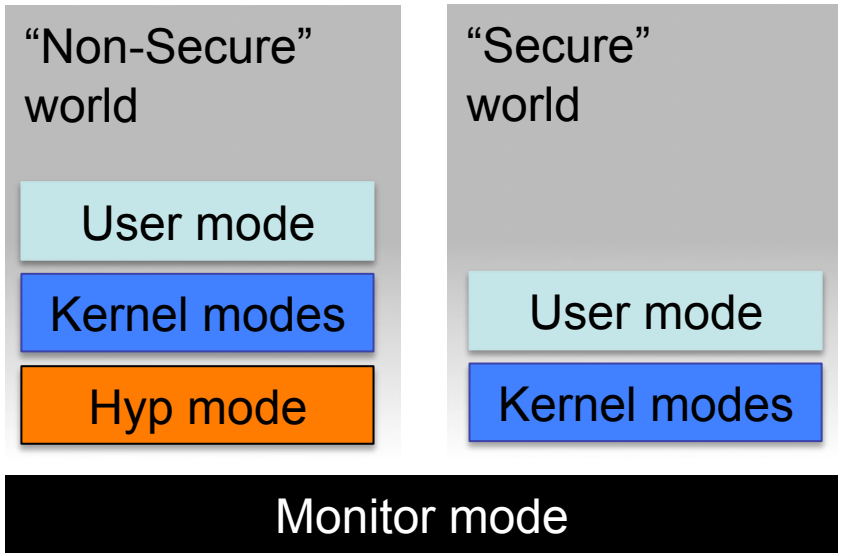


Non-Virtualizable Architectures

- x86: lots of non-virtualizable features
  - e.g. sensitive PUSH of PSW is not privileged
  - segment and interrupt descriptor tables in virtual memory
  - segment description expose privileged level
- Itanium: mostly virtualizable, but
  - interrupt vector table in virtual memory
  - THASH instruction exposes hardware page tables address
- MIPS: mostly virtualizable, but
  - kernel registers k0, k1 (needed to save/restore state) user-accessible
  - performance issue with virtualizing KSEG addresses
- ARM: mostly virtualizable, but
  - some instructions undefined in user mode (banked registers, CPSR)
  - PC is a GPR, exception return in MOVS to PC, doesn't trap
- Most others have problems too
- Modern trend are virtualization extensions to ISA
  - x86, Itanium since ~2006 (VT-x, VT-i)
- Case study: ARM
  - announced '10, samples '11, products '12

ARM Virtualization Extensions (1)

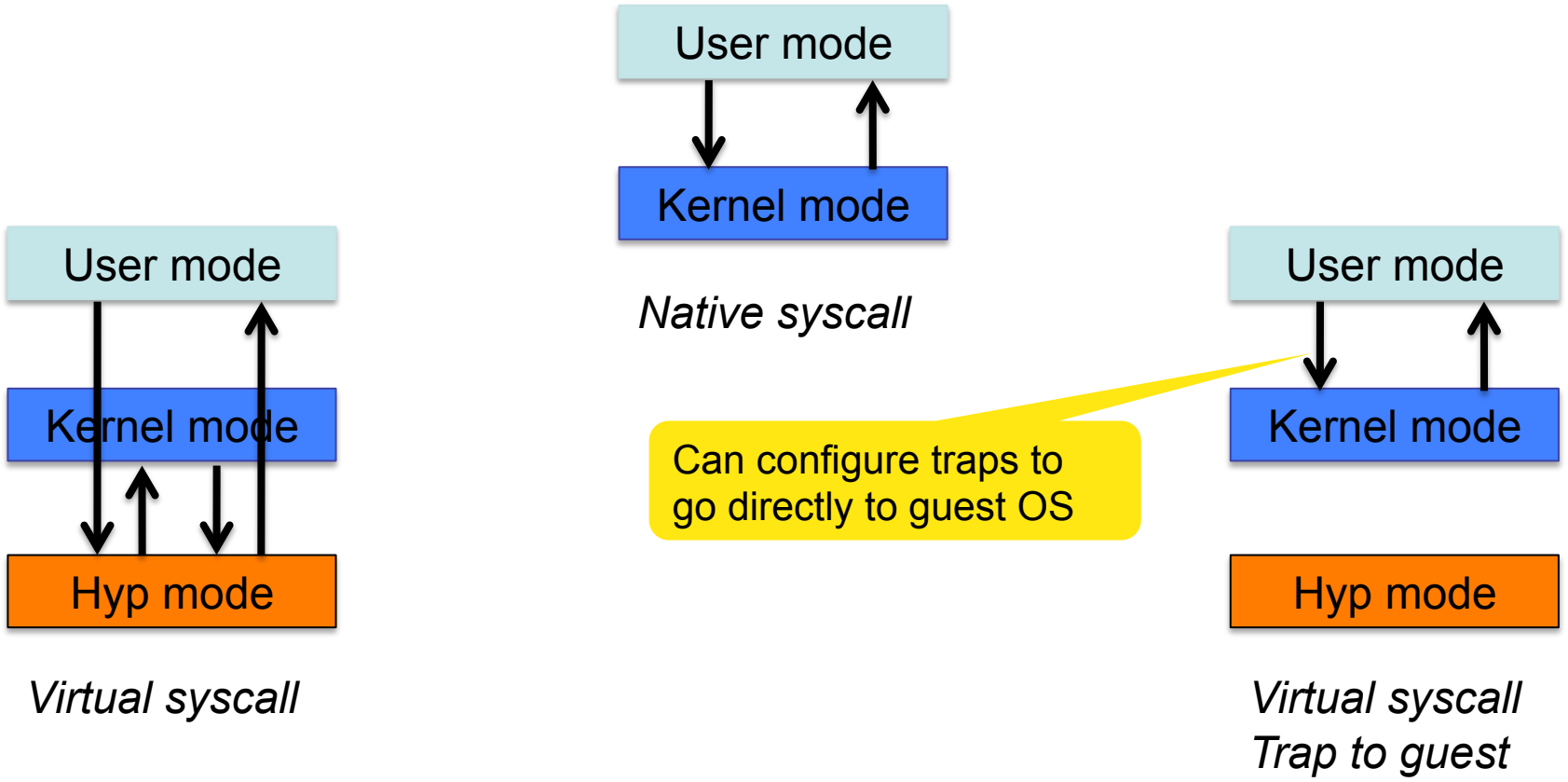
Hyp mode



- New privilege level
  - Strictly higher than kernel
  - Virtualizes or traps *all* sensitive instructions
  - Only available in ARM TrustZone "non-secure" mode
- Note: different from x86
  - VT-x "root" mode is orthogonal to x86 protection rings

ARM Virtualization Extensions (2)

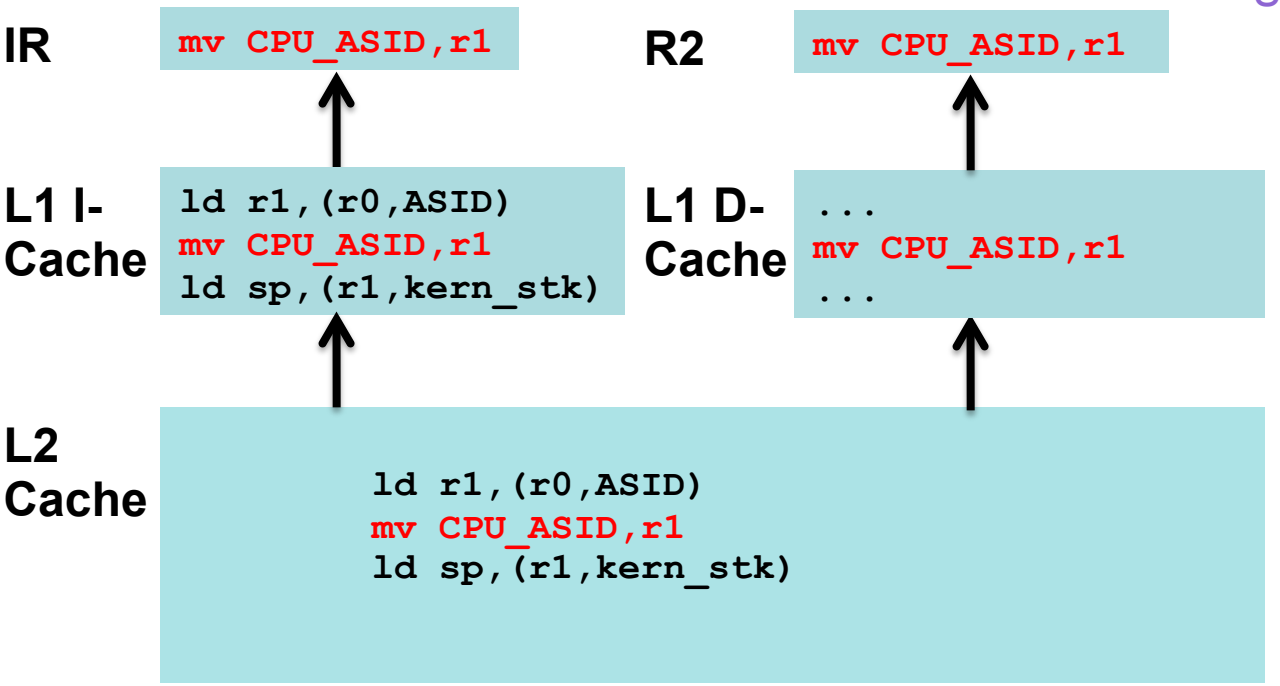
Configurable Traps



ARM Virtualization Extensions (3)

Emulation

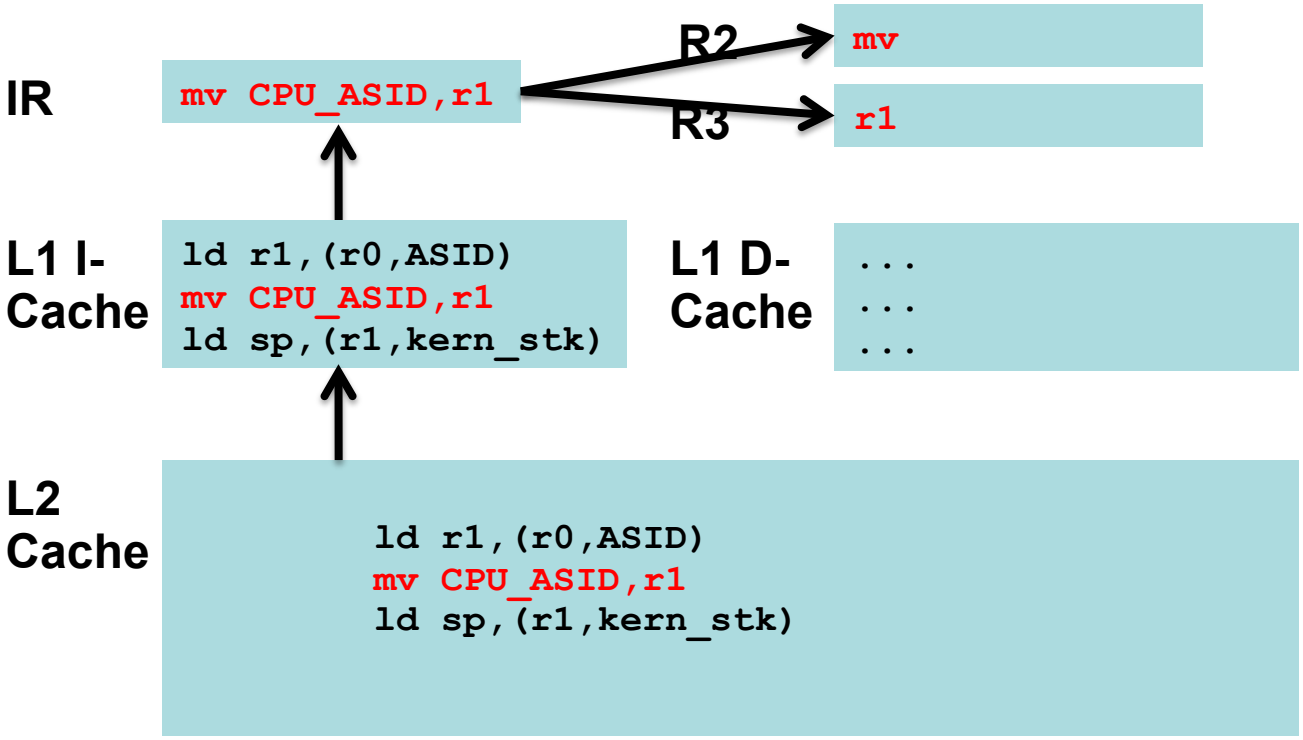
1) Load faulting instruction
   - Compulsory L1-D miss!
2) Decode instruction
   - Complex logic
3) Emulate instruction
   - Usually straightforward



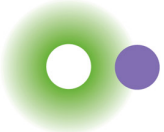
ARM Virtualization Extensions (3)

Emulation Support

- HW decodes instruction
  - No L1 miss
  - No software decode
- SW emulates instruction
  - Usually straightforward

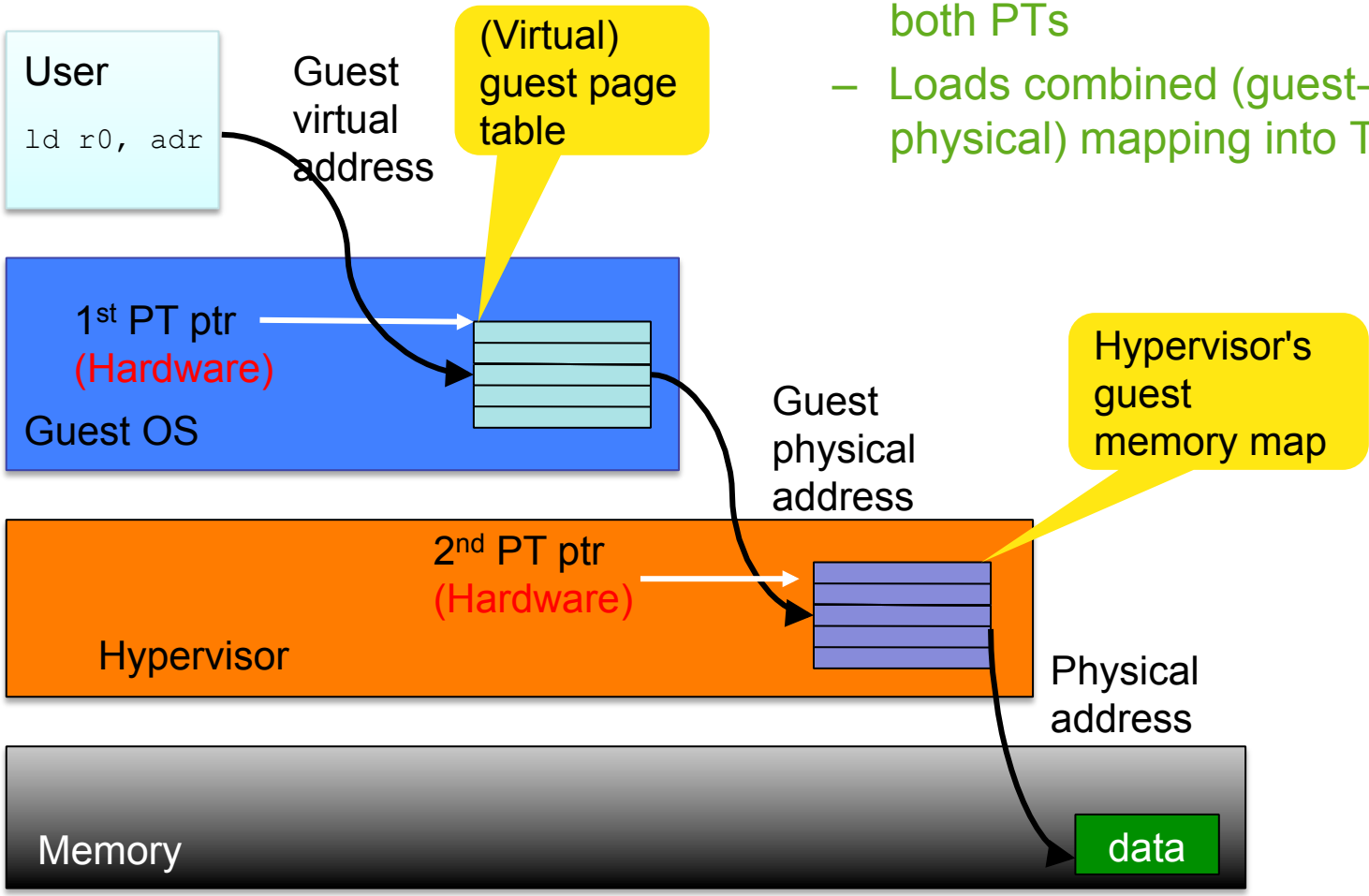


ARM Virtualization Extensions (4)



2-stage translation

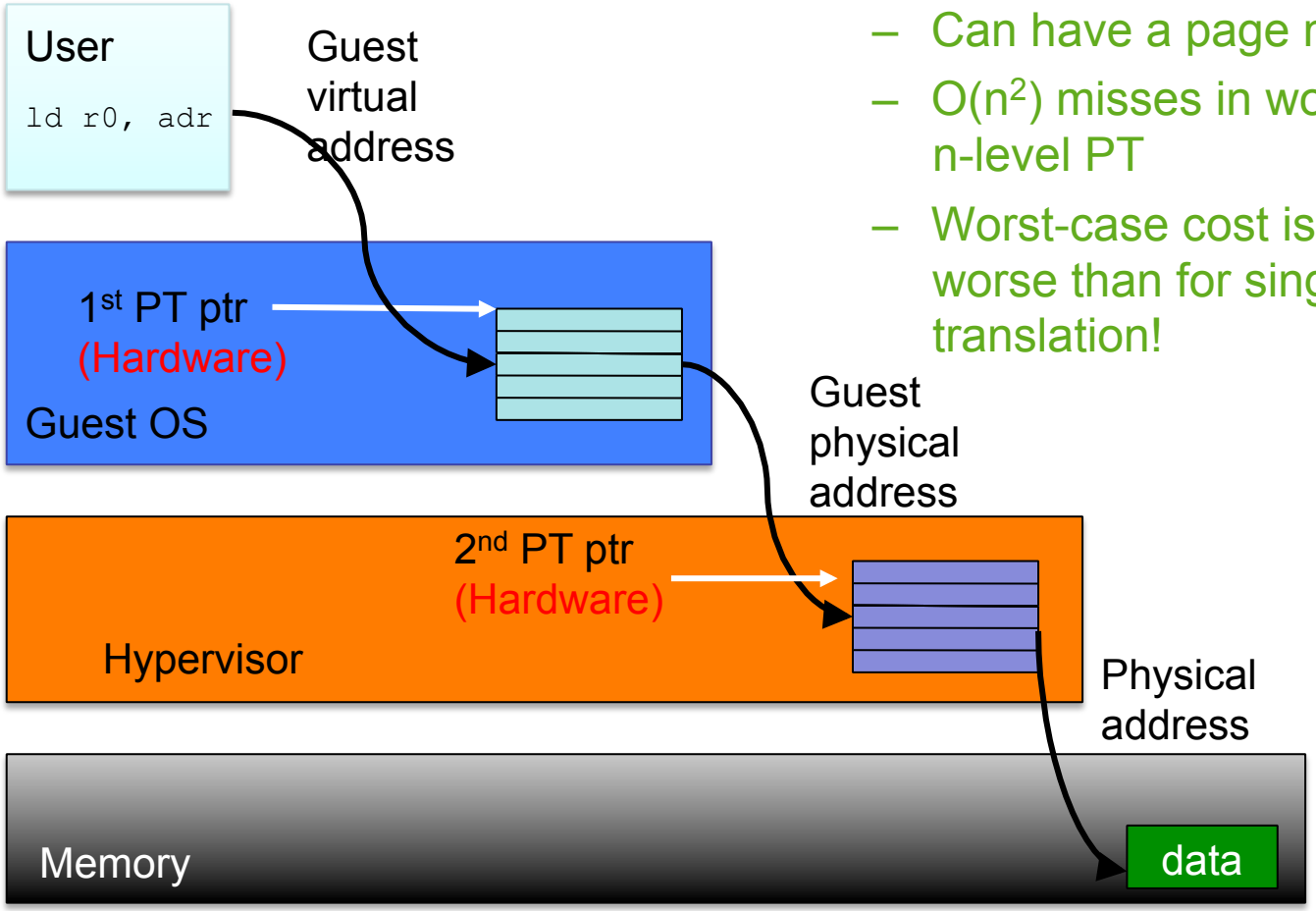
- Hardware PT walker traverses both PTs
- Loads combined (guest-virtual to physical) mapping into TLB



ARM Virtualization Extensions (4)

2-stage translation cost

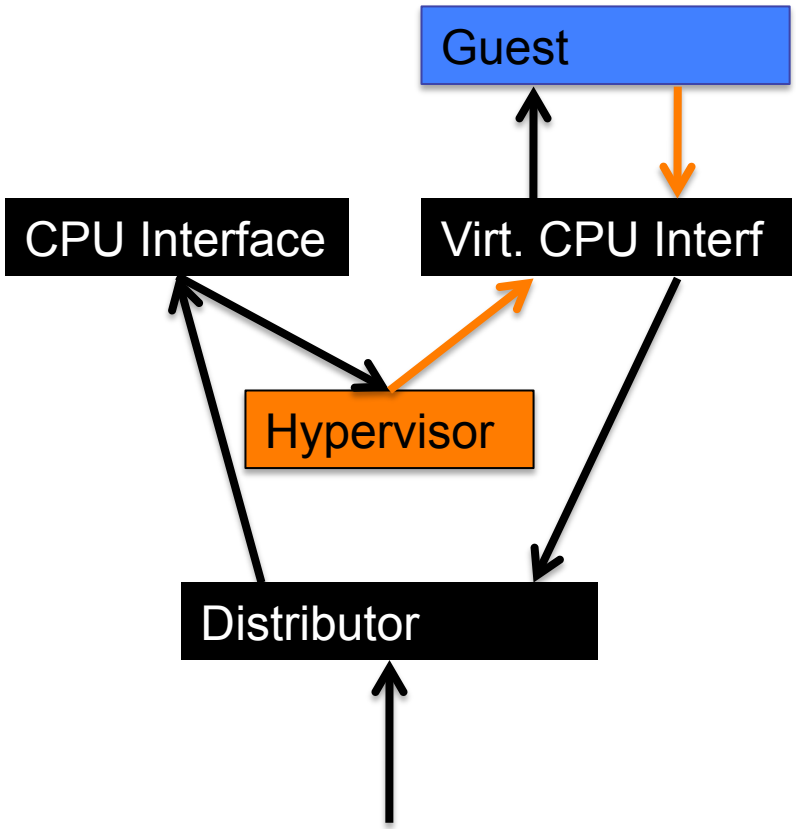
- On page fault walk twice number of page tables!
- Can have a page miss on each
- $O(n^2)$ misses in worst case for n-level PT
- Worst-case cost is massively worse than for single-level translation!



ARM Virtualization Extensions (5)

NICTA

Virtual Interrupts



- ARM has 2-part IRQ controller
  - Global “distributor”
  - Per-CPU “interface”
- New H/W “virt. CPU interface”
  - Mapped to guest
  - Used by HV to forward IRQ
  - Used by guest to acknowledge
- Halves hypervisor entries for interrupt virtualization

Hypervisor Size

Hypervisor	ISA	Type	Kernel	User
OKL4	ARMv7	para-virtualization	9.8 kLOC	0
Prototype	ARMv7	pure virtualization	6 kLOC	0
Nova	x86	pure virtualization	9 kLOC	27 kLOC

- Size (& complexity) reduced about 40% wrt to para-virtualization
- Much smaller than x86 pure-virtualization hypervisor
  - Mostly due to greatly reduced need for instruction emulation

Overheads (Estimated)

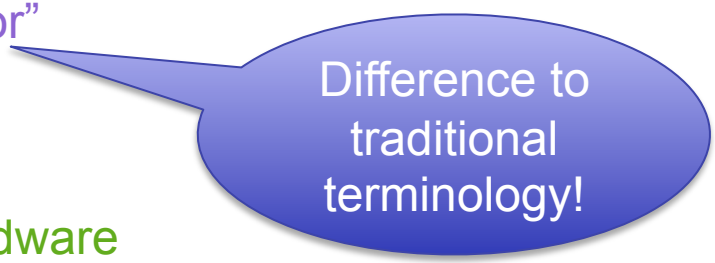
Operation	Pure virtualization		Para-virtualiz.
	Instruct	Cycles (est)	Cycles (approx)
Guest system call	0	0	300
Hypervisor entry + exit	120	650	150
IRQ entry + exit	270	900	300–400?
Page fault	356	1500	700
Device emul.	249	1040	N/A
Device emul. (accel.)	176	740	N/A
World switch	2824	7555	200

- No overhead on regular (virtual) syscall – unlike para-virtualization
- Invoking hypervisor 500–1200 cycles (0.6–1.5 µs) more than para
- World switch in ~10 µs compared to 0.25 µs for para

⇒ Trade-offs differ

Hypervisors vs Microkernels

- Both contain all code executing at highest privilege level
  - Although hypervisor may contain user-mode code as well
    - privileged part usually called “hypervisor”
    - user-mode part often called “VMM”
- Both need to abstract hardware resources
  - Hypervisor: abstraction closely models hardware
  - Microkernel: abstraction designed to support wide range of systems
- What must be abstracted?
  - Memory
  - CPU
  - I/O
  - Communication



What's the difference?

Resource	Hypervisor	Microkernel
Memory	Virtual MMU (vMMU)	Address space
CPU	Virtual CPU (vCPU)	Thread or scheduler activation
I/O	• Simplified virtual device • Driver in hypervisor • Virtual IRQ (vIRQ)	• IPC interface to user-mode driver • Interrupt IPC
Communication	Virtual NIC, with driver and network stack	High-performance message-passing IPC

Just page tables in disguise

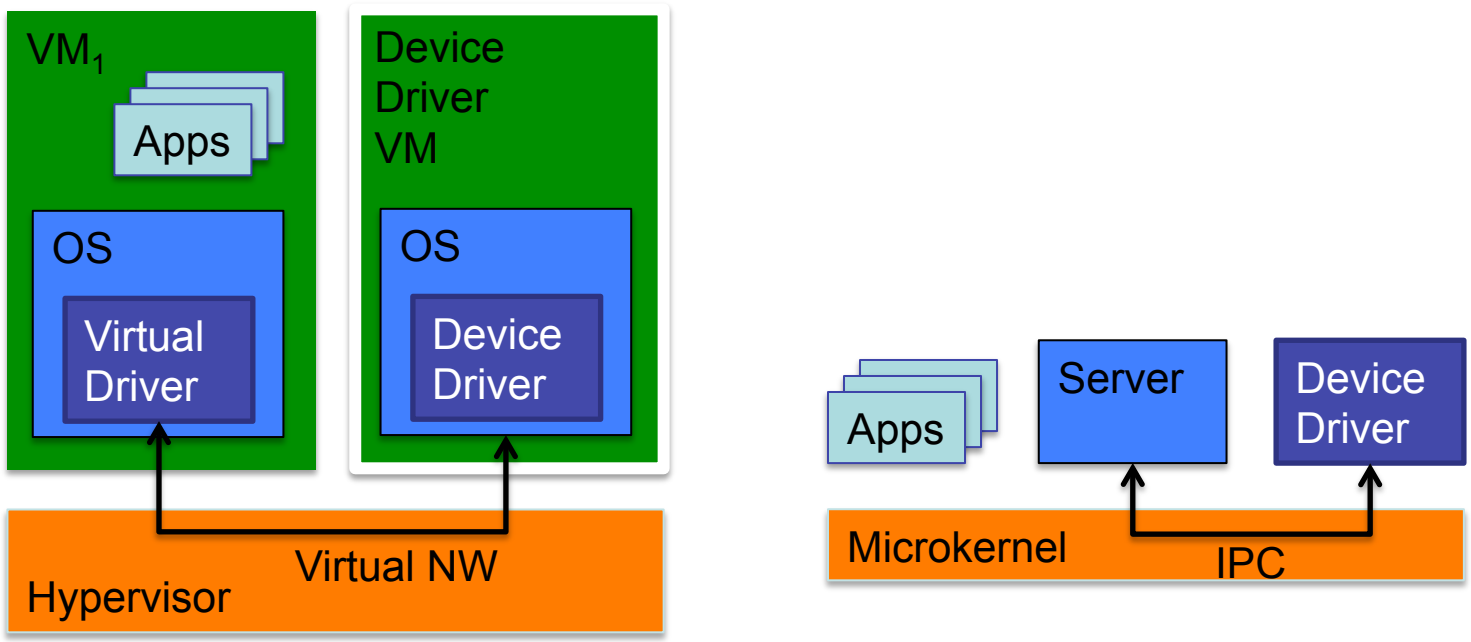
Just kernel-scheduled activities

Real Difference?

Modelled on HW, Re-uses SW

Minimal overhead, Custom API

Closer Look at I/O and Communication



- Communication is critical for I/O
  - Microkernel IPC is highly optimised
  - Hypervisor inter-VM communication is frequently a bottleneck

Hypervisors vs Microkernels: Summary

- Fundamentally, both provide similar abstractions
- Optimised for different use cases
  - Hypervisor designed for virtual machines
    - API is hardware-like to ease guest ports
  - Microkernel designed for multi-server systems
    - seems to provide more OS-like abstractions

Hypervisors vs Microkernels: Drawbacks

Hypervisors:

- Communication is Achilles heel
  - more important than expected
    - critical for I/O
  - plenty improvement attempts in Xen
- Most hypervisors have big TCBs
  - infeasible to achieve high assurance of security/safety
  - in contrast, microkernel implementations can be proved correct

Microkernels:

- Not ideal for virtualization
  - API not very effective
    - L4 virtualization performance close to hypervisor
    - effort much higher
  - Virtualization needed for legacy
- L4 model uses kernel-scheduled threads for more than exploiting parallelism
  - Kernel imposes policy
  - Alternatives exist, eg. K42 uses scheduler activations

More on this later!