School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2023 T3 Week 03 Part 2

Virtualisation Principles

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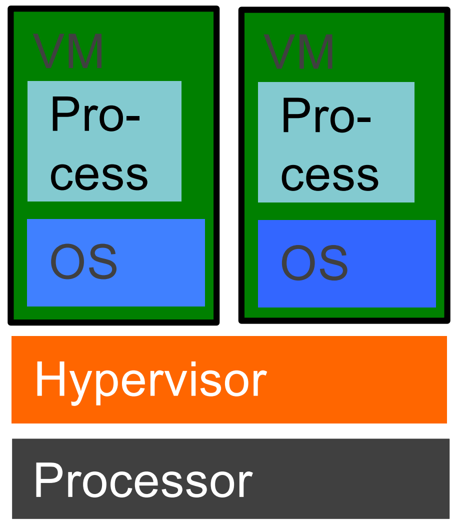

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Today's Lecture

- What are virtual machines, and why do we have them
- Mechanics: how do they work
- Modern hardware support
- Fun and games with hypervisors

Virtual Machine Basics

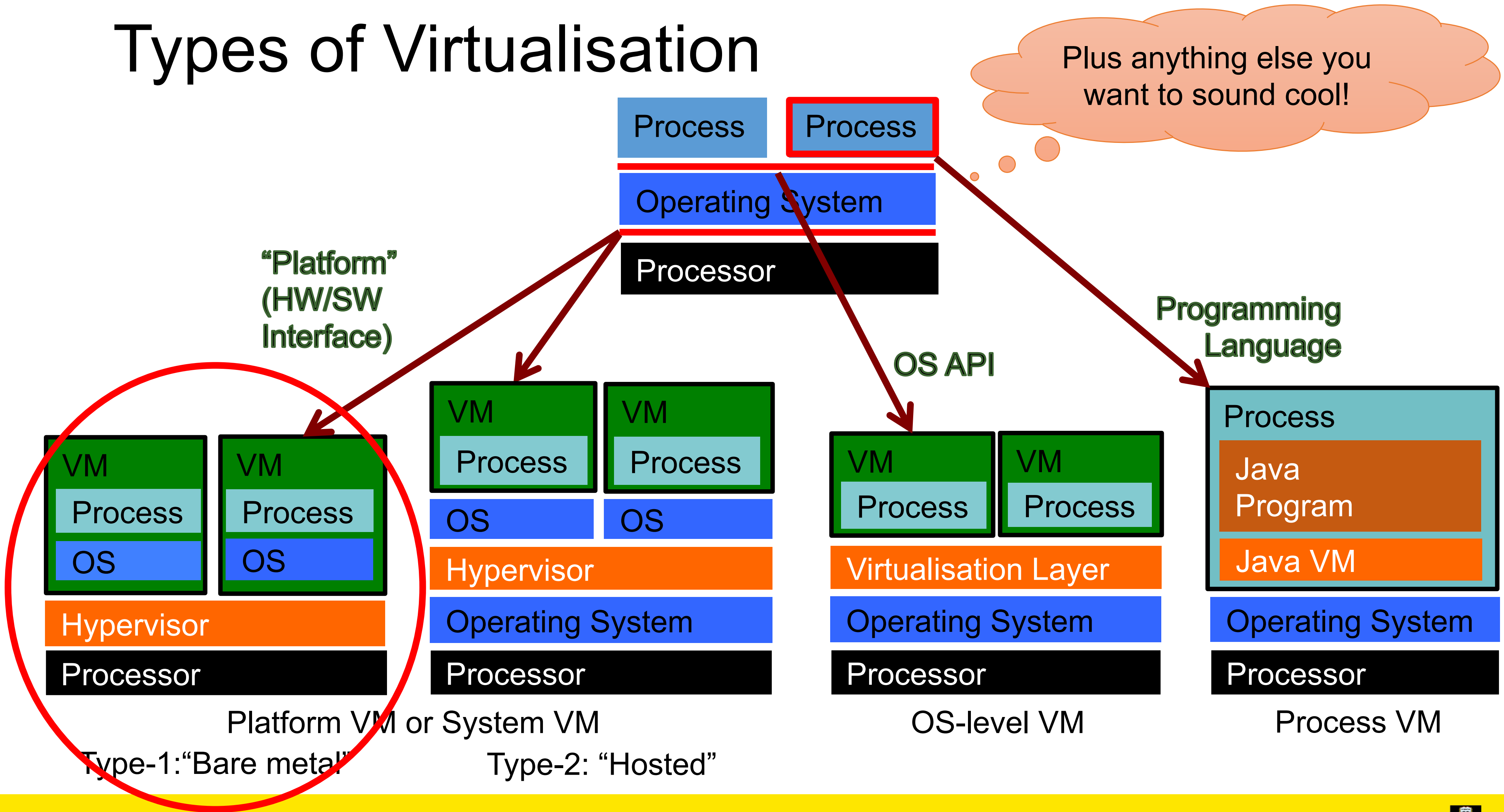
Virtual Machine (VM)

"A VM is an efficient, isolated duplicate of a real machine" [Popek&Goldberg 74]

- **Duplicate**: VM should behave identically to the real machine
  - Programs cannot distinguish between real or virtual hardware
  - Except for:
    - Fewer resources (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 (VMM):
Software layer implementing the VM

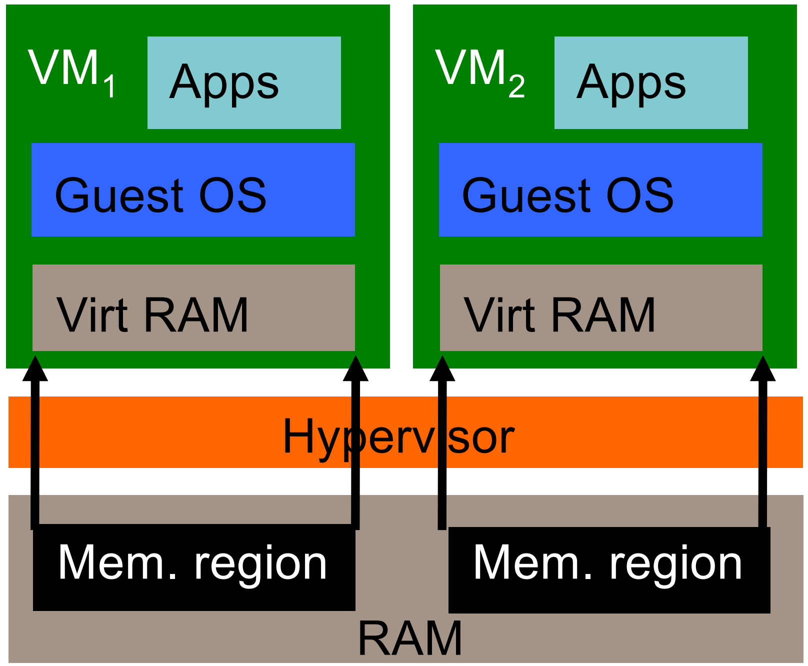
Types of Virtualisation



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

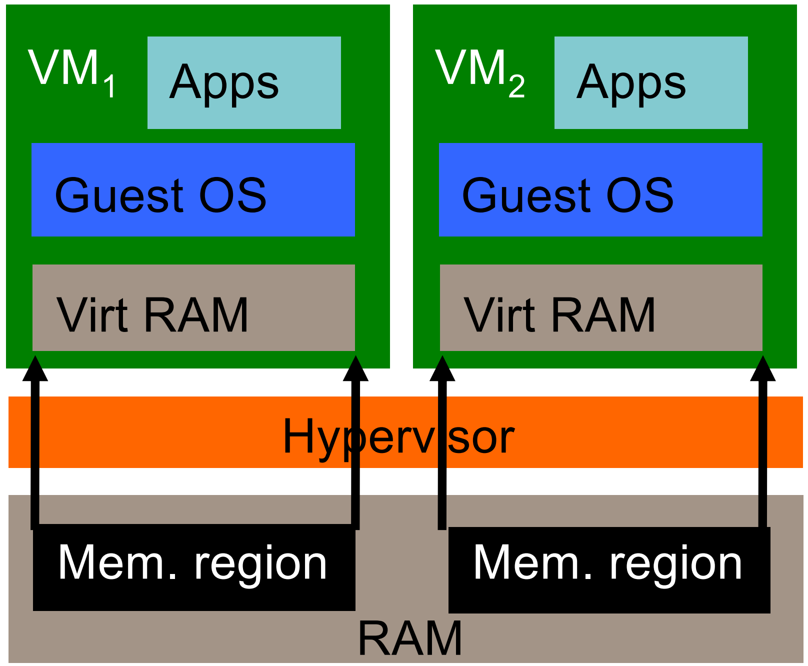
Obsolete by 1980s



Why Virtual Machines?

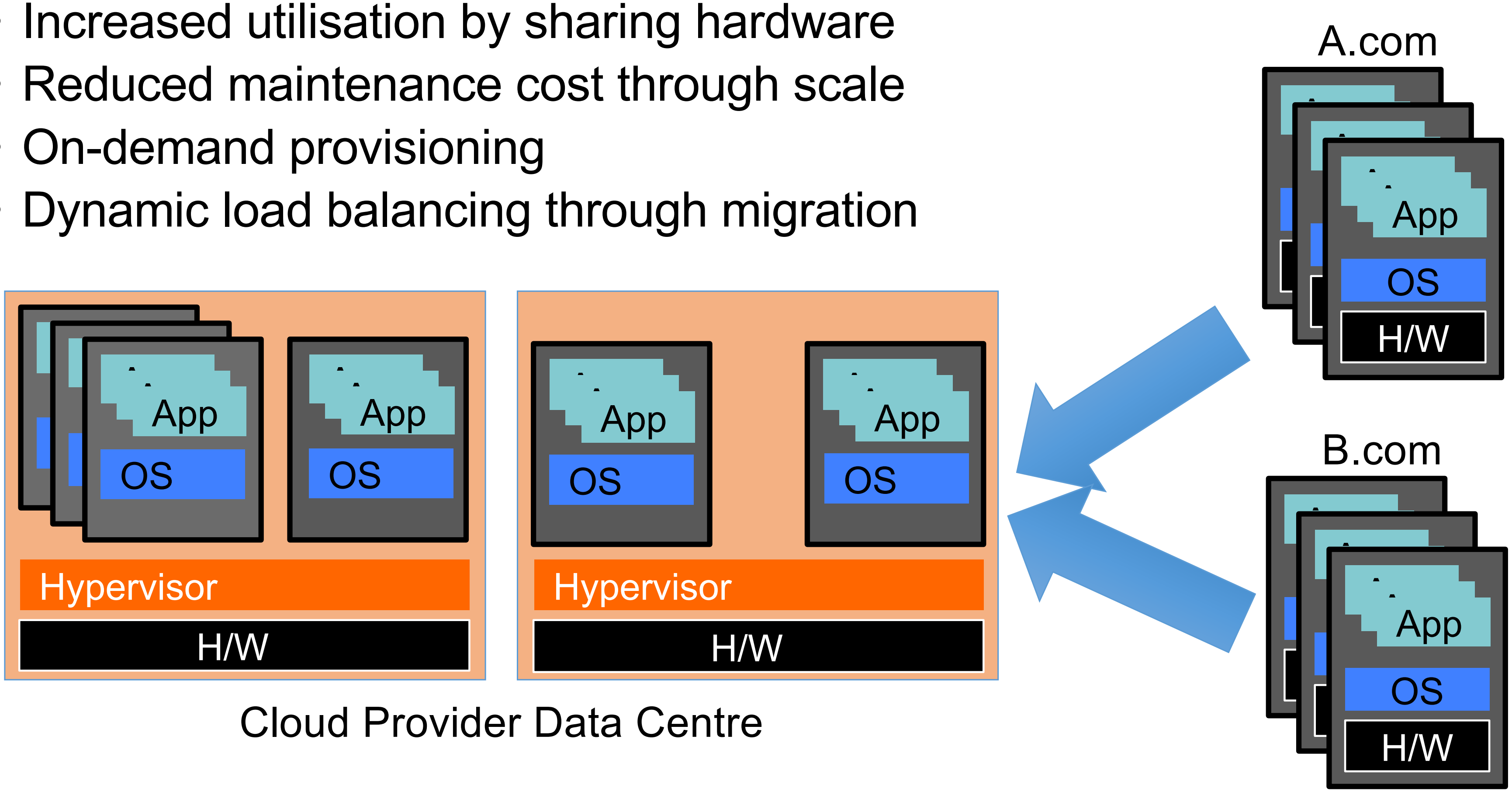
- Heterogenous concurrent guest OSes
  - eg Linux + Windows
- Improved isolation for consolidated servers: QoS & Security
  - total mediation/encapsulation:
    - replication
    - migration/consolidation
    - checkpointing
    - debugging
- Uniform view of hardware

Would not be needed if OSes provided proper security & resource management!



Why Virtual Machines: Cloud Computing

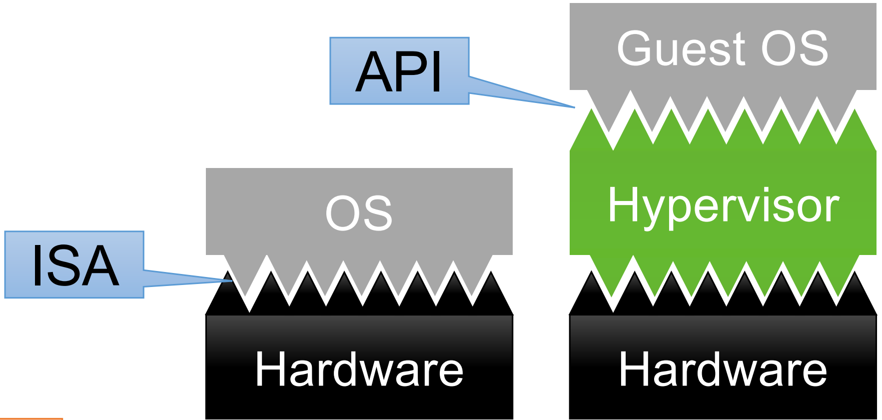
- Increased utilisation by sharing hardware
- Reduced maintenance cost through scale
- On-demand provisioning
- Dynamic load balancing through migration



Cloud Provider Data Centre

Hypervisor aka Virtual Machine Monitor

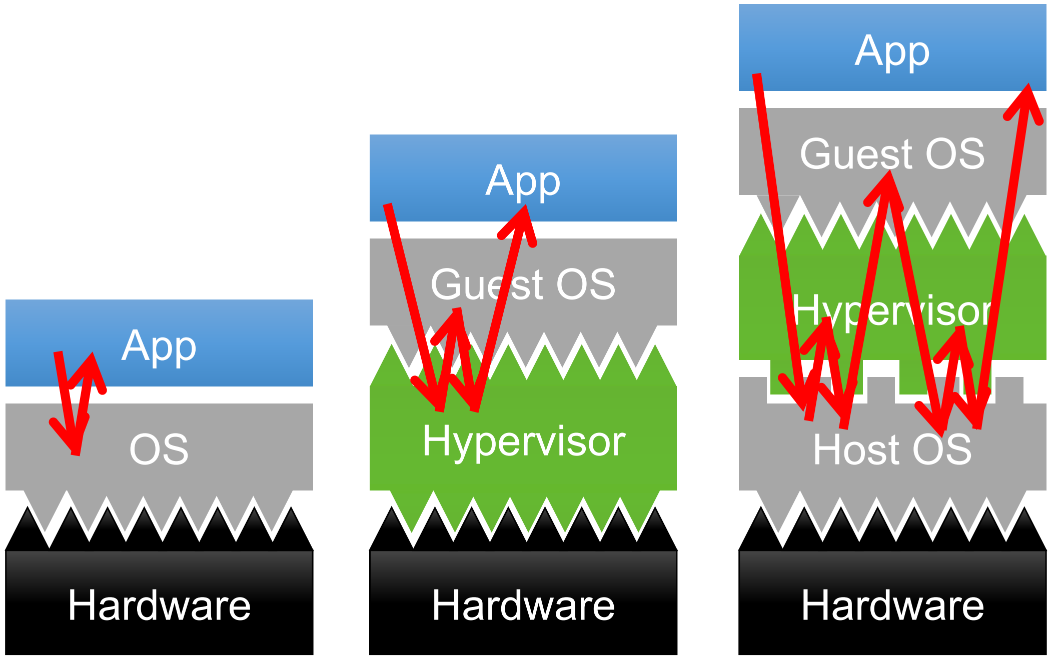
- Software layer that implements virtual machine
- Controls resources
  - Partitions hardware
  - Schedules guests
    - "*world switch*"
  - Mediates access to shared resources
    - e.g. console, network



Implications:
- Hypervisor executes in *privileged* mode
- Guest software executes in *unprivileged* mode

Privileged guest instructions trap to hypervisor

Native vs Hosted Hypervisor



Native execution

Native/ Bare-metal/ Type-I Hypervisor

Hosted/ Type-II Hypervisor

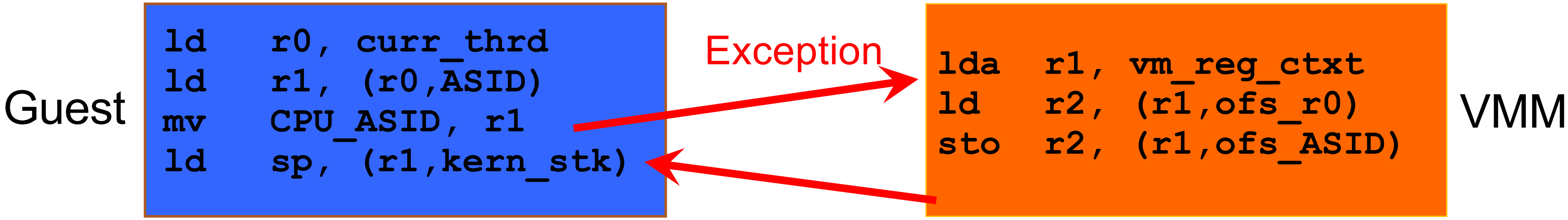
- Hosted VMM besides native apps
  - Sandbox untrusted apps
  - Convenient for running alternative OS on desktop
  - leverage host drivers

Overheads:
- Double mode switches
- Double context switches
- Host not optimised for exception forwarding

Virtualisation Mechanics

Instruction Emulation

- Traditional *trap-and-emulate* (T&E) approach:
  - guest attempts to access physical resource
  - hardware raises exception (trap), invoking HV's exception handler
  - hypervisor emulates result, based on access to virtual resource



Most instructions do not trap
- prerequisite for efficient virtualisation
- requires VM ISA (almost) same as processor ISA

Trap & Emulate Requirements

No-op is insufficient!

- **Privileged instruction:** when executed in user mode will *trap*
- **Privileged state:** determines resource allocation
  - Incl. privilege level, PT ptr, exception vectors…
- **Sensitive instruction:**
  - **control sensitive:** change privileged state
  - **behaviour sensitive:** expose privileged state
    - eg privileged instructions which NO-OP in user state
- **Innocuous instruction:** not sensitive

- Some inherently sensitive, e.g. set interrupt level
- Some context-dependent, e.g. store to page table

Can run unmodified guest binary

T&E virtualisable HW: All sensitive instructions are privileged

”Impure” Virtualisation

- Support non-T&E hardware
- Improve performance

```
ld   r0, curr_thrd
ld   r1, (r0,ASID)
mv   r1, PSR
ld   sp, (r1,kern_stk)
```

Insert trap – “hypercall”

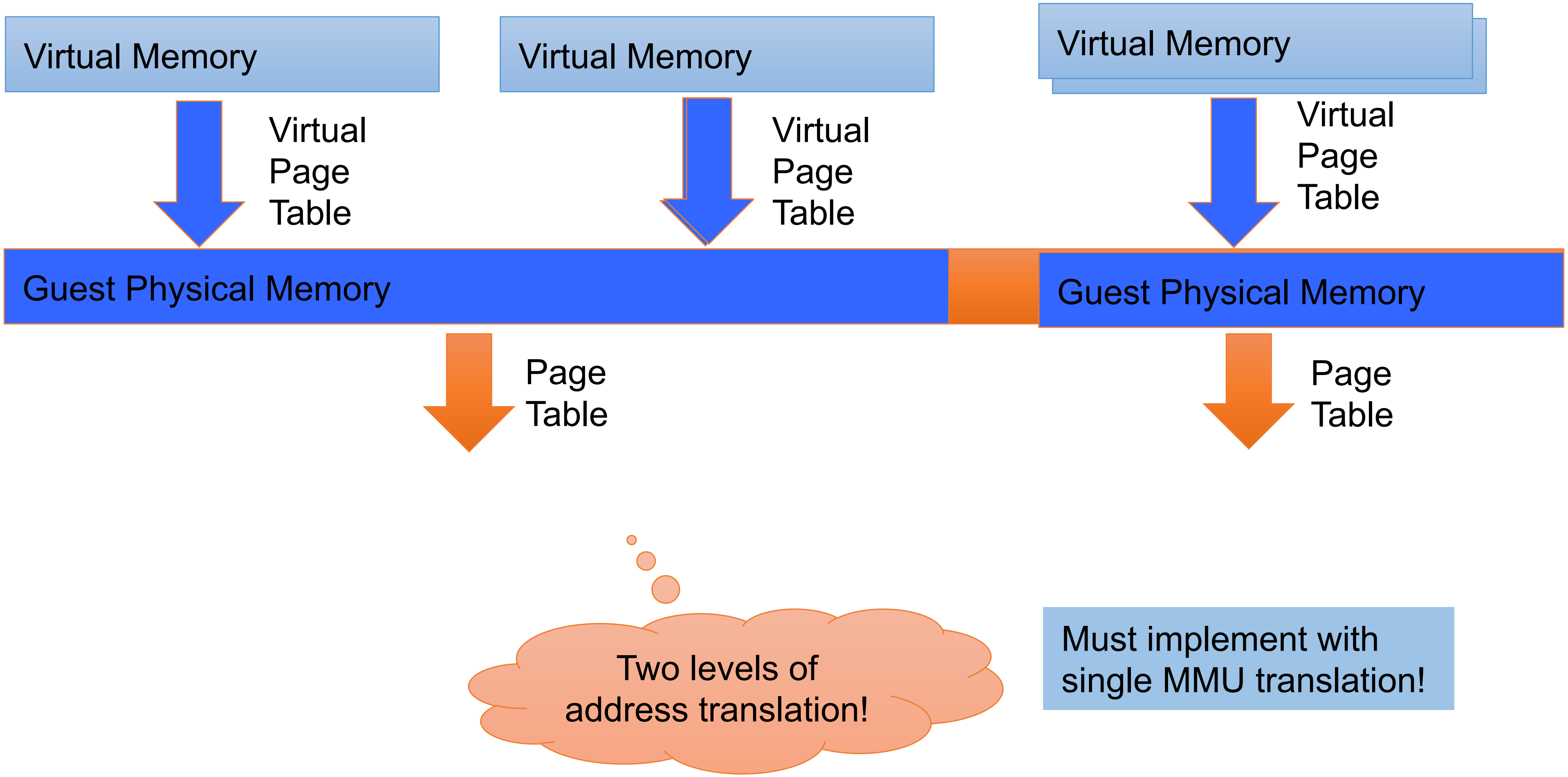
```
ld   r0, curr_thrd
ld   r1, (r0,ASID)
trap
ld   sp, (r1,kern_stk)
```

Insert in-line emulation code

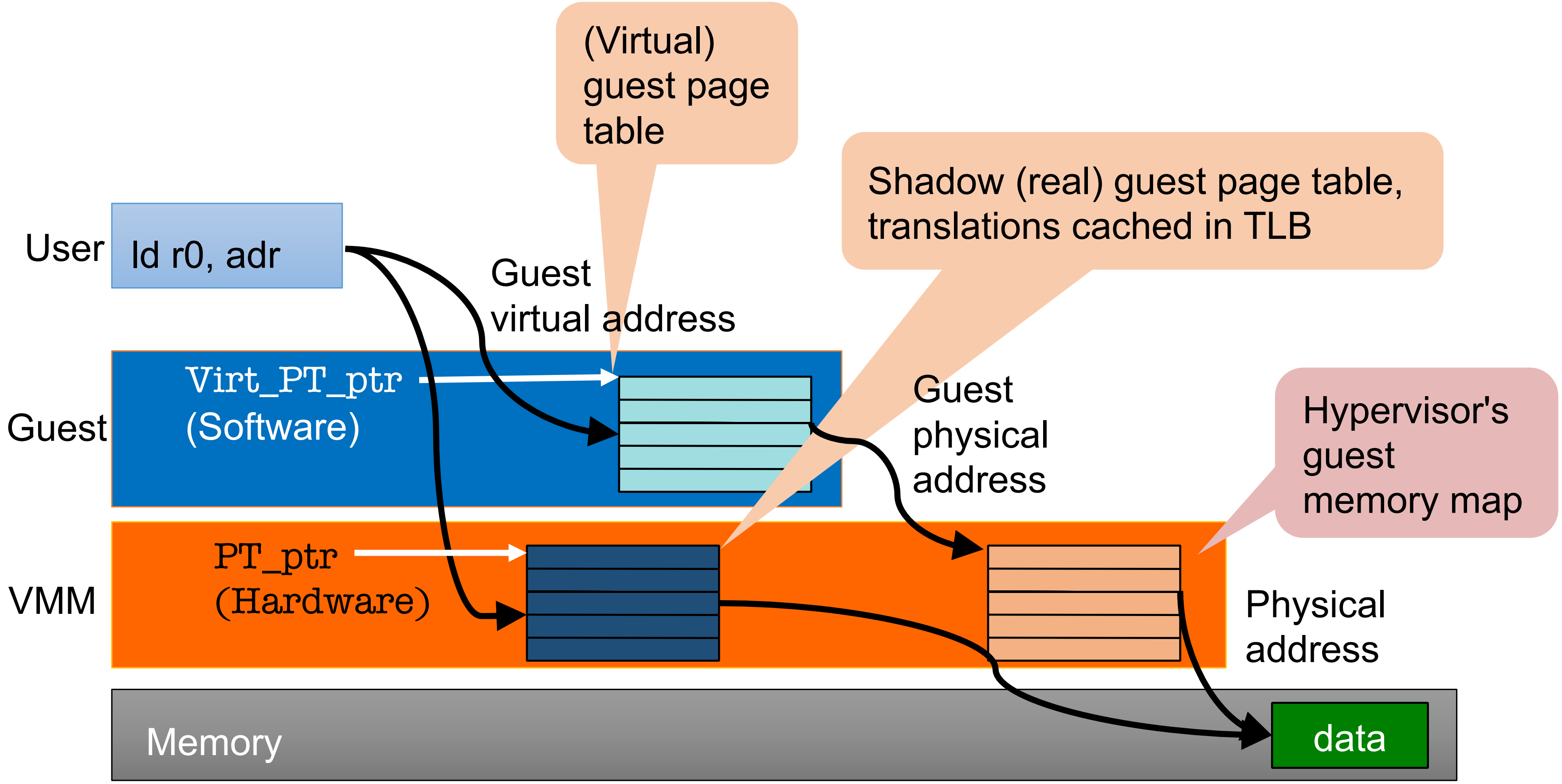
```
ld   r0, curr_thrd
ld   r1, (r0,ASID)
jmp  fixup_15
ld   sp, (r1,kern_stk)
```

- Modify binary: *binary translation* (VMware)
- Modify hypervisor ”ISA”: *para-virtualisation*

Virtualisation vs Address Translation



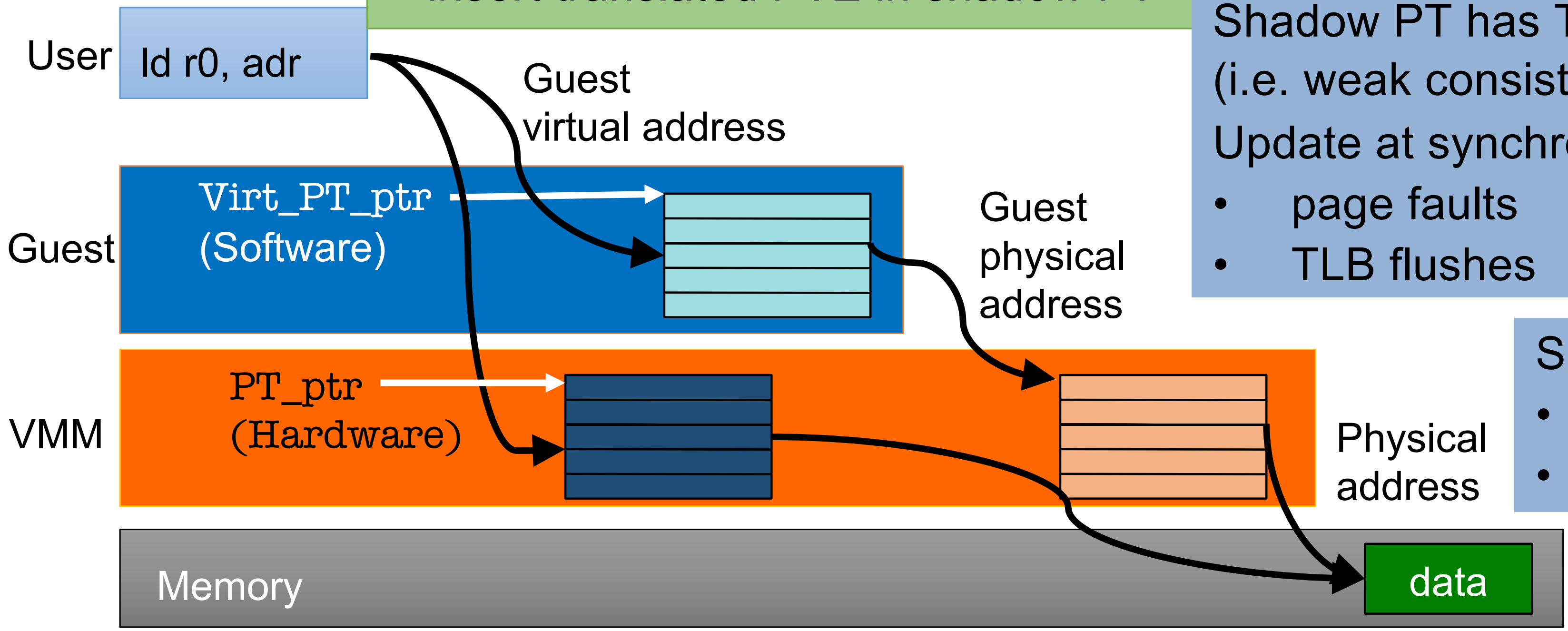
Shadow Page Table



Shadow Page Table

Hypervisor must shadow (virtualize) PT updates by guest:

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



Shadow PT has TLB semantics (i.e. weak consistency) ⇒

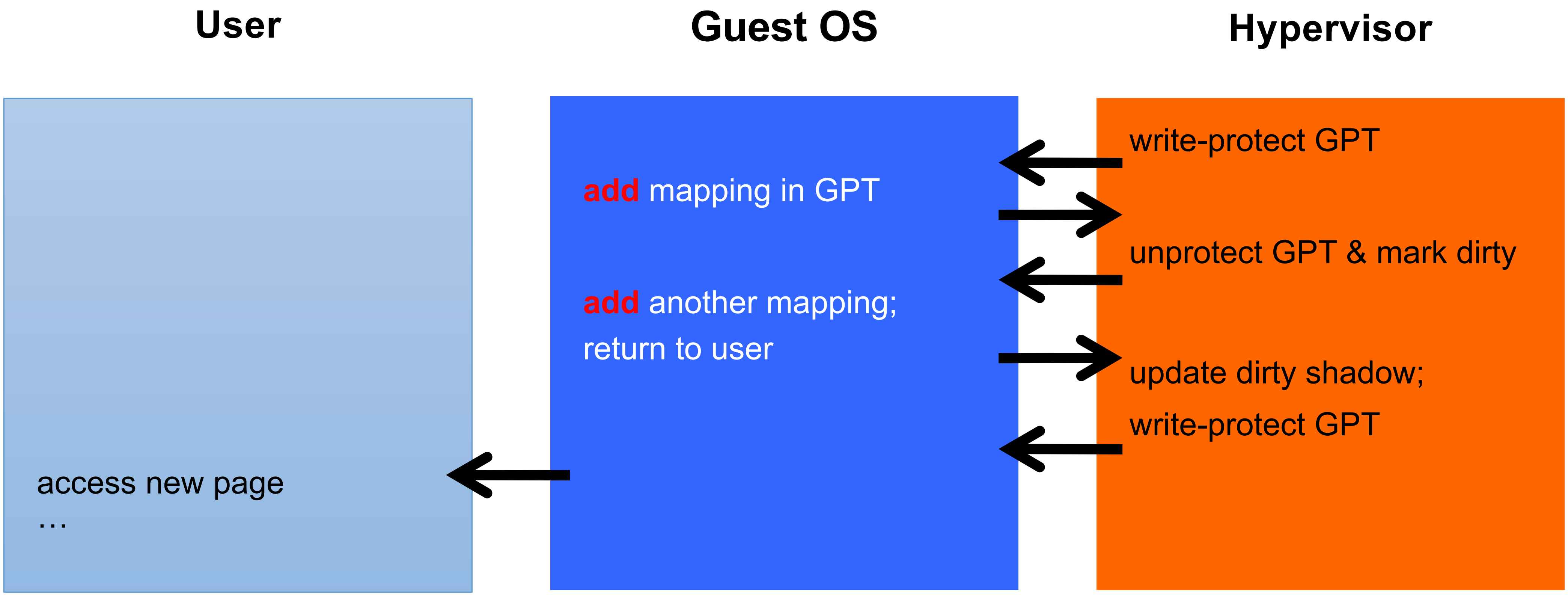
Update at synchronisation points:

- page faults
- TLB flushes

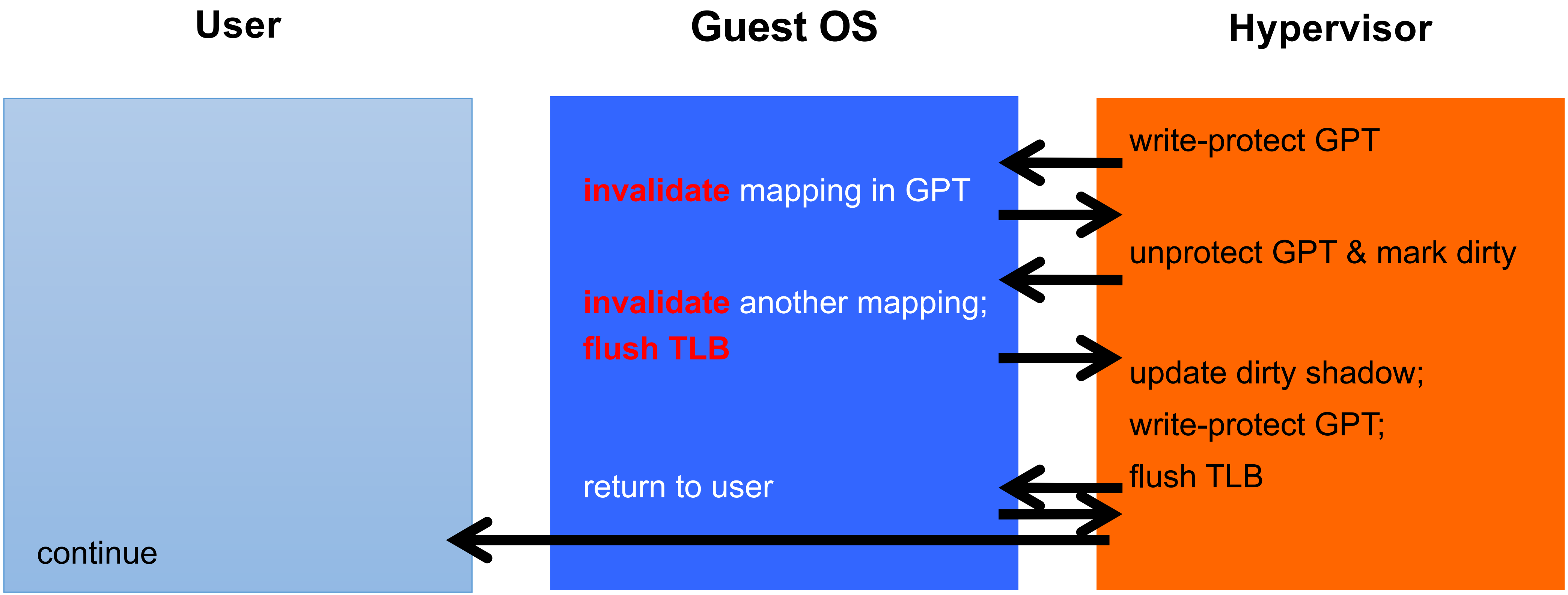
SPT is a *virtual TLB*

- similar semantics
- can be incomplete

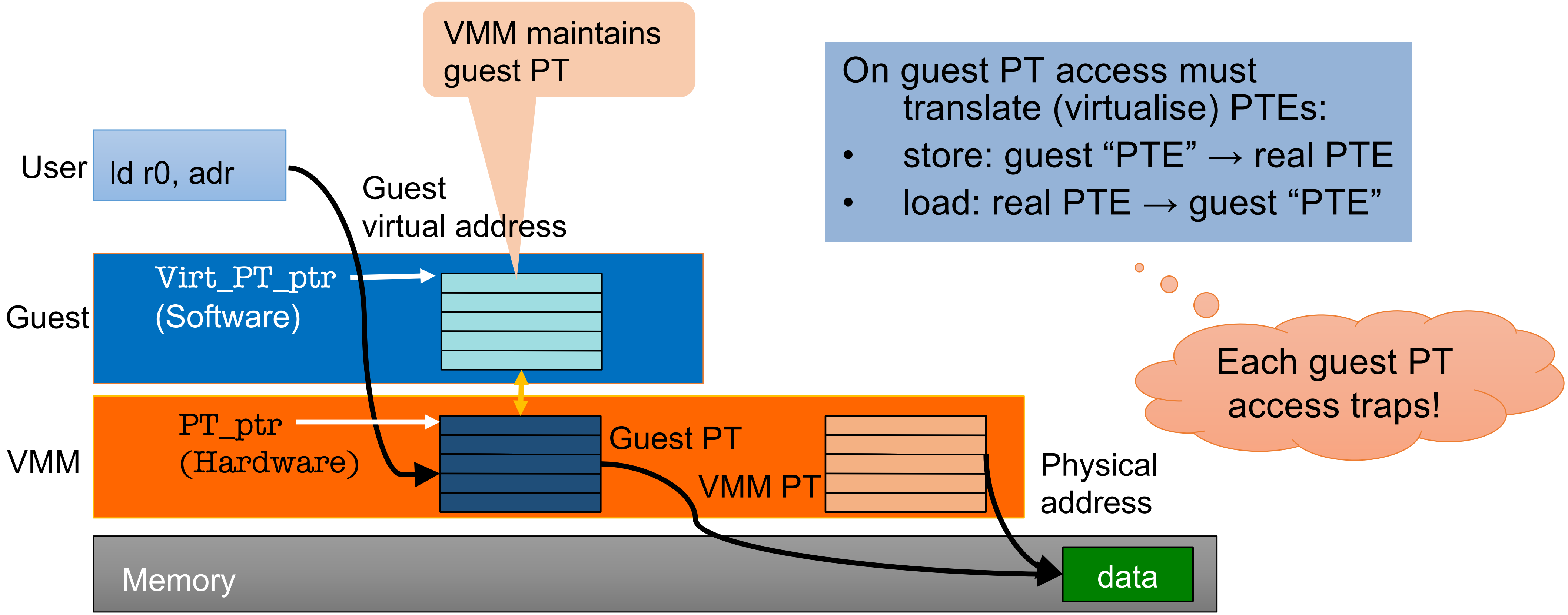
Lazy Shadow Update



Lazy Shadow Update



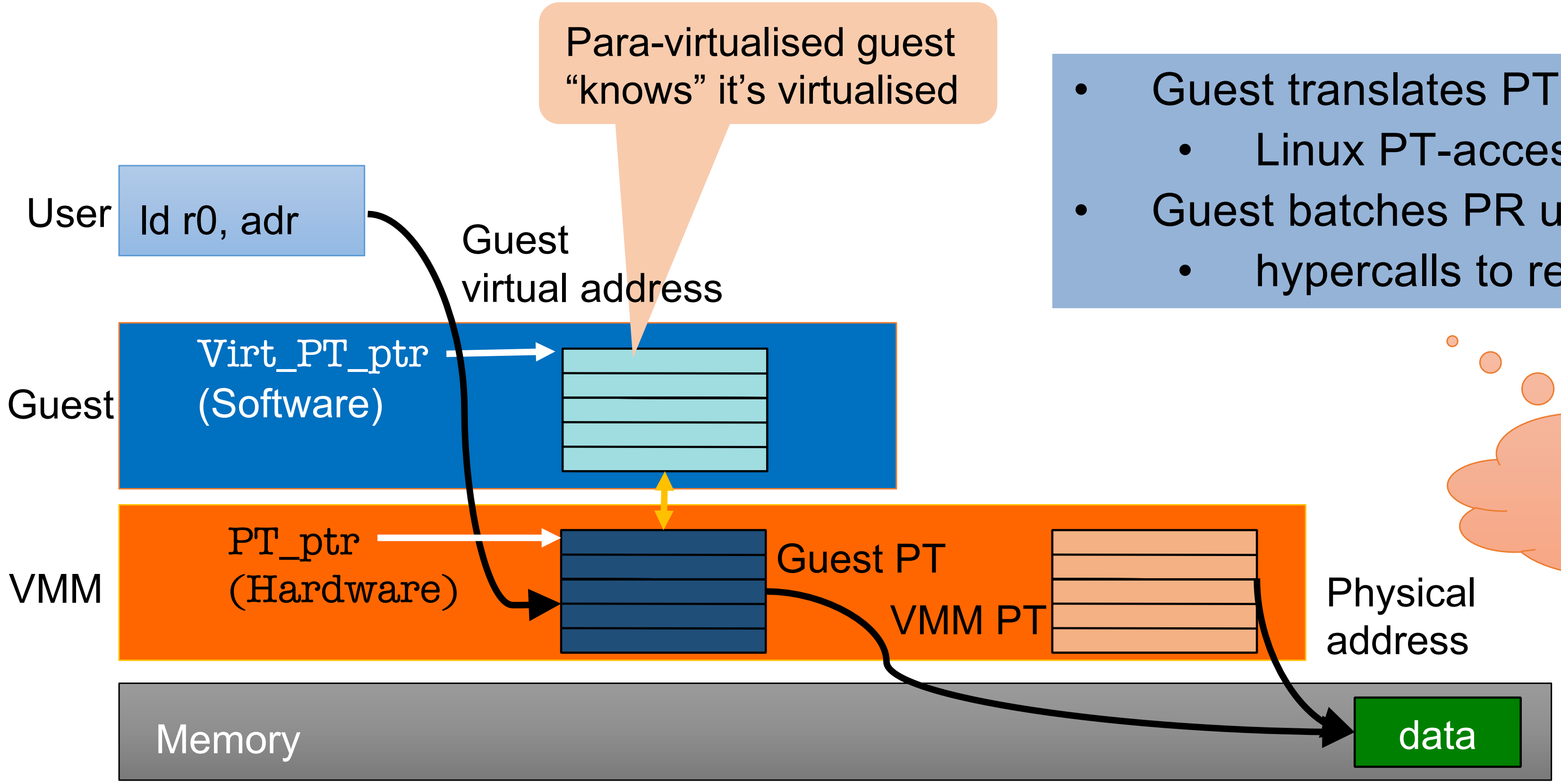
Real Guest Page Table



On guest PT access must translate (virtualise) PTEs:

- store: guest “PTE” → real PTE
- load: real PTE → guest “PTE”

Optimised Guest Page Table



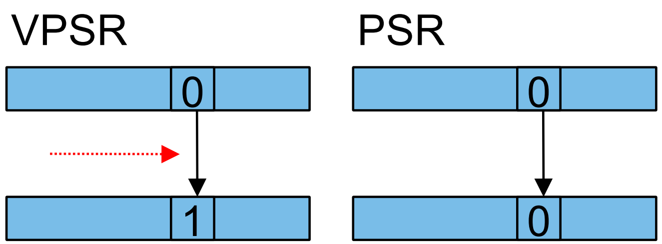
- Guest translates PTE on read from PT
  - Linux PT-access wrappers help
- Guest batches PR updates
  - hypercalls to reduce overhead

Guest Self-Virtualisation

Minimise traps by holding some virtual state inside guest

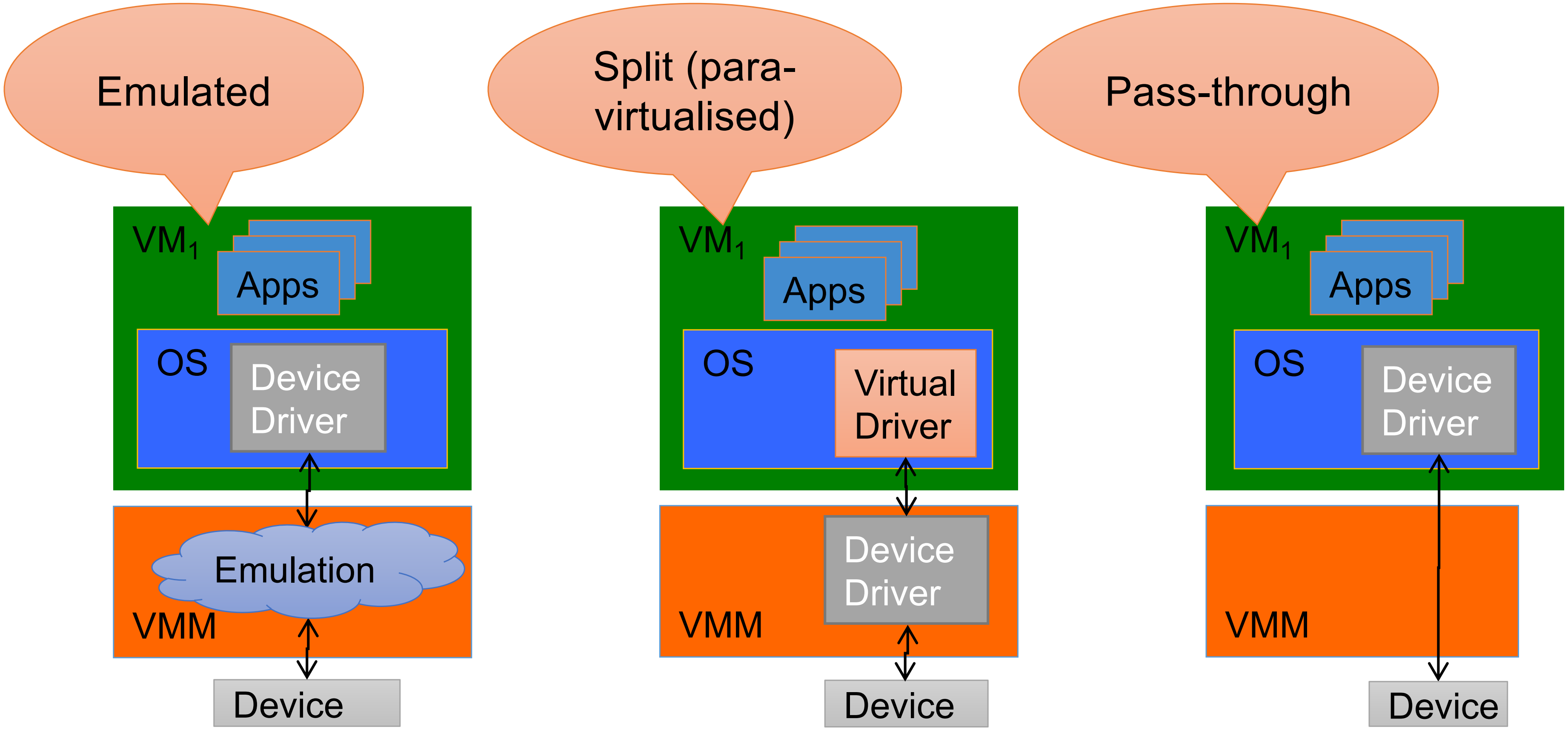
Example: Interrupt-enable in virtual PSR

- guest and VMM agree on VPSR location
- VMM queues guest IRQs when disabled in VPSR

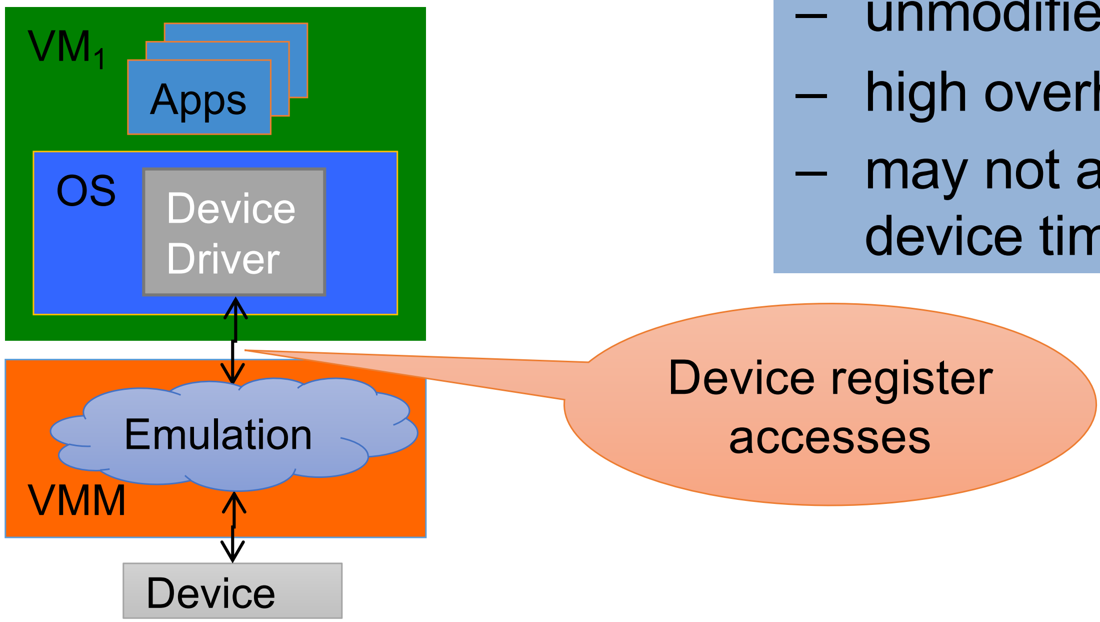



```
mov   r1,#VPSR
ldr   r0,[r1]
orr   r0,r0,#VPSR_ID
sto   r0,[r1]
```

Device Models



Emulated Device



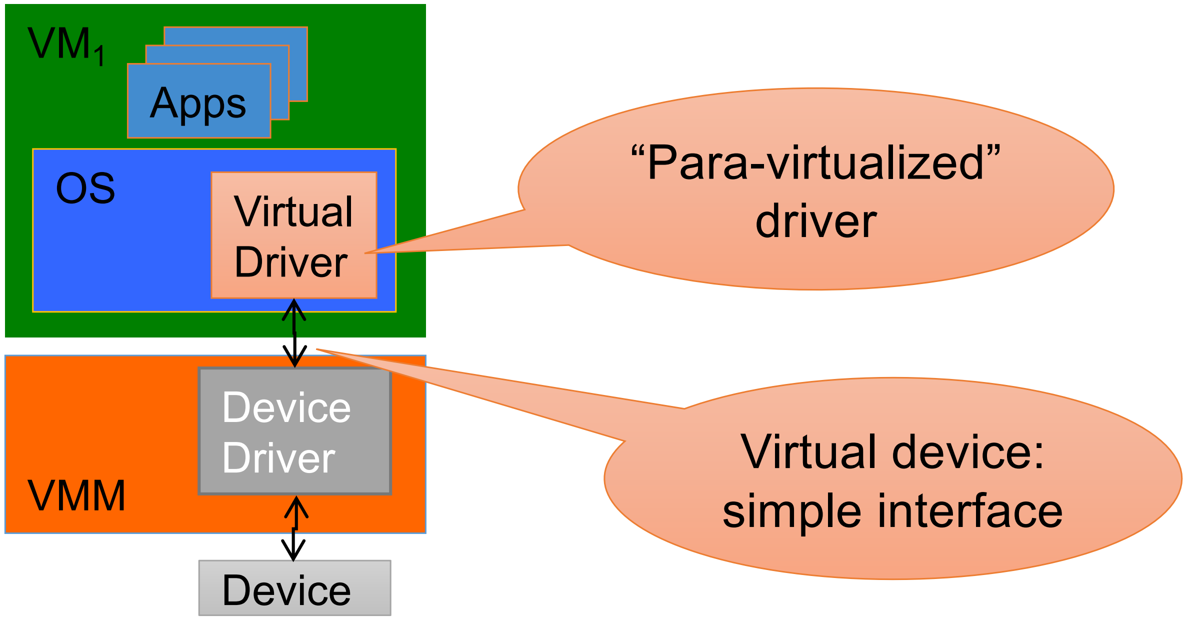
Each device access must be trapped and emulated

- unmodified native driver
- high overhead!
- may not actually work, violate device timing constraints

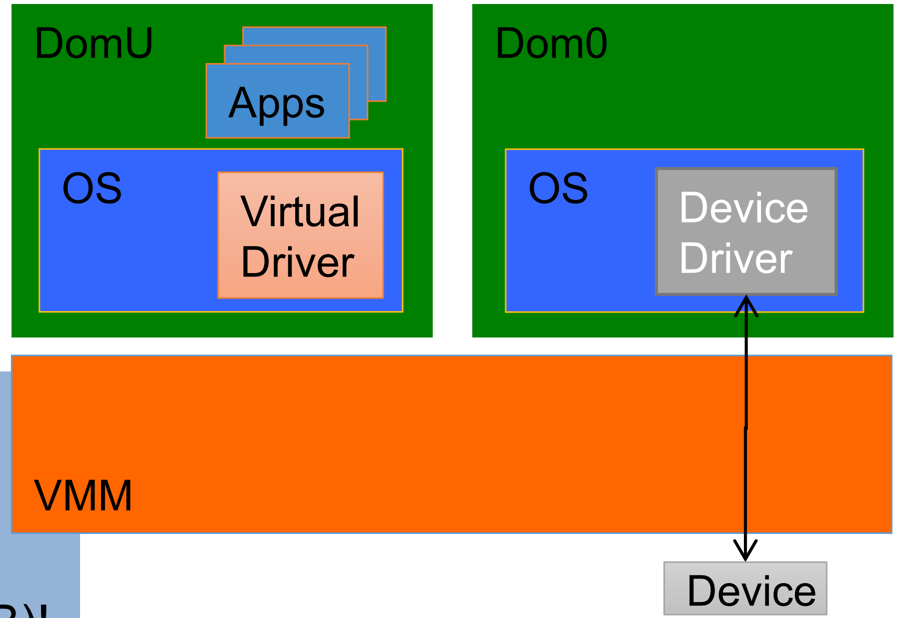
Split Driver

VirtIO: Linux I/O virtualisation interface

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



Driver OS (Xen Dom0)



Leverage native drivers
- no driver porting
- must trust complete driver guest!
- huge *trusted computing base* (TCB)!

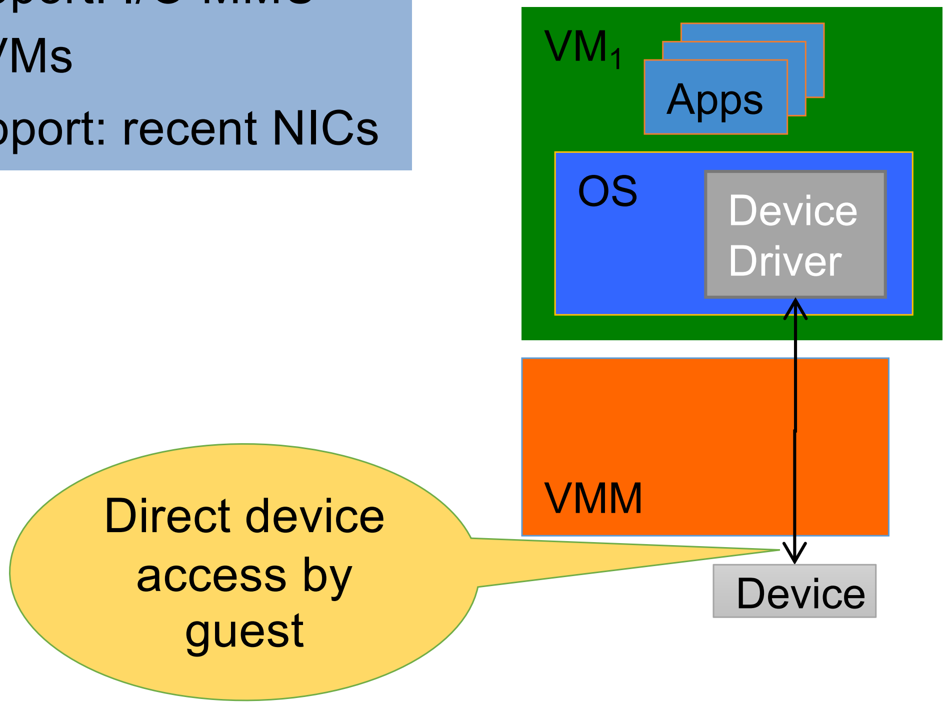
Pass-Through Driver

Unmodified native driver

- Must trust driver (and guest) for DMA
  - except with hardware support: I/O MMU
- Can't share device between VMs
  - except with hardware support: recent NICs

"Self-virtualising" devices:

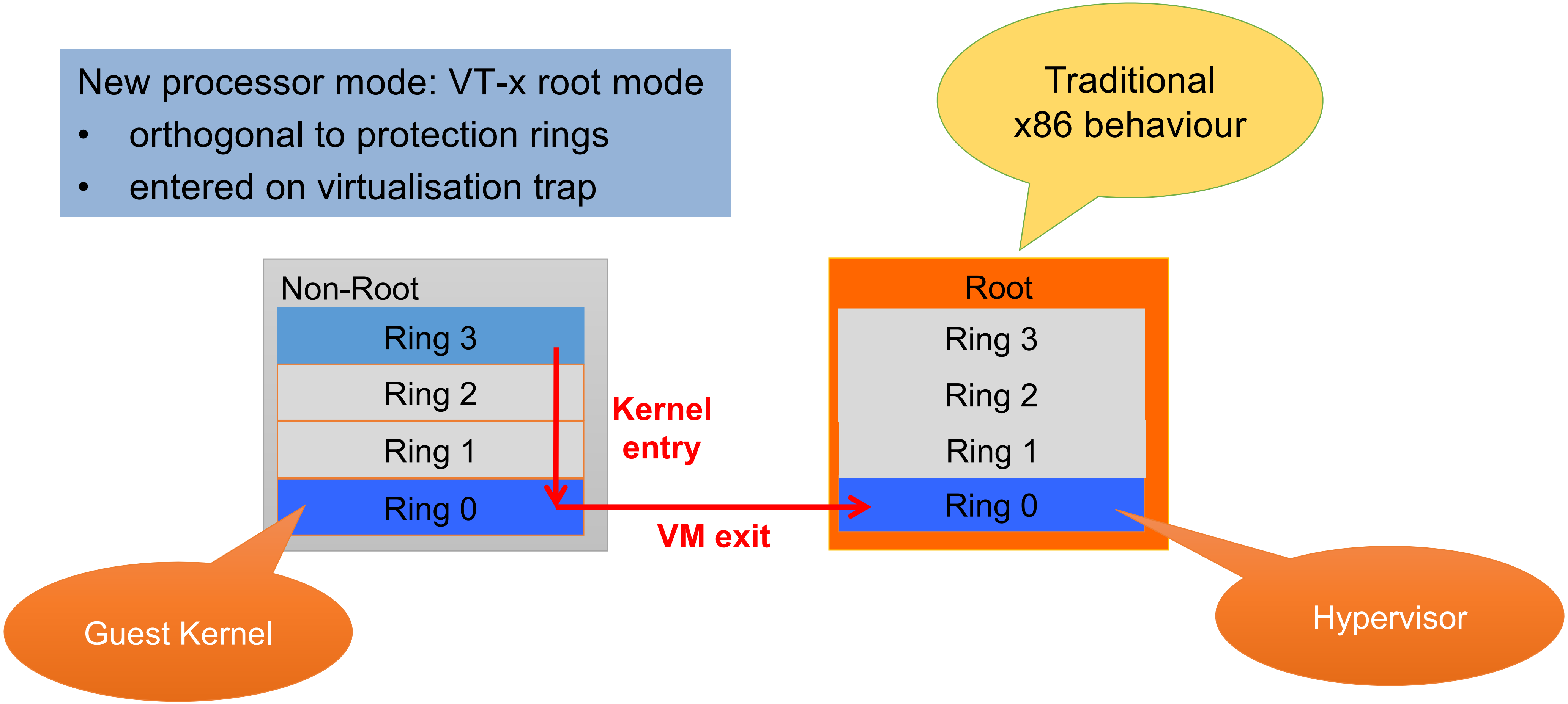
- Single-root I/O virtualisation (SRIOV)
- NIC presenting multiple, isolated virtual NIC interfaces



Modern Hardware Support

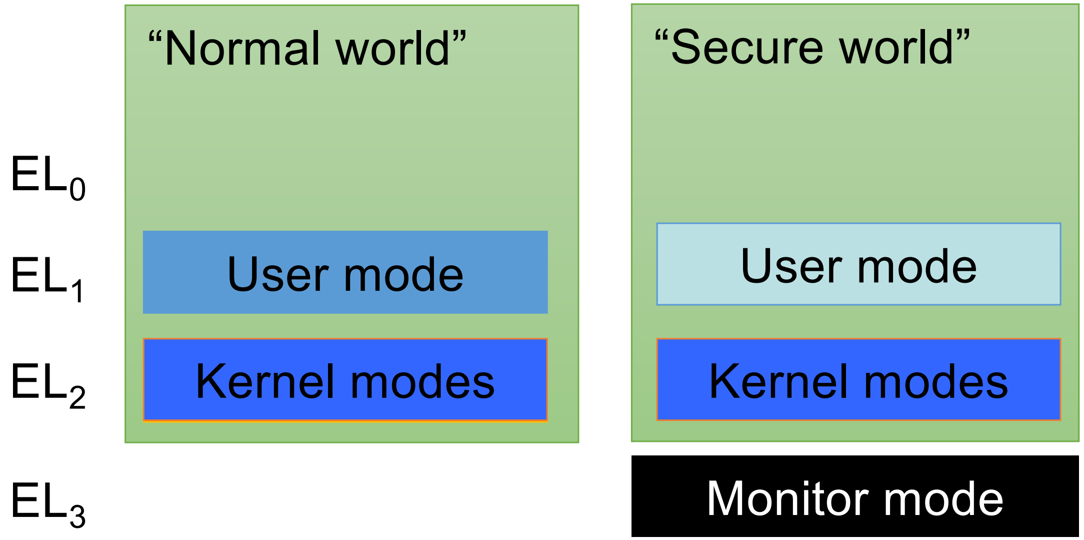
x86 Virtualisation Extensions: VT-x

New processor mode: VT-x root mode
- orthogonal to protection rings
- entered on virtualisation trap



Arm Virtualisation Extensions [1/6]

EL_2 aka "hyp mode"

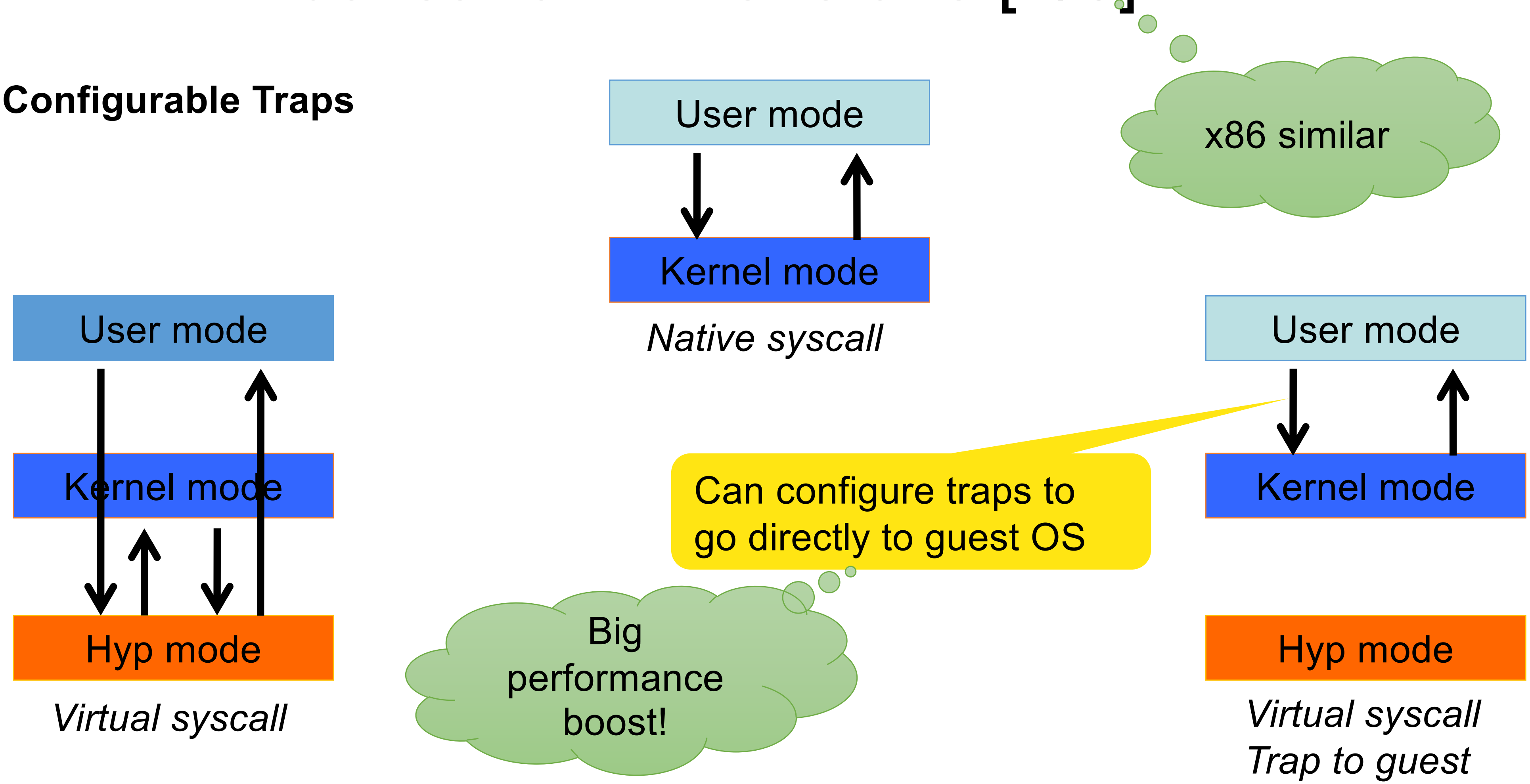


New privilege level

- Strictly higher than kernel (EL_1)
- Virtualizes or traps *all* sensitive instructions
- Presently only available in Arm TrustZone "normal world"
- Latest ISA revision supports it also in "secure world"

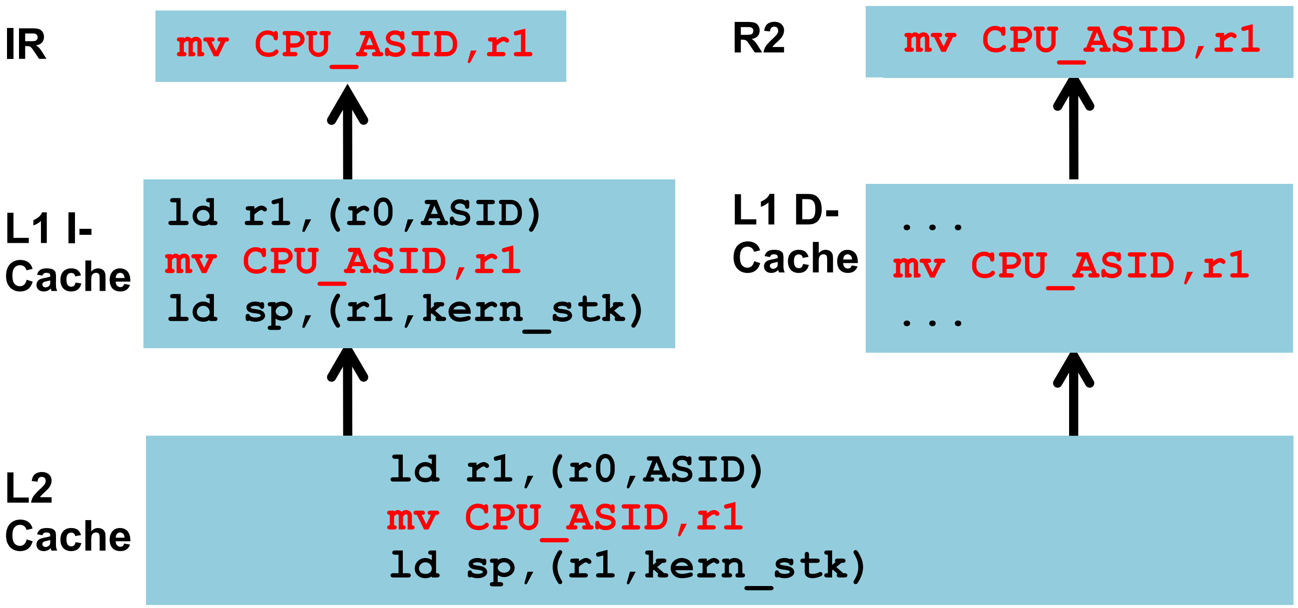
Arm Virtualisation Extensions [2/6]

Configurable Traps



Arm Virtualisation Extensions [3/6]

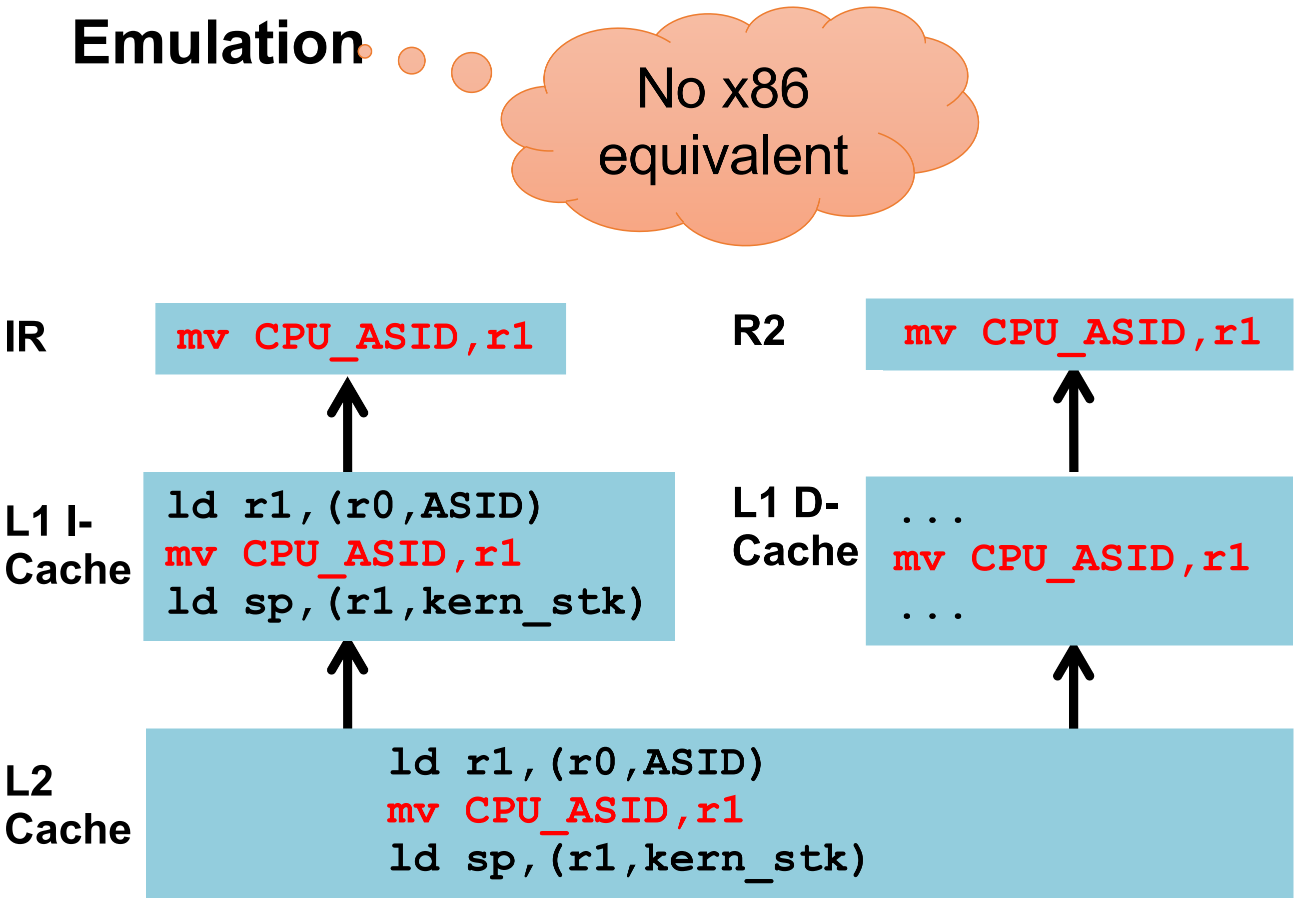
Emulation



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

Arm Virtualisation Extensions [3/6]

Emulation



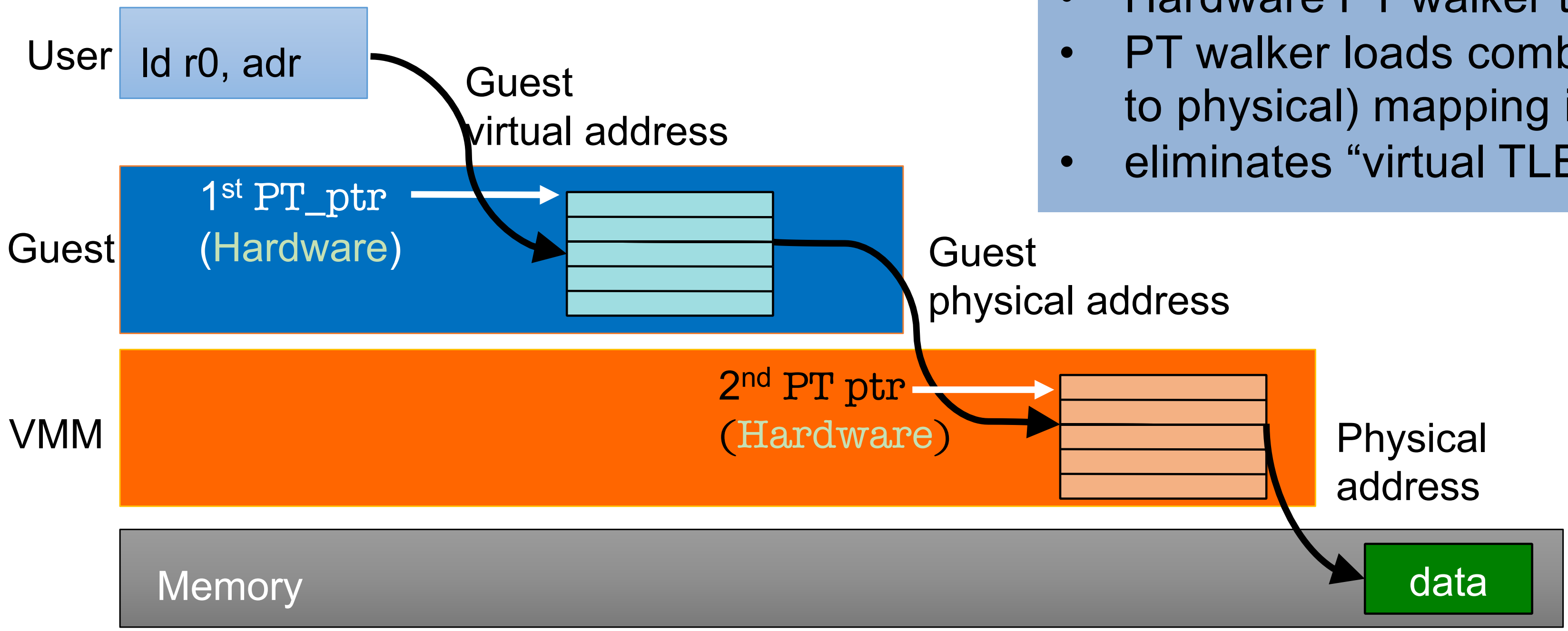
1) HW decodes instruction
   - No L1 miss
   - No software decode
2) SW emulates instruction
   - Usually straightforward

Arm Virtualisation Extensions (4)

2-stage translation

x86 similar (EPTs)

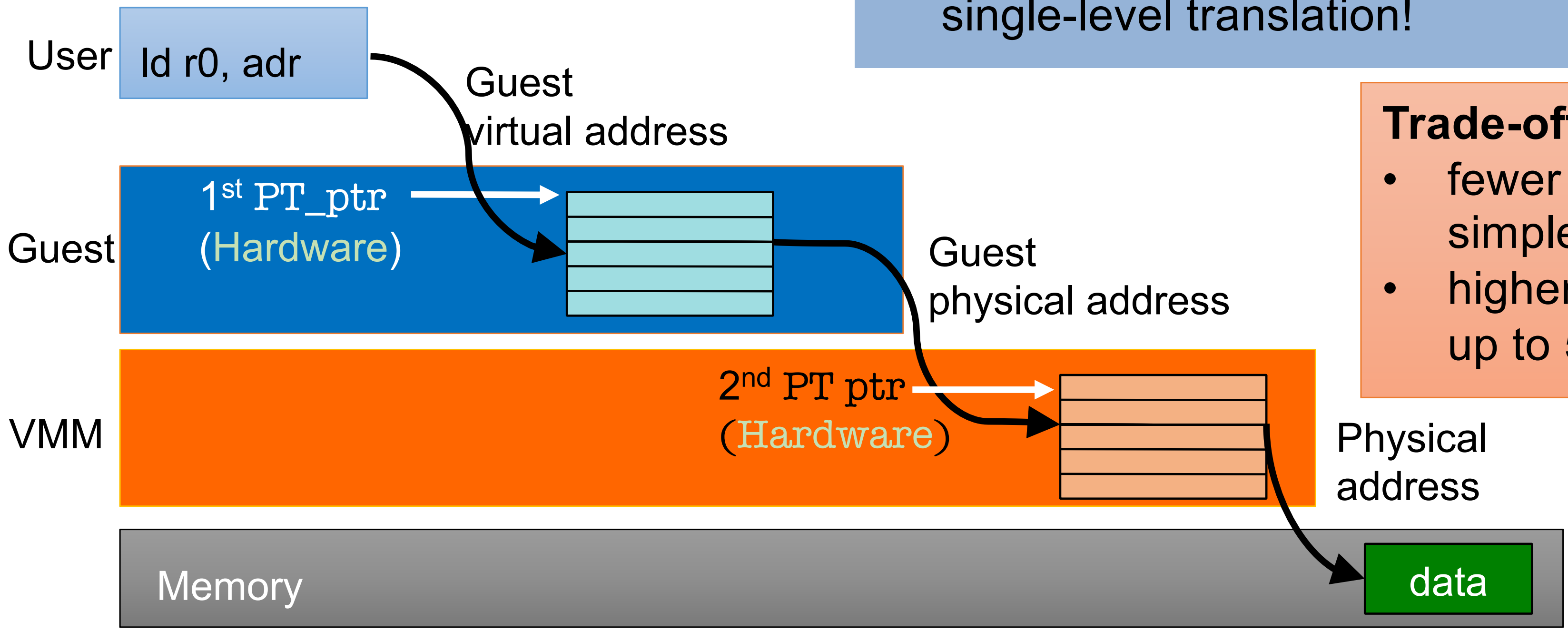
- Hardware PT walker traverses both PTs
- PT walker loads combined (guest-virtual to physical) mapping into TLB
- eliminates "virtual TLB"



Arm Virtualisation Extensions [4/6]

2-stage translation cost

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

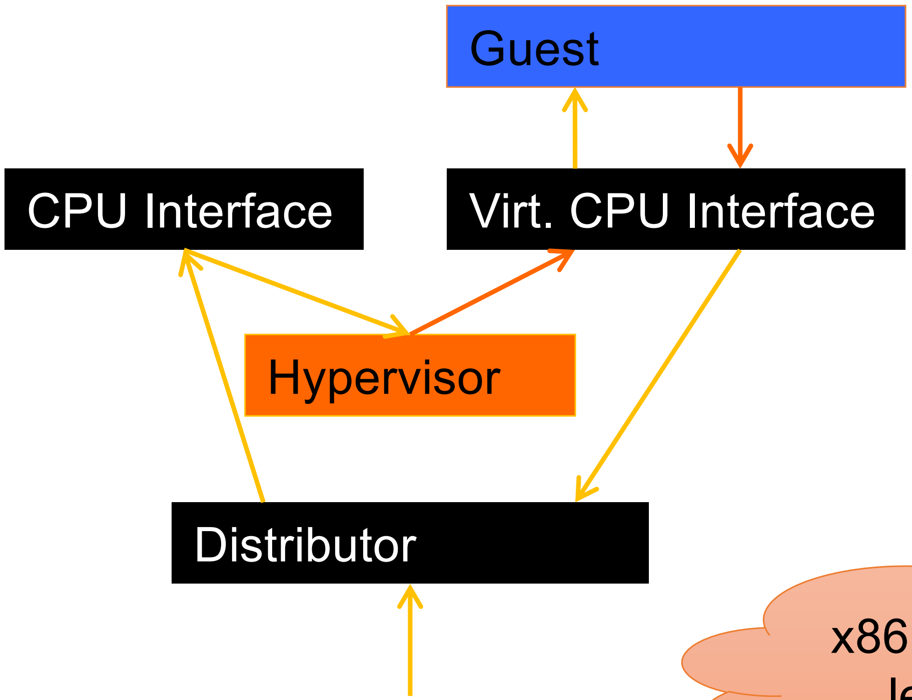


Trade-off:

- fewer traps
  simpler implementation
- higher TLB-miss cost
  up to 50% of run-time!

Arm Virtualisation Extensions [5/6]

Virtual Interrupts

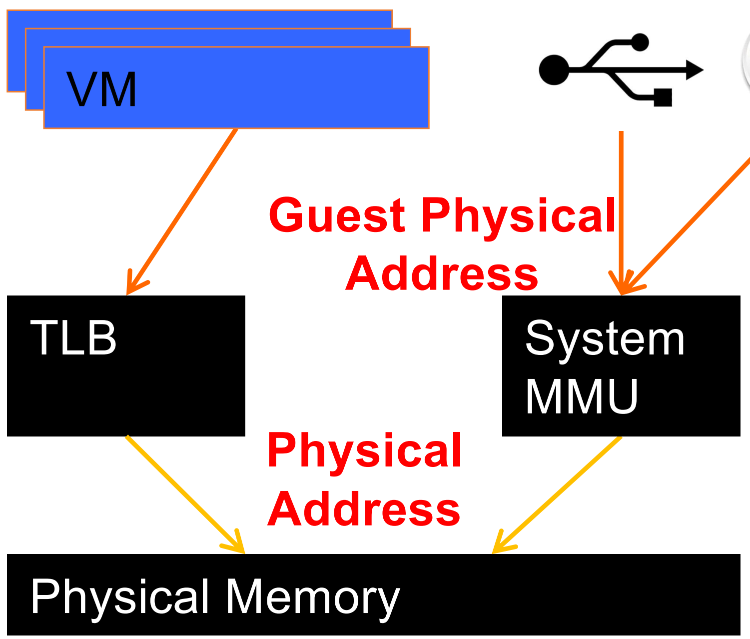


- 2-part IRQ controller
  - global “distributor”
  - per-CPU “interface”
- New H/W “virt. CPU interface”
  - Mapped to guest
  - Used by HV to forward IRQ
  - Used by guest to acknowledge
- Halves hypervisor invocations for interrupt virtualization

x86: issue only for legacy level-triggered IRQs

Arm Virtualisation Extensions [6/6]

System MMU (I/O MMU)



- Devices use virtual addresses
- Translated by *system MMU*
  - elsewhere called IOMMU
  - translation cache, like TLB
  - reloaded from I/O page table

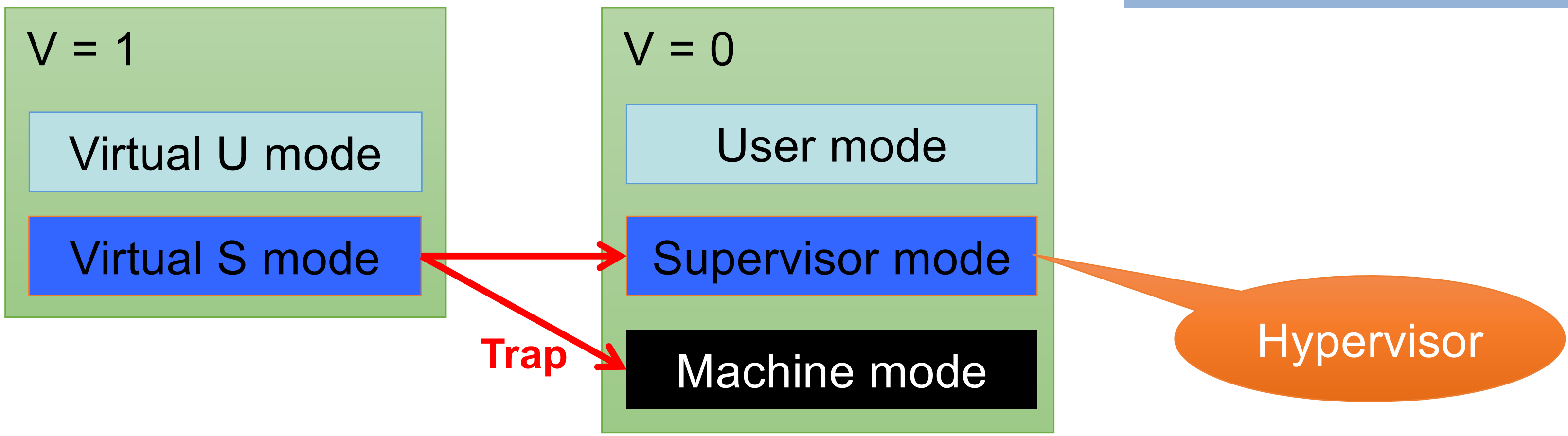
x86 different (VT-d)

Many ARM SoCs different

- Can do pass-through I/O safely
  - guest accesses device registers
  - no hypervisor invocation

RISC-V H Extension

Add virtual U+S modes
- Extra registers for VM state
- Re-direct VS traps to S
- 2-stage address translation
- VIRQ injection



World Switch Comparison

x86

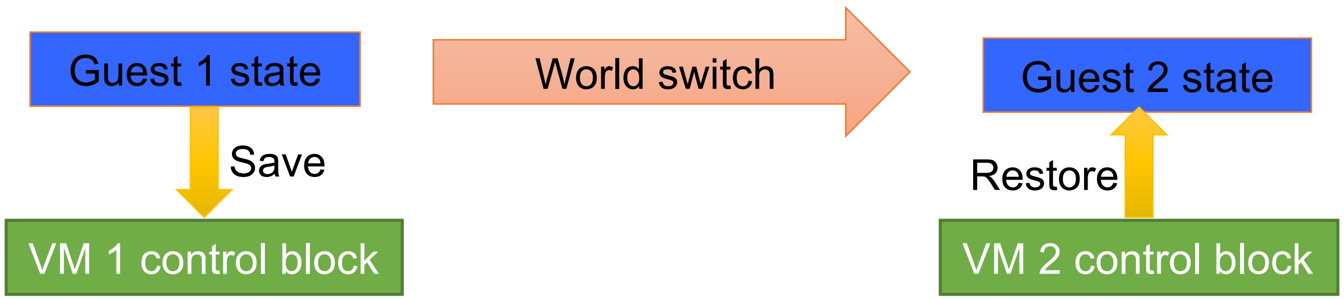
- VM state is ≈ 4 KiB
- Save/restore done by hardware on VMexit/VMentry
- Fast and simple

Arm

- VM state is 488 B
- Save/restore done by hypervisor
- Selective save/restore
  - Eg traps w/o world switch

RISC-V

- VM state ≈ 80 B
- Save/restore done by hypervisor
- Selective save/restore
  - Eg traps w/o world switch



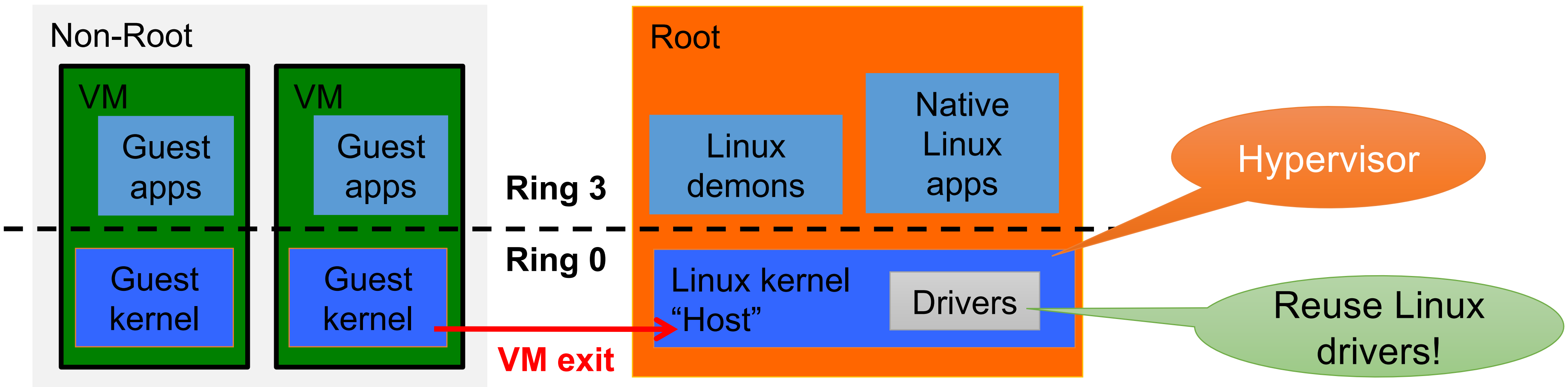
Fun and Games with Hypervisors

Hybrid Hypervisor-OSes

Huge TCB, contains full Linux system (kernel and userland)!

Often falsely called a "Type-2" hypervisor

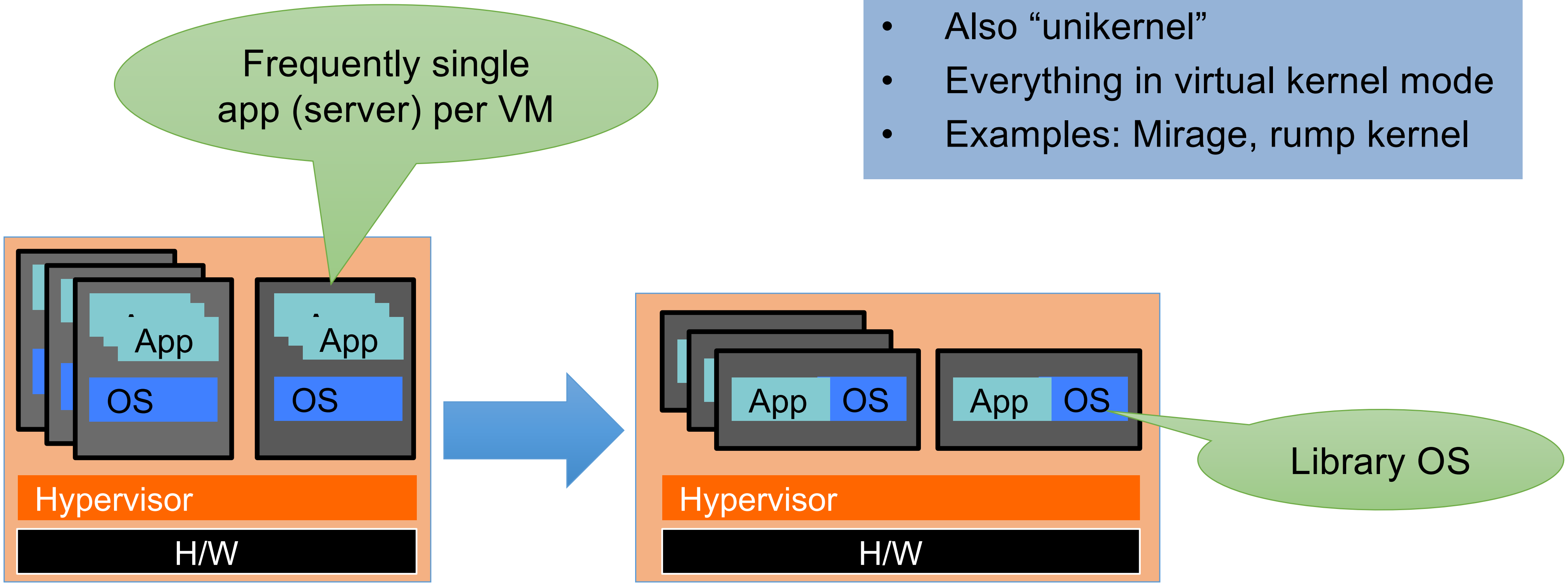
Idea: Turn OS into hypervisor by running in VT-x root mode, pioneered by KVM



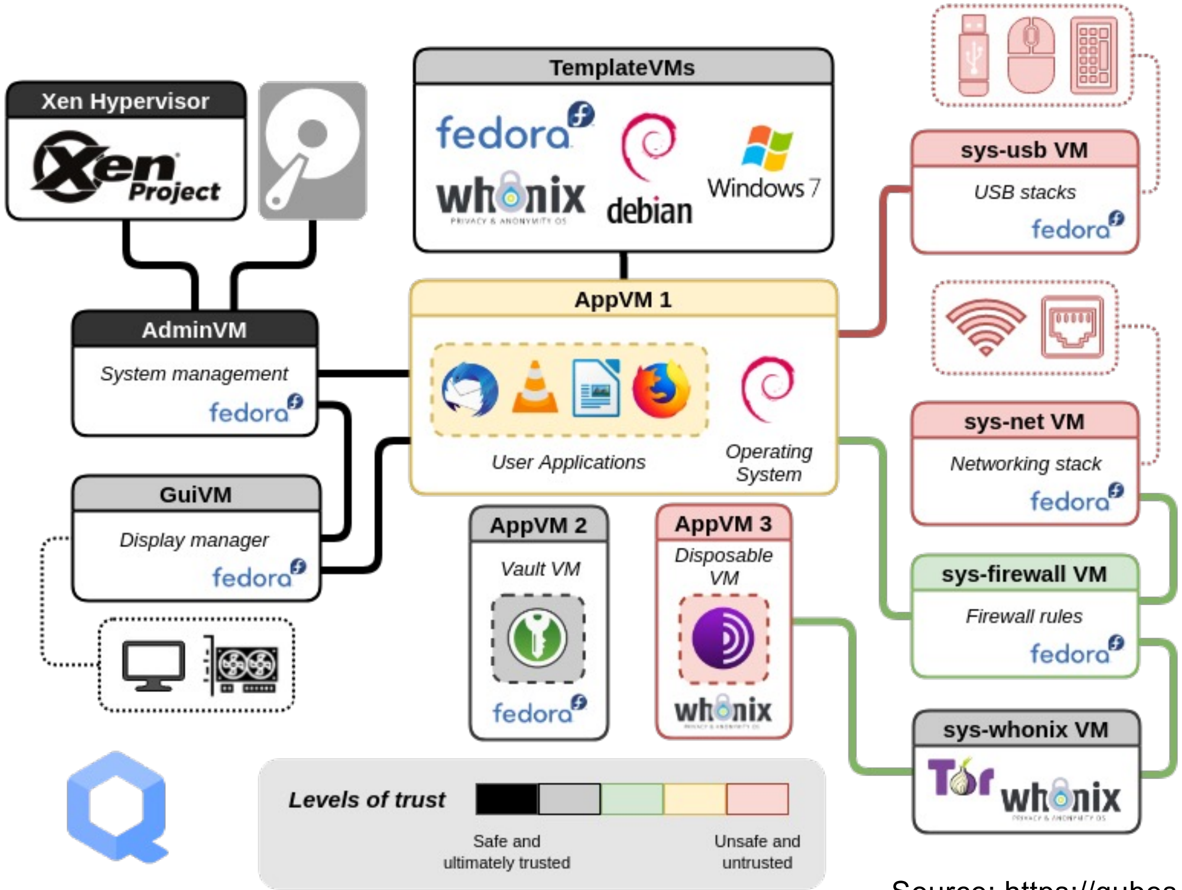
Why Still Have an OS?

Library OS, linked to app

- Also "unikernel"
- Everything in virtual kernel mode
- Examples: Mirage, rump kernel



Qubes OS: Everything Is A VM



Source: https://qubes-os.org

More Fun and Games…

- Time-travelling virtual machines [King ‘05]
  - debug backwards by replaying VM from checkpoint, log state changes
- SecVisor: kernel integrity by virtualisation [Seshadri ‘07]
  - controls modifications to kernel (guest) memory
- Overshadow: protect apps from OS [Chen ‘08]
  - make user memory opaque to OS by transparently encrypting
- Turtles: Recursive virtualisation [Ben-Yehuda ‘10]
  - virtualize VT-x to run hypervisor in VM
- CloudVisor: mini-hypervisor underneath Xen [Zhang ‘11]
  - isolates co-hosted VMs belonging to different users
  - leverages remote attestation (TPM) and Turtles ideas
- Containers (Docker etc):
  - Example of OS API virtualisation

… and many more..