Virtual Machines

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VIRTUAL MACHINE

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Duplicate: VM should behave identical to the real machine (programs cannot distinguish between execution on real or virtual hardware), except for:

- ➜ less 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 a speed close to that of real hardware

- ➜ requires that most instructions are executed directly by real hardware

VIRTUAL MACHINES, SIMULATORS AND EMULATORS

Simulator provides an *functionally accurate* software model of a machine

- ☑ may run on any hardware
- ☒ is typically slow (order of 1000 slowdown)

Emulator provides a *behavioural* model of a machine (and possibly its software)

- ☒ not fully accurate
- ☑ reasonably fast (order of 10 slowdown)

Virtual machine models a machine exactly and efficiently

- ☑ minimal slowdown
- ☒ needs to be run on the physical machine it virtualises

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  ➜ also called *process VM*

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- Call virtual machines even if there is no correspondence to an existing real machine
  - ➜ e.g. *Java virtual machine*
  - ➜ can be viewed as virtualising at the ABI level
  - ➜ also called *process VM*
- We only concern ourselves with virtualising at the ISA level
  - ➜ ISA = *instruction-set architecture* (hardware-software interface)
  - ➜ also called *system VM* [SN05]
  - ➜ will later see subclasses of this

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- Renaissance in recent years for improved isolation [RG05]
  - ⋆ improved QoS and security
  - ⋆ uniform view of hardware
  - ⋆ complete encapsulation
    - ➜ for replication, migration, checkpoint/restart, debugging
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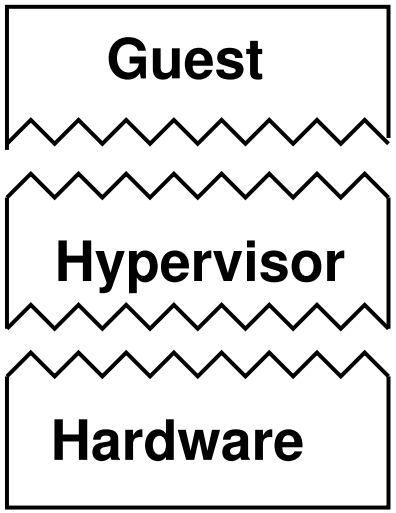
- Isn't that exactly the job description of an OS????
  - ➜ This really means that mainstream OSes suck!

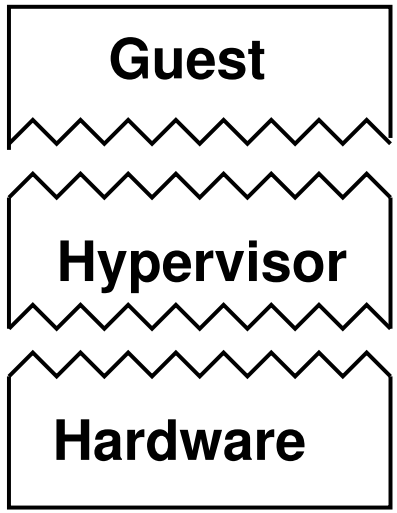
Virtual Machine Monitor (VMM) aka Hypervisor

- Program that runs on real hardware to implement the virtual machine
- Controls resources and schedules guests



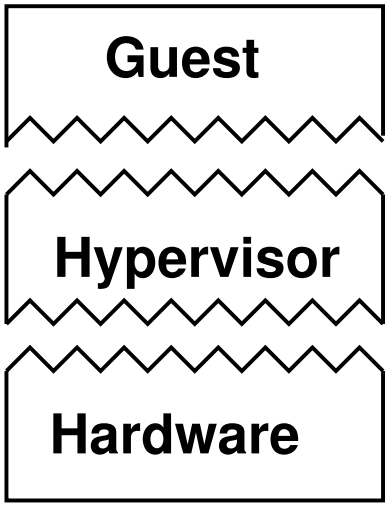
Virtual Machine Monitor (VMM) aka Hypervisor

- Program that runs on real hardware to implement the virtual machine
- Controls resources and schedules guests
- Implications:
  - ➜ hypervisor executes in privileged mode
  - ➜ guest software executes in unprivileged mode
  - ➜ *privileged instructions* in guest cause a trap into the hypervisor
  - ➜ hypervisor interprets/emulates them



Native vs. Hosted VMM

Native/classic/bare-metal



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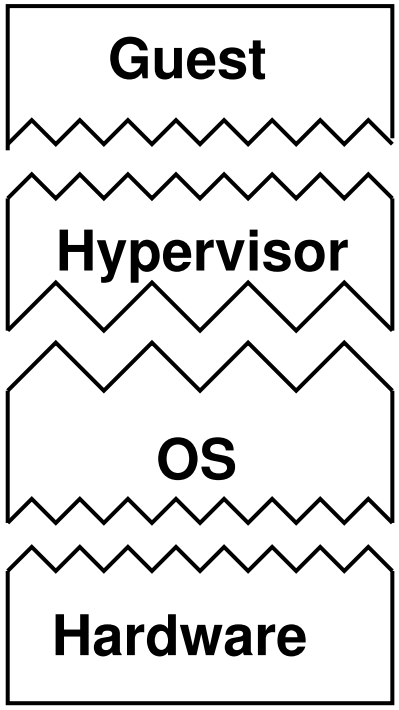

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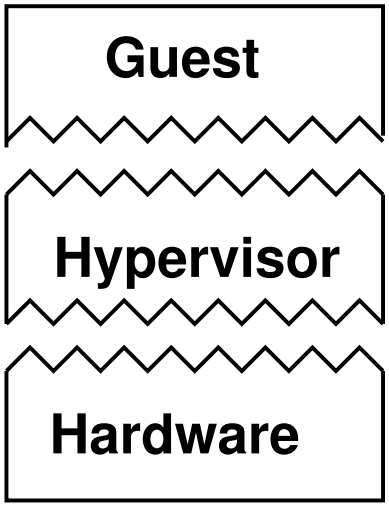

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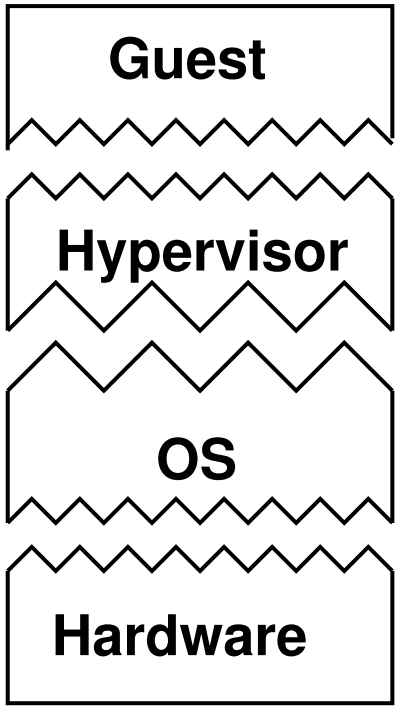

- Hosted VMM can run besides native apps
  - ⋆ sandbox untrusted apps
  - ⋆ run second OS
  - ⋆ less efficient:
    - ☒ guest privileged instruction traps into OS, forwarded to hypervisor
    - ☒ return to guest requires a native SO system call

VMM Types

Classic as above

Hosted e.g. VMware GSX Server

Whole-system virtual hardware and operating system

- ➜ really an emulation
- ➜ e.g. Virtual PC (for Macintosh)

Physically partitioned allocate actual processors to each VM

Logically partitioned time-share processors between VMs

Co-designed hardware specifically designed for VMM

- ➜ e.g. Transmeta Crusoe, IBM i-Series

Requirements for Virtualisation

Definitions

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➜ Note: trap is required, NOOP is insufficient!

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➜ includes privilege mode, addressing context, exception vectors, ...

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  - ➜ guest's sensitive instructions trap and are emulated by VMM
  - ➜ guest's innocuous instructions are executed directly
  - ➜ VMM controls resources
- Virtualised execution is indistinguishable from native, except:
  - ➜ resources more limited (running on *smaller* machine)
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- Architecture is *recursively virtualizable* if VMM without timing dependency can be built

VIRTUALISATION OVERHEADS

- VMM needs to maintain virtualised privileged machine state
  - ➜ processor status
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- VMM needs to simulate privileged instructions
  - ➜ synchronise virtual and real privileged state as appropriate
  - ➜ e.g. *shadow page tables* to virtualize hardware

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- Frequent virtualisation traps can be expensive
  - ➜ STI/CLI for mutual exclusion
  - ➜ frequent page table updates
  - ➜ MIPS KSEG addresses used for physical addressing in kernel

Unvirtualisable Architectures

- x86: lots of unvirtualisable features
  - ➜ e.g. sensitive PUSH of PSW is not privileged
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  - ➜ performance issue with virtualising `KSEG` addresses
- Most others have problems too

Impure Virtualisation

- Used for two reasons:
  - ➜ unvirtualisable architectures
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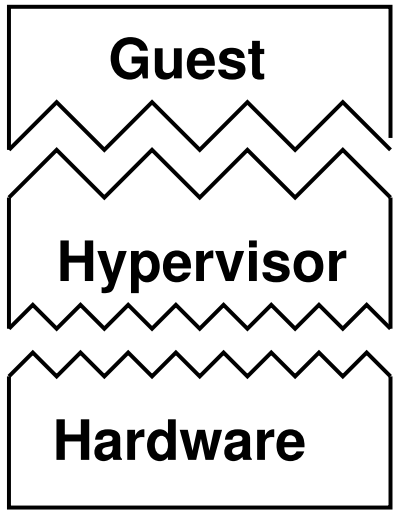
IMPURE VIRTUALISATION

- Used for two reasons:
  - ➜ unvirtualisable architectures
  - ➜ performance problems of virtualisation
- Two standard approaches:
  1. paravirtualisation
  2. binary translation

PARAVIRTUALISATION

- New name, old technique
  - ➜ Used in Mach Unix server, L^{4}Linux [HHL+97], Disco [BDGR97]
  - ➜ Name coined by Denali [WSG02], popularised by Xen [BDF+03]



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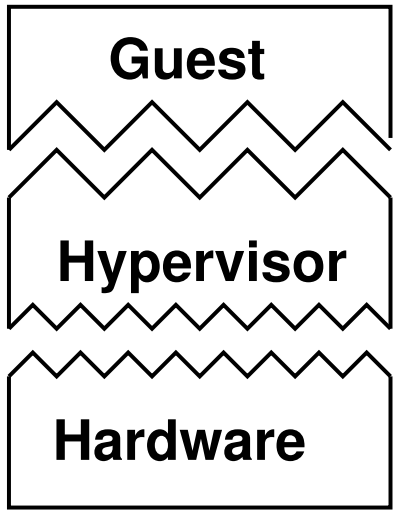

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- Manually port the guest OS to modified ISA
  - ➜ augmented by explicit hypervisor calls (*hypercalls*)
  - ☑ idea is to provide more high-level API to reduce the number of traps
  - ☑ remove unvirtualisable instructions
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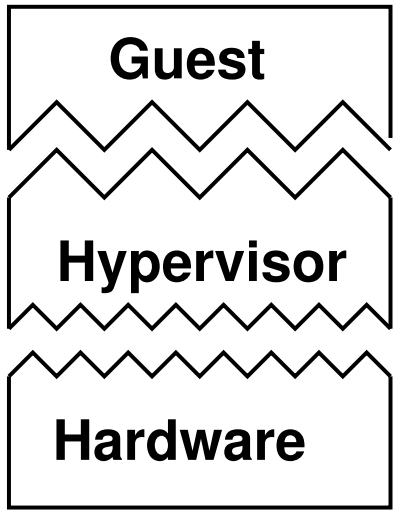

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- Drawbacks:
  - ☒ significant engineering effort
  - ☒ needs to be repeated for each guest, ISA, hypervisor combination
  - ☒ paravirtualised guest needs to be kept in sync with native guest
  - ☒ requires source

Binary Translation

- Locate unvirtualisable instructions in guest binary and replace on-the-fly by emulation code or hypercall

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☑ can also detect combinations of sensitive instructions and replace by single emulation

☑ doesn't require source

☑ may (safely) do some emulation in user space for efficiency

☒ very tricky to get right (especially on x86!)

☒ needs to make some assumptions on sane behaviour of guest

Virtualisation Techniques: Memory

- Shadow page tables
  - ➜ Guest accesses shadow PT
  - ➜ VMM detects changes (e.g. making them R/O) and syncs with real PT
  - ➜ can over-commit memory (similar to virtual-memory paging)

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- Memory reclamation: *Ballooning* (VMware ESX Server)
  - ➜ load cooperating pseudo-device driver into guest
  - ➜ to reclaim, balloon driver requests physical memory from guest
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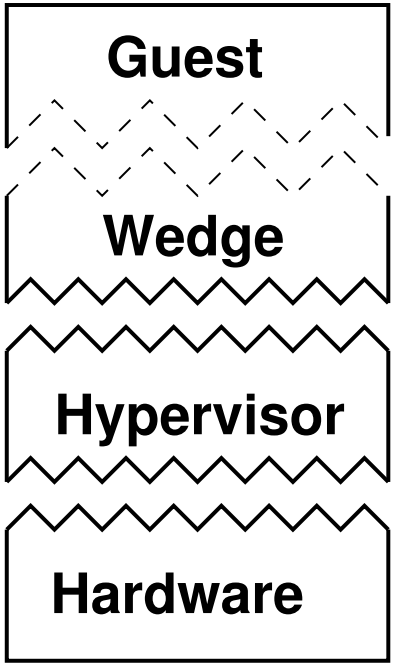
- Page sharing
  - ➜ VMM detects pages with identical content
  - ➜ establishes (copy-on-write) mappings to single page via shadow PT
  - ➜ significant savings when running many identical guest OSes

VIRTUALISATION TECHNIQUES: DEVICES

- Drivers in VMM
  - ➜ maybe ported legacy drivers
- Host drivers
  - ➜ for hosted VMMs
- Legacy driver in separate driver VM
  - ➜ e.g. separate Linux guest for each device [LUSG04]
- Virtualisation-friendly devices
  - ➜ IBM channel architecture
  - ➜ can safely be accessed by guest drivers if physical memory access is restricted (I/O-MMU)

PREVIRTUALISATION

- Combines advantages of pure and paravirtualisation



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- Multi-stage process

① During build, pad sensitive instructions with NOPs and keep record
② During profiling run, trap sensitive memory operations (e.g. PT accesses) and record
③ Redo build, also padding sensitive memory operations
④ Link emulation library (*wedge*) with guest
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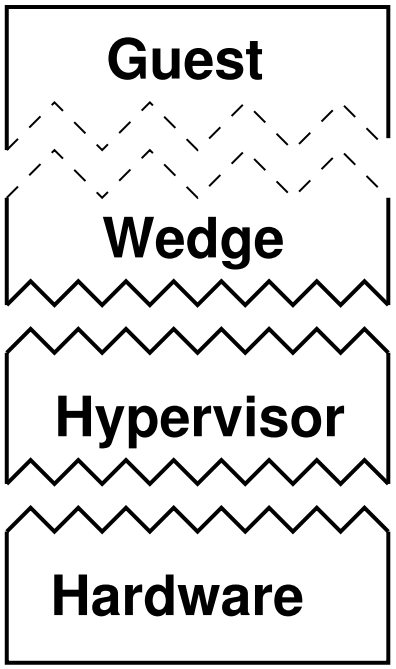

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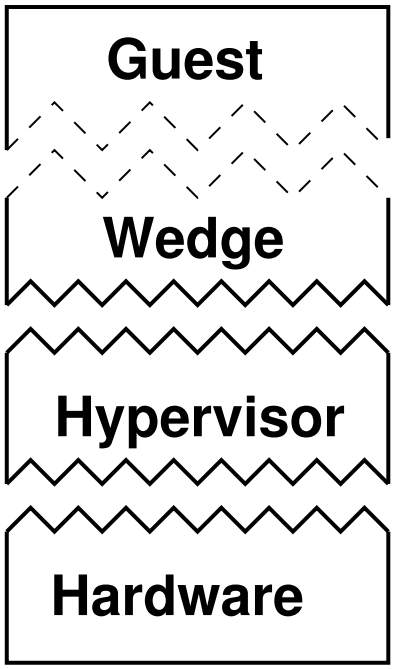

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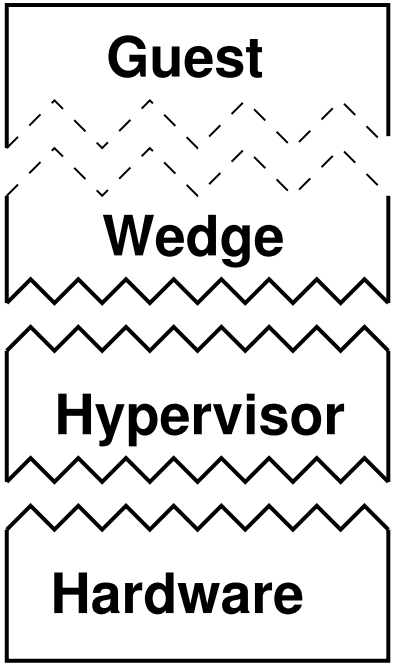

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  - ➜ See `http://l4ka.org/projects/virtualization/afterburn/`

Hardware Support

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  - ⋆ introduces new processor mode: *root mode* for hypervisor
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  - ➜ also memory and device segregation
- Aim is virtualisation of unmodified legacy OSes

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