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Virtual Machines

COMP9242
2008/S2 Week 11

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Virtual Machines

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- *"A virtual machine (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 a speed close to that of real hardware
  - Requires that most instruction are executed directly by real hardware

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Virtual Machines, Simulators and Emulators

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Simulator

☐ Provides a *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 hardware (and possibly S/W)
☒ Not fully accurate
√ Reasonably fast (order of 10 slowdown)

Virtual machine

☐ Models a machine exactly and efficiently
√ Minimal showdown
☒ Needs to be run on the physical machine it virtualizes (more or less)

Types of Virtual Machines

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- Contemporary use of the term VM is more general
- Call virtual machines even if there is nor correspondence to an existing real machine
  - E.g: *Java virtual machine*
  - Can be viewed as virtualizing at the ABI level
  - Also called *process VM*
- We only concern ourselves with virtualizing at the ISA level
  - ISA = *instruction-set architecture* (hardware-software interface)
  - Also called *system VM*
  - Will later see subclasses of this

Virtual Machine Monitor (VMM), aka Hypervisor

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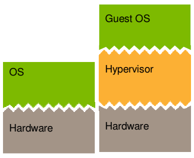
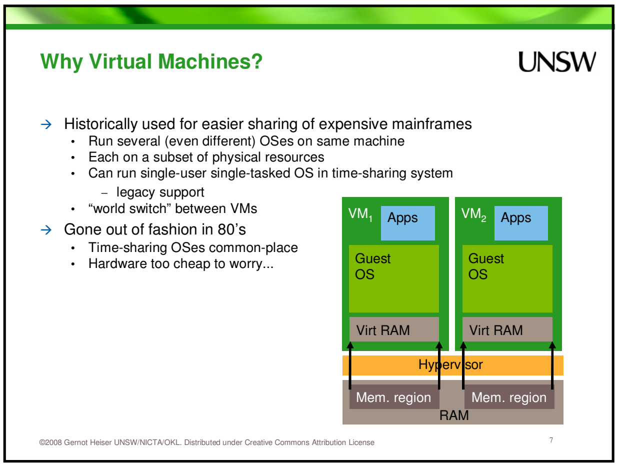


- Program that runs on real hardware to implement the virtual machine
- Controls resources
  - Partitions hardware
  - Schedules guests
  - Mediates access to shared resources
    - e.g. console
  - Performs *world switch*
- Implications:
  - Hypervisor executes in *privileged* mode
  - Guest software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



Why Virtual Machines?

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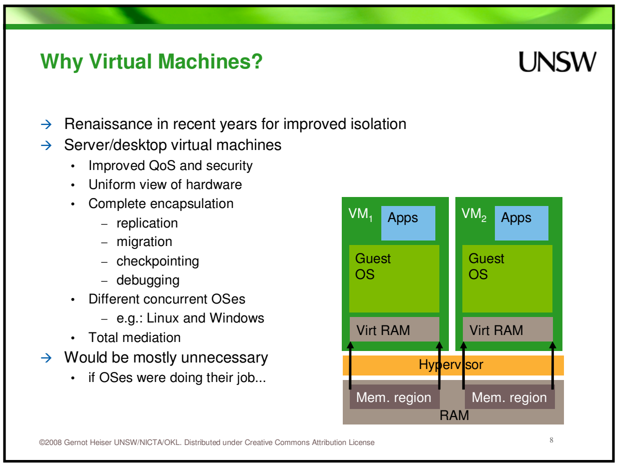
- Historically used for easier sharing of expensive mainframes
  - Run several (even different) OSes on same machine
  - Each on a subset of physical resources
  - Can run single-user single-tasked OS in time-sharing system
    - legacy support
  - "world switch" between VMs
- Gone out of fashion in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



Why Virtual Machines?

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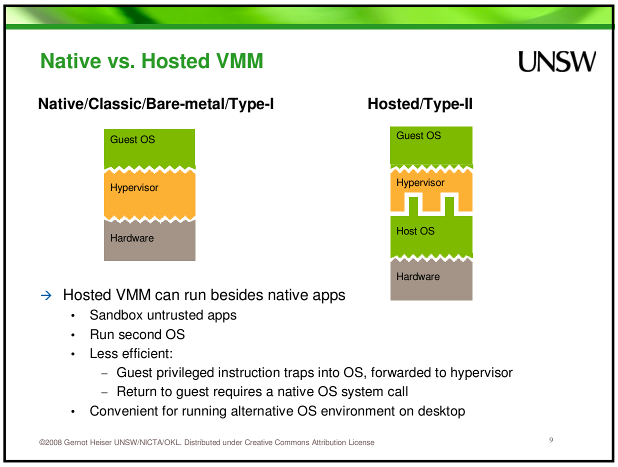
- Renaissance in recent years for improved isolation
- Server/desktop virtual machines
  - Improved QoS and security
  - Uniform view of hardware
  - Complete encapsulation
    - replication
    - migration
    - checkpointing
    - debugging
  - Different concurrent OSes
    - e.g.: Linux and Windows
  - Total mediation
- Would be mostly unnecessary
  - if OSes were doing their job...



Native vs. Hosted VMM

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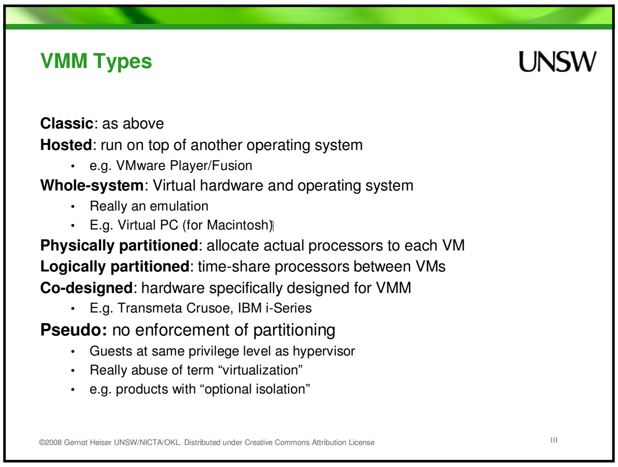
Native/Classic/Bare-metal/Type-I

Hosted/Type-II

- 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 OS system call
  - Convenient for running alternative OS environment on desktop



VMM Types

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Classic: as above

Hosted: run on top of another operating system
- e.g. VMware Player/Fusion

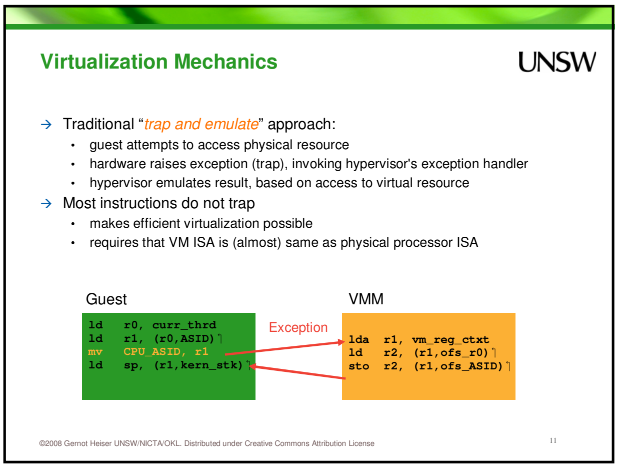
Whole-system: Virtual hardware and operating system
- Really an emulation
- E.g. Virtual PC (for Macintosh)

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

Pseudo: no enforcement of partitioning
- Guests at same privilege level as hypervisor
- Really abuse of term "virtualization"
- e.g. products with "optional isolation"



Virtualization Mechanics

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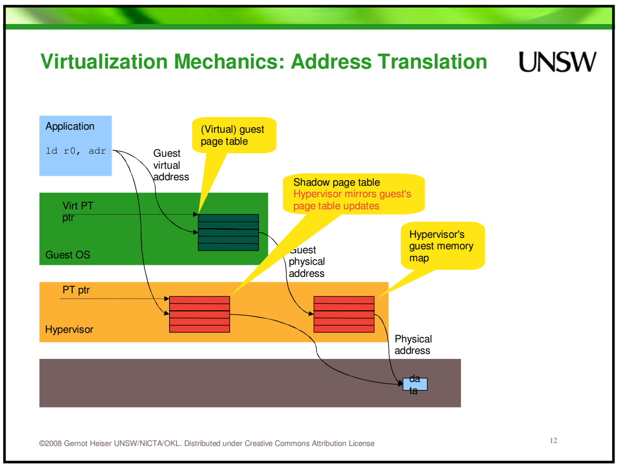
- Traditional "*trap and emulate*" approach:
  - guest attempts to access physical resource
  - hardware raises exception (trap), invoking hypervisor's exception handler
  - hypervisor emulates result, based on access to virtual resource
- Most instructions do not trap
  - makes efficient virtualization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

Guest

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

VMM

```
lda  r1, vm_reg_ctxt
ld   r2, (r1,ofs_r0)
sto  r2, (r1,ofs_ASID)
```



Virtualization Mechanics: Address Translation

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Requirements for Virtualization

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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 Requirements

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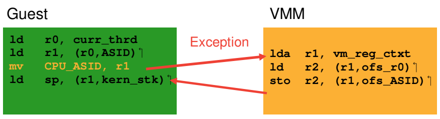
- An architecture is *virtualizable* if all *sensitive* instructions are *privileged*
- Can then achieve accurate, efficient guest execution
  - by simply running guest binary on hypervisor
- VMM controls resources
- Virtualized execution is indistinguishable from native, except:
  - Resources more limited (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



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

```
lda  r1, vm_reg_ctxt
ld   r2, (r1,ofs_r0)
sto  r2, (r1,ofs_ASID)
```

Virtualization Overheads

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- 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 (x86)
- 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

Unvirtualizable Architectures

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- x86: lots of unvirtualizable 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
- Recent architecture extensions provide virtualization support hacks

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Impure Virtualization

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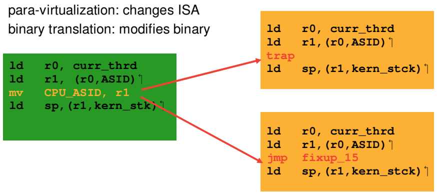
- Used for two reasons:
  - unvirtualizable architectures
  - performance problems of virtualization
- Change the guest OS, replacing sensitive instructions
  - by trapping code (hypercalls)
  - by in-line emulation code
- Two standard approaches:
  - para-virtualization: changes ISA
  - binary translation: modifies binary



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

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

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

Binary Translation

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- 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!)
  - needs to make some assumptions on sane behaviour of guest

Para-Virtualization

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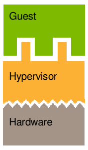
- → New name, old technique
  - Mach Unix server [Golub et al, 90], L⁴Linux [Härtig et al, 97], Disco [Bugnion et al, 97]
  - Name coined by Denali [Whitaker et al, 02], popularised by Xen [Barham et al, 03]
- → Idea: manually port the guest OS to modified ISA
  - Augment by explicit hypervisor calls (*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 Techniques

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- → 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)
  - guest can update without (expensive) hypervisor invocation
    - – 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

Virtualization Techniques

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- → 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

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Virtualization Techniques

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Page table implementation options

- → Strict shadowing of virtual page table
  - write protect PTs □ force trap into hypervisor on each update
  - can combine multiple updates in single hypercall
    - – e.g. during fork()
- → Lazy shadowing of virtual page table
  - identify synchronisation points
  - possible due to TLB semantics
    - – real PT updates only become effective once loaded into TLB
    - – explicit TLB loads and flushes are natural synchronisation points
  - PTs are big □ need to tell hypervisor which part to sync
- → Expose real page tables (write-protected)
  - emulate updates
  - guest must deal with PT reads differing from what was written
- → Complex trade-offs
  - Xen changed approach several times

Virtualization Techniques

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Virtual memory tricks

- → Over-committing memory
  - like classical virtual memory
  - sum of guest physical RAM > physical RAM
- → Page sharing
  - multiple VMs running the same guest have a lot of common pages
    - – text segments, zeroed pages
  - hypervisor detects pages with same content
    - – keeps hash of every page
  - uses copy-on-write to map those to a single copy
    - – up to 60% memory savings [Waldspurger 02]
- → Memory reclamation using ballooning
  - load pseudo device driver into guest, colludes with hypervisor
  - to reclaim memory, hypervisor instructs driver to request memory
  - hypervisor can re-use memory hoarded by ballooning driver
  - guest controls which memory it gives up

Device Virtualization Techniques

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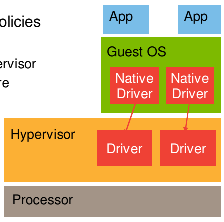
Full virtualization of device

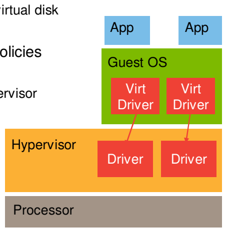
- → Hypervisor contains real device driver
- → Native guest driver accesses device as usual
  - implies virtualizing all device registers etc
  - trap on every device access
- → Virtualizes at *device interface*
- → Hypervisor implements device-sharing policies
- → Drawbacks:
  - must re-implement/port all drivers in hypervisor
    - – unfeasible for contemporary hardware
  - very expensive (frequent traps)
  - will not work on most devices
    - – timing constraints violated



Device Virtualization Techniques

Virtual device drivers

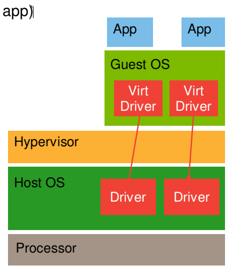
- Guest OS contains virtual drivers
  - forwards guest I/O requests to real driver via hypercalls
  - very simple driver
- Need only support small number of different virtual devices
  - e.g. one type of virtual NIC, one type of virtual disk
- Virtualizes at *driver interface*
- Hypervisor implements device-sharing policies
- Drawback:
  - must re-implement/port all drivers in hypervisor
  - unfeasible for contemporary hardware



Device Virtualization Techniques

Driver inside host (for Type-II VMMs)

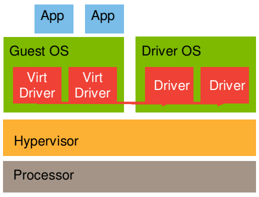
- Guest OS contains virtual drivers
- Hypervisor passes requests through to host
- Fits Type-II model (VMM is just an app)



Device Virtualization Techniques

Device-driver OS

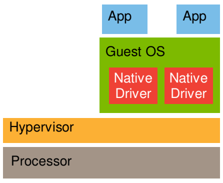
- Special guest OS contains real drivers
  - Xen “Dom$_0$ guest”
- Hypervisor passes requests from virtual driver through to driver OS
- Can re-use driver guest's native drivers unchanged
- Drawbacks:
  - driver invocation requires full context switch
  - driver OS + all drivers becomes part of VMM
    - very large TCB
- Can improve TCB by running each driver in its own guest OS instance
  - full encapsulation of drivers [LeVasseur et al 04]



Device Virtualization Techniques

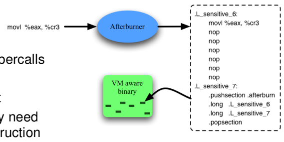
Native real driver in guest

- Guest allowed to “own” device
- Hypervisor not involved in I/O
  - native I/O performance!
- In general insecure and thus infeasible
- Possible for:
  - simple devices not doing DMA
    - but sharing is an issue
  - with hardware support
    - virtualization-friendly devices
      - e.g. IBM channel architecture
    - IO-MMU
      - maps IO space to RAM
      - under control of hypervisor
      - e.g. Intel VT-d



Soft Layering aka Pre-Virtualization

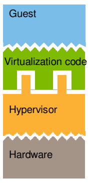
- Combines advantages of pure and para-virtualization [LeVasseur et al, 08]
- Automated para-virtualization, not unlike binary translation
- Core idea: *Post-process assembly code* (compiler output)
  - prepares (“*pre-virtualizes*”) code
  - more flexible than binary re-writing
  - use semantic info from compiler
  - replace instruction sequences by hypercalls
    - hook onto macros etc
  - no need to keep addresses invariant
    - jump (to virtualization code) may need more space than virtualized instruction
    - linker will fix up address changes
  - can expand code for virtualization
    - can do much virtualization in-line
    - avoid branches to virtualization code
- Disadvantage: needs source (at least assembler output of compiler)



```
.L_sensitive_6:
        movl %eax, %cr3
        nop
        nop
        nop
        nop
        nop
        nop
.L_sensitive_7:
        .pushsection .afterburn
        .long   .L_sensitive_6
        .long   .L_sensitive_7
        .popsection
```

Soft Layering aka Pre-Virtualization

- 2nd idea: *do actual fix-up at load time*
  - leave original (unvirtualized) instructions in binary
  - pad with no-ops where virtualization expands code
  - add info to ELF file describing where to patch
  - over-write unvirtualized instructions (and no-ops) during load
  - link in hypervisor-specific user-level VMM code (“wedge”)
- Advantage: actual binary is *hypervisor-neutral*
  - can be patched (at load time) for *any* supported hypervisor
  - can run on bare hardware without any patching
    - no-ops have very little performance effect (0.15%)
  - has most of the properties of pure virtualization
  - ... except for much improved performance
  - pre-virtualization doesn't have to be perfect
    - no harm if some sensitive instructions are missed
      - will be subject to normal (pure) virtualization
      - ... as long as the instruction traps
    - e.g. page table updates (PTs are write-protected)



Soft Layering aka Pre-Virtualization

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- 3rd idea: *feedback loop for optimisation*
  - initially only substitute most important subset of instructions
    - non-trapping sensitive instructions
    - obviously performance-critical
  - profile virtualization traps at run-time
    - hypervisor records location and frequency
  - use this to reduce virtualization overheads
    - identify hot spots from profiling data
    - annotate hot spots in source code
    - add replacement rules to pre-virtualizer
    - re-run pre-virtualization and link
- Advantage: guided optimization
  - similar to "optimized para-virtualization" [Magenheimer & Christian 04]
  - but less ad-hoc

Hardware Virtualization Support

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- Intel VT-x/VT-i: virtualization support for x86/Itanium
  - Introduces new processor mode: *VMX root mode* for hypervisor
  - In root mode, processor behaves like pre-VT x86
  - In non-root mode, all sensitive instructions trap to root mode ("*VM exit*")
    - orthogonal to privilege rings, i.e. each has 4 ring levels
    - very expensive traps (700+ cycles on Core processors)
    - not used by VMware for that reason [Adams & Agesen 06]
  - Supported by Xen for pure virtualization (as alternative to para-virtualization)
  - Used exclusively by KVM
    - KVM uses whole Linux system as hypervisor!
    - Implemented by loadable driver that turns on root mode
  - VT-i (Itanium) also reduces virtual address-space size for non-root
- Similar AMD (Pacifica), PowerPC
- Other processor vendors working on similar feature
  - ARM TrustZone is partial solution
- Aim is virtualization of unmodified legacy OSes

Virtualization Performance Enhancements (VT-x)

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- Hardware shadows some privileged state
  - "guest state area" containing segment registers, PT pointer, interrupt mask etc
  - swapped by hardware on VM entry/exit
  - guest access to those does *not* cause VM exit
  - reduce hypervisor traps
- Hypervisor-configurable register makes some VM exits optional
  - allows delegating handling of some events to guest
    - e.g. interrupt, floating-point enable, I/O bitmaps
    - selected exceptions, eg syscall exception
  - reduce hypervisor traps
- Exception injection allows forcing certain exceptions on VM entry
- Extended page tables (EPT) provide two-stage address translation
  - guest virtual → guest physical by guest's PT
  - guest physical → physical by hypervisor's PT
  - TLB refill walks both PTs in sequence

I/O Virtualization Enhancements (VT-d)

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- Introduce separate *I/O address space*
- Mapped to physical address space by I/O MMU
  - under hypervisor control
- Makes DMA safely virtualizable
  - device can only read/write RAM that is mapped into its I/O space
- Useful not only for virtualization
  - safely encapsulated user-level drivers for DMA-capable devices
  - ideal for microkernels
- AMD IOMMU is essentially same
- Similar features existed on high-end Alpha and HP boxes
- ... and, of course, IBM channels since the '70s...

Halfway There: ARM TrustZone

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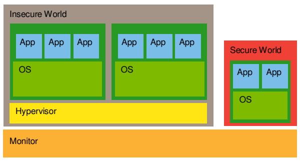
- ARM TrustZone extensions introduce:
  - new processor mode: *monitor*
    - similar to VT-x root mode
    - banked registers (PC, LR)
    - can run unmodified guest OS binary in non-monitor kernel mode
  - new privileged instruction: SMI
    - enters monitor mode
  - new processor status: *secure*
  - partitioning of resources
    - memory and devices marked secure or insecure
    - in secure mode, processor has access to all resources
    - in insecure mode, processor has access to insecure resources only
  - monitor switches world (secure ↔ insecure)
  - really only supports one virtual machine (guest in insecure mode)
    - need another hypervisor and para-virtualization for multiple guests



Uses of Virtual Machines

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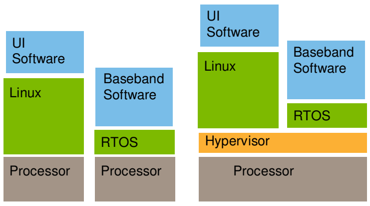
- Multiple (identical) OSes on same platform
  - the original *raison d'être*
  - these days driven by server consolidation
  - interesting variants of this:
    - different OSes (Linux + Windows)
    - old version of same OS (Win2k for stuff broken under Vista)
    - OS debugging (most likely uses Type-II VMM)
- Checkpoint-restart
  - minimise lost work in case of crash
  - useful for debugging, incl. going backwards in time
    - re-run from last checkpoint to crash, collect traces, invert trace from crash
  - life system migration
    - load balancing, environment take-home
- Ship application with complete OS
  - reduce dependency on environment
  - "Java done right"
- How about embedded systems?

Why Virtualization for Embedded Systems?

Use case 1: Mobile phone processor consolidation

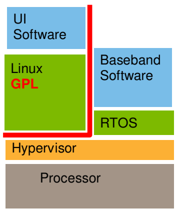
- High-end phones run high-level OS (Linux) on app processor
  - supports complex UI software
- Base-band processing supported by real-time OS (RTOS)
- Medium-range phone needs less grunt
  - can share processor
  - two VMs on one physical processor
  - hardware cost reduction



Why Virtualization for Embedded Systems?

Use case 1a: License separation

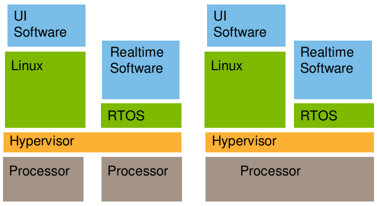
- Linux desired for various reasons
  - familiar, high-level API
  - large developer community
  - free
- Other parts of system contain proprietary code
- Manufacturer doesn't want to open-source
- User VM to contain Linux + GPL



Why Virtualization for Embedded Systems?

Use case 1b: Software-architecture abstraction

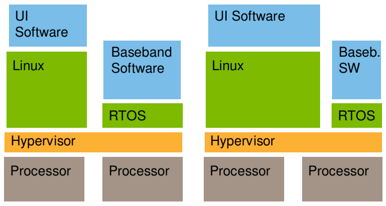
- Support for *product series*
  - range of related products of varying capabilities
- Same low-level software for high- and medium-end devices
- Benefits:
  - time-to-market
  - engineering cost



Why Virtualization for Embedded Systems?

Use case 1c: Dynamic processor allocation

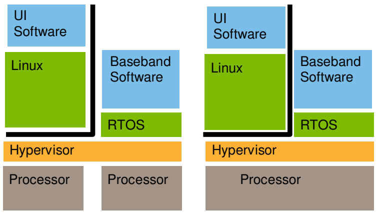
- Allocate share of base-band processor to application OS
  - Provide extra CPU power during high-load periods (media play)
  - Better processor utilisation → higher performance with lower-end hardware
  - HW cost reduction



Why Virtualization for Embedded Systems?

Use case 2: Certification re-use

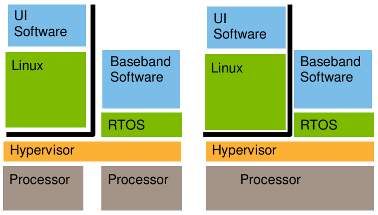
- Phones need to be certified to comply with communication standards
- Any change that (potentially) affects comms needs re-certification
- UI part of system changes frequently
- Encapsulation of UI
  - provided by VM
  - avoids need for costly re-certification

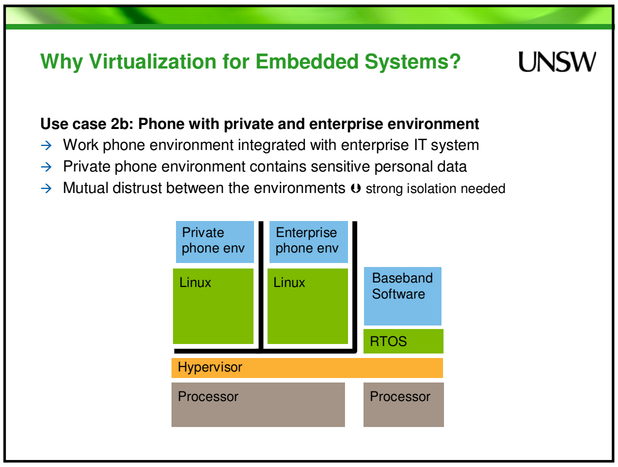


Why Virtualization for Embedded Systems?

Use case 2a: Open phone with user-configured OS

- Give users control over the application environment
  - perfect match for Linux
- Requires strong encapsulation of application environment
  - without undermining performance!





Why Virtualization for Embedded Systems?

Use case 2b: Phone with private and enterprise environment
- Work phone environment integrated with enterprise IT system
- Private phone environment contains sensitive personal data
- Mutual distrust between the environments ⇒ strong isolation needed

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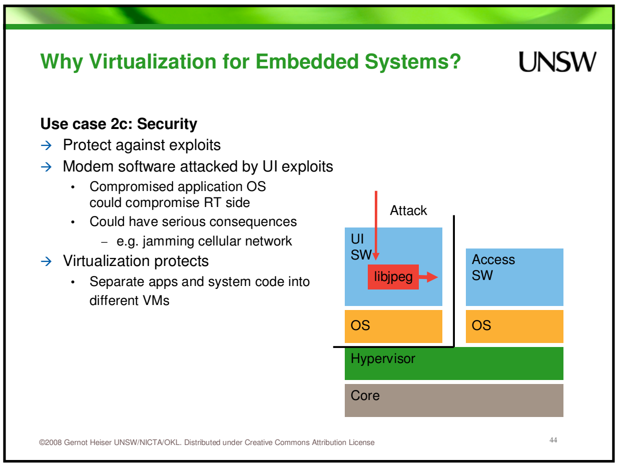
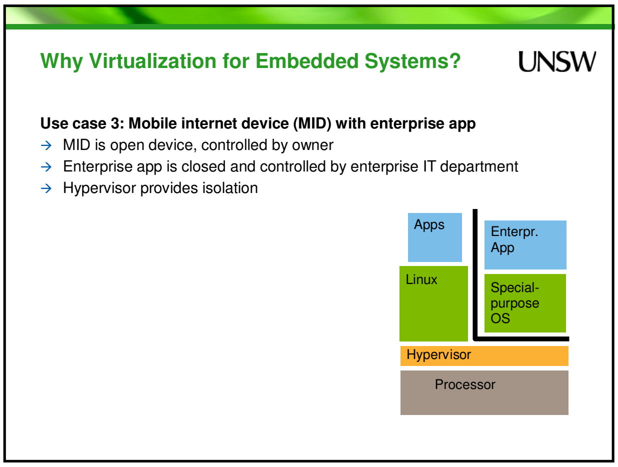


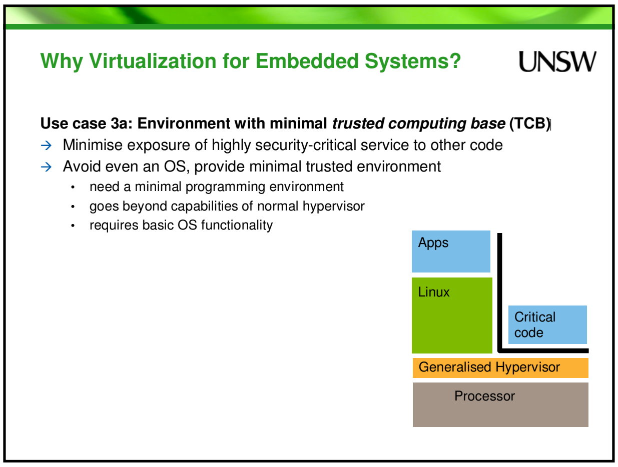
Why Virtualization for Embedded Systems?

Use case 2c: Security
- Protect against exploits
- Modem software attacked by UI exploits
  - Compromised application OS could compromise RT side
  - Could have serious consequences
    - e.g. jamming cellular network
- Virtualization protects
  - Separate apps and system code into different VMs



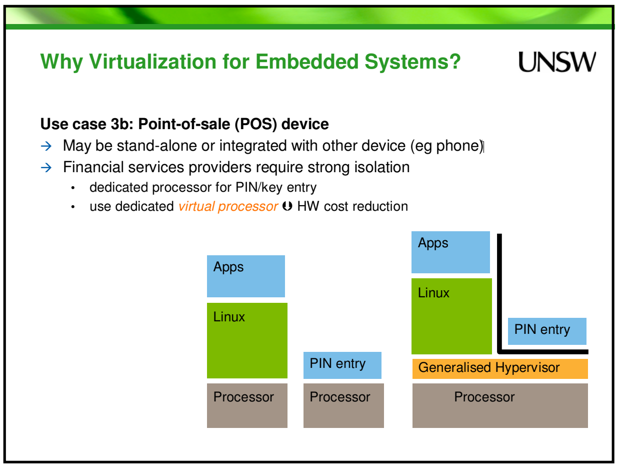
Why Virtualization for Embedded Systems?

Use case 3: Mobile internet device (MID) with enterprise app
- MID is open device, controlled by owner
- Enterprise app is closed and controlled by enterprise IT department
- Hypervisor provides isolation



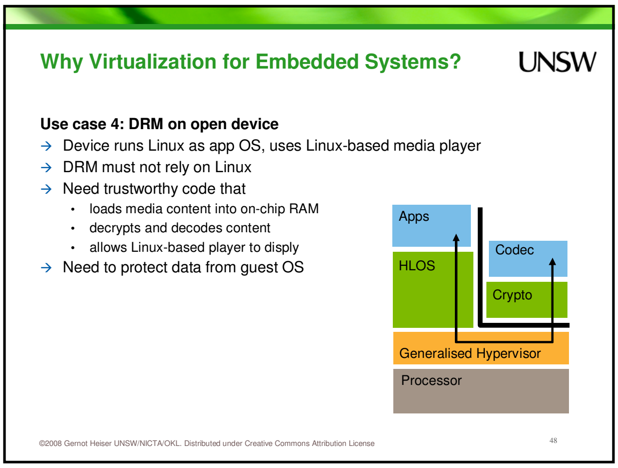
Why Virtualization for Embedded Systems?

Use case 3a: Environment with minimal *trusted computing base* (TCB)
- Minimise exposure of highly security-critical service to other code
- Avoid even an OS, provide minimal trusted environment
  - need a minimal programming environment
  - goes beyond capabilities of normal hypervisor
  - requires basic OS functionality



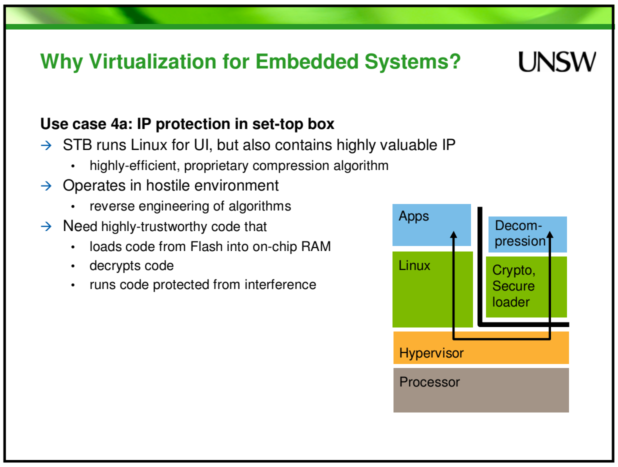
Why Virtualization for Embedded Systems?

Use case 3b: Point-of-sale (POS) device
- May be stand-alone or integrated with other device (eg phone)
- Financial services providers require strong isolation
  - dedicated processor for PIN/key entry
  - use dedicated *virtual processor* ⇒ HW cost reduction



Why Virtualization for Embedded Systems?

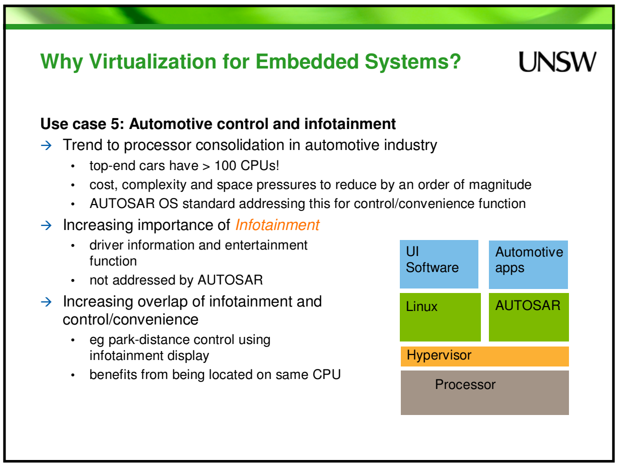
Use case 4: DRM on open device
- Device runs Linux as app OS, uses Linux-based media player
- DRM must not rely on Linux
- Need trustworthy code that
  - loads media content into on-chip RAM
  - decrypts and decodes content
  - allows Linux-based player to disply
- Need to protect data from guest OS



Why Virtualization for Embedded Systems?

Use case 4a: IP protection in set-top box

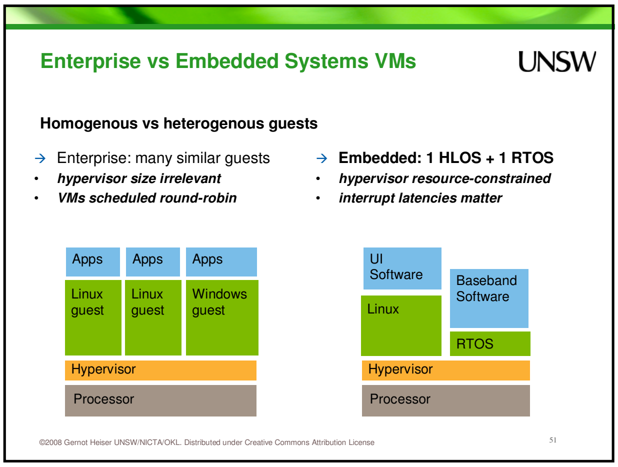
- → STB runs Linux for UI, but also contains highly valuable IP
  - highly-efficient, proprietary compression algorithm
- → Operates in hostile environment
  - reverse engineering of algorithms
- → Need highly-trustworthy code that
  - loads code from Flash into on-chip RAM
  - decrypts code
  - runs code protected from interference



Why Virtualization for Embedded Systems?

Use case 5: Automotive control and infotainment

- → Trend to processor consolidation in automotive industry
  - top-end cars have > 100 CPUs!
  - cost, complexity and space pressures to reduce by an order of magnitude
  - AUTOSAR OS standard addressing this for control/convenience function
- → Increasing importance of *Infotainment*
  - driver information and entertainment function
  - not addressed by AUTOSAR
- → Increasing overlap of infotainment and control/convenience
  - eg park-distance control using infotainment display
  - benefits from being located on same CPU

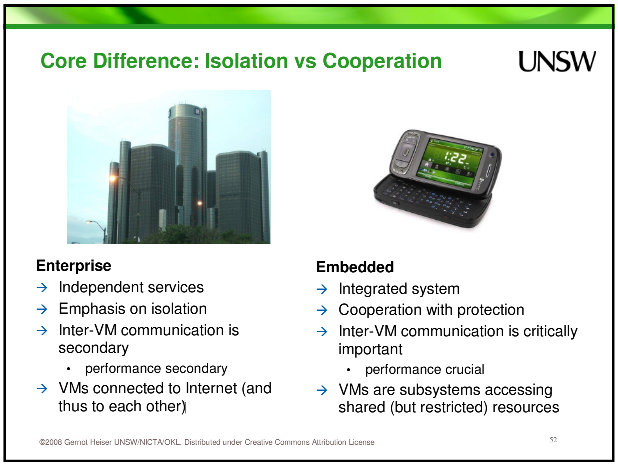


Enterprise vs Embedded Systems VMs

Homogenous vs heterogenous guests

- → Enterprise: many similar guests
- ***hypervisor size irrelevant***
- ***VMs scheduled round-robin***

- → **Embedded: 1 HLOS + 1 RTOS**
- ***hypervisor resource-constrained***
- ***interrupt latencies matter***



Core Difference: Isolation vs Cooperation

Enterprise

- → Independent services
- → Emphasis on isolation
- → Inter-VM communication is secondary
  - performance secondary
- → VMs connected to Internet (and thus to each other)

Embedded

- → Integrated system
- → Cooperation with protection
- → Inter-VM communication is critically important
  - performance crucial
- → VMs are subsystems accessing shared (but restricted) resources

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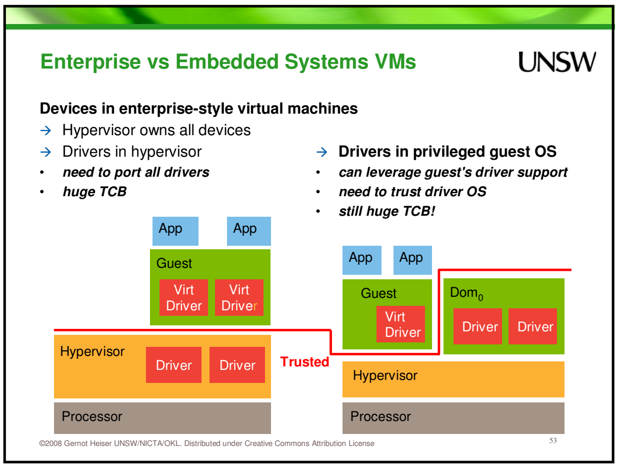
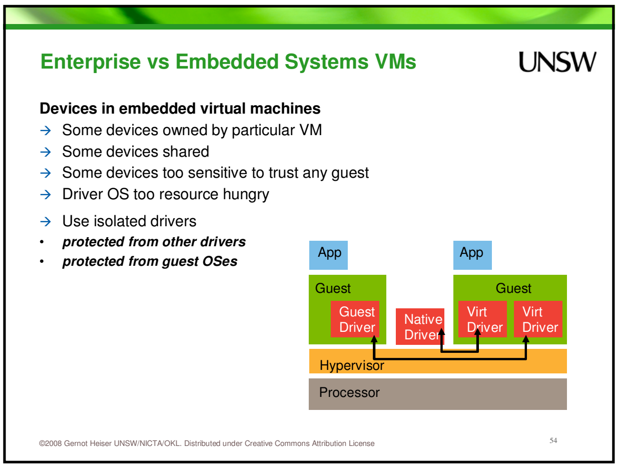


Enterprise vs Embedded Systems VMs

Devices in enterprise-style virtual machines

- → Hypervisor owns all devices
- → Drivers in hypervisor
- ***need to port all drivers***
- ***huge TCB***

- → **Drivers in privileged guest OS**
- ***can leverage guest's driver support***
- ***need to trust driver OS***
- ***still huge TCB!***



Enterprise vs Embedded Systems VMs

Devices in embedded virtual machines

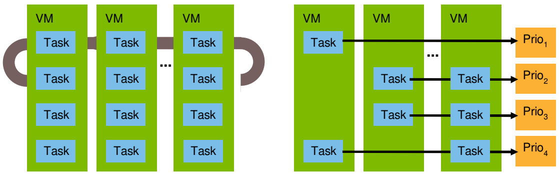
- → Some devices owned by particular VM
- → Some devices shared
- → Some devices too sensitive to trust any guest
- → Driver OS too resource hungry
- → Use isolated drivers
- ***protected from other drivers***
- ***protected from guest OSes***

Isolation vs Cooperation: Scheduling

UNSW

Enterprise
- → Round-robin scheduling of VMs
- → Guest OS schedules its apps

Embedded
- → Global view of scheduling
- → Schedule threads, not VMs

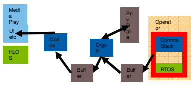


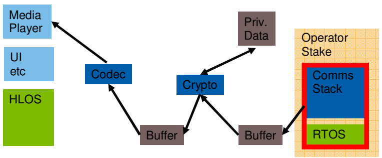
- → Similar for *energy management*:
  - energy is a global resource
  - optimal per-VM energy policies are not globally optimal

Inter-VM Communication Control

UNSW

Modern embedded systems are multi-user devices!
- → Eg **a phone has three** *classes* **of "users":**
  - ***the network operator(s)***
    - ***assets: cellular network***





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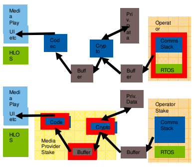

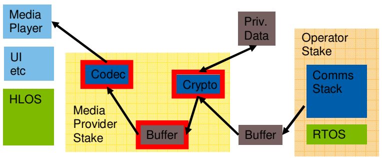

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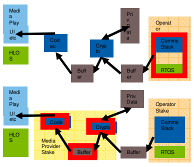

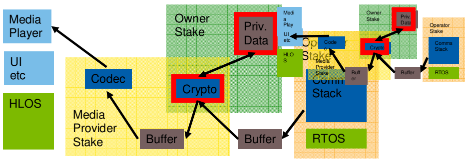

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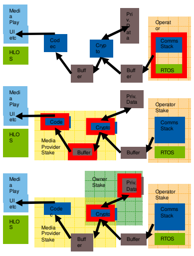
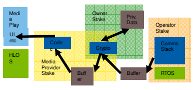


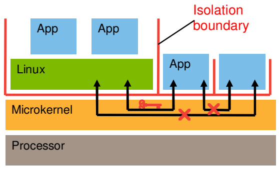
- → They are mutually distrusting
  - need to protect integrity and confidentiality against *internal* exploits
  - need control over *information flow*
    - strict control over who has access to what
    - strict control over communication channels

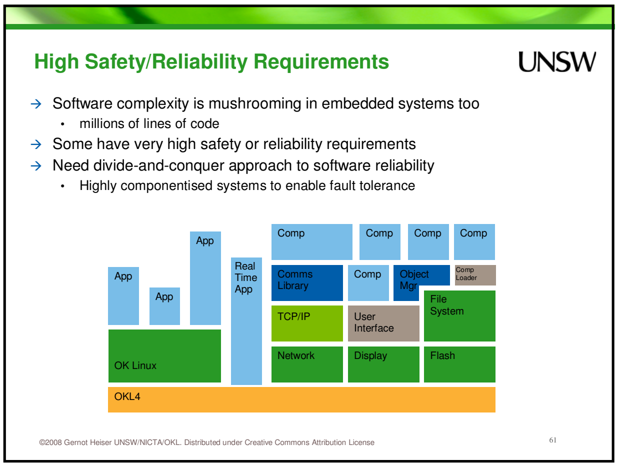
Inter-VM Communication Control

UNSW

- → Different "users" are mutually distrusting
- → Need strong protection / information-flow control between them
- → Isolation boundaries ≠ VM boundaries
  - some are much smaller than VMs
    - – individual buffers, programs
  - some contain VMs
  - some overlap VMs
- → Need to define information flow between isolation domains



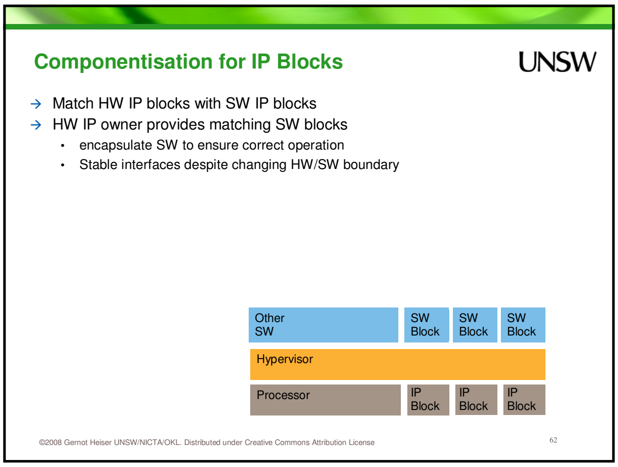




High Safety/Reliability Requirements

UNSW

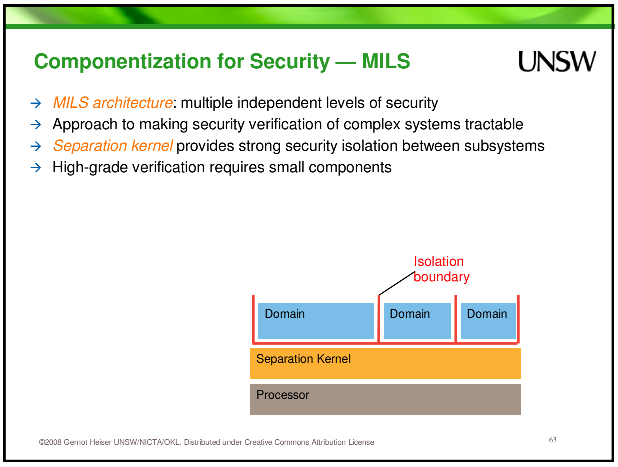
- Software complexity is mushrooming in embedded systems too
  - millions of lines of code
- Some have very high safety or reliability requirements
- Need divide-and-conquer approach to software reliability
  - Highly componentised systems to enable fault tolerance



Componentisation for IP Blocks

UNSW

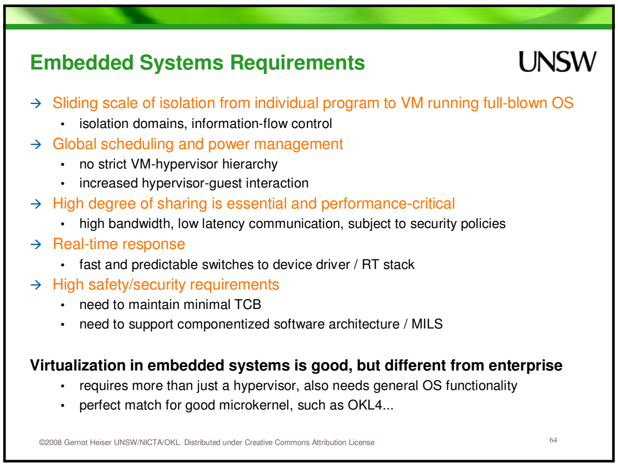
- Match HW IP blocks with SW IP blocks
- HW IP owner provides matching SW blocks
  - encapsulate SW to ensure correct operation
  - Stable interfaces despite changing HW/SW boundary



Componentization for Security — MILS

UNSW

- *MILS architecture*: multiple independent levels of security
- Approach to making security verification of complex systems tractable
- *Separation kernel* provides strong security isolation between subsystems
- High-grade verification requires small components



Embedded Systems Requirements

UNSW

- Sliding scale of isolation from individual program to VM running full-blown OS
  - isolation domains, information-flow control
- Global scheduling and power management
  - no strict VM-hypervisor hierarchy
  - increased hypervisor-guest interaction
- High degree of sharing is essential and performance-critical
  - high bandwidth, low latency communication, subject to security policies
- Real-time response
  - fast and predictable switches to device driver / RT stack
- High safety/security requirements
  - need to maintain minimal TCB
  - need to support componentized software architecture / MILS

Virtualization in embedded systems is good, but different from enterprise
- requires more than just a hypervisor, also needs general OS functionality
- perfect match for good microkernel, such as OKL4...