Virtualization in Embedded Systems

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Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

NICTA Members
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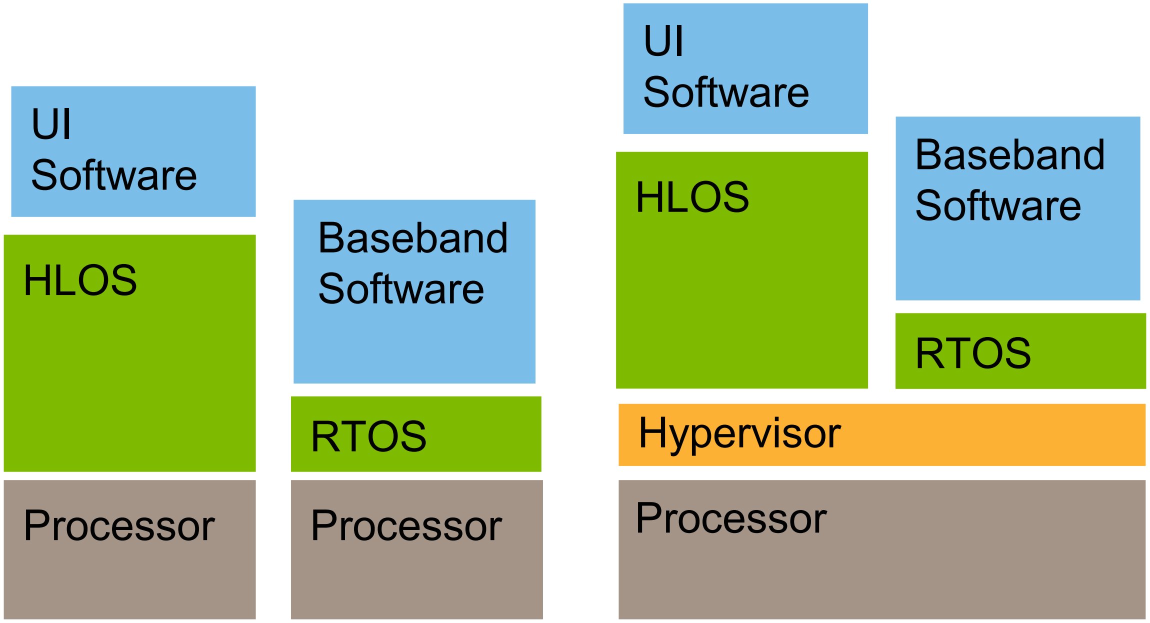
Outline

- Embedded virtualization use cases
- Enterprise vs embedded: main differences
- Trustworthy hypervisor for embedded systems
- Wishlist for Intel

Why Virtualization in Embedded Systems?

Use case 1: Mobile phone processor consolidation

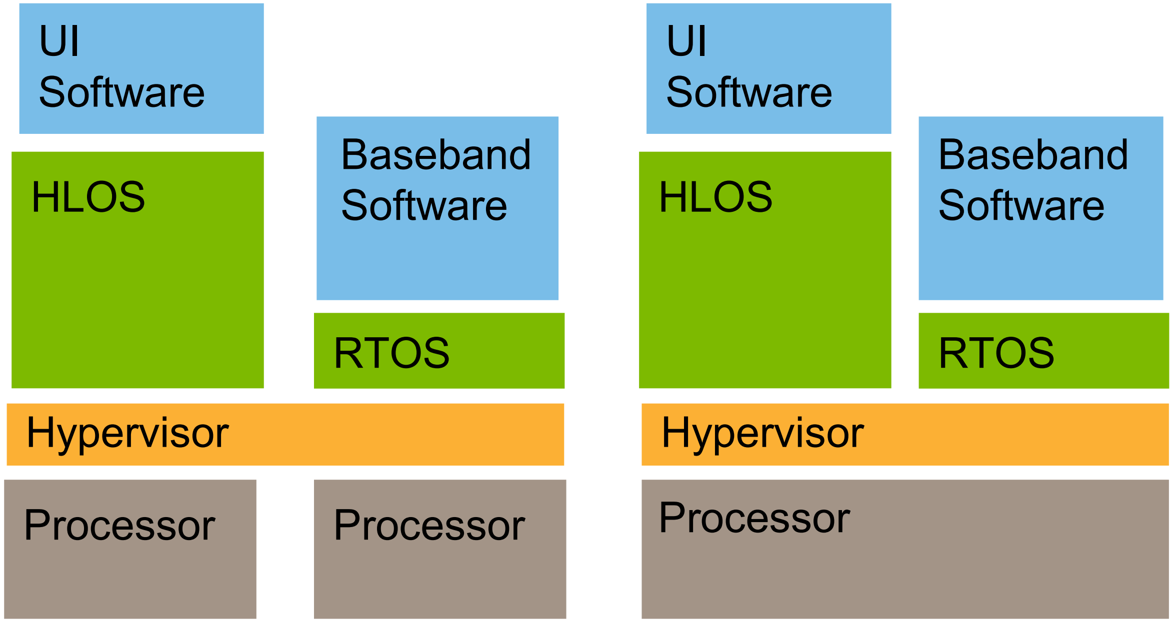
- High-end phones run high-level OS (Linux/WinCE/Symbian) on app processor
  - supports complex UI software
- Baseband processing supported by real-time OS (RTOS)
- Medium-range phone needs less grunt
  - can share processor
  - two VMs on one physical processor
  - hardware cost reduction



Why Virtualization in Embedded Systems?

Use case 1a: 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

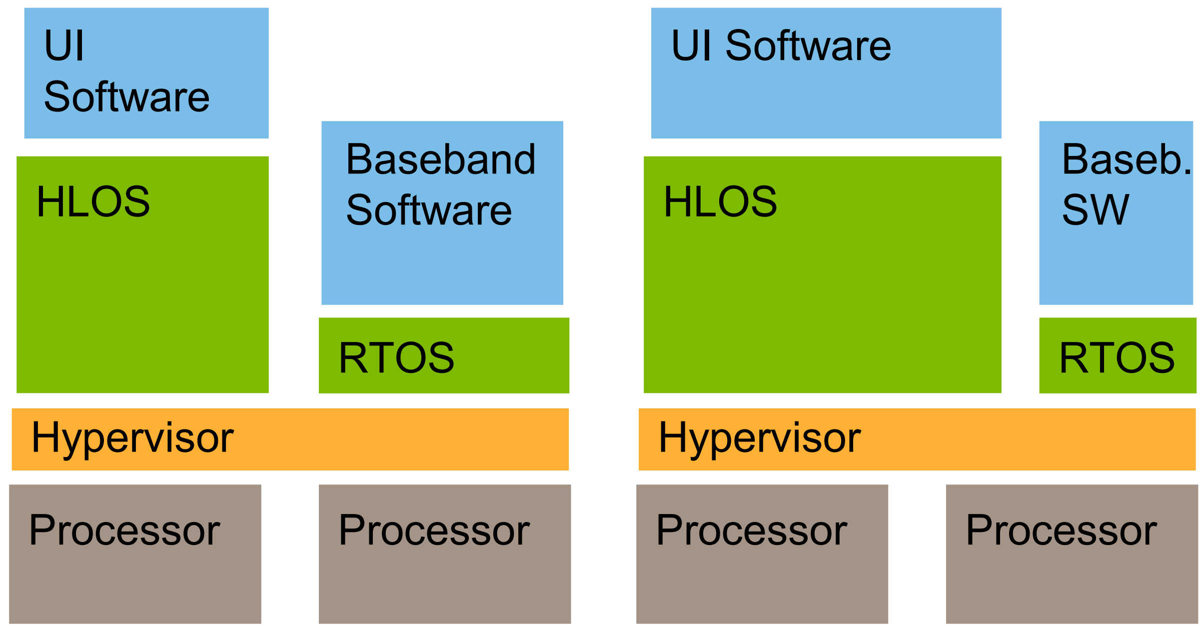


Why Virtualization in Embedded Systems?

Use case 1b: Dynamic processor allocation

→ Allocate share of baseband processor to application OS

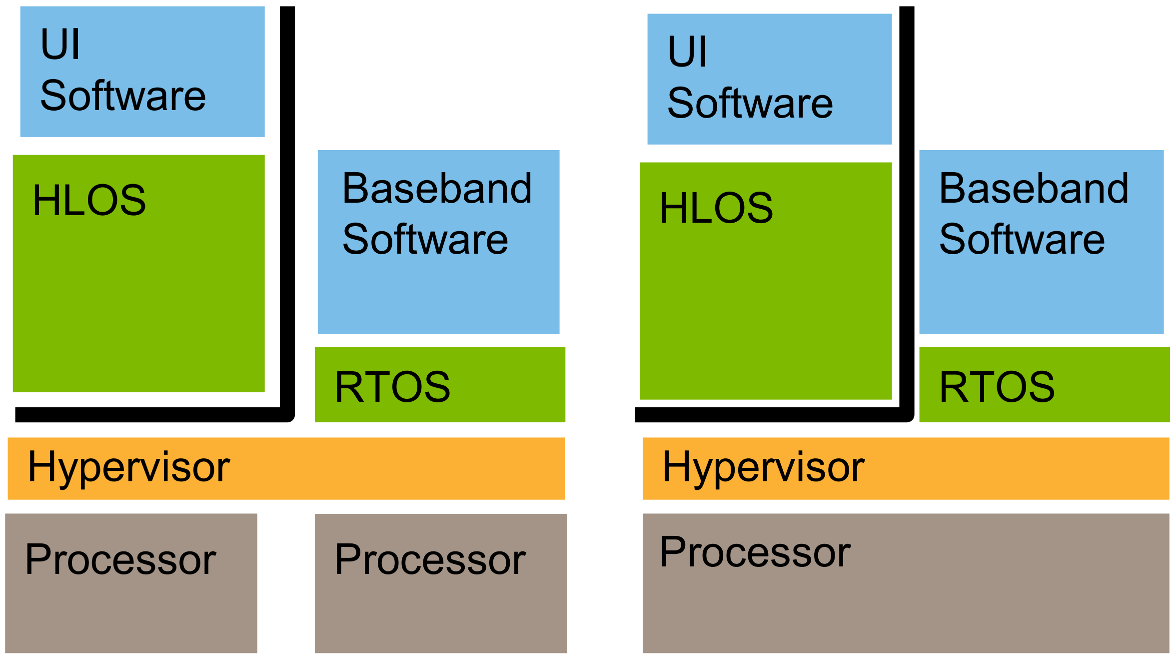
- Provide extra CPU power during high-load periods (media play)
- Better processor utilisation ⇒ higher performance with lower-end hardware
- HW cost reduction



Why Virtualization in Embedded Systems?

Use case 2: Certification re-use

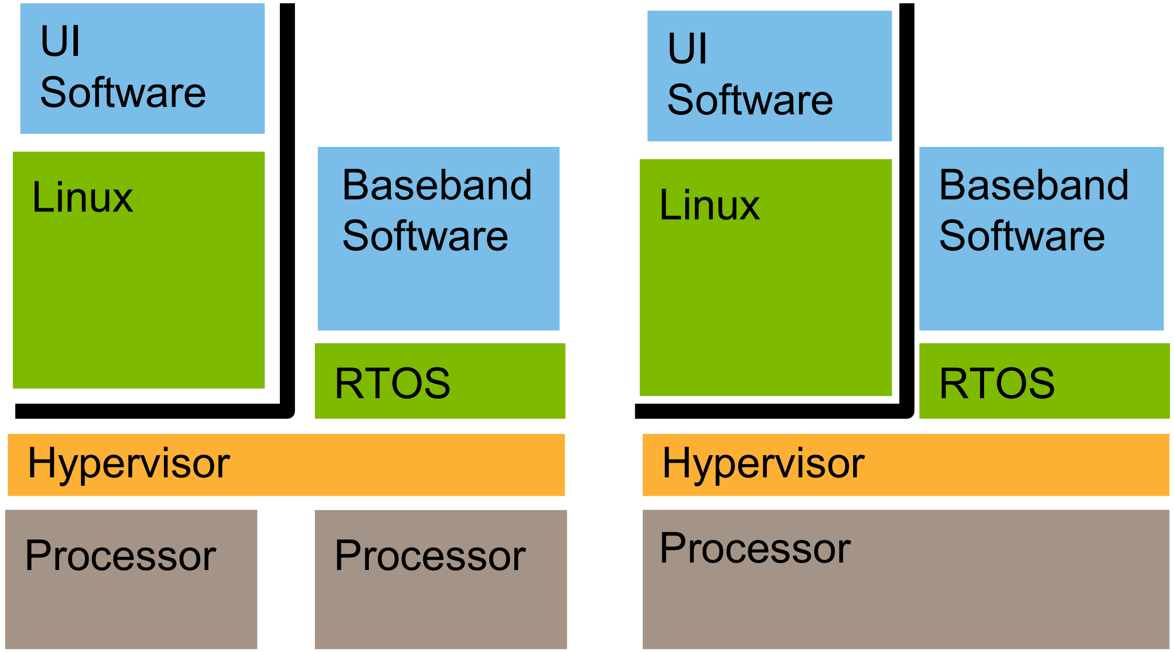
- Phones need to be certified to comply with communication standards
- Any change that (potentially) affects comms needs re-certification
- UI part of system changes frequently
- Encapsulation of UI
  - provided by VM
  - avoids need for costly re-certification



Why Virtualization in Embedded Systems?

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

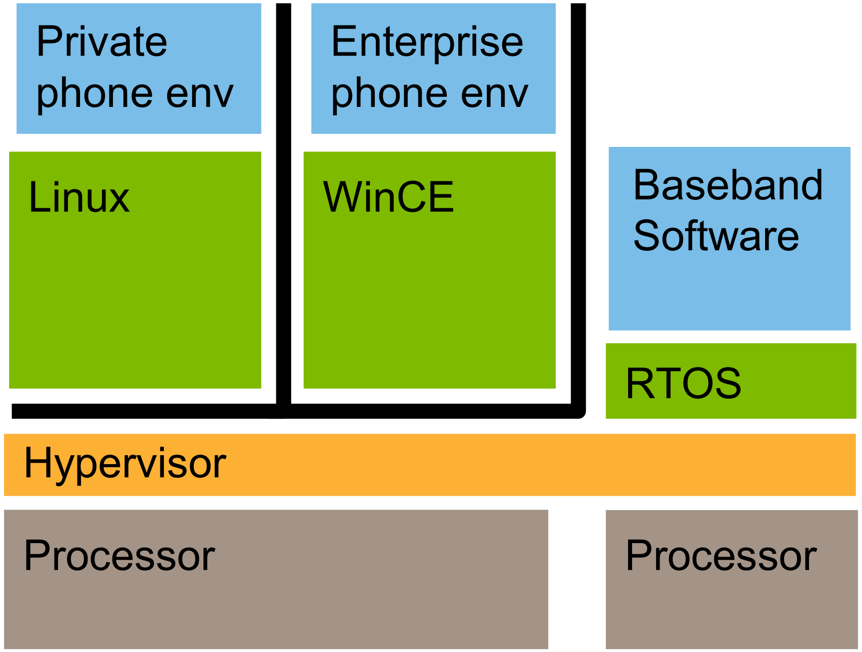
- Give users control over the application environment
  - perfect match for Linux
- Requires strong encapsulation of application environment
  - without undermining performance!



Why Virtualization in Embedded Systems?

Use case 2b: Phone with private and enterprise environment

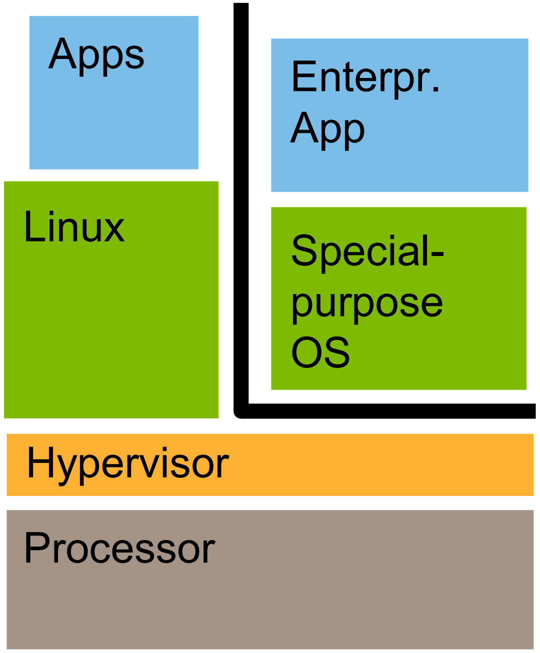
- → Work phone environment integrated with enterprise IT system
- → Private phone environment contains sensitive personal data
- → Mutual distrust between the environments ⇒ strong isolation needed



Why Virtualization in 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 dept
- Hypervisor provides isolation



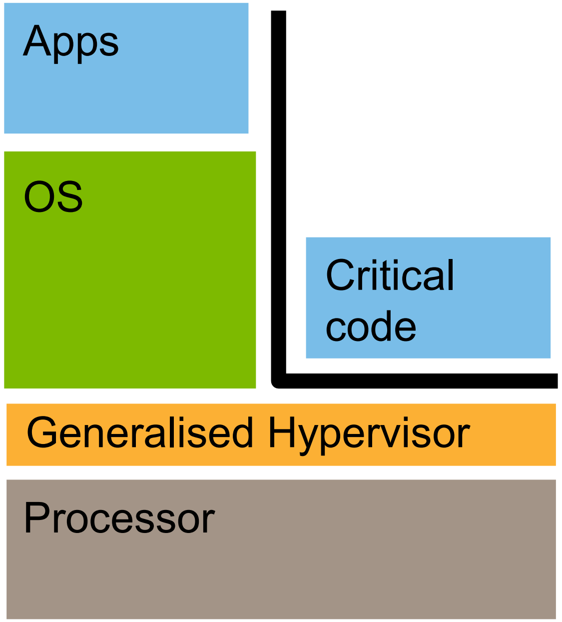
Why Virtualization in Embedded Systems?

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 in Embedded Systems?

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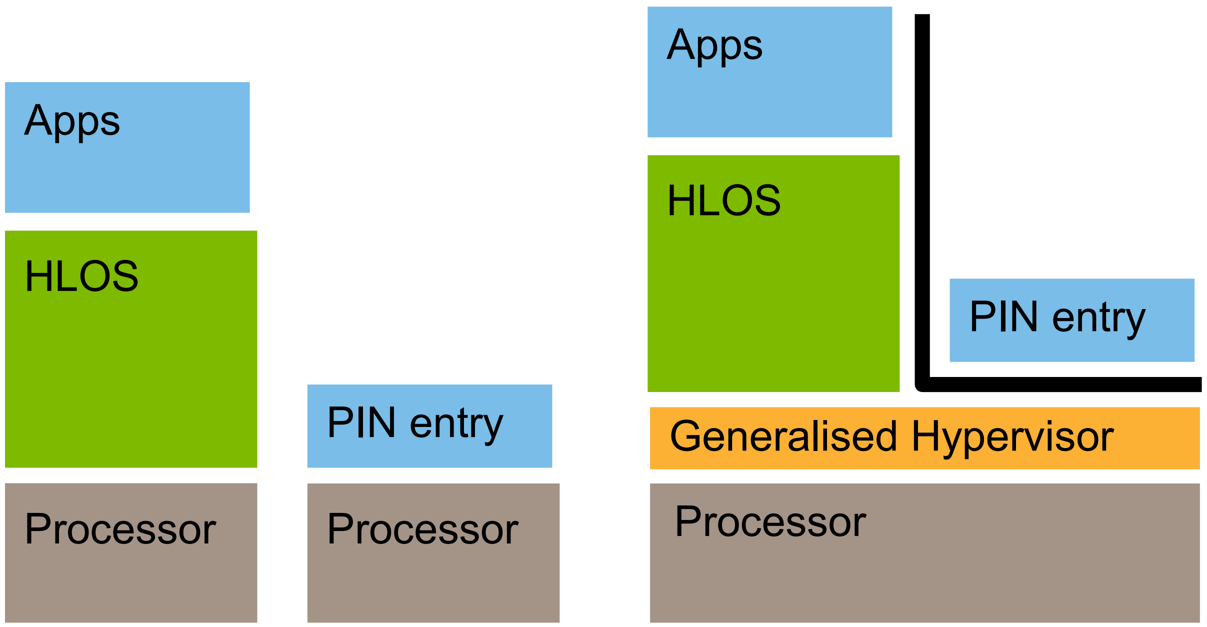
Use case 3b: Point-of-sale (POS) device

→ May be stand-alone or integrated with other device (eg phone)

→ Financial services providers require strong isolation

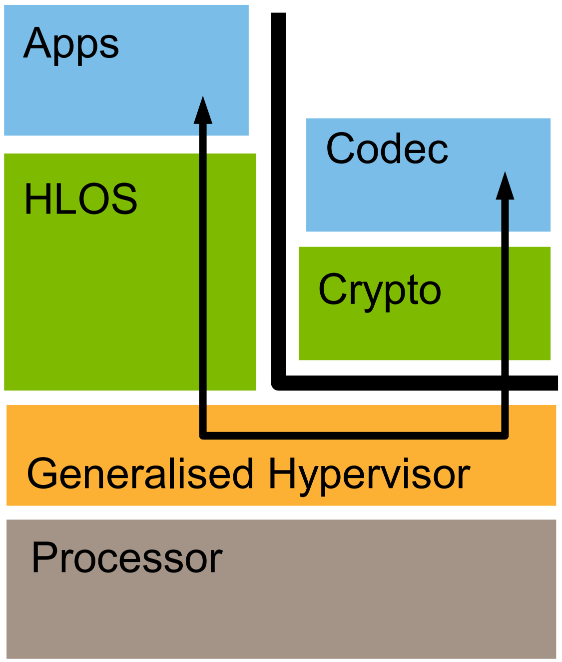
- dedicated processor for PIN/key entry
- use dedicated *virtual processor* ⇒ HW cost reduction



Why Virtualization in Embedded Systems?

Use case 4: DRM on open device

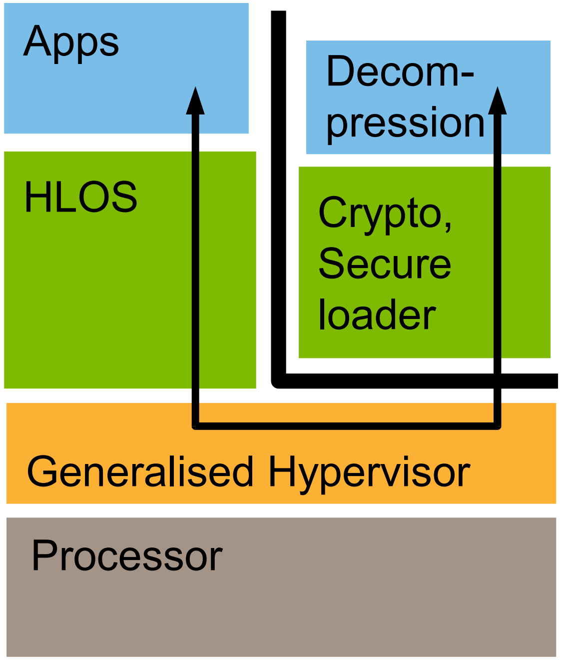
- → Device runs Linux as app OS, uses Linux-based media player
- → DRM must not rely on Linux
- → Need trustworthy code that
  - loads media content into on-chip RAM
  - decrypts and decodes content
  - allows Linux-based player to disply
- → Need to protect data from guest OS



Why Virtualization in 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 in Embedded Systems?

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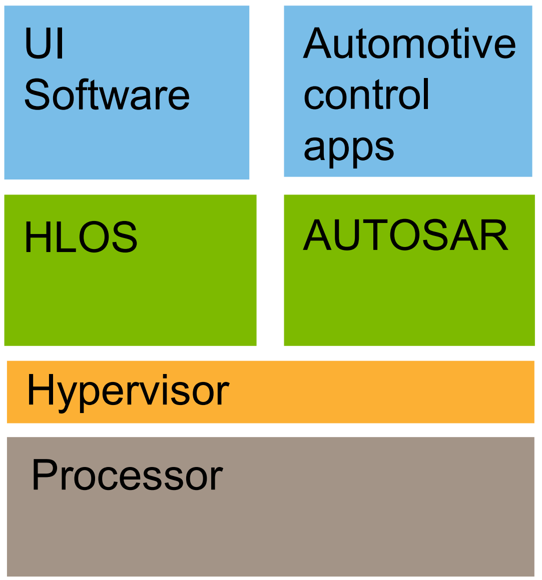
Use case 5: Automotive control and infotainment

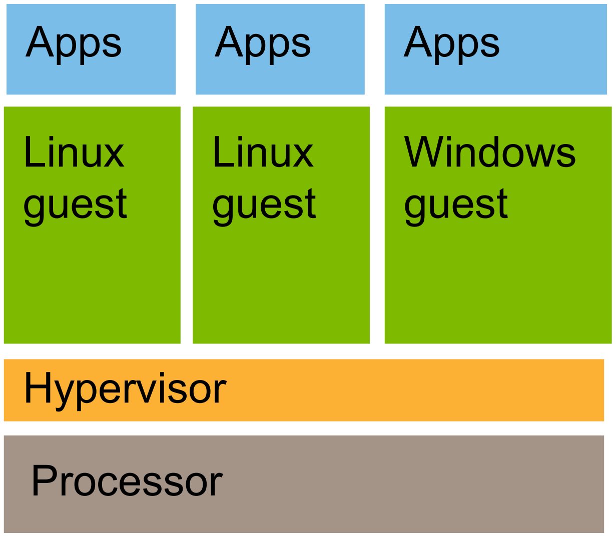
- Trend to processor consolidation in automotive industry
  - top-end cars have > 100 CPUs!
  - cost, complexity and space pressures to reduce by an order of magnitude
  - AUTOSAR OS standard addressing this for control/convenience function
- Increasing importance of *Infotainment*
  - driver information 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

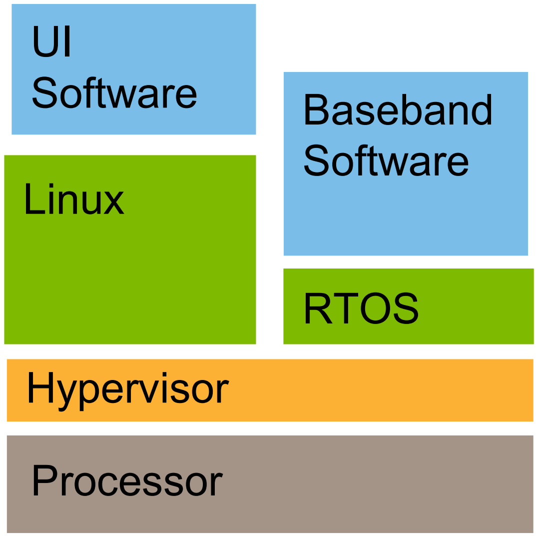


Enterprise vs Embedded Virtualization

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)

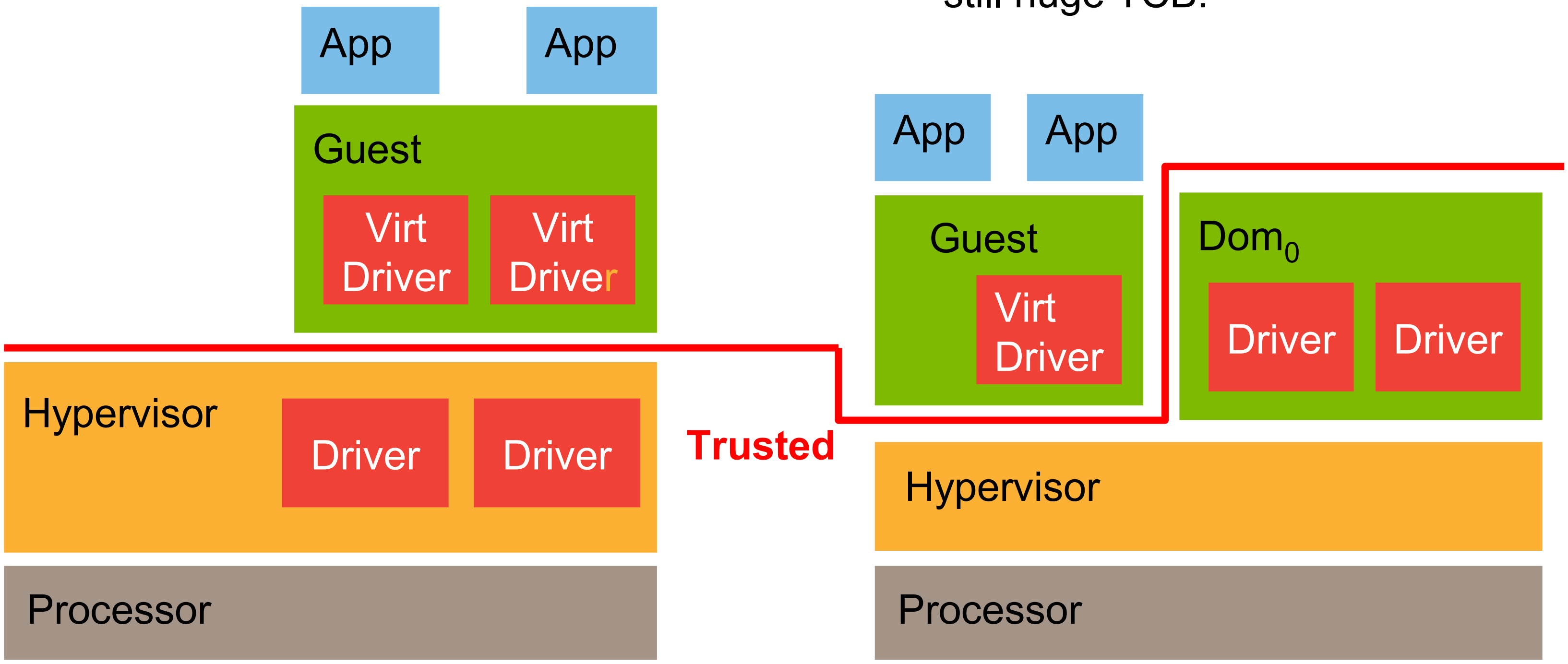
Embedded

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

Enterprise vs Embedded Virtualization

Devices in enterprise-style virtual machines

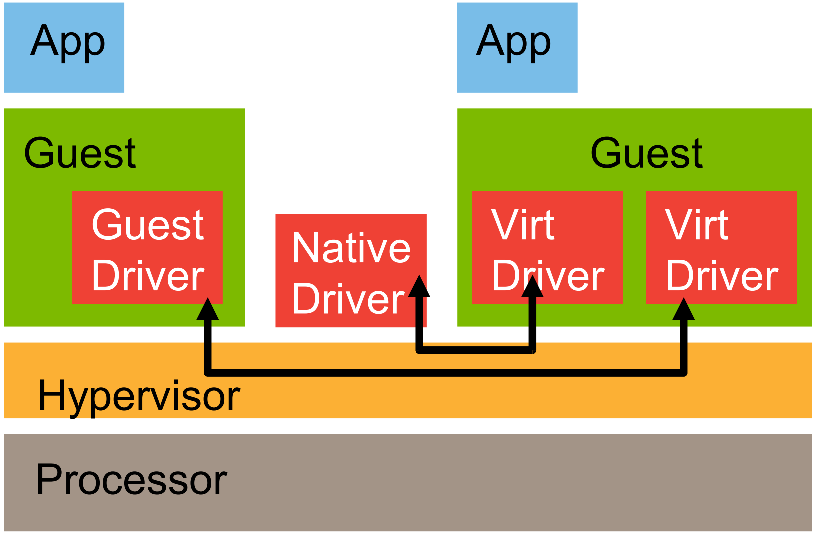
- Hypervisor owns all devices
- Drivers in hypervisor
  - need to port all drivers
  - huge TCB
- Drivers in privileged guest OS
  - can leverage guest's driver support
  - need to trust driver OS
  - still huge TCB!



Enterprise vs Embedded Virtualization

Devices in embedded virtual machines

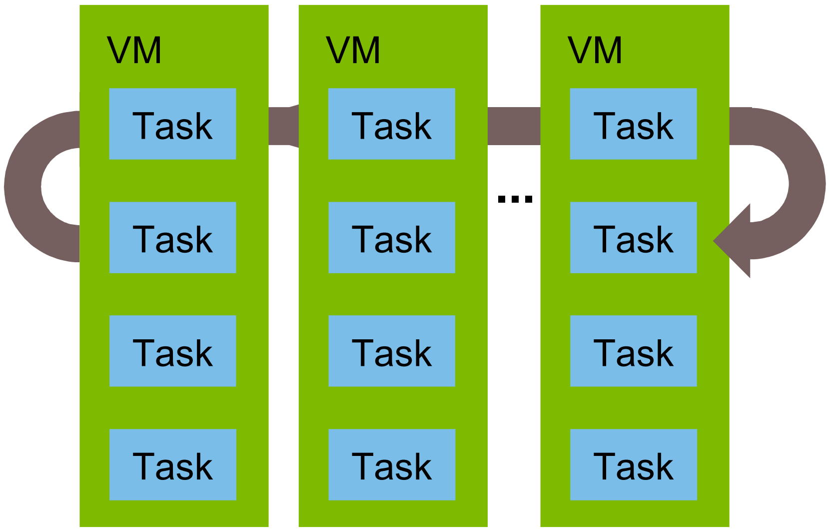
- Some devices owned by particular VM
- Some devices shared
- Some devices too sensitive to trust any guest
- Driver OS too resource hungry
- Use isolated drivers
  - protected from other drivers
  - protected from guest OSes



Isolation vs Cooperation: Scheduling

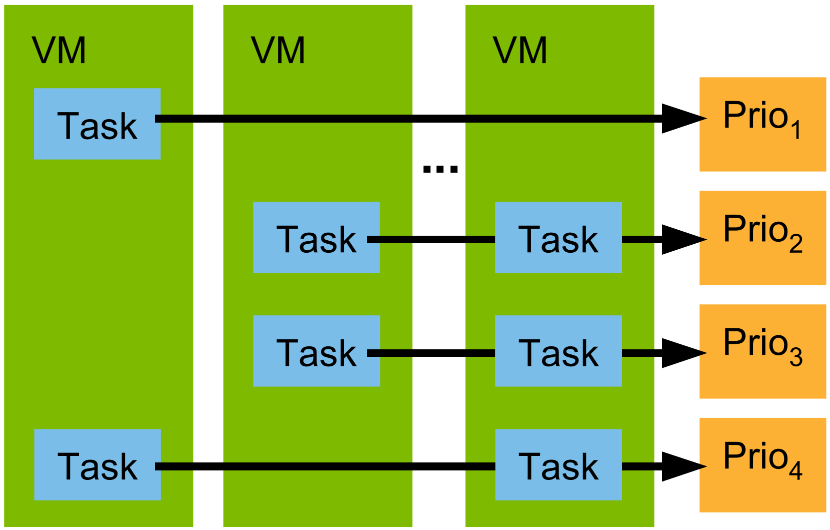
Enterprise

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



Embedded

- Global view of scheduling
- Schedule threads, not VMs

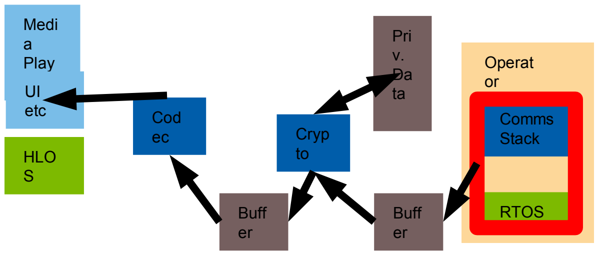


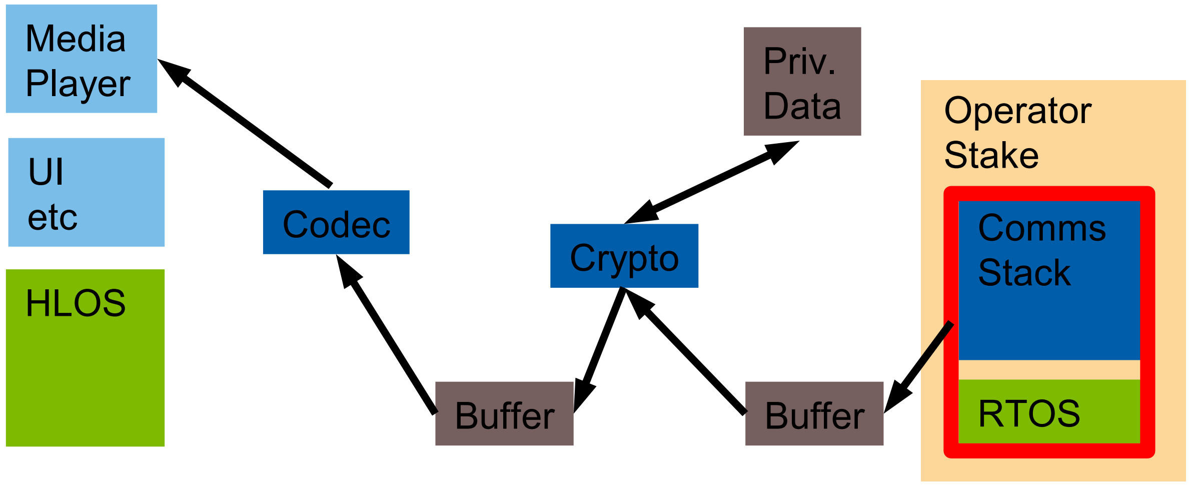
- Similar for *energy management*:
  - energy is a global resource
  - optimal per-VM energy policies are not globally optimal

Inter-VM Communication Control

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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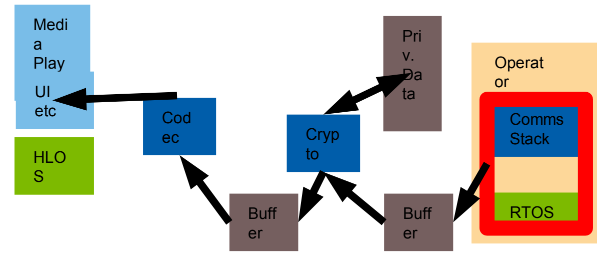
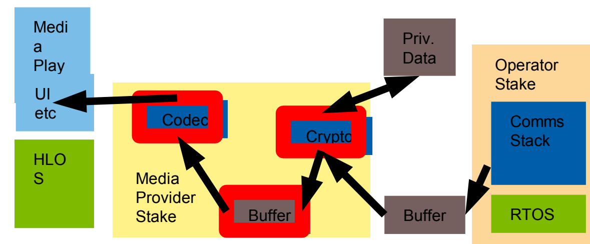
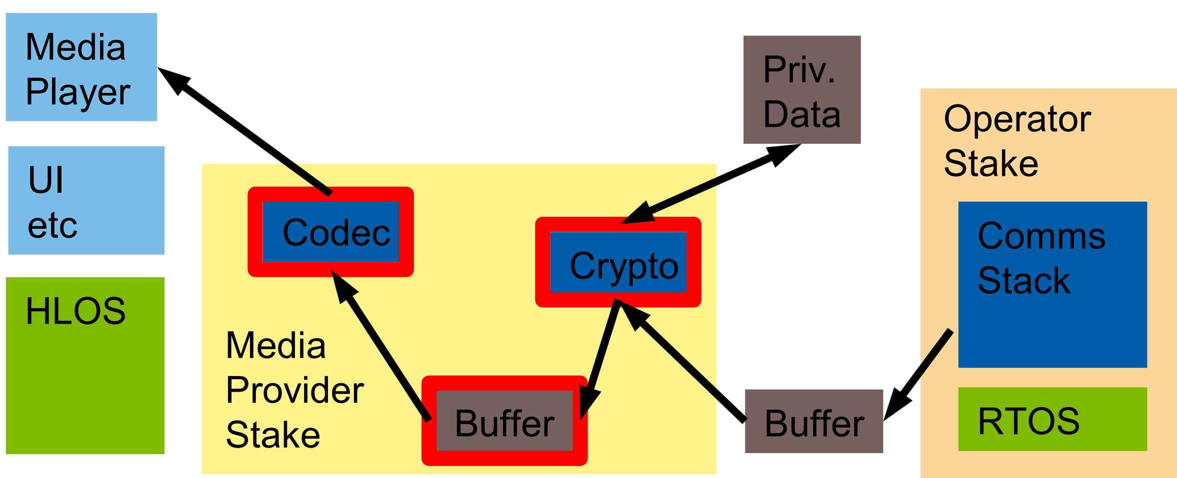
    - media content







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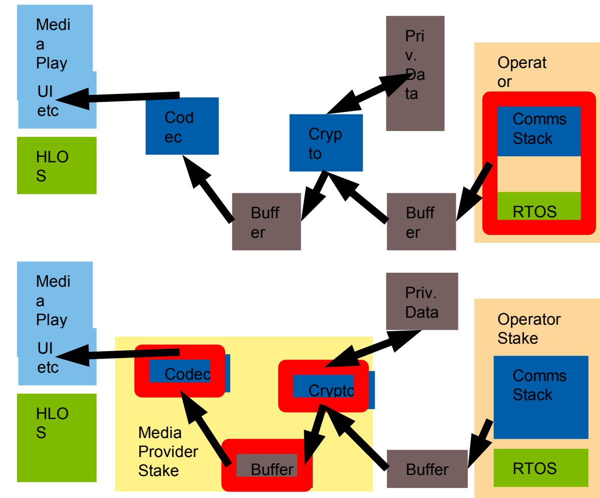
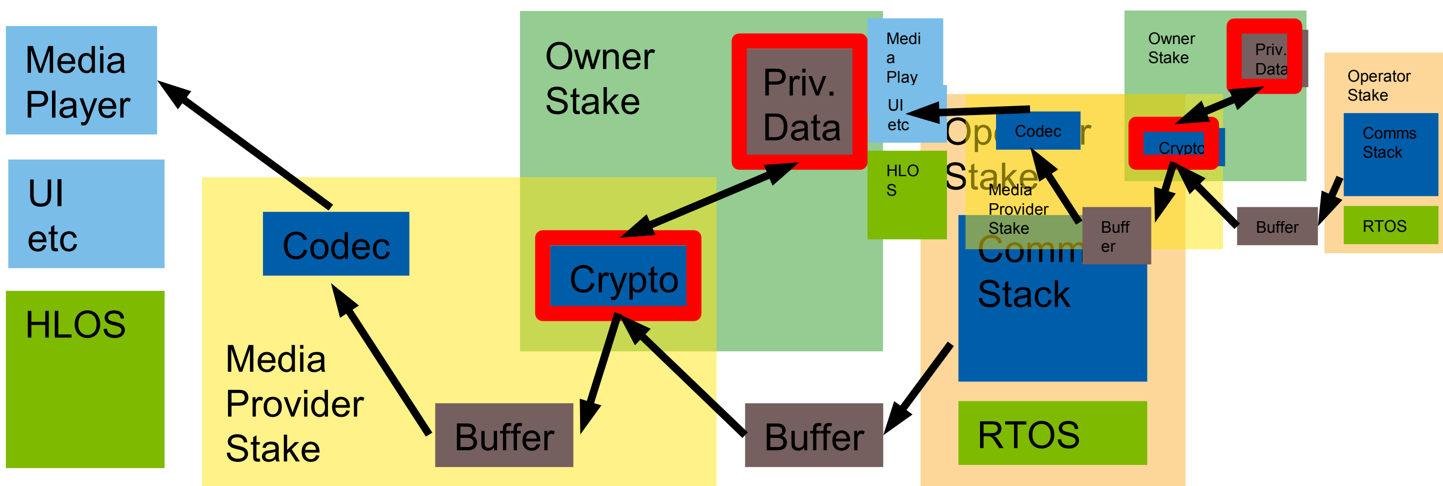
    - assets: private data, access keys





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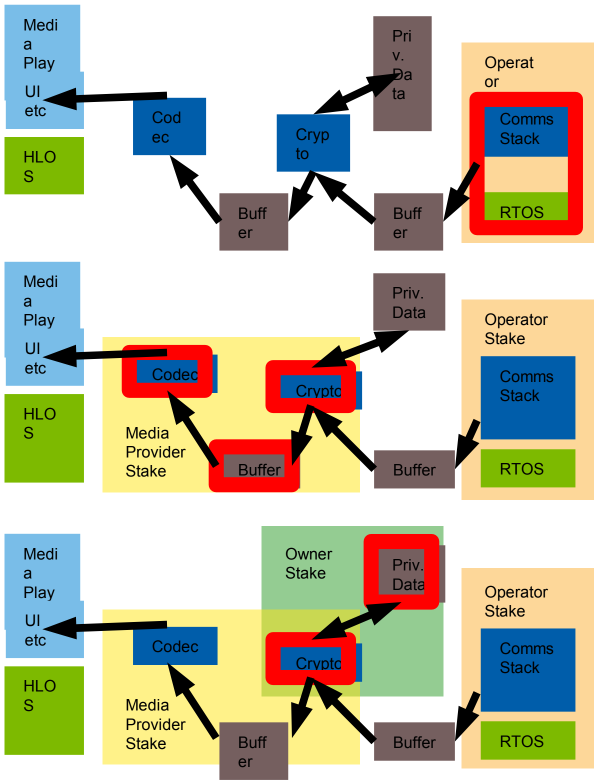
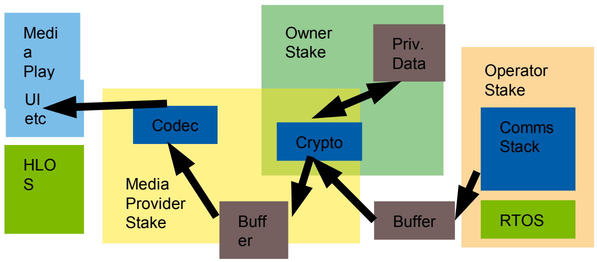
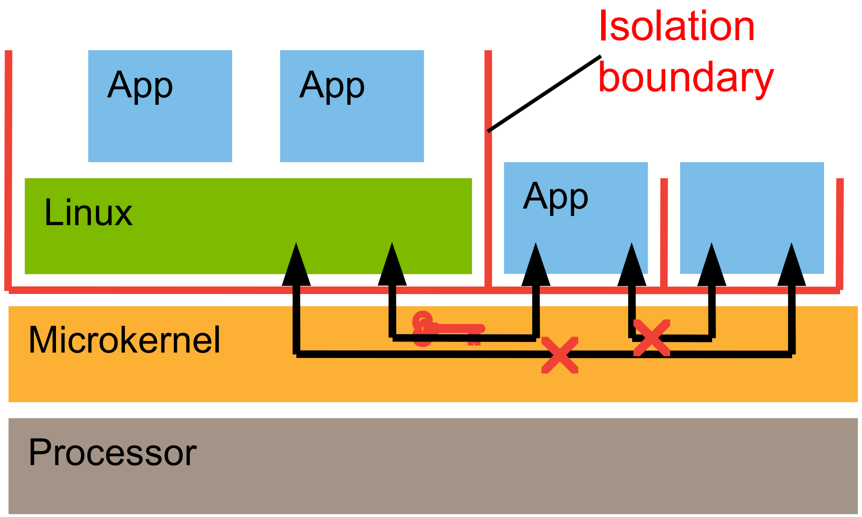
  - the network operator(s)
    - assets: cellular network
  - content providers
    - media content
  - the owner of the physical device
    - assets: private data, access keys
- They are mutually distrusting
  - need to protect integrity and confidentiality against *internal* exploits
  - need control over *information flow*
    - strict control over who has access to what
    - strict control over communication channels



Inter-VM Communication Control

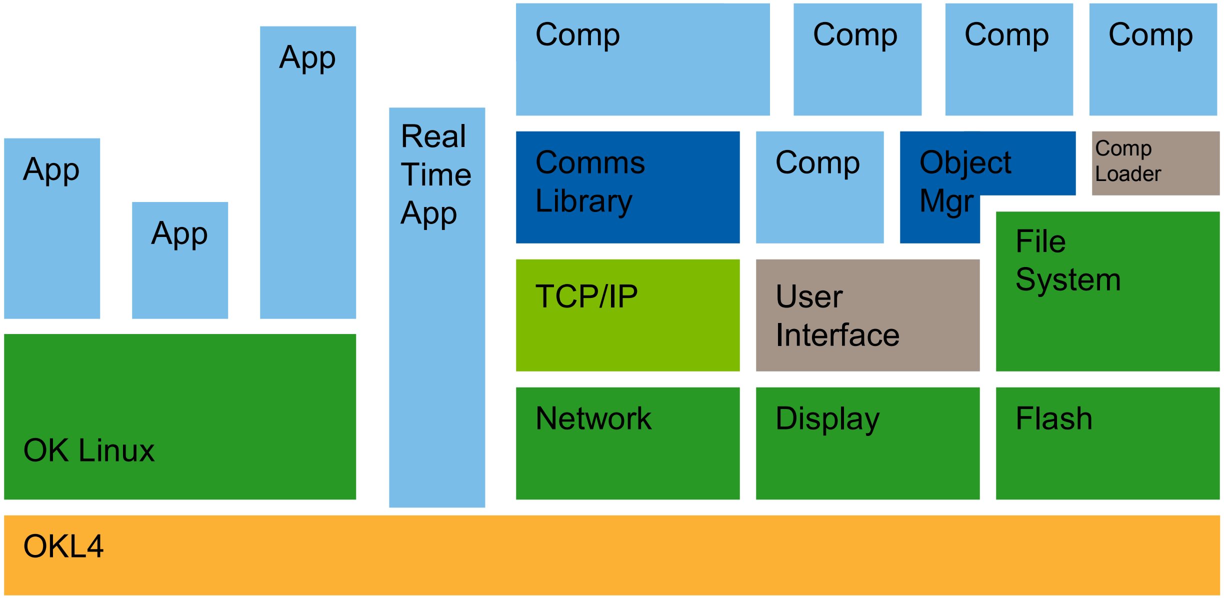
- Different "users" are mutually distrusting
- Need strong protection / information-flow control between them
- Isolation boundaries ≠ VM boundaries
  - some are much smaller than VMs
    - individual buffers, programs
  - some contain VMs
  - some overlap VMs
- Need to define information flow between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





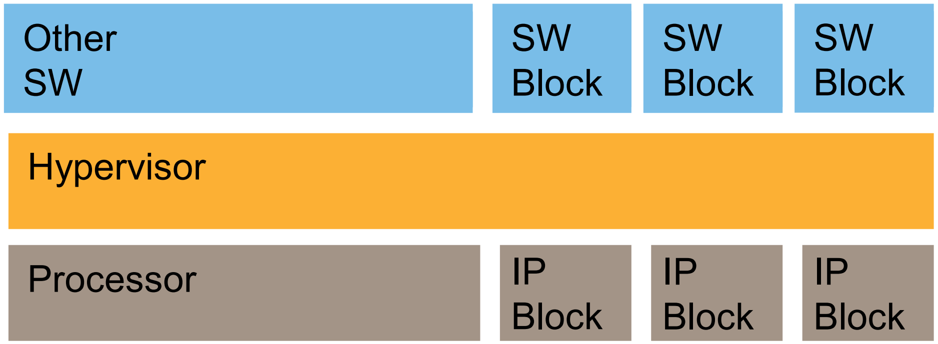
High Safety/Reliability Requirements

- 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 componentized systems to enable fault tolerance



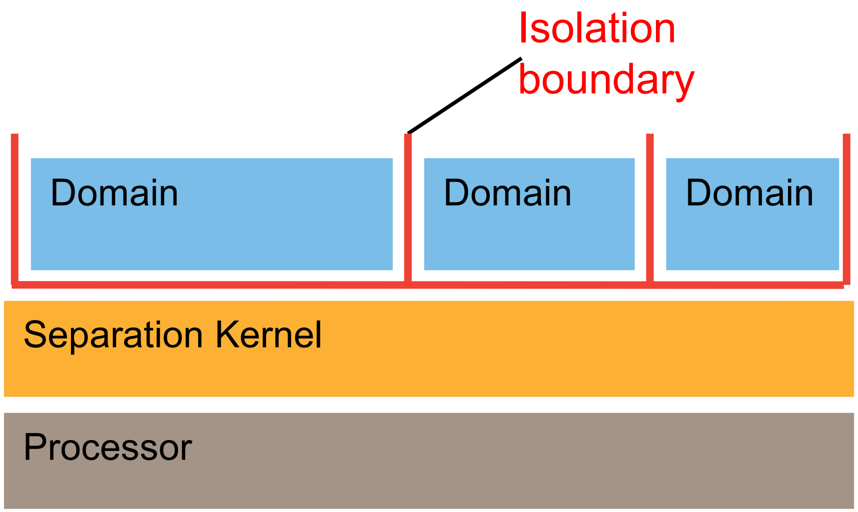
Componentization for IP Blocks

- 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

- *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

- 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 range of isolation granularities
- requires efficient context switching

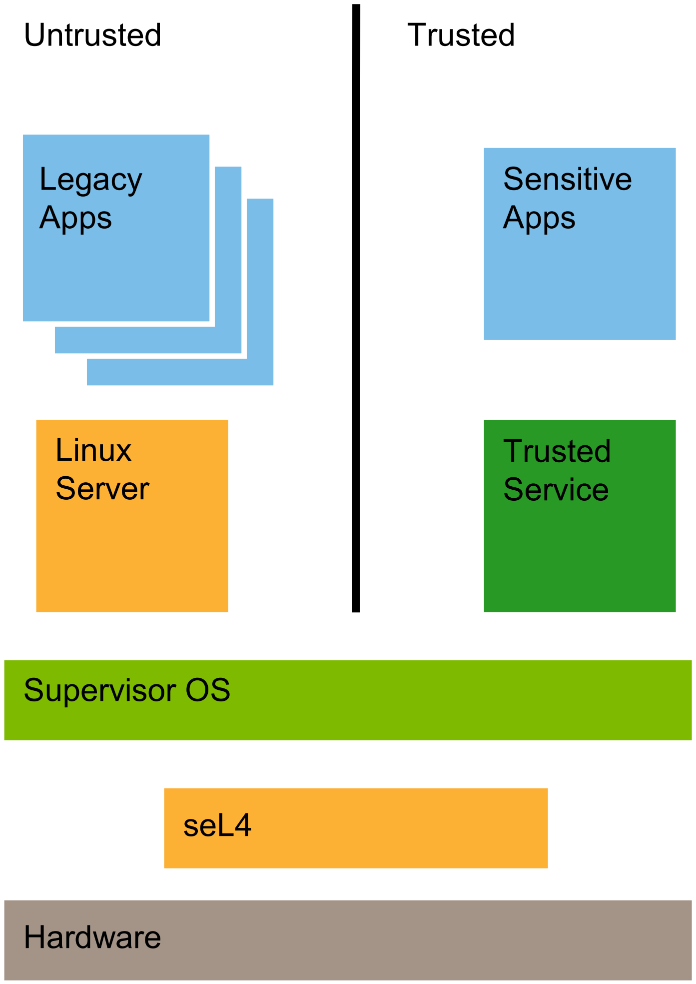
The seL4 Microkernel

Goals

- Platform for building arbitrary embedded-systems software
  - general OS
  - hypervisor
  - separation kernel
- High-performance implementation
  - no more than 15 cycles slower on IPC than L4
- Formal specification
- Formal proof of security properties
- Formal verification of implementation

Innovation over other L4 kernels:

- Access control based on capabilities
- Kernel resource accounting



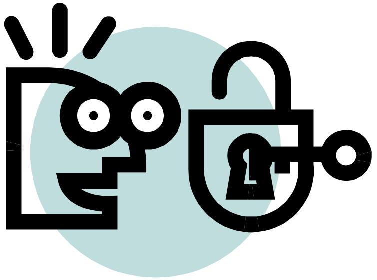
seL4 Capability-Based Protection

All authority conferred via capabilities

- Capabilities are like keys
  - Possess the key, and you can invoke the operation
- All system calls are invoked via capabilities
  - No ambient authority

Established body of knowledge on capabilities

- Can *reason* about them
- Models for confining authority



seL4 Physical Memory Management

Some kernel memory is statically allocated at boot time

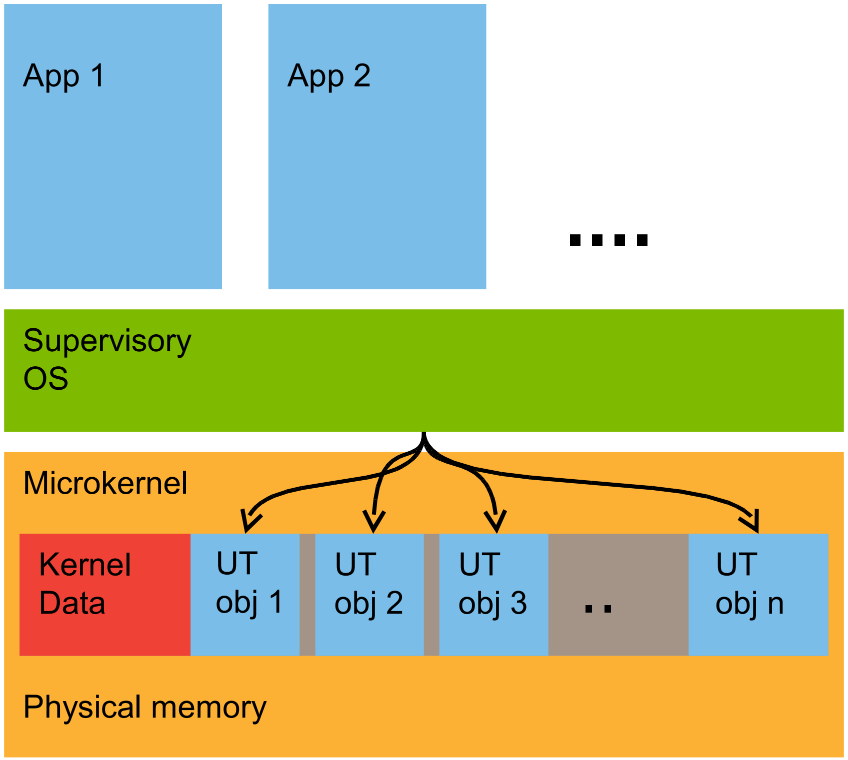
Remainder is divided into untyped (UT) objects

- 2^n region of physical memory
- Size aligned

Supervisor gets authority over these objects

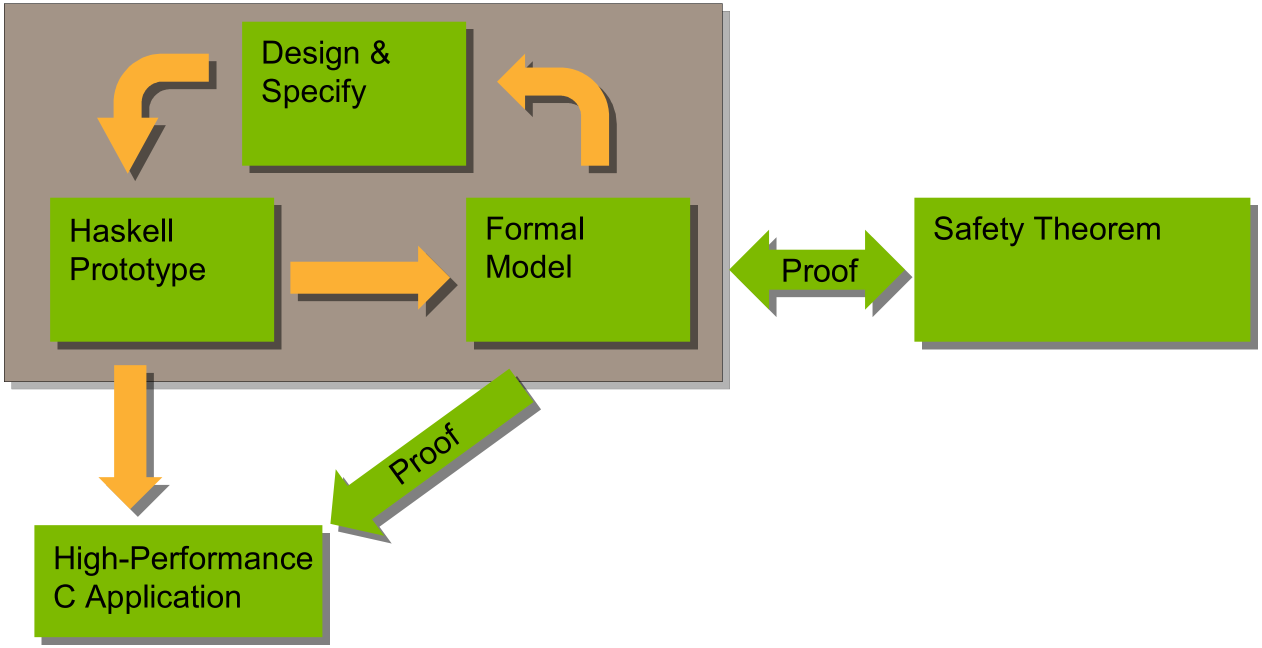
- Authority conferred by capabilities

Kernel never allocates dynamic memory

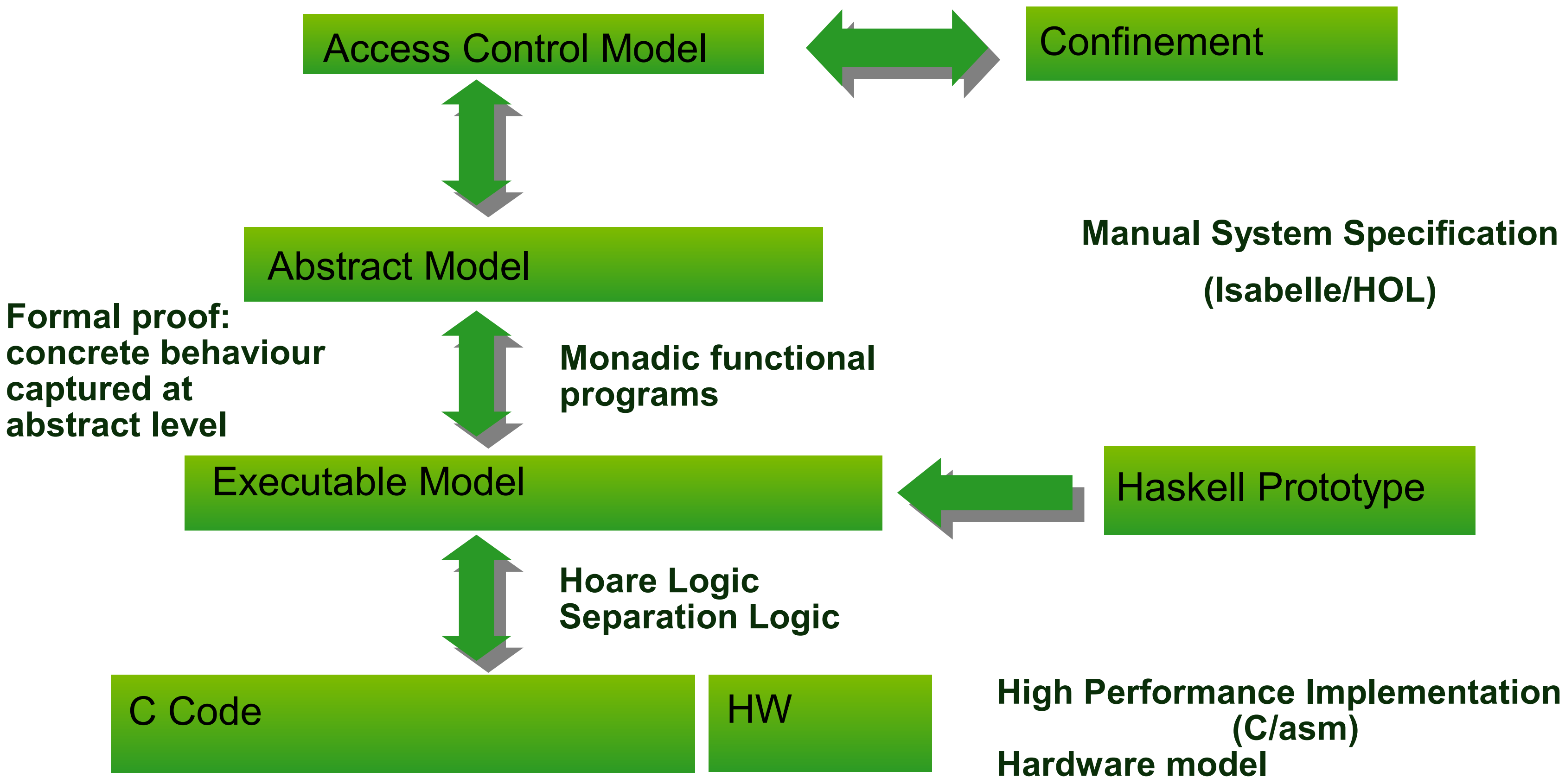


Iterative Design and Formalisation

- Prototype kernel executes native binaries on simulator
- Exposes usability issues early
- Tight formal design integration



The Proofs


Access Control Model
Confinement
Manual System Specification
(Isabelle/HOL)
Abstract Model
Formal proof:
concrete behaviour
captured at
abstract level
Monadic functional
programs
Executable Model
Haskell Prototype
Hoare Logic
Separation Logic
C Code
HW
High Performance Implementation
(C/asm)
Hardware model

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```
datatype
  rights = Read
         | Write
         | Grant
         | Create

record cap =
  entity :: entity_id
  rig
reco
ty
```

```
lemma isolation:
  "⟦sane s;
    s' ∈ execute cmds s;
    isEntityOf s e_s;
    sEntityOf s e;
    ntity c = e;
    :> subSysCaps s e_s⟧
    Caps s' e_s"
```

```
constdefs
  schedule :: "unit s_monad"
  "schedule ≡ do
```

```
schedule :: Kernel ()
schedule = do
        action <- getSchedulerAction
                                                    read
```

```
tcb_t * scheduler_t::find_next_thread(prio_queue_t * prio_queue)
{
    ASSERT(DEBUG, prio_queue);

    if (prio_queue->index_bitmap) {
        word_t top_word = msb(prio_queue->index_bitmap);
        word_t offset = BITS_WORD * top_word;

        for (long i = top_word; i >= 0; i--)
        {
            word_t bitmap = prio_queue->prio_bitmap[i];

            if (bitmap == 0)
                goto update;

            do {
                word_t bit = msb(bitmap);
                word_t prio = bit + offset;
                tcb_t *tcb = prio_queue->get(prio);
```

ecification

DL)

be

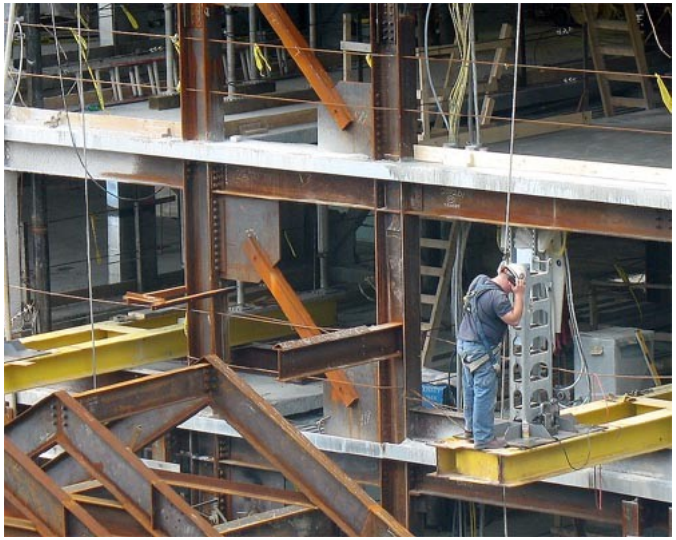
ce Implementation
C/asm)

Common Criteria Assurance and L4.verified

NICTA

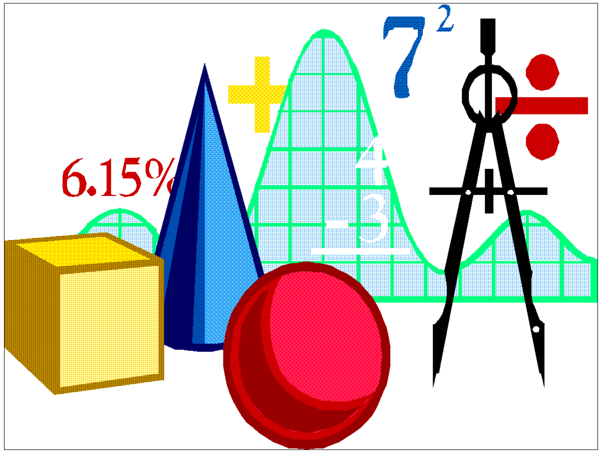
EAL	Requirem.	Funct Spec	HLD	LLD	Implem.
EAL 1	Informal	Informal	Informal	Informal	Informal
EAL 2	Informal	Informal	Informal	Informal	Informal
EAL 3	Informal	Informal	Informal	Informal	Informal
EAL 4	Informal	Informal	Informal	Informal	Informal
EAL 5	Formal	Semiformal	Semiformal	Informal	Informal
EAL 6	Formal	Semiformal	Semiformal	Semiformal	Informal
EAL 7	Formal	Formal	Formal	Semiformal	Informal
L4.verified	Formal	Formal	Formal	Formal	*Formal*

seL4 Summary



Implementation Status

- seL4 operational on ARM11
  - runs Linux etc...
- Performance in line with other L4 kernels
- Port to x86 in progress
- Security evaluation by Australian DoD
- To be integrated with commercial OKL4
  - OKL4 presently deployed in 150N devices

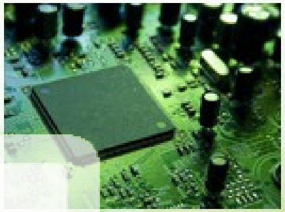


Proof Status

- Refinement proof to low-level model complete
- Already most deeply formally-verified general-purpose kernel ever
- C/asm implementation proof due December
- Working on proving more security properties

My Wishlist for Intel

- Need fine-grained isolation
  - *Please give us IO-MMUs on embedded processors!*
- Need fast context switches
  - *Please do something about context-switching costs*
  - *... such as tagged TLBs!*
- Need clear definition of hardware for formal verification
  - *Please give us an RTL-level description of the ISA!*



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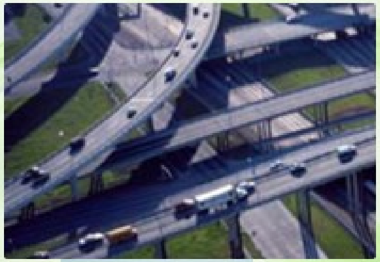
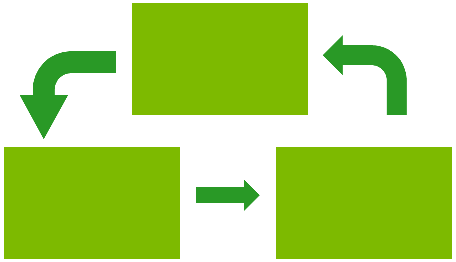


From **imagination** to **impact**

seL4 Project Overview

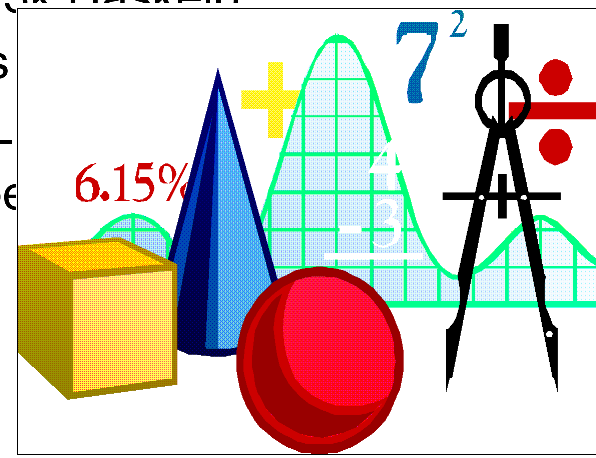
- Size of the project
  - Average 4–5 people (full time equivalent)
  - 5 years
  - Ends December 2008
- Interesting Problems
  - Designing and formalising an OS kernel
  - Refinement on monadic functional programs
  - Refinement on C programs
  - Formalizing machine details
  - Access control



seL4 Verification Summary

Statistics

- 3.5k LOC abstract, 7kLOC concrete spec (about 3k Haskell)
- Abstract / Haskell done: 100kLOP (more features
- Access control model + security proofs done (1kL
- 109 patches to Haskell kernel, 132 to abstract spe
- Performance in line with other L4 kernels



Kinds of properties proved

- Well typed references, aligned objects, ..
- Well formed thread states, endpoint and scheduler queues, ...
- All syscalls terminate, reclaiming memory is safe, ...
- Authority is distributed by caps only
- Access control is decidable
- Subsystems can be isolated / confined