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Towards a Practical, Verified Kernel

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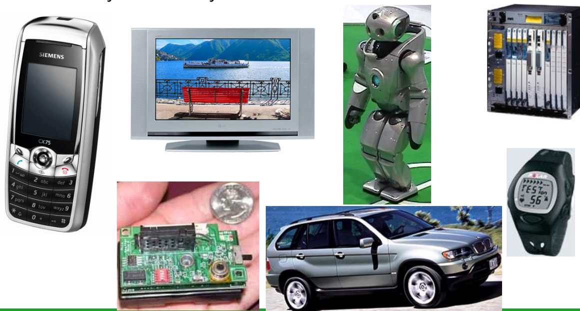
Feature-Rich Embedded Systems

Are they trustworthy?



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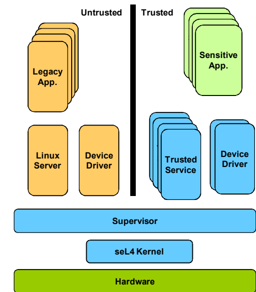
Small Kernels

- Smaller, more trustworthy foundation
  - Hypervisor, microkernel, nano-kernel, virtual machine monitor, isolation kernel, partitioning kernel, exokernel.....
  - Fault isolation, fault identification, IP protection, modularity.....
  - High assurance components in presence of other components
- Only as trustworthy as the foundation
  - Code reviews?
  - Testing?
  - Static analysis?
    - Sound and unsound



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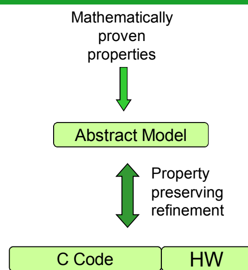
Our Goal – A Formally Verified Kernel

- A formally specified API (abstract model)
  - Proven properties such as spatial partitioning.
- High-performance implementation in C
  - A formal refinement between model and *implementation*
- Guaranteed correct ***implementation!!!!***



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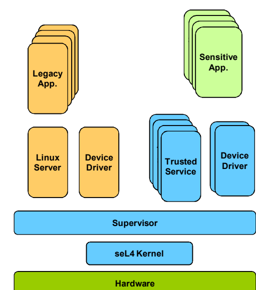
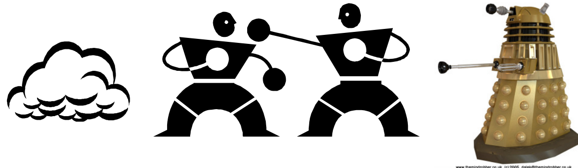
Success creates problems....

- Verified kernel is rigid
  - Changes invalidate proofs
- Kernel
  - "Mechanism not policy"
  - Flexible distribution of authority
    - Capabilities (KeyKOS/EROS)
  - Address spaces
    - Memory objects implemented at user level (L4/Xen/Nemesis)
  - Partitioning to hold within the kernel
    - No implicit memory allocation in kernel (Cambridge CAP)
  - Event-based/Atomic (Fluke)



Kernel Developers
Versus
Formal Methods Practitioners



Abstract Model
C Code
HW

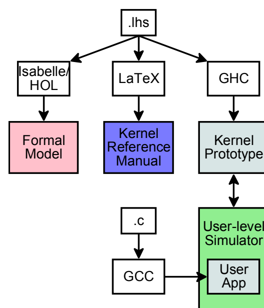
Bridging the gap

Modelling?

- Well defined semantics
- Readily formalisable
- Exposed implementation details
- Programming language

Our Prototyping Approach

- Model the kernel in detail
- Literate Haskell to model
  - Pure functional programming language
  - Embedded documentation
  - Close to Isabelle/HOL
- Executable
  - Supports running user-level code



Kernel Modelling in Haskell

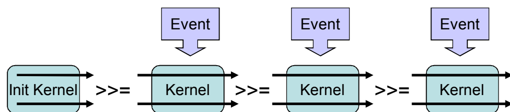
Kernel is event-based (single stack) mostly atomic API.

- Kernels are big state machines with events as input
  - Imperative
  - Rely on side-effects all the time
    - P(s), make_runnable(tcb)
- Kernels manipulate the low-level machine
  - Interrupts, TLBs, caches
- Preemption required
  - Kernels can't always perform operations to completion

Kernel Code in a State Monad

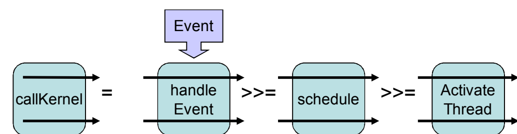
- State monads are *units* of computation which consume and produce state
  - State transformers
- Kernel monad encapsulates a state transformer of the kernel and machine

- Monads can be bound together using the *bind* operator
  - Sequencing the computation
  - Connects the plumbing to pass the state along



Kernel Code in a Monad

```
type Kernel = StateT KernelState MachineMonad
callKernel :: Event -> Kernel ()
callKernel ev =
    handleEvent ev >>= (\x -> schedule >>=
                              (\y -> activateThread))
```



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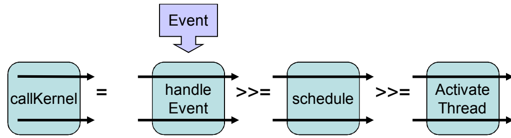
Kernel Code in a Monad

```
type Kernel = StateT KernelState MachineMonad
callKernel :: Event -> Kernel ()
callKernel ev = do
    handleEvent ev
    schedule
    activateThread
```

Imperative in "style"

Lowers barrier to entry for kernel developers



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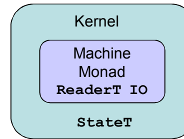
Kernel Monad



- Machine monad contains state to interface to simulator
- Kernel contains the state of physical memory

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Machine Monad – Lowest Level of Model

- `getMemoryTop :: MachineMonad (PPtr ())`
- `getDeviceRegions :: MachineMonad [(PPtr (), Int)]`
- `loadWord :: PPtr Word -> MachineMonad Word`
- `storeWord :: PPtr Word -> Word -> MachineMonad ()`
- `insertMapping :: PPtr Word -> VPtr -> Int -> Bool -> MachineMonad ()`
- `flushCaches :: MachineMonad ()`
- `getActiveIRQ :: MachineMonad (Maybe IRQ)`
- `maskInterrupt :: Bool -> IRQ -> MachineMonad ()`
- `ackInterrupt :: IRQ -> MachineMonad ()`
- `waitForInterrupt :: MachineMonad IRQ`
- `configureTimer :: MachineMonad IRQ`
- `resetTimer :: MachineMonad ()`

- Foreign Function Interface (FFI)
- Approximate machine-level C functions
- Close to "real" as possible
  - Forces us to manage "hardware"

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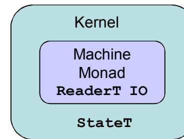
KernelState Monad



- Statically allocated global kernel data
  - Current thread
  - Scheduler queues
- Physical Memory

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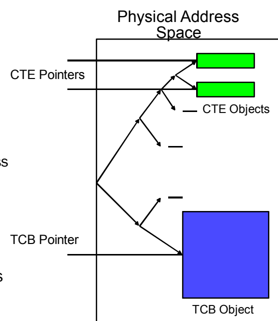
KernelState Monad

- Physical memory model
  - Contents of dynamically-allocated memory
  - Typed data used by the kernel
    - Thread control blocks
    - Capability and page tables
    - …
  - Indexed by physical memory address
- Forces us to model memory management (30% of kernel)
- Reduces the gap to C
  - Pointers,not Haskell's heap
- Still provides strongly typed pointers



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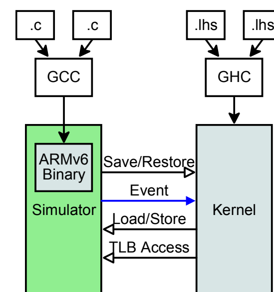
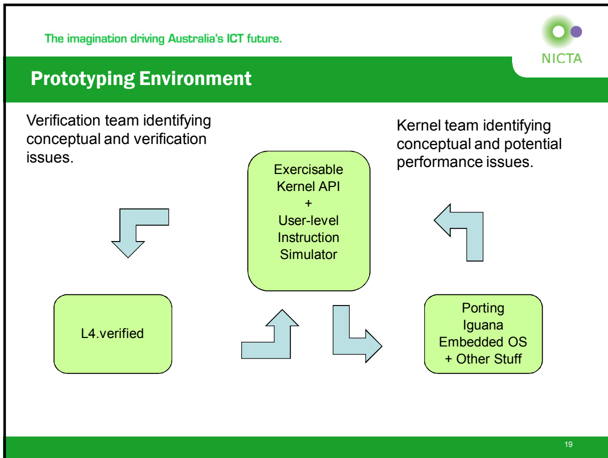
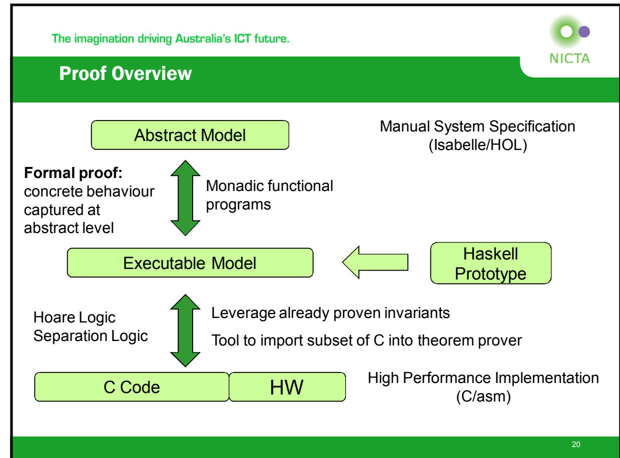
User-level Simulation

- User-level CPU simulator
  - M5 Alpha simulator
  - Locally-developed ARMv6 simulator
  - QEMU
- Executes compiled user-level binaries
- Sends events to the Haskell kernel







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The Proof - Summary

- Statistics:
  - 3.5kloc abstract, 7kloc concrete spec (about 3k Haskell)
  - 53kloc proof so far (estm. 60kloc final, about 10kloc/month)
  - 37 patches to Haskell kernel, 110 to abstract spec
- Proven lots of invariants:
  - well typed references, aligned objects
  - thread states and port queues
  - well formed current thread, scheduler queues
- Proof of termination
- Expect to prove “does not fail”
- Pen-paper proof of spatial partitioning
  - Identified set of invariants required of supervisor

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Conclusions

- Significant gap between kernel development and formal verification
- Haskell (Functional Programming) middle ground
  - Programming language
  - Model low-level details
  - Readily formalisable
  - Make proving easier – explicitly manage side-effects

Overall Status

- Very close to a verified detailed executable kernel model
- Immature ‘C’ version of the design

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Questions

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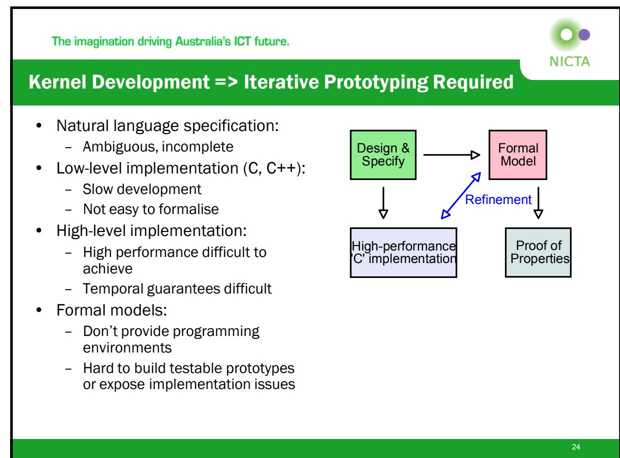

Kernel Code in a Monad

```
type Kernel = StateT KernelState MachineMonad
callKernel :: Event -> Kernel ()
callKernel ev = do
    runErrorT $ handleEvent ev
        `catchError` \irq -> withoutPreemption $
                            handleInterrupt irq
    schedule
    activateThread
```