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Operating System Verification for Real Use

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

NICTA Members

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Windows
An exception 06 has occured at 0028:C11B3ADC in VxD DiskTSD(03) + 00001660. This was called from 0028:C11B40C8 in VxD voltrack(04) + 00000000. It may be possible to continue normally.
* Press any key to attempt to continue.
* Press CTRL+ALT+RESET to restart your computer. You will lose any unsaved information in all applications.
Press any key to continue

OS Reliability is a Problem

- The consequences of OS failure are getting worse

OS Reliability is a Problem

- Any computer system can only be as reliable/trustworthy as its operating system
- Life-critical systems should have *bullet-proof operating systems*
- Formal verification should be the obvious way to achieve this?
- How does military-grade *assurance* look like?

Common Criteria and Verification

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

→**No certainty of implementation correctness ⇒ not good enough!**

Operating System Verification

OS Verification — Is It Feasible?

- Benefits seem clear, but
  - Can it be done?
  - Can it be done for a system suitable for real use?
  - Is it doable at a reasonable cost?
- Past attempts:
  - UCLA Secure Unix (1980)
    - Pascal kernel, 90% specifications, 20% implementation proofs
  - PSOS (1973–83)
    - 17 specification layers (hardware to apps)
    - some refinement proofs between layers
    - no implementation proofs completed
  - KIT (1987)
    - minimal kernel, some 100 LOC assembly
    - full implementation proof
    - very basic services on idealised machine

Aim of NICTA OS Verification Work

- Formally verify a complete OS kernel
- ... which is suitable for commercial use
  - on real hardware
  - fully functional
  - good performance

Main Challenges

- Size:
  - operating systems tend to be big
  - Linux, Windows: millions of lines of code (LOC)
- Ugly code: low-level and unsafe
  - Low-level language — C is the *lingua franca* of OS
    - could be worse — some use C++
  - Frequently has to bypass type-checking
    - hardware registers are untyped
    - various efficiency tricks, bit fiddling
  - Side effects are unavoidable — hardware is that way
  - Assembler code is unavoidable
    - and used voluntarily for efficiency
- Efficiency: if it's slow, no-one will use it

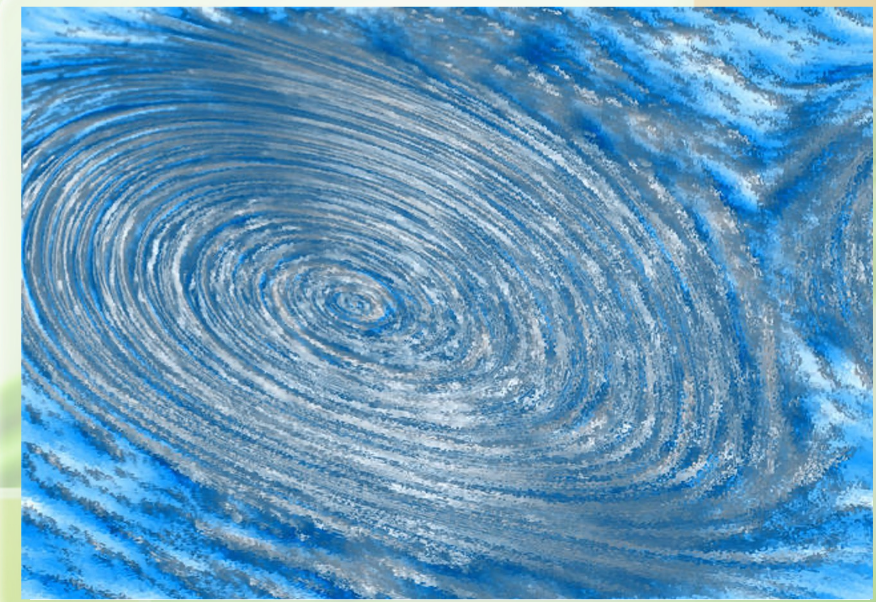
Prerequisites for Success

- Need a target system that is tractable
  - ☐10,000 LOC is about the limit (so they tell me)
- Need a world-class formal-methods team
  - so I suspect, based on historic track record...
- Need a world-class OS team
  - ... or they won't end up with a useful kernel
  - really correct and really slow won't do!
- Need to ensure communication between teams!
  - only practical safeguard against the two teams diverging

With hindsight:

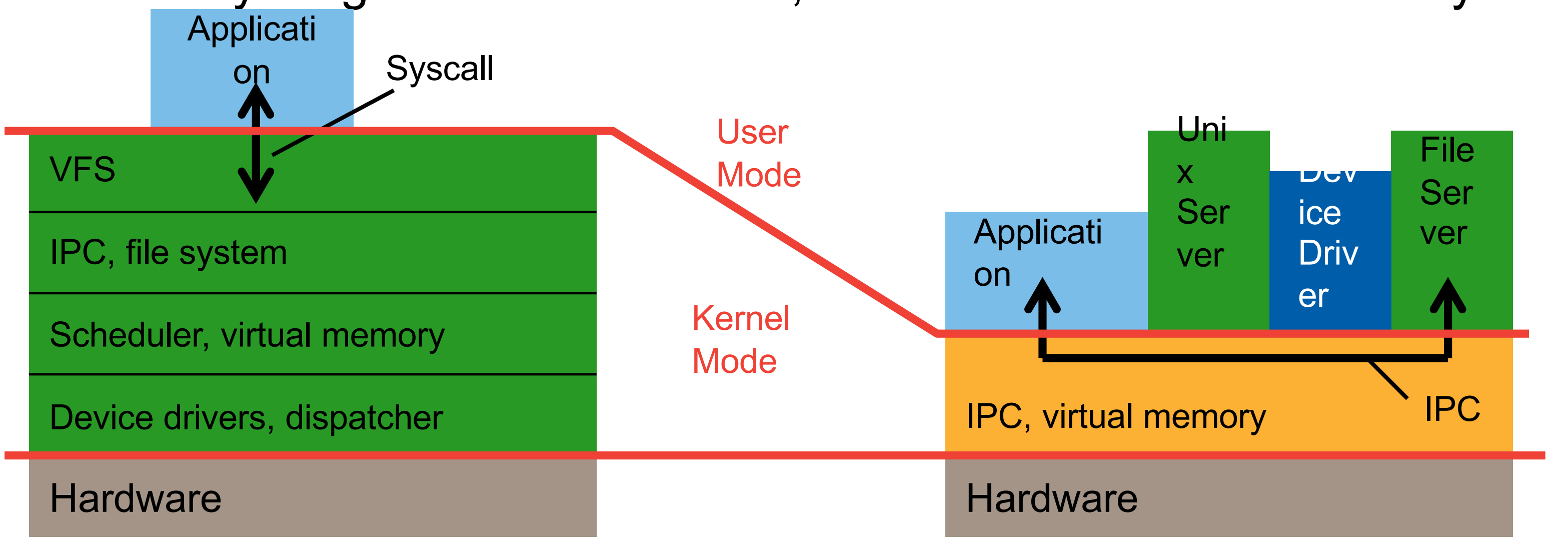
- Need control over tools!

The Target



Tractable System

- 10kLOC and practically usable ⇒ microkernel
  - Very small platform that allows constructing arbitrary systems on top
  - OS functionality reduced to its essence:
    - fundamental mechanisms
    - no policies
  - Only microkernel runs in privileged mode
    - everything else in user mode, incl "normal" OS functionality



Tractable System: L4 Microkernel

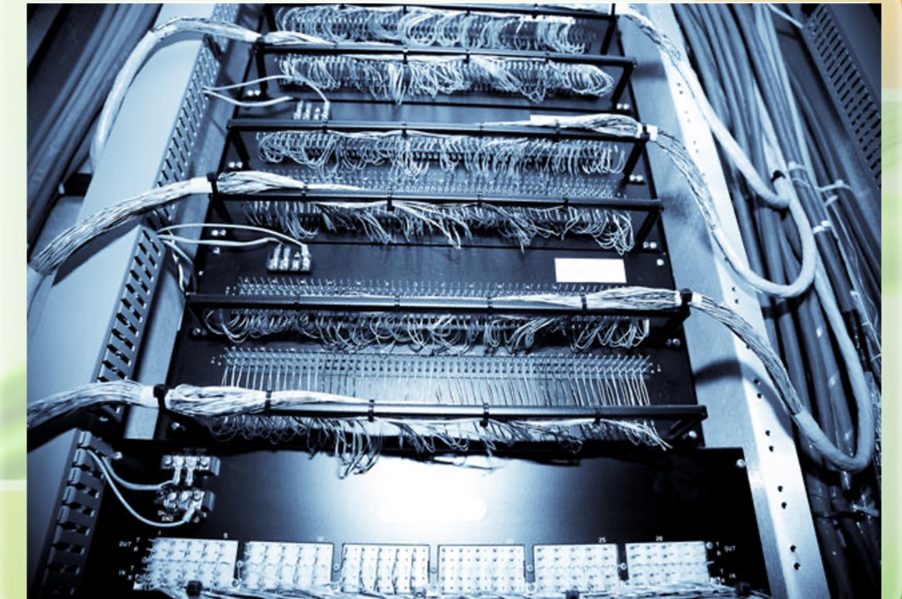
- Right size: ☐10,000 LOC
  - mostly C, some (100's LOC) assembler
- Very general-purpose: supports
  - componentised OSes
  - small embedded environments
  - virtualized main-stream OSes (Linux)
- Famous for performance
  - the benchmark for microkernel performance
- Ready for commercial use
  - ... or so we hoped at the time
  - now deployed on some 150,000,000 devices
- However, not fully suitable
  - several security issues:
    - inefficient communication control mechanisms
    - isolation of user domains broken by management of kernel resources
  - needed API overhaul

The Challenge

- Formally verify a secure version of L4
  - Need to develop a new kernel API as we go
  - Concurrent to verification effort
- Outcome to be suitable for practical use
  - Performance within 10% of existing high-performance L4

- Succeed!
  - Unsuccessful multi-M$ project doesn't look good
  - Some careers were on the line

The Ingredients



Formal-Methods Team

- Gerwin Klein — newly recruited researcher
- Project leader verification
  - *L4.verified* project
- Developed project plan
- Built team of up to 10 people across two cities

OS Team

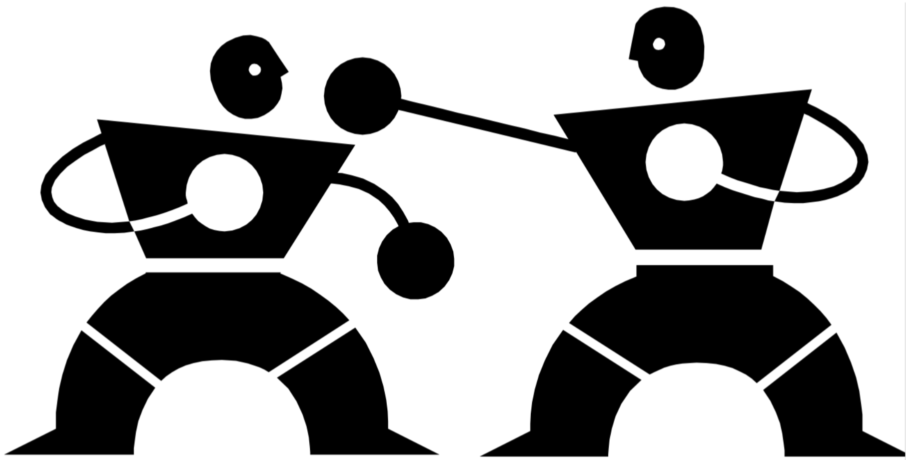
- Kevin Elphinstone — recent recruitment to UNSW
- Project leader kernel API
  - *seL4* project
- Built (smaller) kernel team
- Lead design and implementation of new L4 API

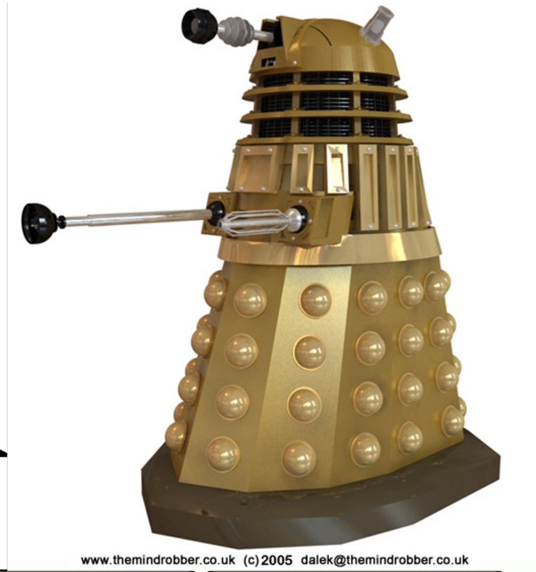
The Interface Part 1: The Human Side

- Needed at least one person I could trust to understand both sides
- Don't have one? Need to bake your own!
  - Take one top class systems hacker with Maths aptitude
  - Let Gerwin work on him for a year
- The result?

- Approach tested in 1-year pilot project
  - Seemed to work, resulting in 3-year main project
  - Learned some lessons on approach
  - Developed idea of overall effort required

The Interface Part 2: The Language



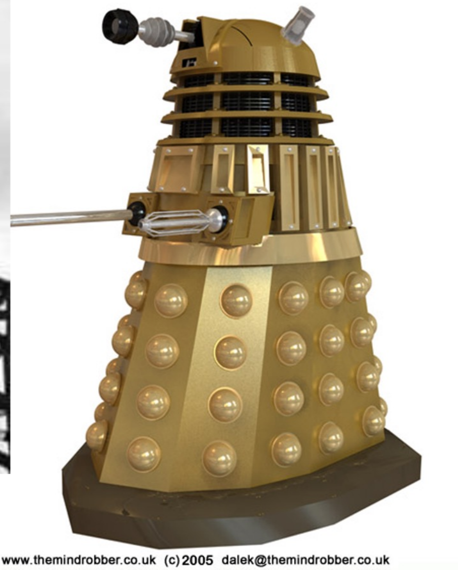


Abstract Model

C Code | HW

Where is the common ground?

Bridging the Gap

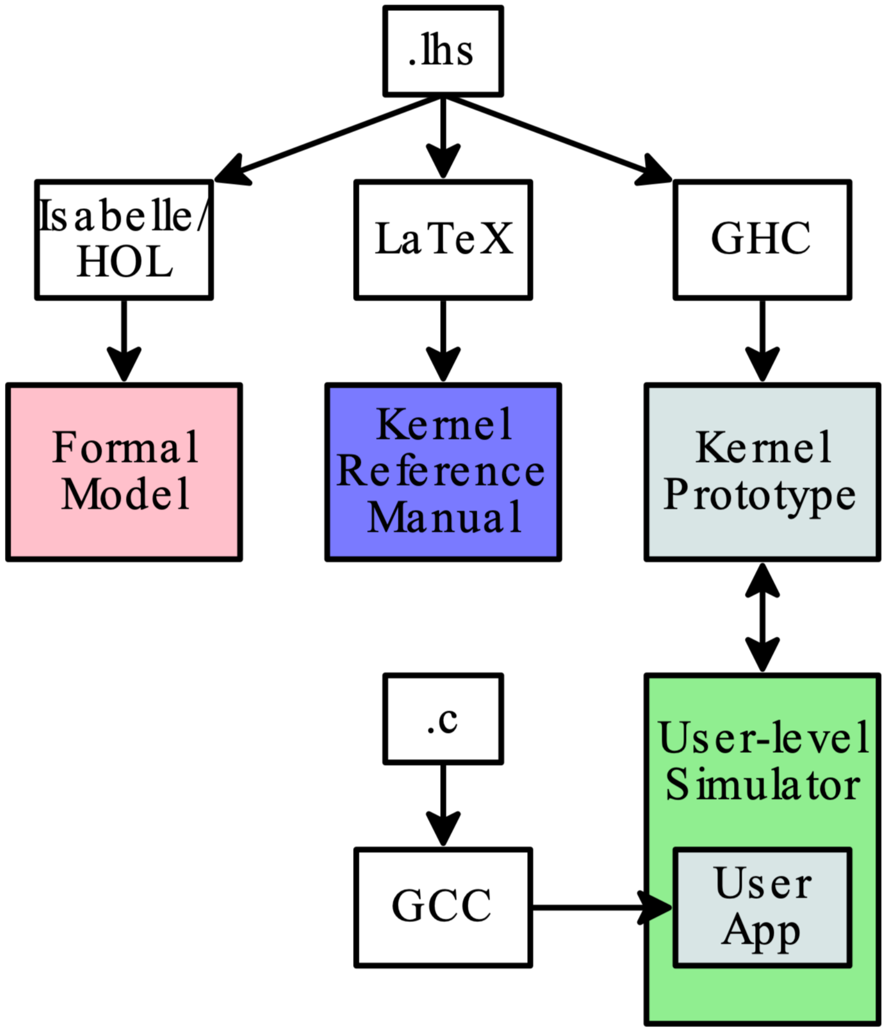


Modelling?

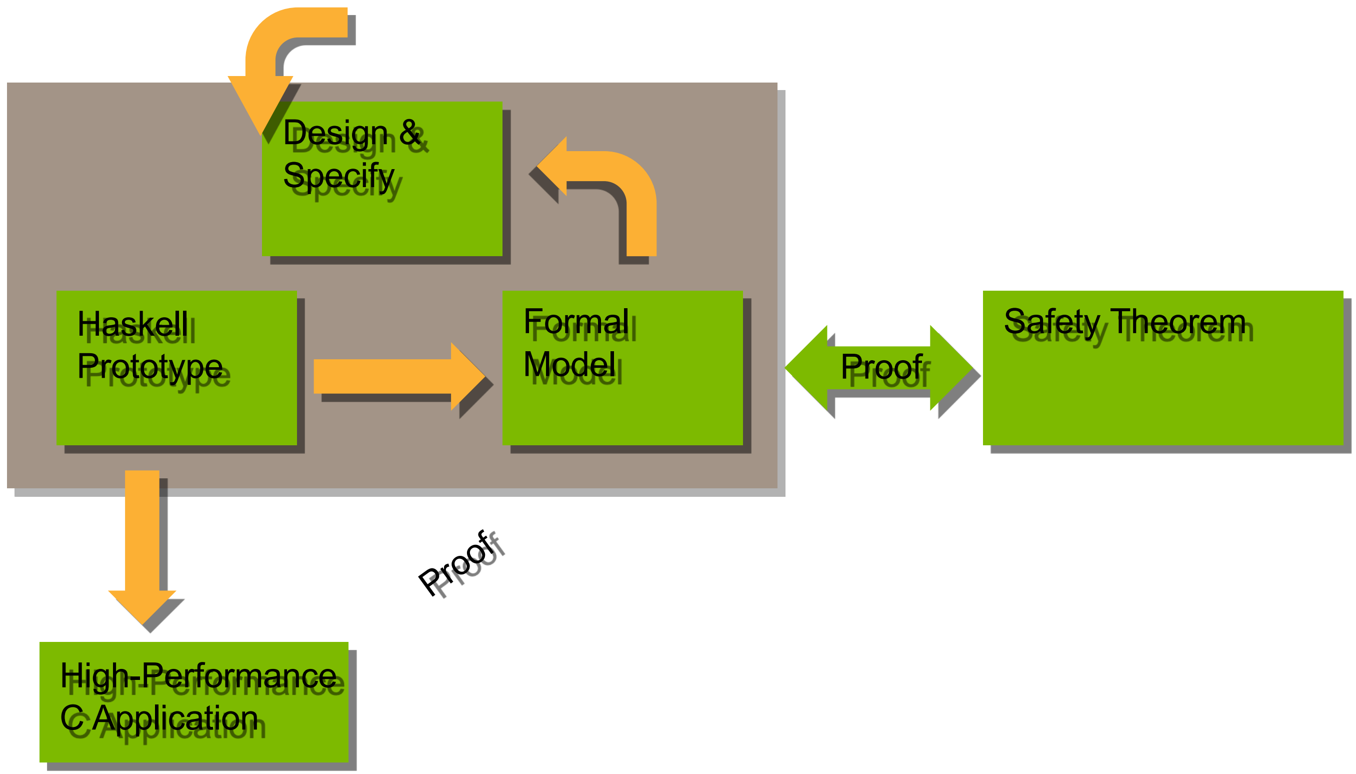
- Well defined semantics
- Readily formalisable
- Exposed implementation details
- Programming language

Haskell — The New *Lingua Franca*?

- Used *Literate Haskell* as modelling language
  - pure functional language
  - embedded documentation
  - close to Isabelle/HOL
- Familiar to most kernel hackers
  - First-year teaching language at UNSW
- Executable
  - Supports running user-level code
  - Useful for exercising the API
    - gain experience with API
    - port user-level software
- Used to model kernel in detail



Iterative Design and Formalisation



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

Kernel Modelling

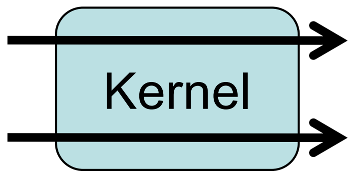
Kernel Modelling in Haskell

Kernel API is event-based, mostly atomic

- 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

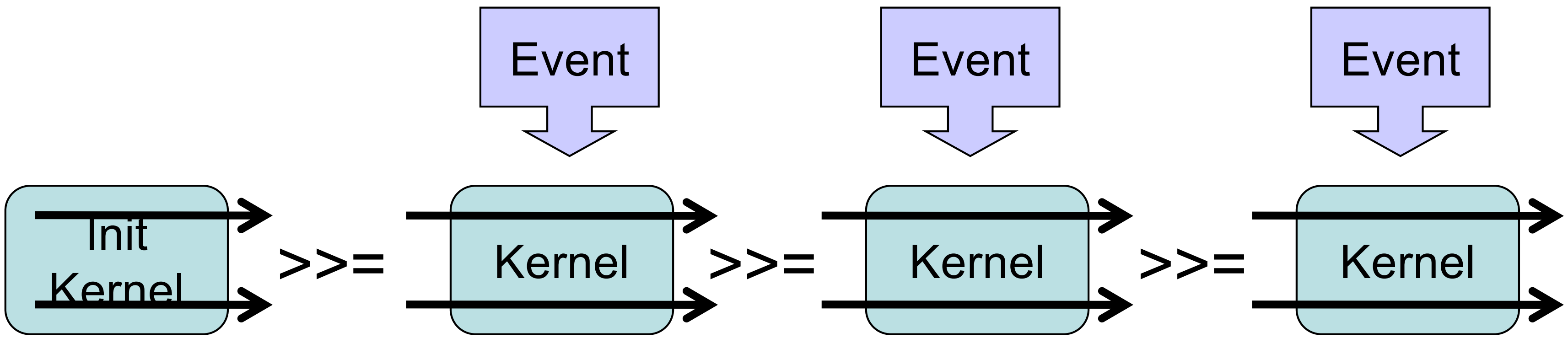
- Preemption required
  - Kernels can't always perform operations to completion

Kernel Code in a State Monad



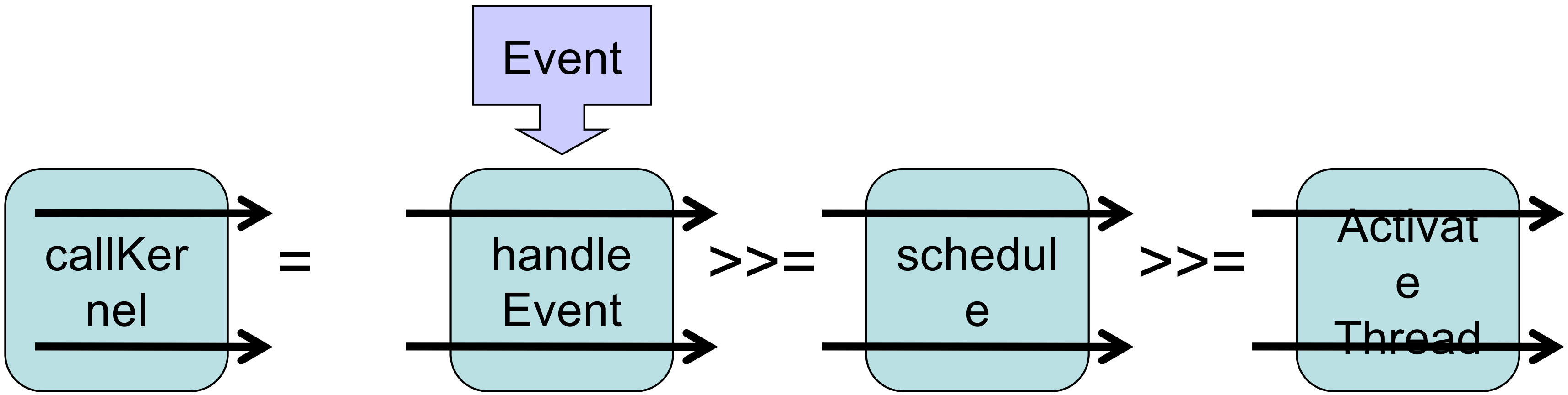
- State monads are *units* of computation which consume and produ
  - state transformers
- Kernel monad encapsulates a state transformer of the kernel and

- 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))
```

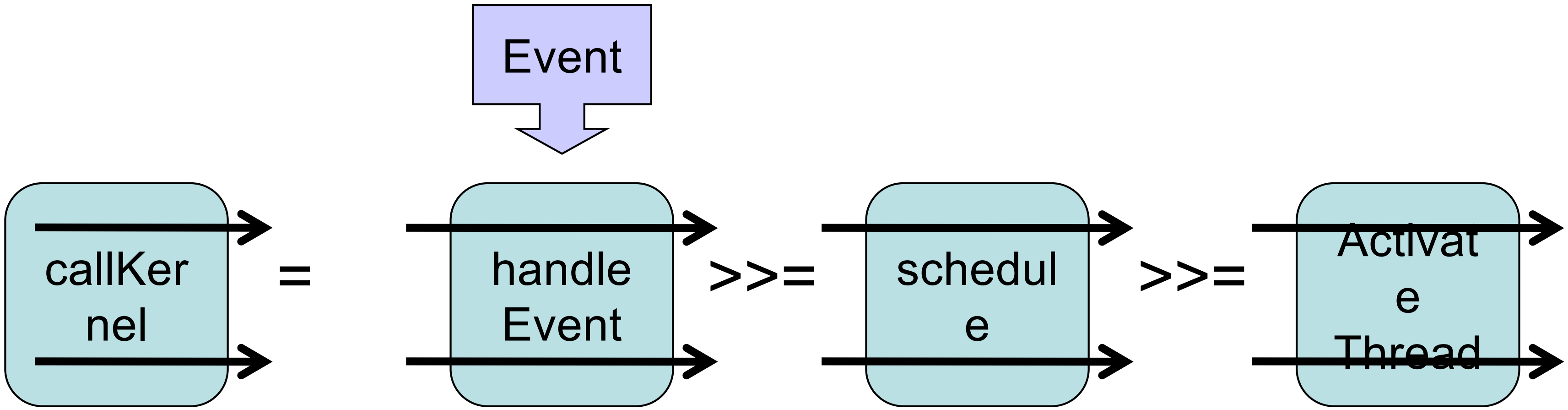


Kernel Code in a Monad

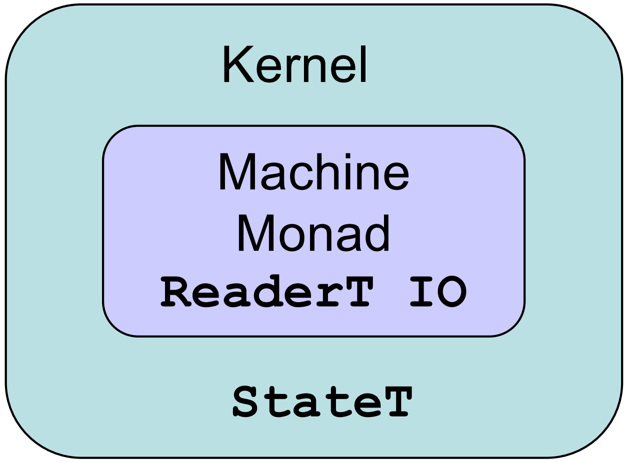
```
type Kernel = StateT KernelState MachineMonad
callKernel :: Event -> Kernel ()
callKernel ev = do
    handleEvent ev
    schedule
    activateThread
```

Imperative in “style”

Lowers barrier to entry for kernel developers



Kernel Monad



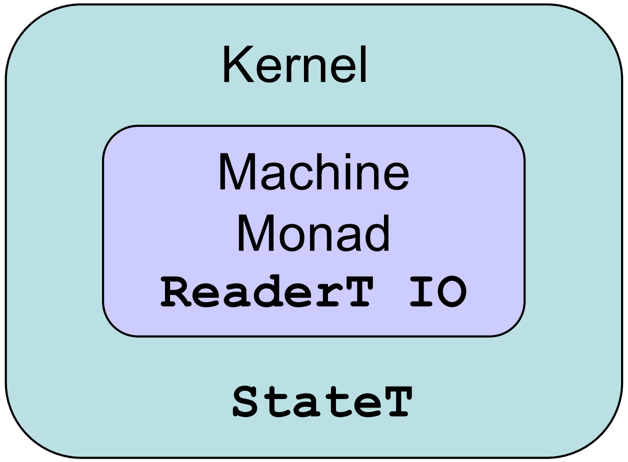
- Machine monad contains state to interface to
- Kernel contains the state of physical memory

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 ->`
- `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”

KernelState Monad



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

The Proof

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```
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);
```

```
hread
ooseThread
```

Abstract Model

Manual System Specification

(Isabelle/HOL)

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

Common Criteria and L4.verified

EAL	Requirem.	Funct Spec	HLD	LLD	Implem.
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EAL 6	Formal	Semiformal	Semiformal	Semiformal	Informal
EAL 7	Formal	Formal	Formal	Semiformal	Informal
L4.verified	Formal	Formal	Formal	Formal	*Formal*

Lessons Learned

The Tools

- Isabelle/HOL generally worked well
  - Gerwin's experience clearly helped
- But we were frequently pushing the boundaries
  - of techniques
  - of tools
- Crucially important to have control over tools
  - Need to be able to fix a limitation you run into
  - Source-code access is essential
  - Open-source tool is ideal
- Good support from tool supplier helps massively
  - The TUM folks were great!

It's Not Quite Over Yet!

- Refinement to low-level design (Haskell) complete
  - most formally analysed general-purpose kernel
- source-code level refinement in progress
  - due December '08
  - no-one doubts that it will succeed
- Work on proving security properties on-going

Verification Summary

Statistics

- 3.5 kLOC abstract, 7 kLOC concrete spec (about 3k Haskell)
- Abstract to Haskell: 100 kLOP (more features coming)
- Access control model + initial security proofs: 1 kLOP
- Haskell to C/asm: expect 80kLOP
- 109 patches to Haskell kernel, 132 to abstract spec
- 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

Proof Maintenance

- Challenge: adapting proofs to changes in implementation
  - Will minor changes result in massive reworking of proofs?
- Inevitably tested as a result of project structure:
  - concurrent work on proofs and kernel design
  - frequently verification work progressed on frozen kernel
  - merging of source trees required update of proofs
- Experience: depends on how changes affect invariants
  - Some changes took weeks to port
    - new syscall,
    - additional parameters to syscall decoded deep down
  - Others, breaking existing invariants, took months
    - fundamentally changing operation of IPC, eg. reply caps
    - required discovering new invariants
- Experience increases confidence in practicability of OS verification

Cost: Is OS Verification Affordable?

- Estimated cost of complete project: A$4–5M
  - seL4 and L4.verified combined, until December '08
- Estimated cost of re-doing on latest kernel: A$2M
  - on commercial OKL4 kernel
- Cost of traditional assurance: US$10k/LOC
  - industry estimate for Common Criteria EAL6 certification
  - means *US$100M* for L4-like kernel!
- Challenge: Convince authorities that verification is superior!

Conclusion

- Complete verification of a fully-functional OS kernel seems doable
- Cost seems small compared to traditional assurance schemes
- However, probably can't succeed without:
  - top-notch verifiers
  - top-notch kernel experts
  - excellent communication between the two sides
    - need some people who understand both
    - good languages and tools help
- A microkernel is only the start!
  - Need to work on actual OS services
  - Multiple independent levels of security (MILS)

The Team

- **Gerwin Klein**
- June Andronick
- David Cock
- Philip Derrin
- Kai Engelhardt
- Jia Meng
- Michael Norrish
- David Tsai
- Simon Winwood

- **Kevin Elphinstone**
- Andrew Boyton
- Jeremy Dawson
- Dhammika Elkaduwe
- Rafal Kolanski
- Catherine Menon
- Thomas Sewell
- Harvey Tuch

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