OS Research at NICTA

COMP9242 Advanced Operating Systems

2010 Week 12

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

NICTA Funding and Supporting Members and Partners

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

Trust Without Trustworthiness

What's Next?

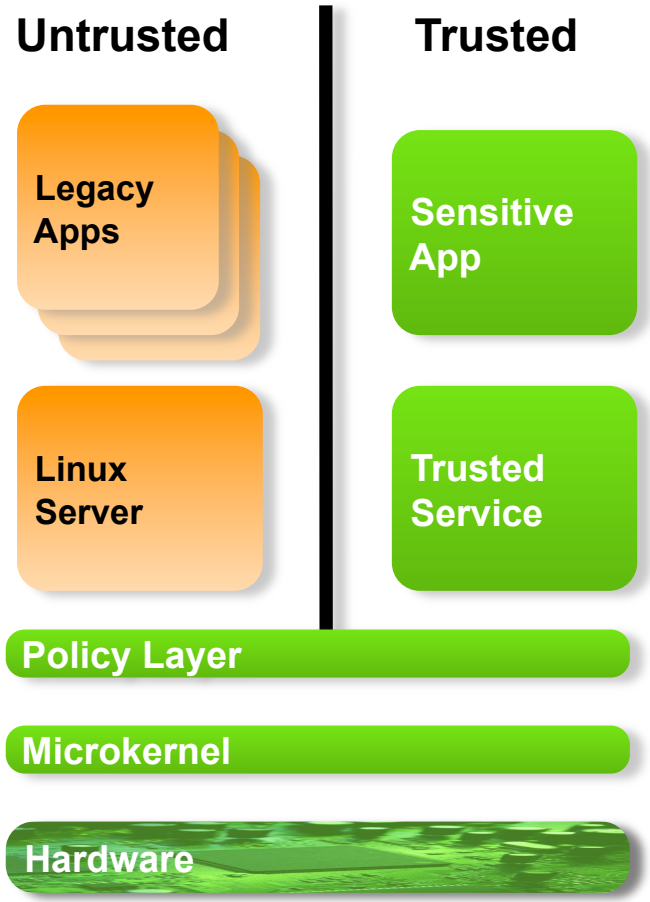
Our Vision: Trustworthy Systems

- We will change industry's approach to the design and implementation
- of embedded software, resulting in systems which are *trustworthy*.

Trustworthy means *truly dependable* in that there are *hard guarantees* about the *security*, *safety* or *reliability* of the software.

Approach: Microkernel Technology

- Protect critical components by sandboxing complex components
- Provide tightly-controlled communication channels
- *Trustworthy microkernel* enforces security/safety policies
- Microkernel becomes core of trusted computing base
  - System trustworthiness only as good as microkernel



Trustworthy Systems Agenda

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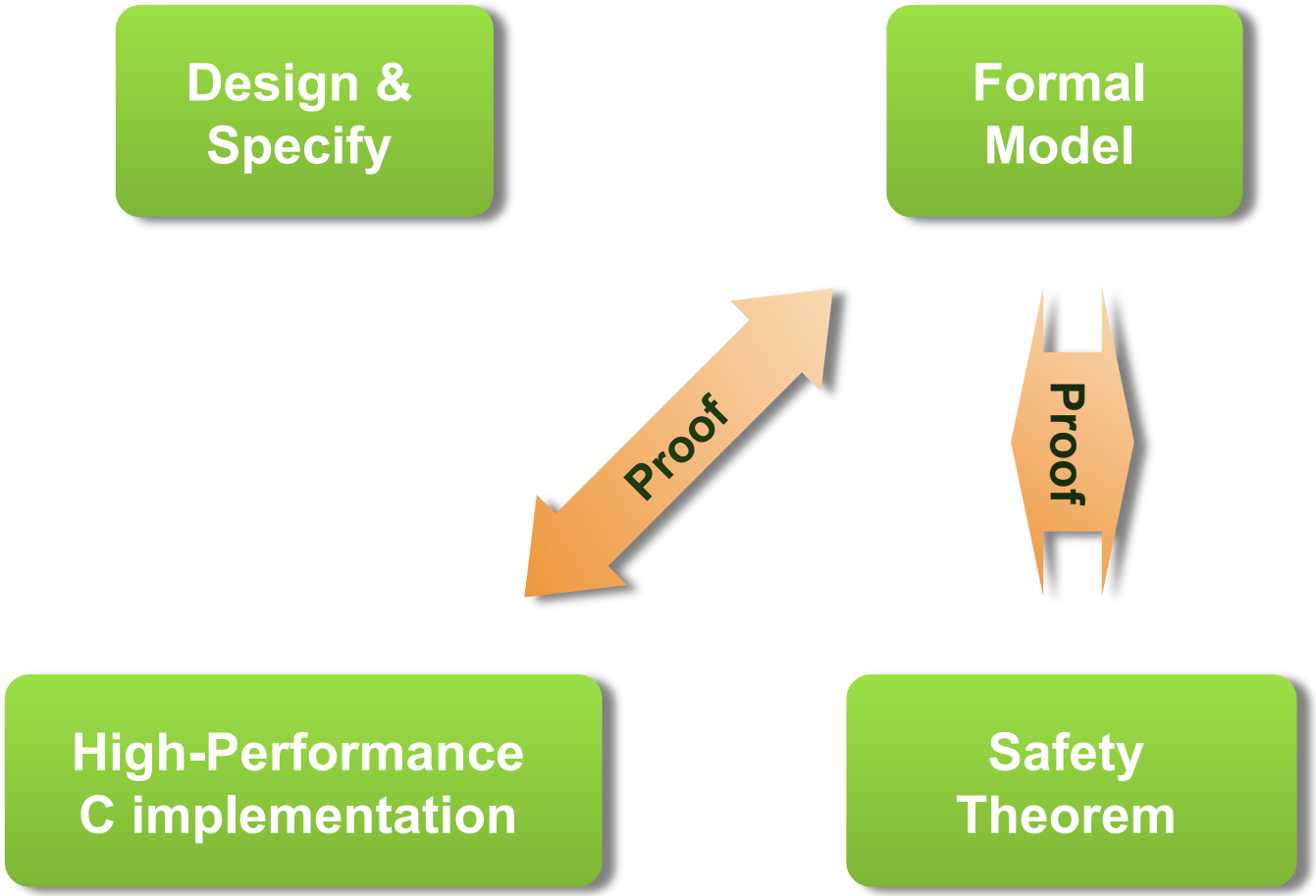
1. **Ensure microkernel trustworthiness (seL4)**
   - Proof of functional correctness
   - Proof of safety/security properties
2. **Lift microkernel guarantees to whole system**
   - Use safety/security guarantees
   - Prove correctness of balance of trusted computing base
   - Prove safety/security of complete system

Ingredients:

- Functional correctness
- Isolation / non-interference / information flow
- Timeliness / worst-case latency guarantees
- Energy management

seL4: Designing and Formalising



Two Mentalities

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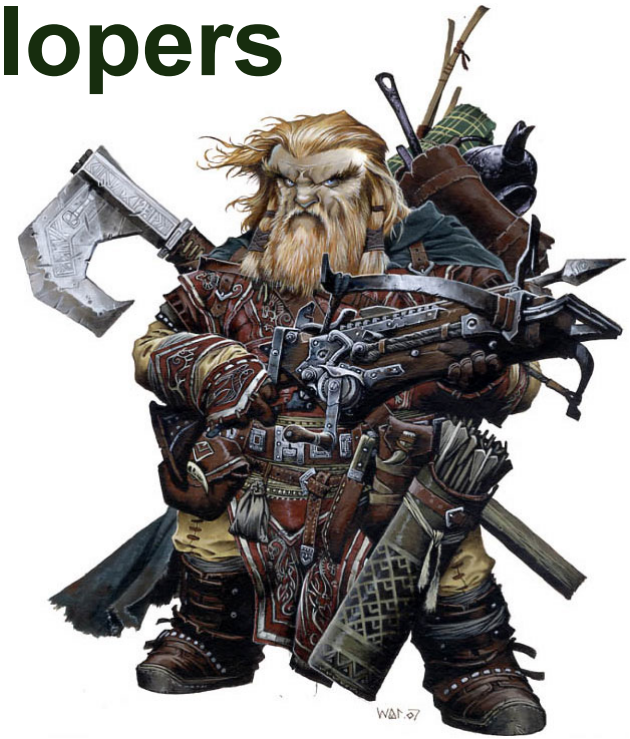
Formal Methods Practitioners
vs
Kernel Developers



Standard Kernel Design

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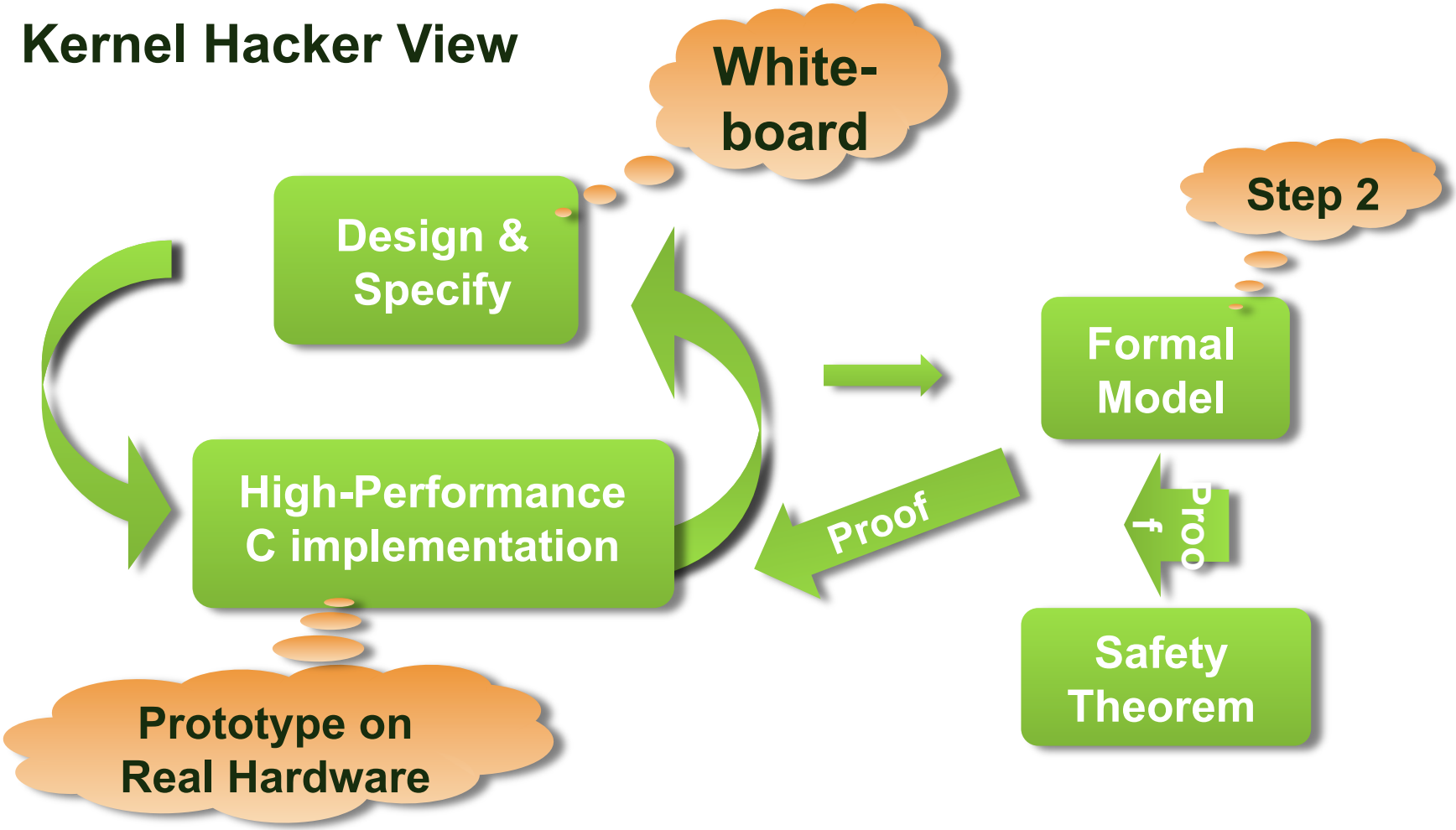
Kernel Hacker View



Formal Design

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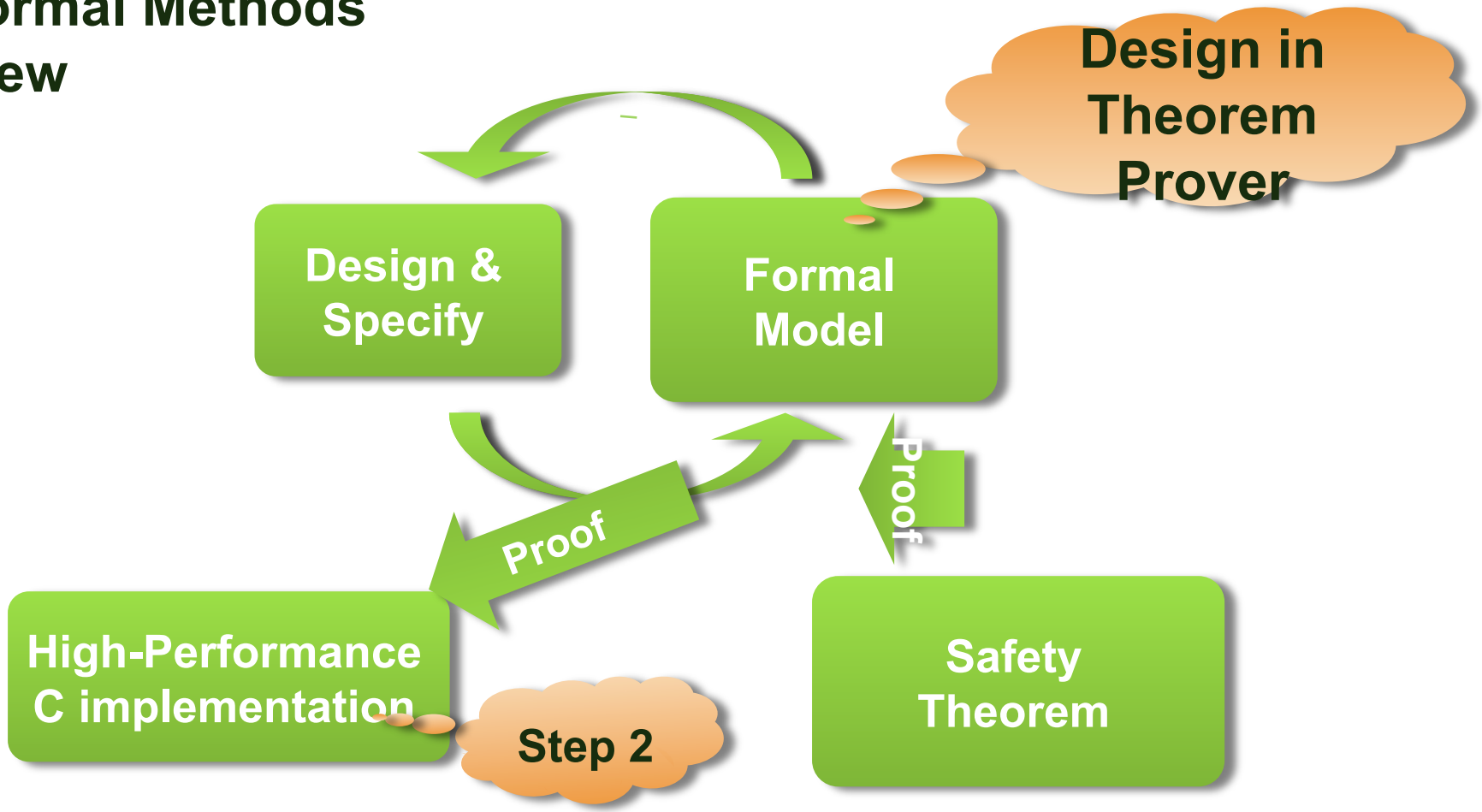
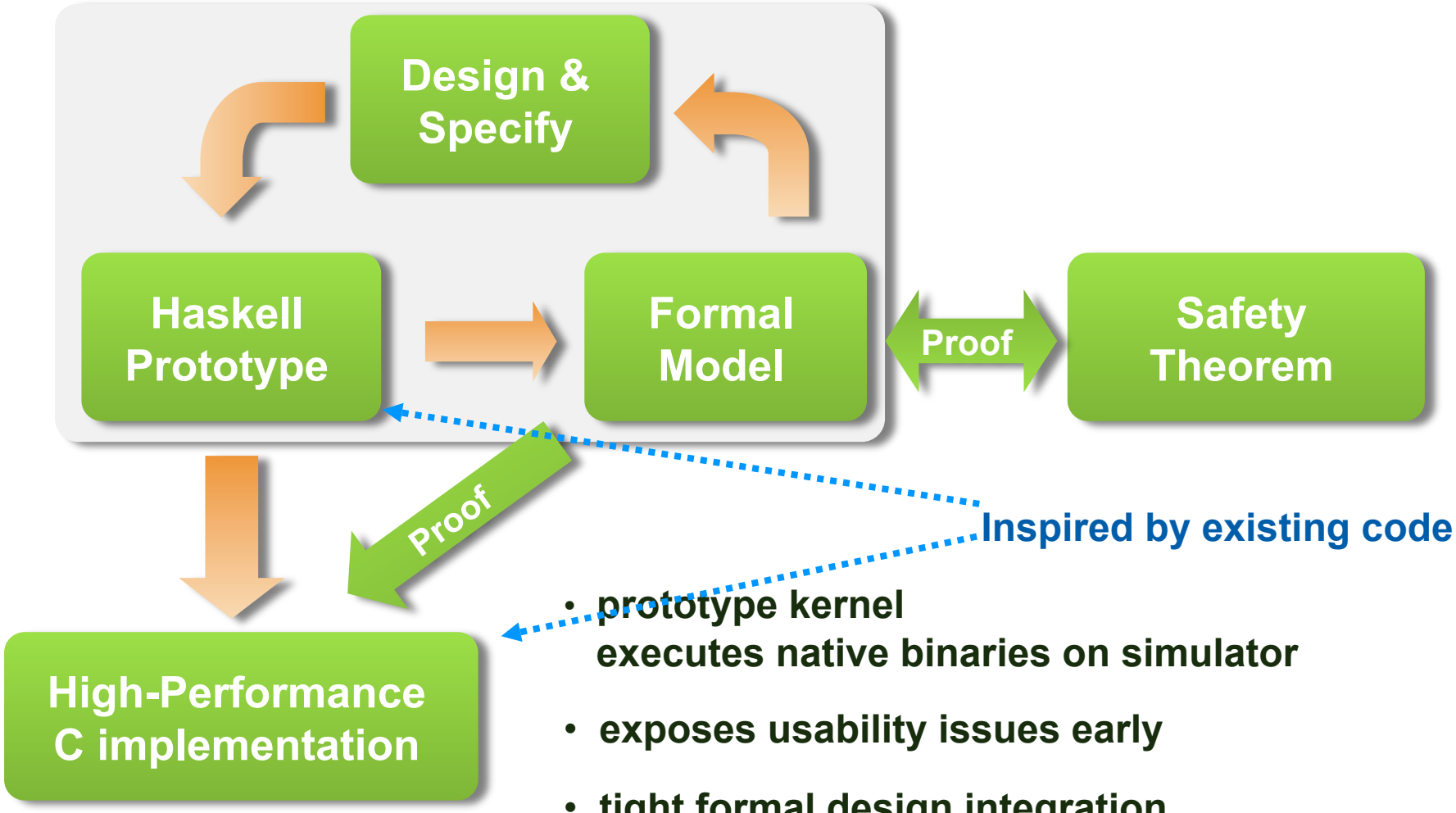
Formal Methods View



Iterative Design and Formalisation



- prototype kernel
  executes native binaries on simulator
- exposes usability issues early
- tight formal design integration

Kernel Design for Verification

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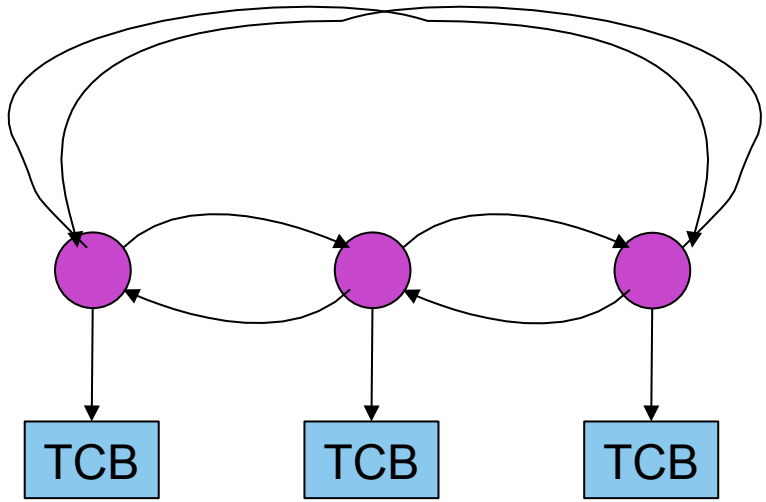
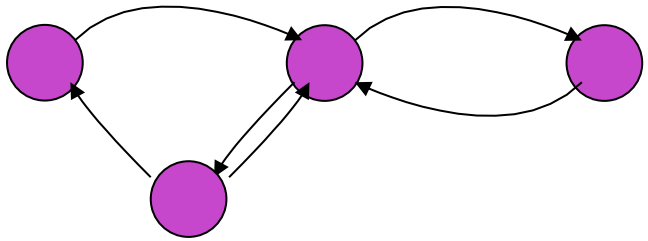
- Main objective: minimise complexity
  - global invariants must be proven for each state change
  - must prove pre- and post-conditions for statements/blocks
  - effort determined by complexity of conditions and state change
- … without sacrificing performance
- Affects design in many ways
  - global variables, side effects
  - kernel memory management
  - concurrency and non-determinism
  - I/O

Global Variables

- Not a difficulty per se, but potential source of complexity
- Eg: scheduler queue as doubly-linked list
  - show that
    - all pointers are to valid nodes
    - front- and back-pointers are consistent
    - nodes point to TCBs

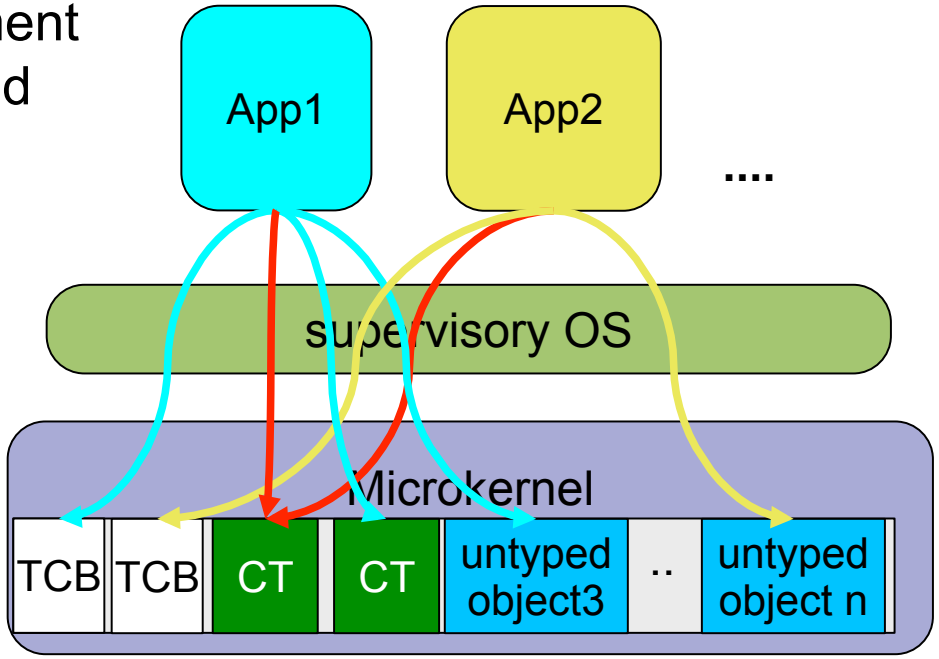


- Requires proof that any pointer operation maintains invariants
- Challenge is temporary violation
  - eg adding a node
  - requires ensuring atomicity



Kernel Memory

- seL4 kernel memory management model pushes policy to userland
  - aids verification
  - need to ensure strict hierarchy
  - capability derivation tree
- Challenge is re-use
  - most difficult part of verification!
  - use derivation tree to detect all references
  - global data structure that requires invariants in all parts of the system



Concurrency

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- Proofs about concurrent programs are inherently hard!
- seL4 strictly limits concurrency to the bare minimum
  - single processor
  - user-level device drivers
  - non-preemptible, event-based
    - single kernel stack
  - interrupt points to limit real-time latencies
    - poll interrupt status
    - insert new kernel event (ahead of user)
    - return to user boundary and re-enter kernel
    - allows maintaining all invariants

Concurrency

- Preempting object destruction
- Keep one cap as zombie during object cleanup
  - only retained to reference partially cleaned-up object
  - stores state of cleanup, maintaining invariants
  - attempt by preemptor to remove zombie can just execute

- Exceptions in kernel
- Prevent memory exceptions
  - ensure kernel page tables are complete
  - map into every address space
- Disallow other exceptions
  - verification is its own friend

I/O

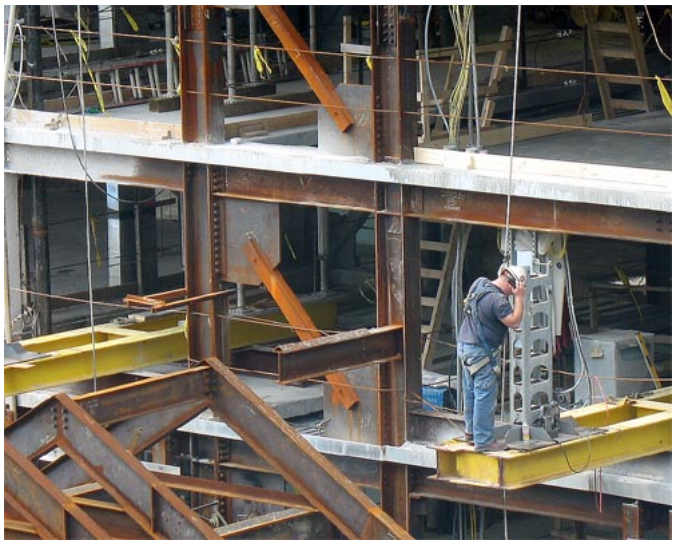
- Mostly a non-issue
  - user-level drivers
    - IOMMU support for DMA security
  - non-preemptible kernel
- Exception is timer tick
  - essentially a source of interrupts
  - handled in-kernel as separate event
  - no real complication

Lessons for Kernel Design

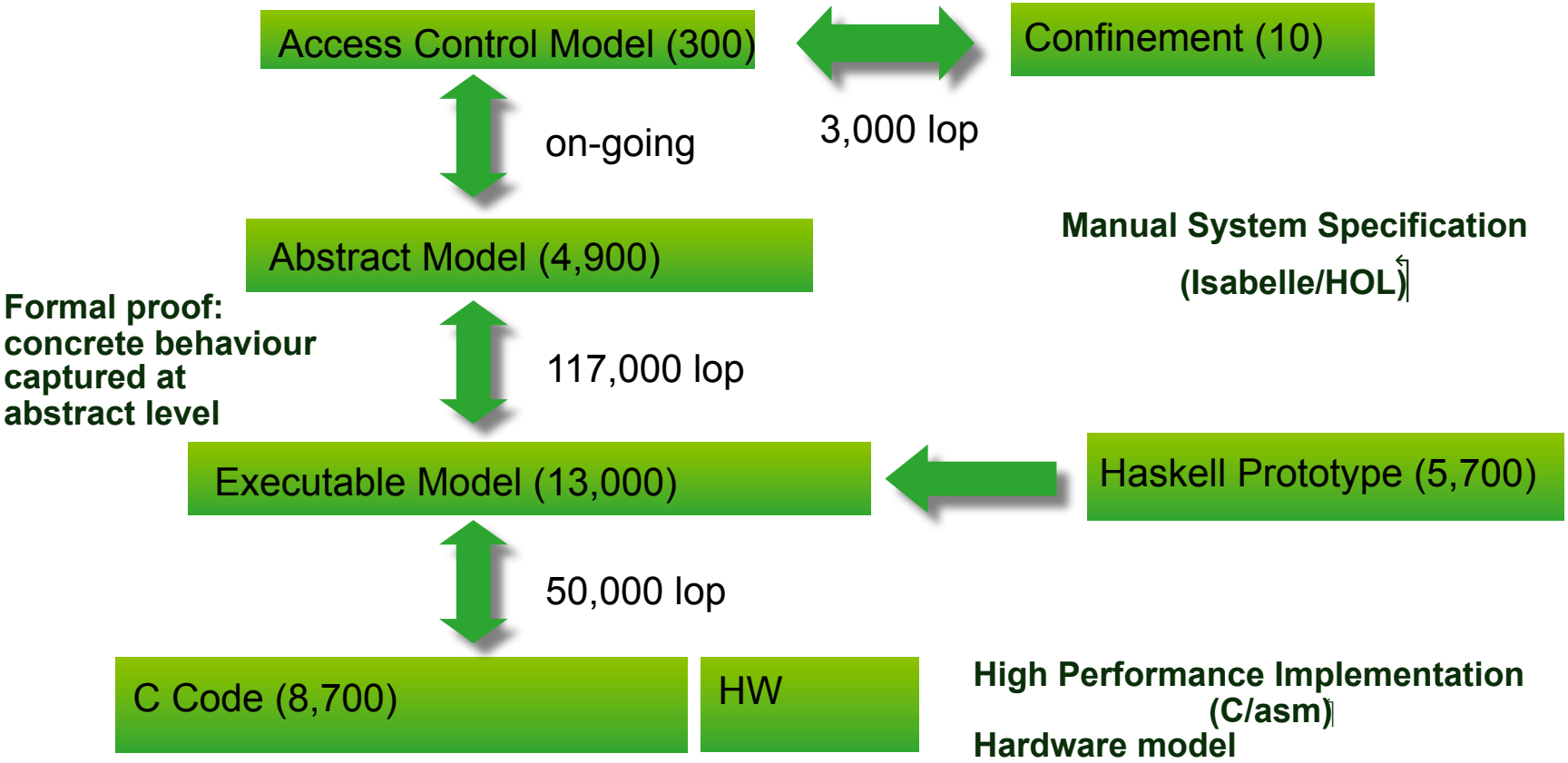
- Need to reduce complexity forced simple and clean design
  - beneficial even with traditional validation
  - does not necessarily impact performance
- Some design decision beneficial for other reasons too
  - single kernel stack for memory footprint
  - interrupt handling by polling has performance advantages

seL4 Status

- seL4 operational on ARM11 and x86
  - runs Linux etc...
- Performance in line with other L4 kernels
  - 300 cycle IPC (ARM11 with IPC fastpath in C)
  - Exception handling slow (no fastpath yet)
    - Virtualization performance sub-obtimal
- Multiprocessor version in progress
- Userland being developed
  - Eg memory-management



Proof of Functional Correctness



Correctness

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

record cap =
  entity :: entity_id
  ri
```

```
reco
```

```
type
```

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

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

```
schedule :: Kernel ()
schedule = do
```

```
void
setPriority(tcb_t *tptr, prio_t prio) {
    prio_t oldprio;

    if(thread_state_get_tcbQueued(tptr->tcbState)) {
        oldprio = tptr->tcbPriority;
        ksReadyQueues[oldprio] = tcbSchedDequeue(tptr, ksReadyQueues[(
        if(isRunnable(tptr)) {
            ksReadyQueues[prio] = tcbSchedEnqueue(tptr, ksReadyQueues
        }
        else {
            thread_state_ptr_set_tcbQueued(&tptr->tcbState, false);
        }
    }

    tptr->tcbPriority = prio;
}

void
yieldTo(tcb_t *target) {
    target->tcbTimeSlice += ksCurThread->tcbTimeSlice;
```

ecification
L)

d
Thread

be (5,700)

mance Implementation
(C/asm)
odel

Formal Verification Summary

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Kinds of properties proved

- Behaviour of C code is fully captured by abstract model
- Behaviour of C code is fully captured by executable model
  - Can prove many interesting properties on higher-level models
- Kernel never fails, behaviour is always well-defined
  - assertions never fail
  - will never de-reference null pointer
  - cannot be subverted by misformed input
- All syscalls terminate, reclaiming memory is safe, ...
- Well typed references, aligned objects, kernel always mapped…
- Access control is decidable

Effort:

- Average 6 people over 5.5 years

Verification vs Certification

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Common Criteria: Military-Strength Security

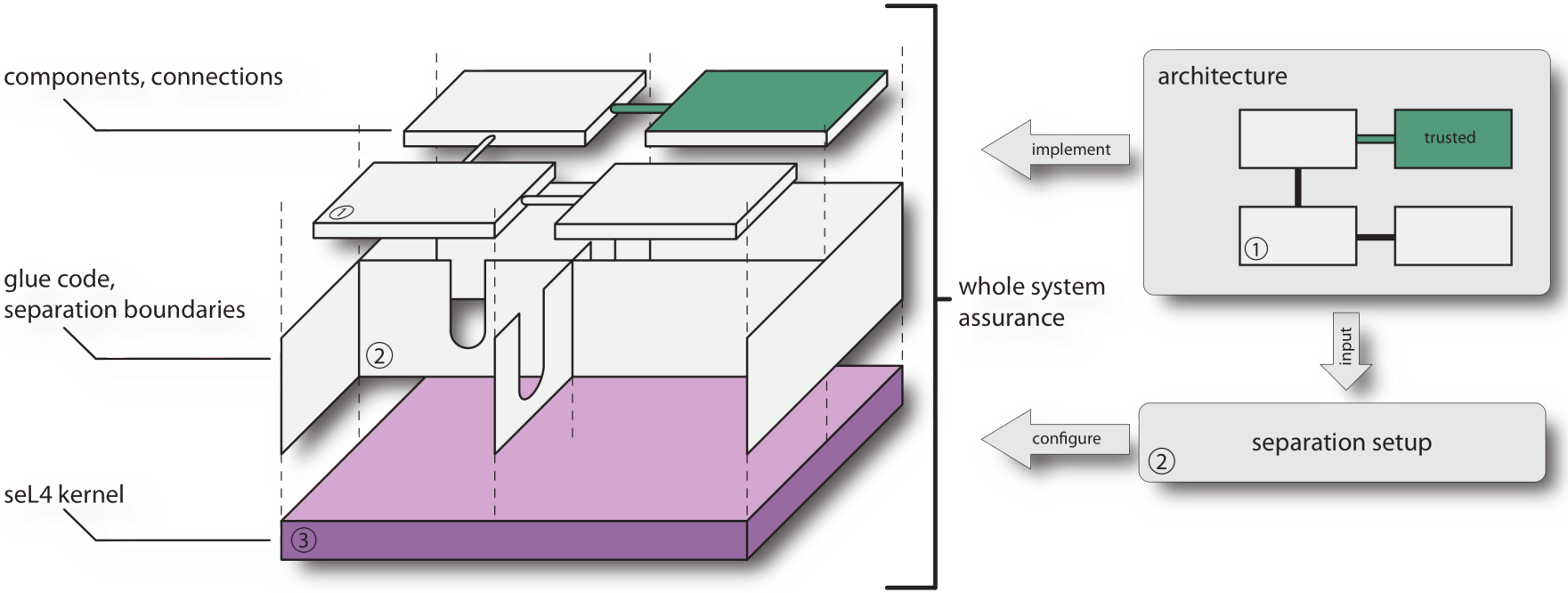
Evaluation Level	Requirements	Functional Specification	Top Down Design	Imple-mentation	Cost
EAL1		Informal			
EAL2		Informal	Informal		
EAL3		Informal	Informal		
EAL4		Informal	Informal	Informal	
EAL5		Semi-formal	Semi-formal	Informal	
EAL6	Formal	Semi-formal	Semi-formal	Informal	1K/LoC
EAL7	Formal	Formal	Formal	Informal	
seL4	Formal	Formal	Formal	Formal	0.6K/LoC

Phase Two: Full-System Guarantees

- Achieved: Verification of microkernel (8,700 LOC)

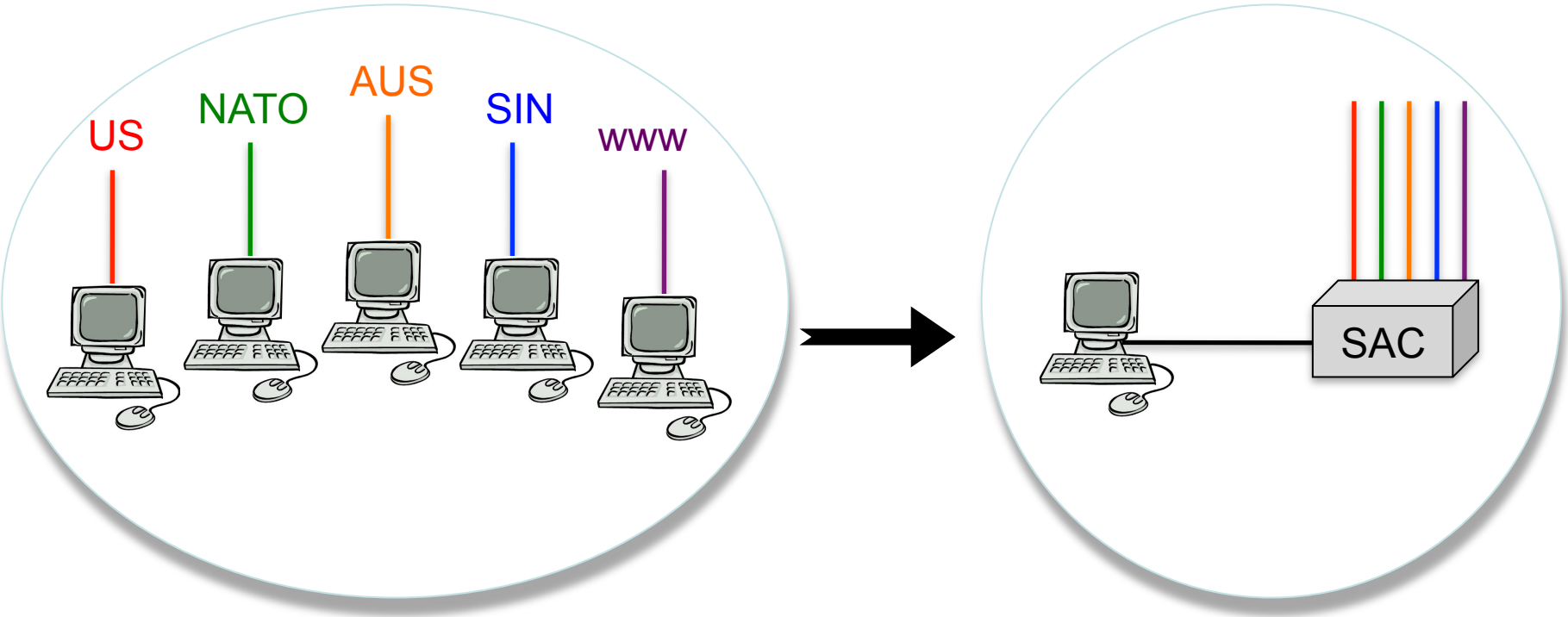
- Next step: Guarantees for real-world systems (1,000,000 LOC)

Overview of Approach

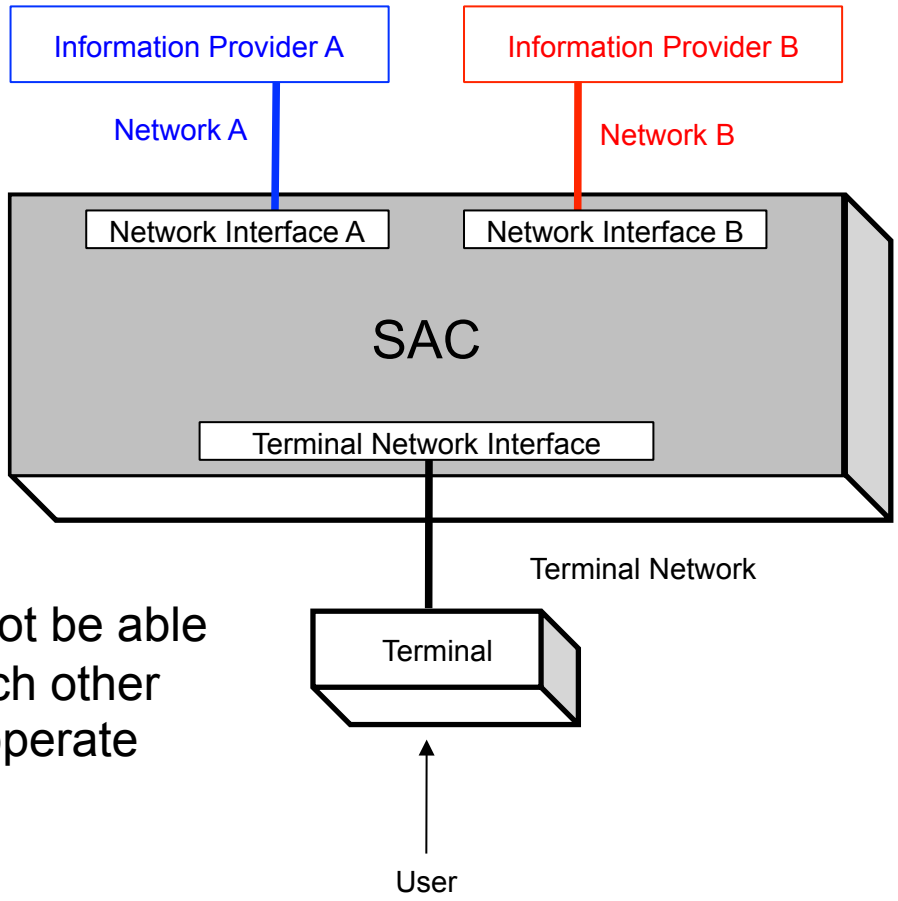


- Build system with minimal TCB
- Formalize and prove security properties about architecture
- Prove correctness of trusted components
- Prove correctness of setup
- Prove temporal properties (isolation, WCET, …)
- Maintain performance

Proof of Concept: Secure Access Controller

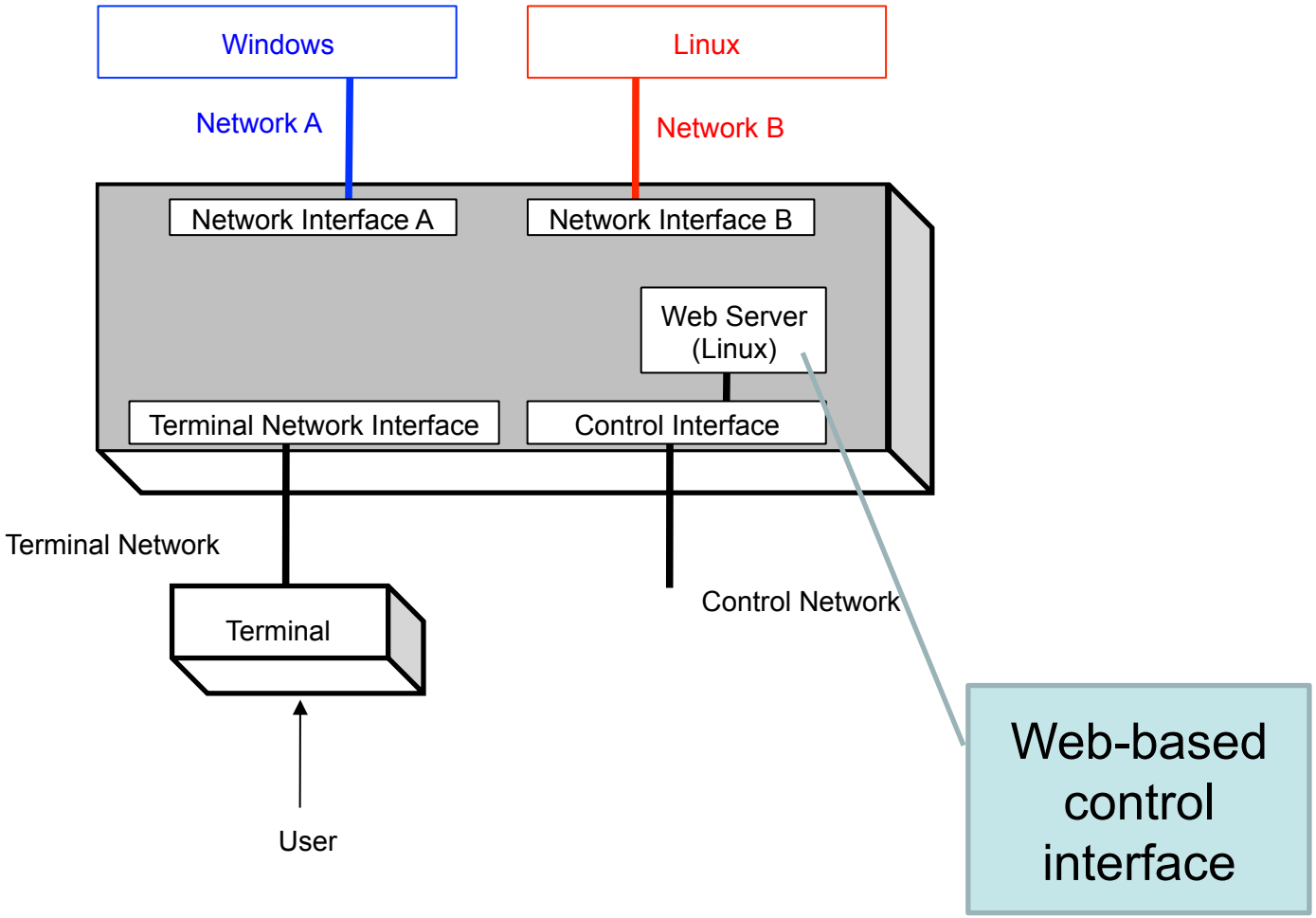


SAC Aim

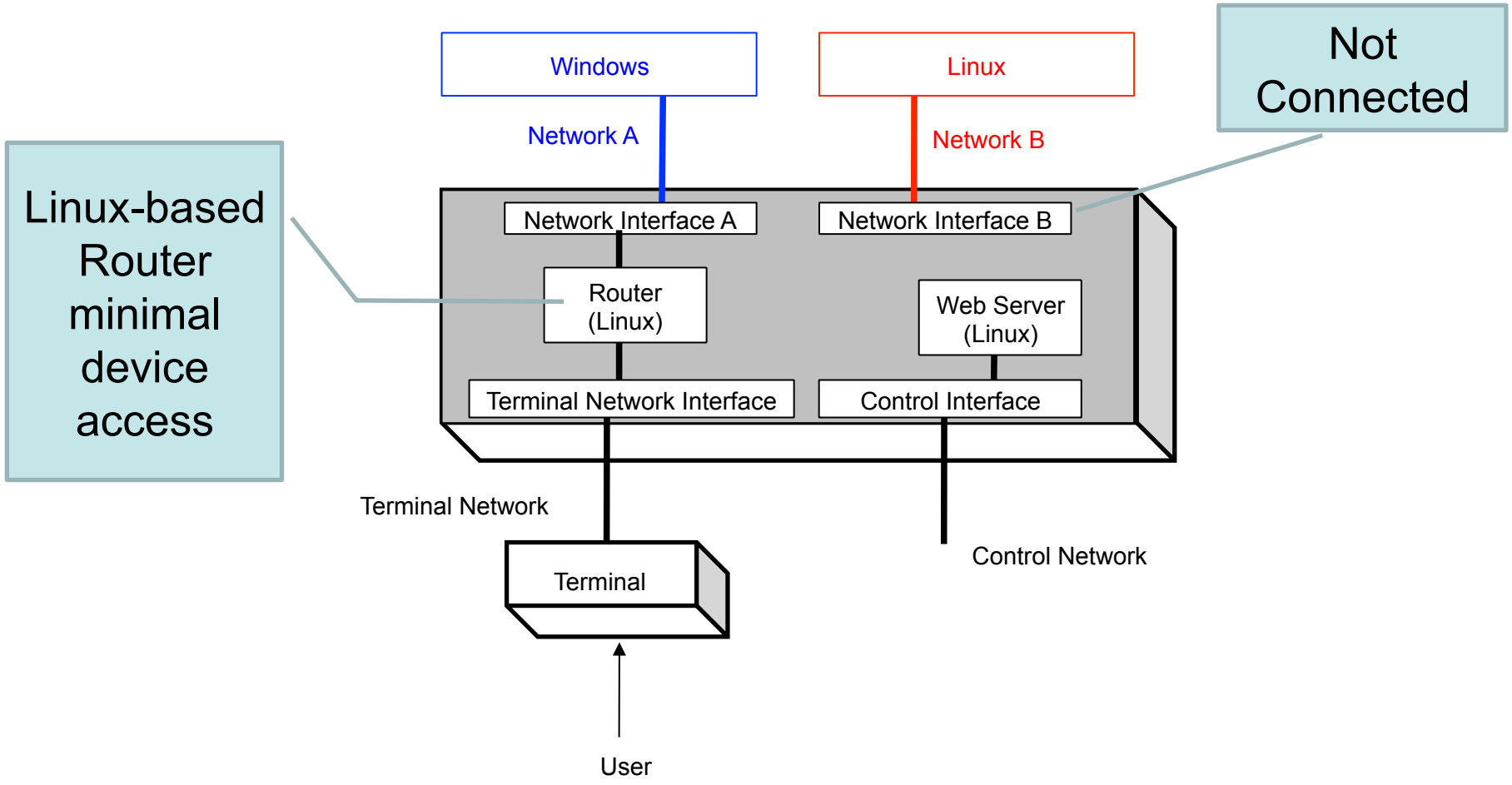


Provider A & B should not be able to leak info between each other even if they actively cooperate

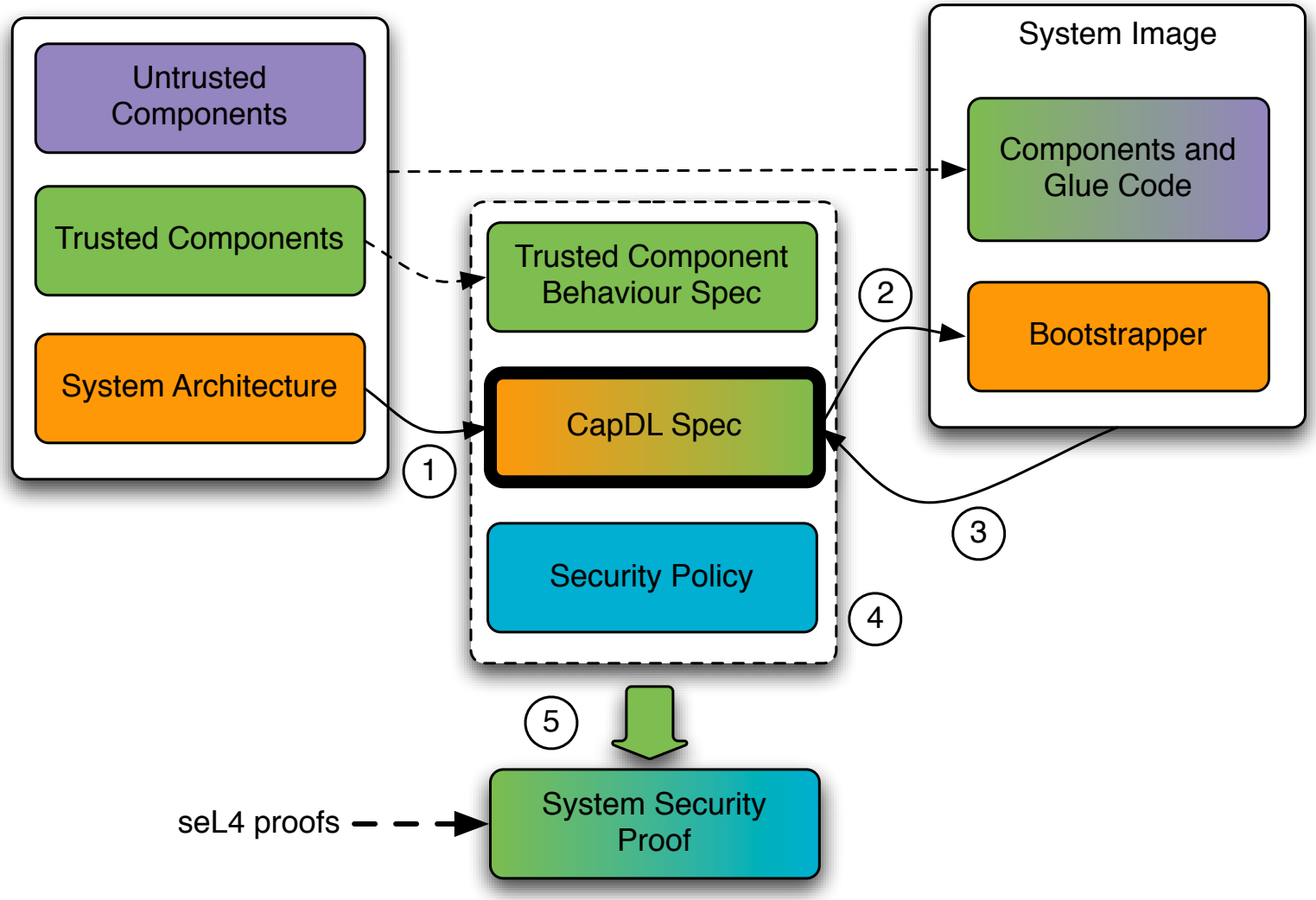
Our Solution Overview



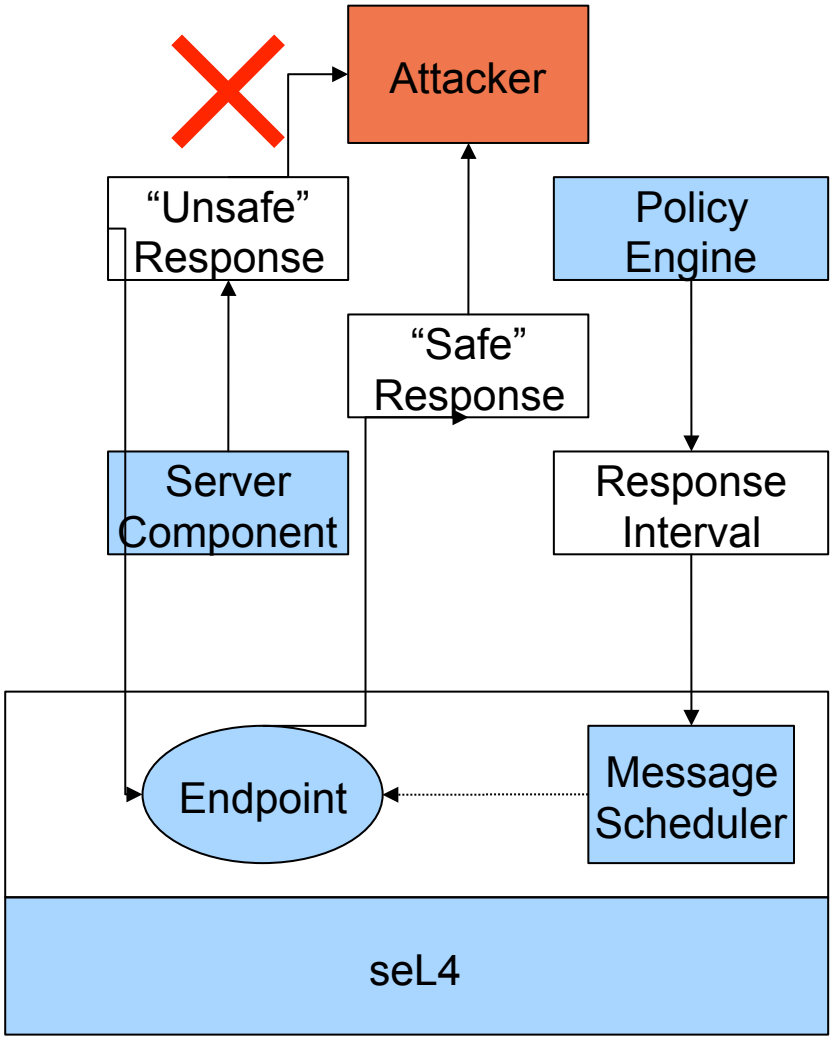
Solution Overview



Specifying Security Architecture



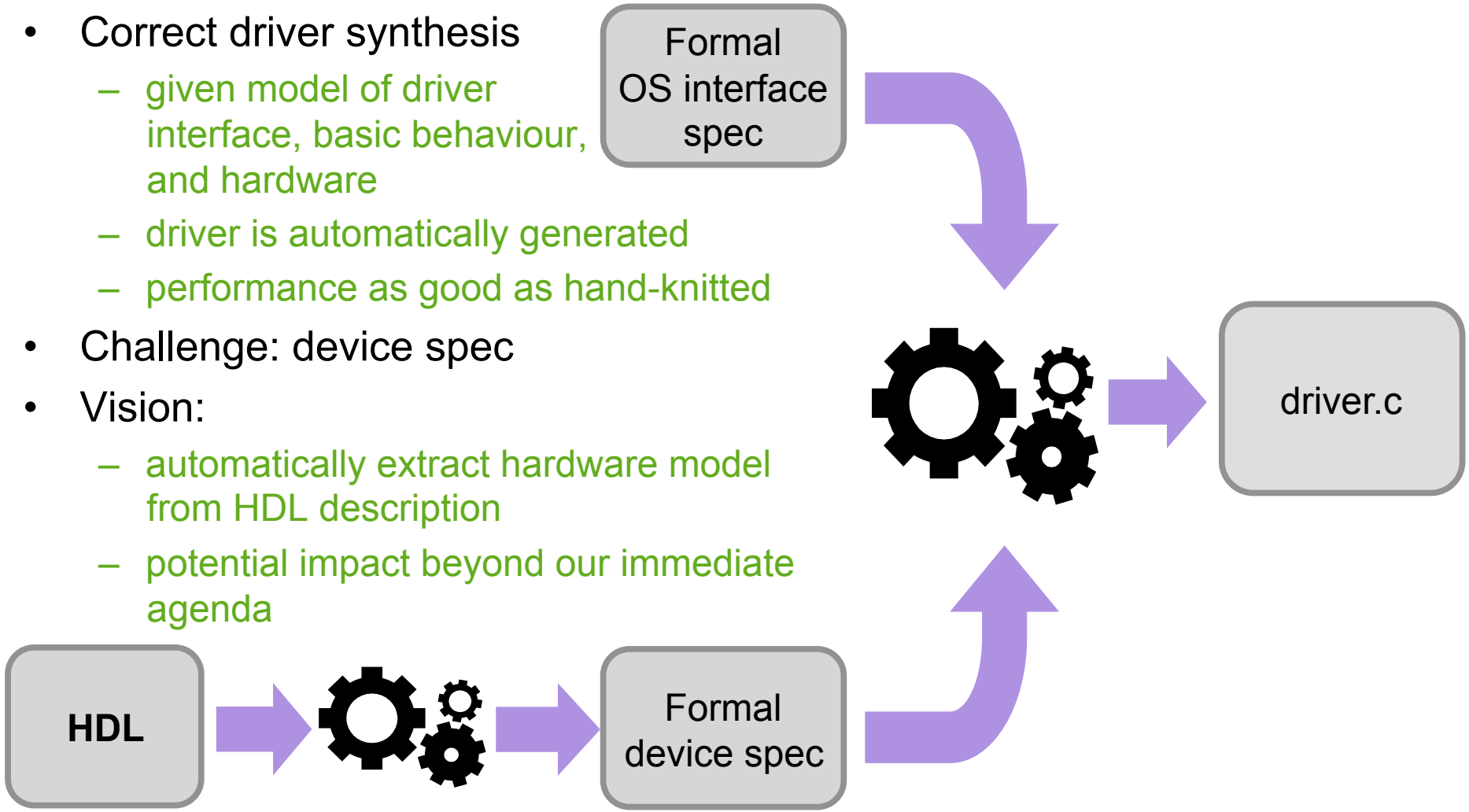
Component Side-Channel Mitigation



- Component response time variability exposes secrets.
- Add a response time control policy.
- Real-time scheduling gives a mechanism.
- seL4 endpoints give a framework.

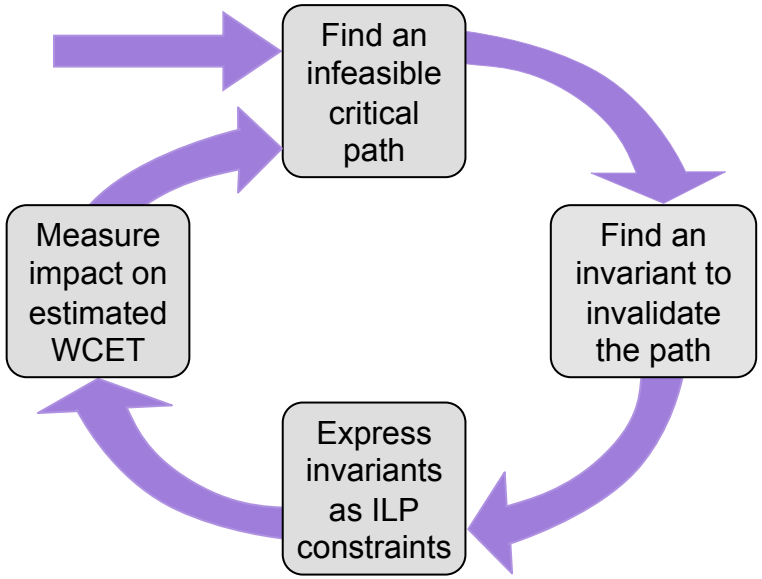
Trusted Synthesized Drivers

- Correct driver synthesis
  - given model of driver interface, basic behaviour, and hardware
  - driver is automatically generated
  - performance as good as hand-knitted
- Challenge: device spec
- Vision:
  - automatically extract hardware model from HDL description
  - potential impact beyond our immediate agenda

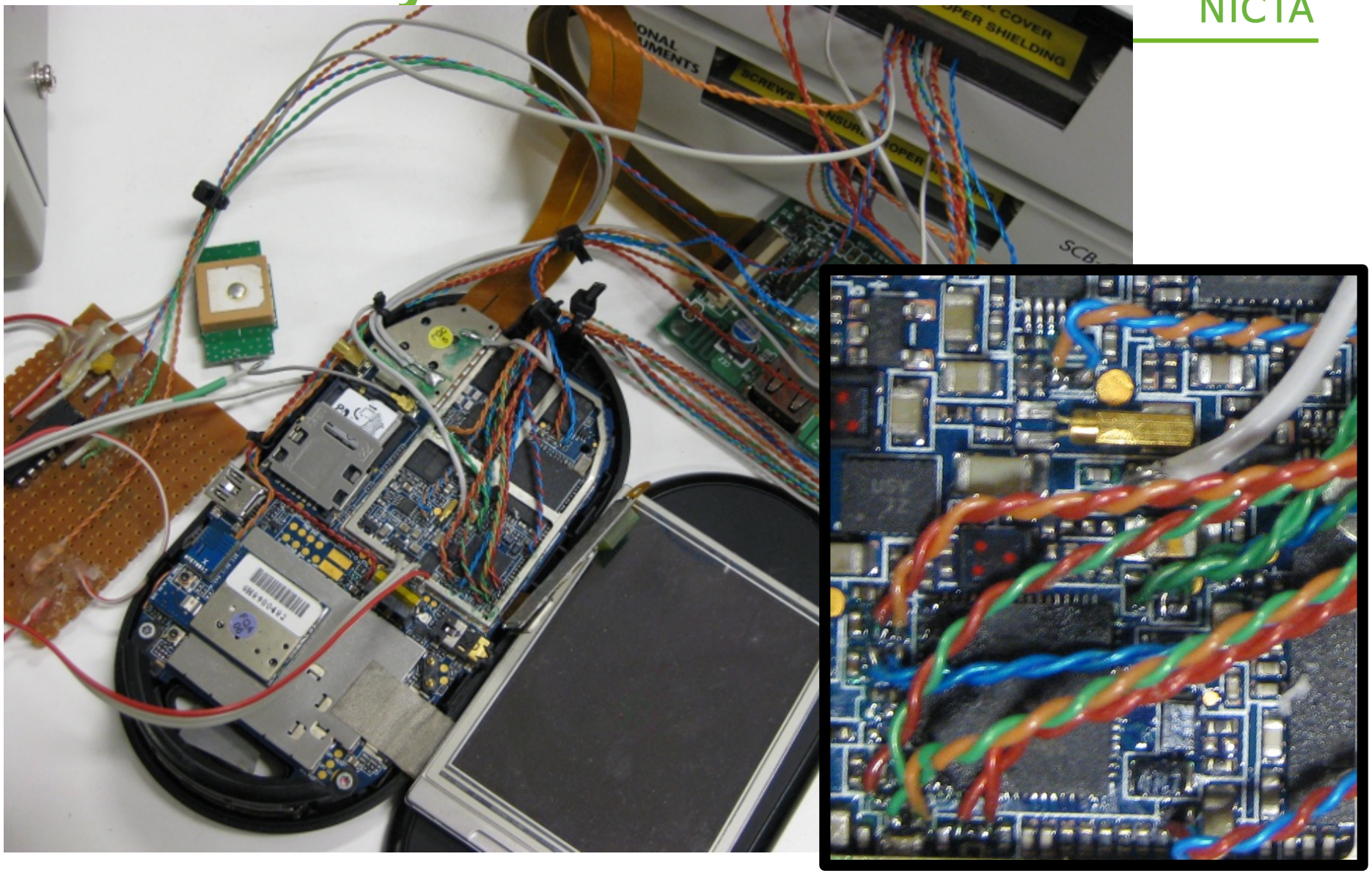


Kernel Worst-Case Execution Time

- seL4 is small as an OS kernel (9 kLOC)
  - … but large as an object for WCET analysis
  - … and full of performance optimisations
- However, we know a lot about it (in a very formal way!)
  - Plenty of invariants proved during verification
  - E.g. loop iteration counts, non-interference
- Can make use of this for WCET analysis
  - Collaboration with WCET experts at NUS (Abhik Roychoudhury)



Power Analysis



Energy Management

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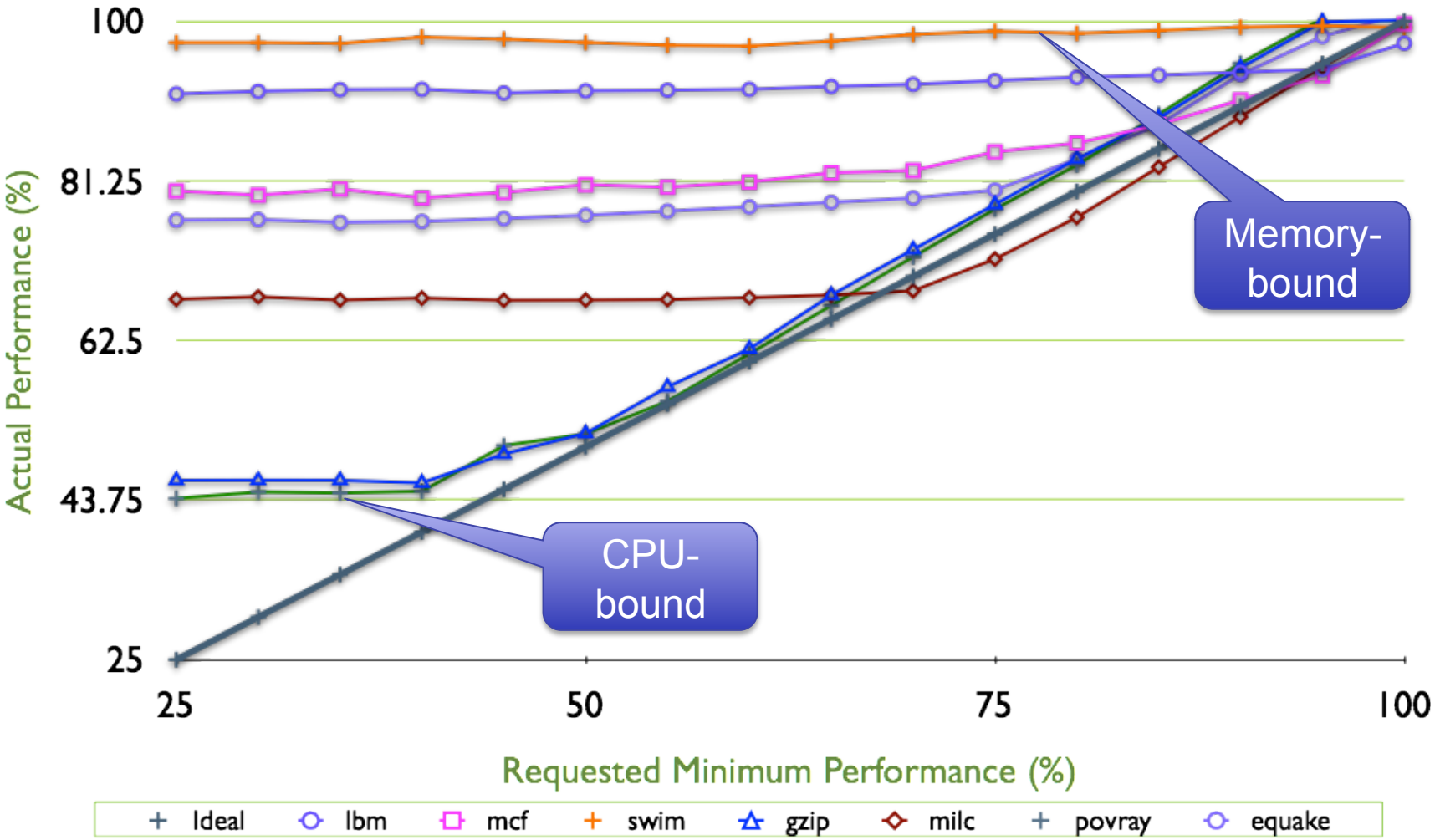
Koala: accurate model of CPU and memory energy use

- Driven by performance counters
- Model predicts energy consumption and relative execution speed
  - at present frequency
  - at different frequencies
- Accurately predicts energy- and performance response to DVFS
  - within a few %
- Can use this for *informed* energy-management decisions
- Developed OS-level policy framework

Accuracy of Approach



How About Peripherals?

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Exploring approach similar to DVFS work:

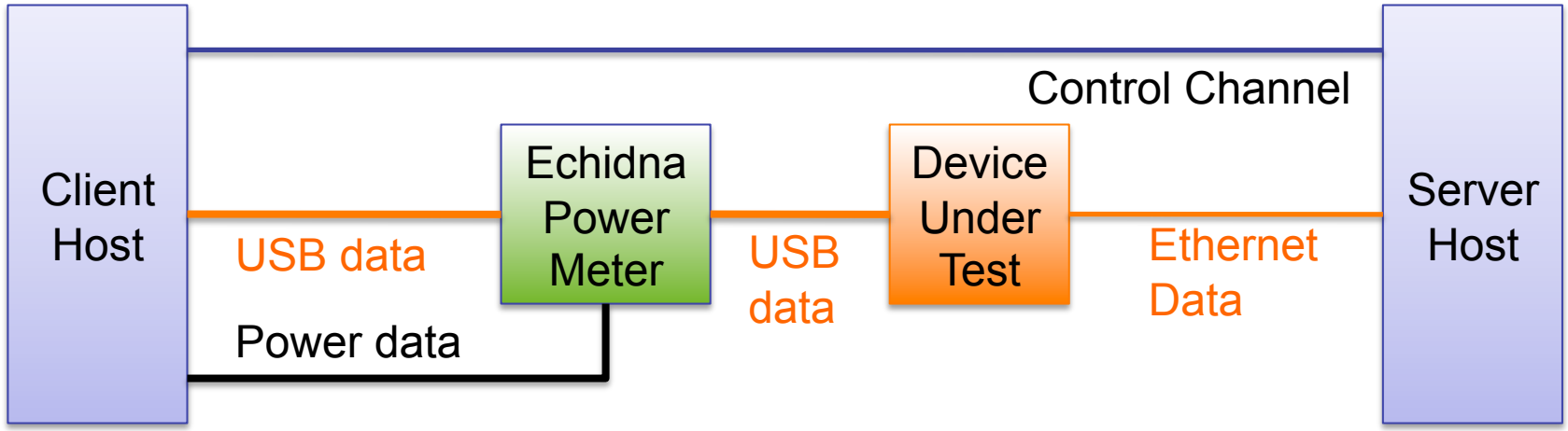
- Assume we can predict device energy from known workload
- General energy model of device parameterised by I/O events
  - Observable by device driver
  - Device-class specific, device-independent
- Model gauged through (random) characterisation work load
  - Varying data rates and packet sizes
  - Using linear regression on model parameters
- Evaluated with evaluation benchmark suite

Example: Network Devices

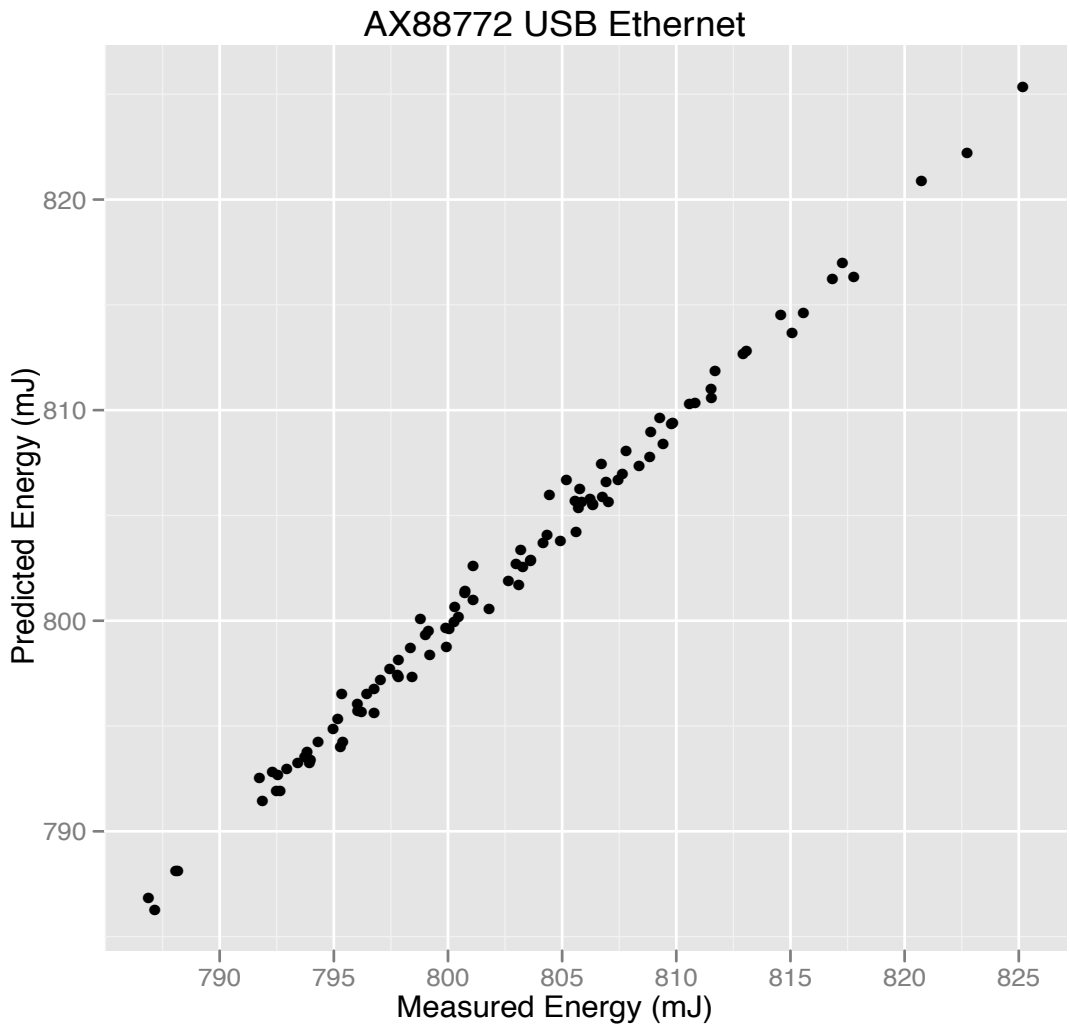
Energy model:

$$P = P_0 + E_1 b_r + E_2 b_w + E_3 p_r + E_4 p_w + P_i i$$

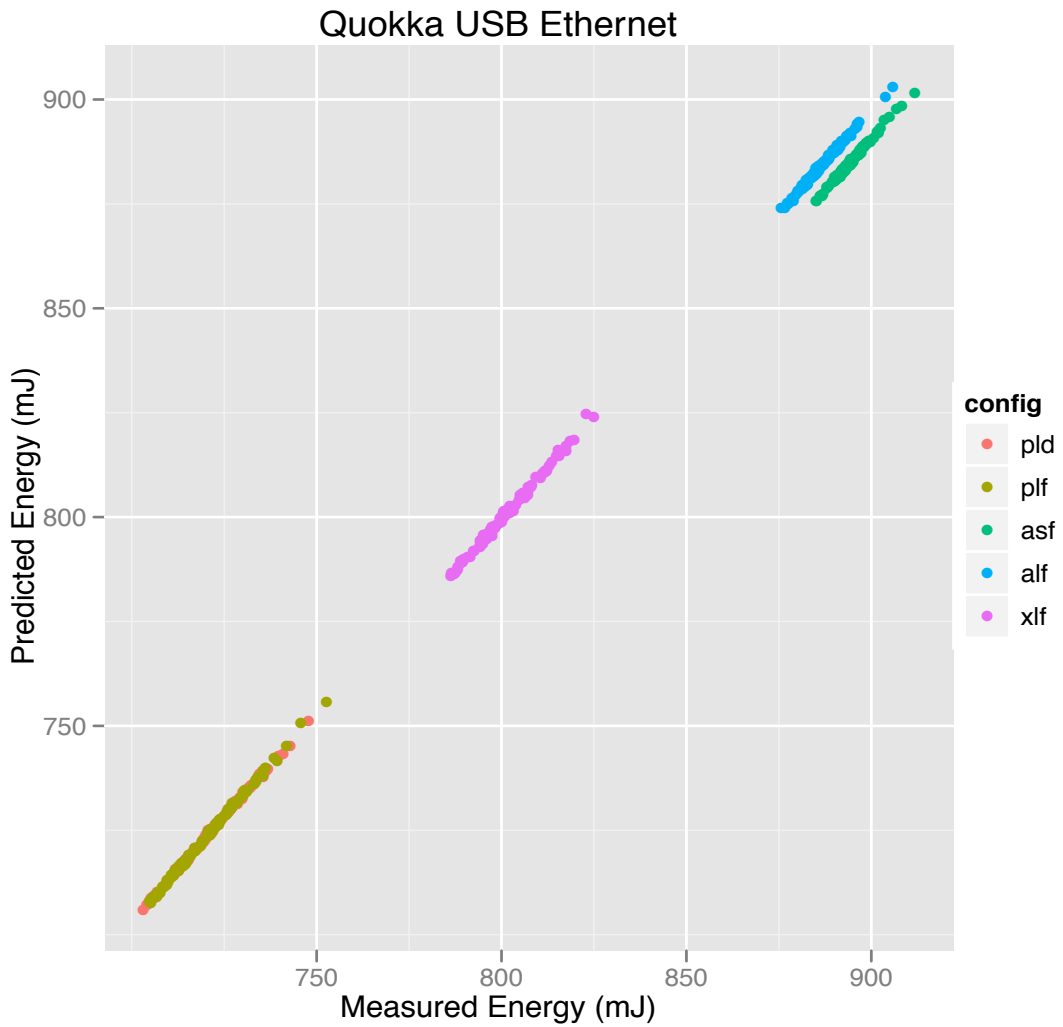
- b_r, b_w: data (byte) read, write rate
- p_r, p_w: packet read, write rate
- i: 1=active, 0=idle (accounts for idle state)



USB Ethernet Device



Several USB Ethernet Devices

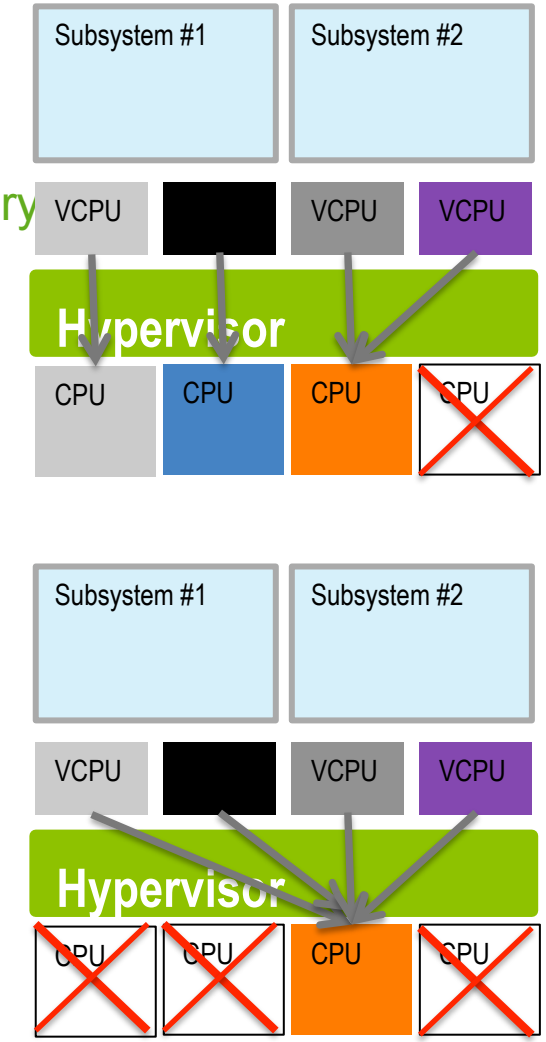


Device Power

- Device class family driver collects energy stats
- Initial results look very promising
  - USB-connected network devices
    - Ethernet, WiFi
  - Also did (earlier) Flash storage devices
    - Less mature approach, re-doing now
- Work in progress, planning to look at other device classes
  - Disks (incl head movement)
  - Audio (speakers)

Multicore Energy Management

- Additional degree of freedom
  - DVFS + sleep states + core shutdown
  - Hypervisor supports transparent, temporary consolidation of cores
    - Unneeded cores turned off to reduce power
- Different tradeoffs
  - Performance vs power close to linear
- Important to manage cores globally
  - In average more cores off than with per-guest management
    - Can use deeper sleep state
    - Less overall energy use



UNSW OS Students Pipeline