COMP9242 Advanced OS

S2/2016 W12: **Local Systems Research**

@GernotHeiser

UNSW AUSTRALIA

Never Stand Still | Engineering | Computer Science and Engineering

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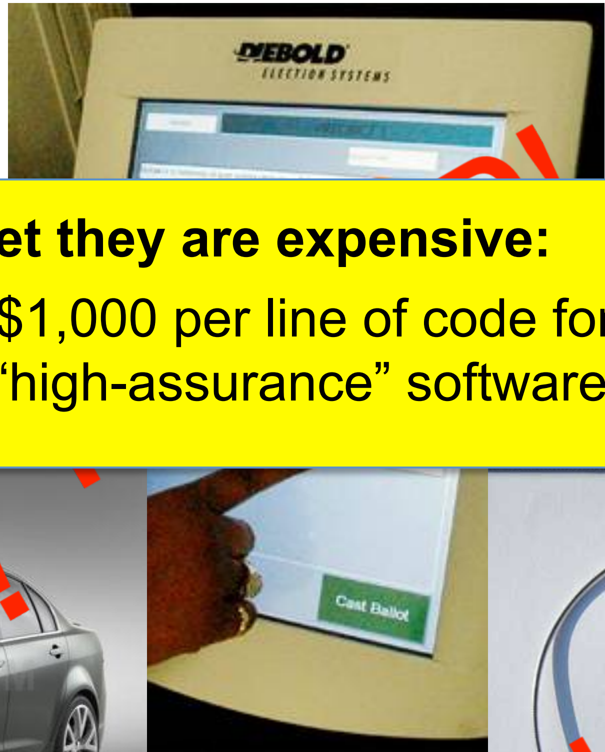
Present Systems are *NOT* Trustworthy!



Yet they are expensive:

- $1,000 per line of code for "high-assurance" software!

Trustworthy Systems Vision

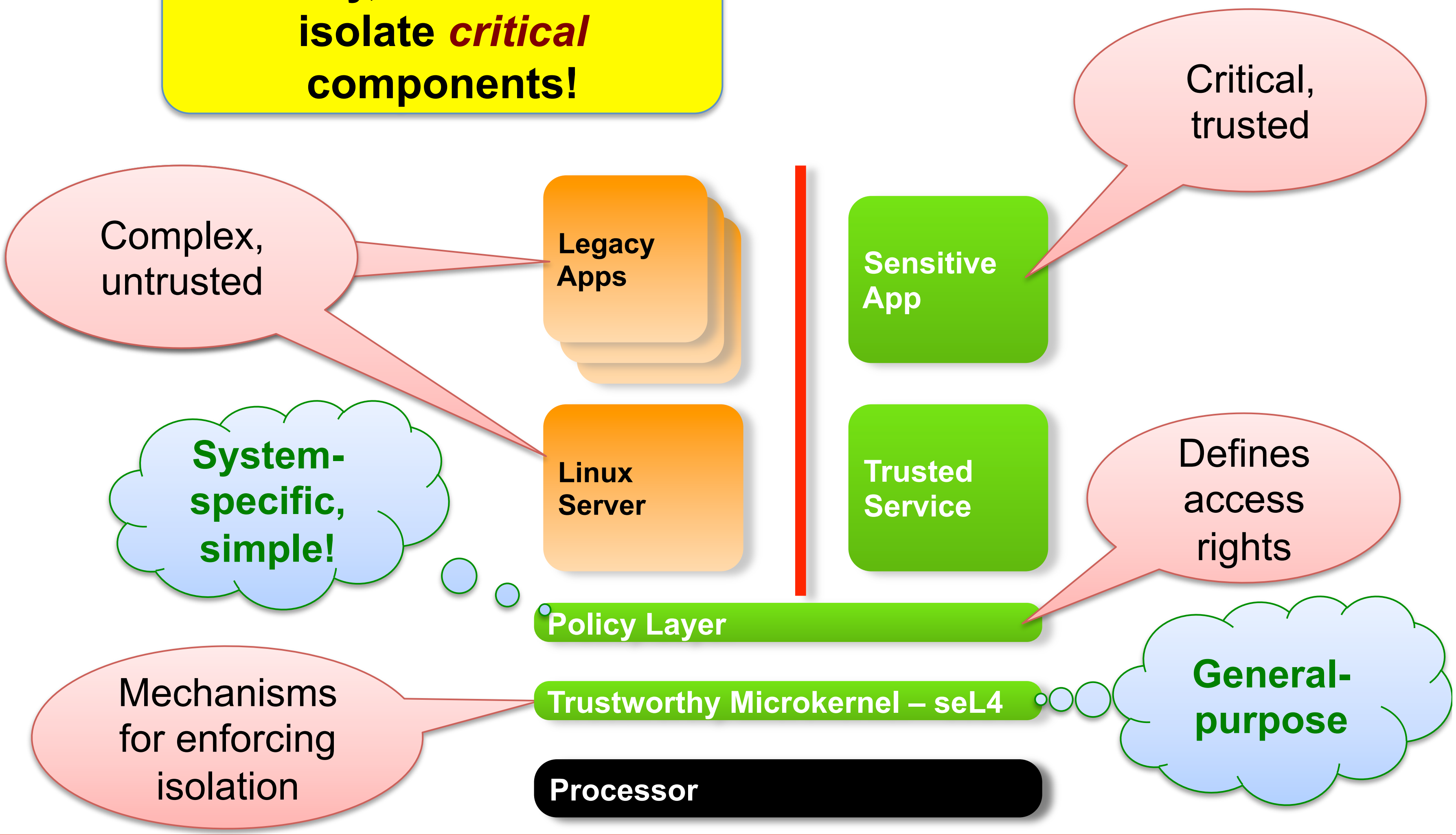
Suitable for real-world systems

We will change the *practice* of designing and implementing critical systems, using rigorous approaches to achieve *true trustworthiness*

Hard *guarantees* on safety/security/ reliability

Isolation is Key!

Identify, minimise and isolate *critical* components!



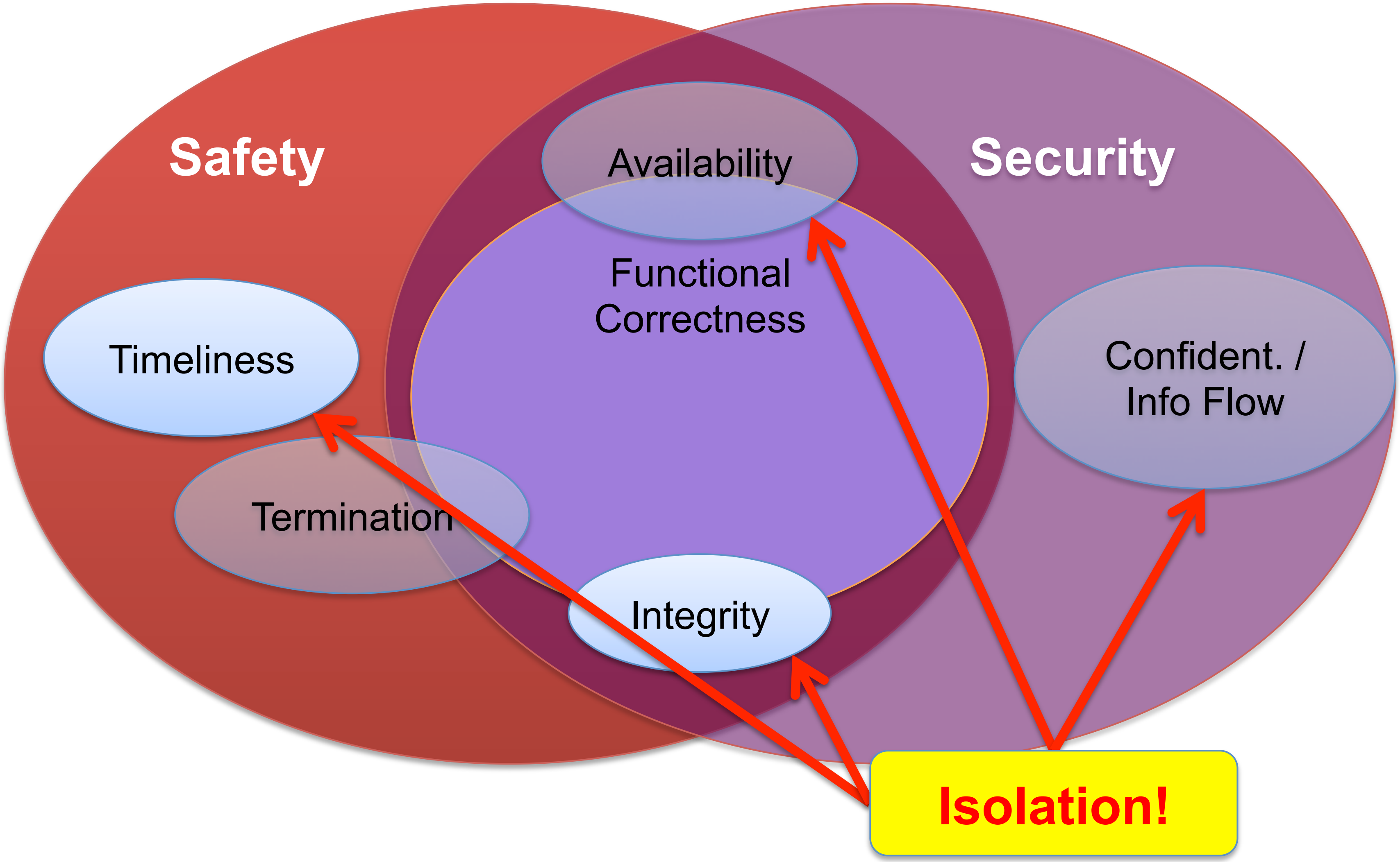
Trustworthy Systems Agenda

1. **Dependable microkernel (seL4) as a rock-solid base**
   – Formal specification of functionality
   – Proof of functional correctness of implementation
   – Proof of safety/security properties

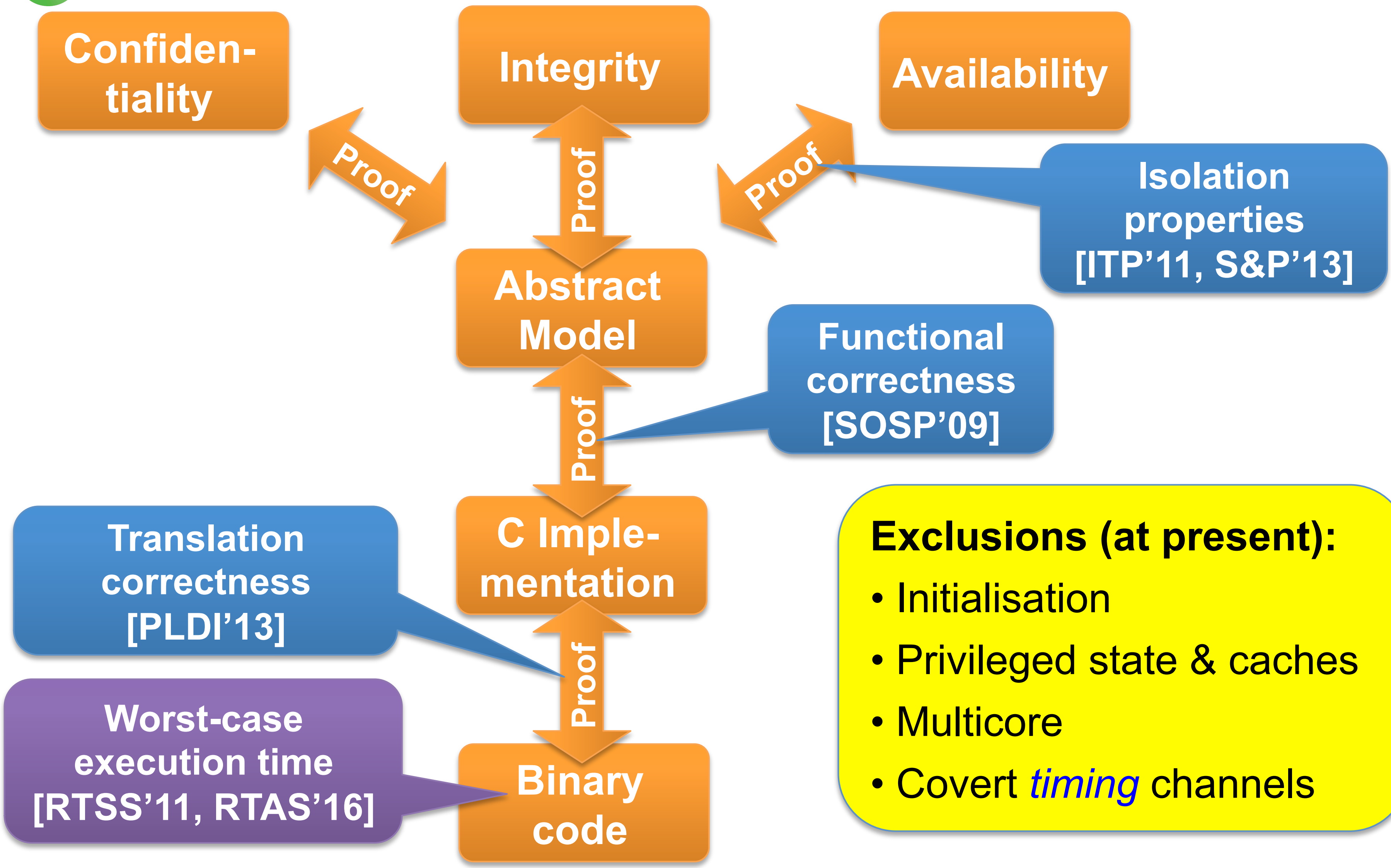
DONE

2. **Lift microkernel guarantees to whole system**
   – Use kernel correctness and integrity to guarantee critical functionality
   – Ensure correctness of balance of trusted computing base
   – Prove dependability properties of complete system
      ○ despite 99 % of code untrusted!

Requirements for Trustworthy Systems



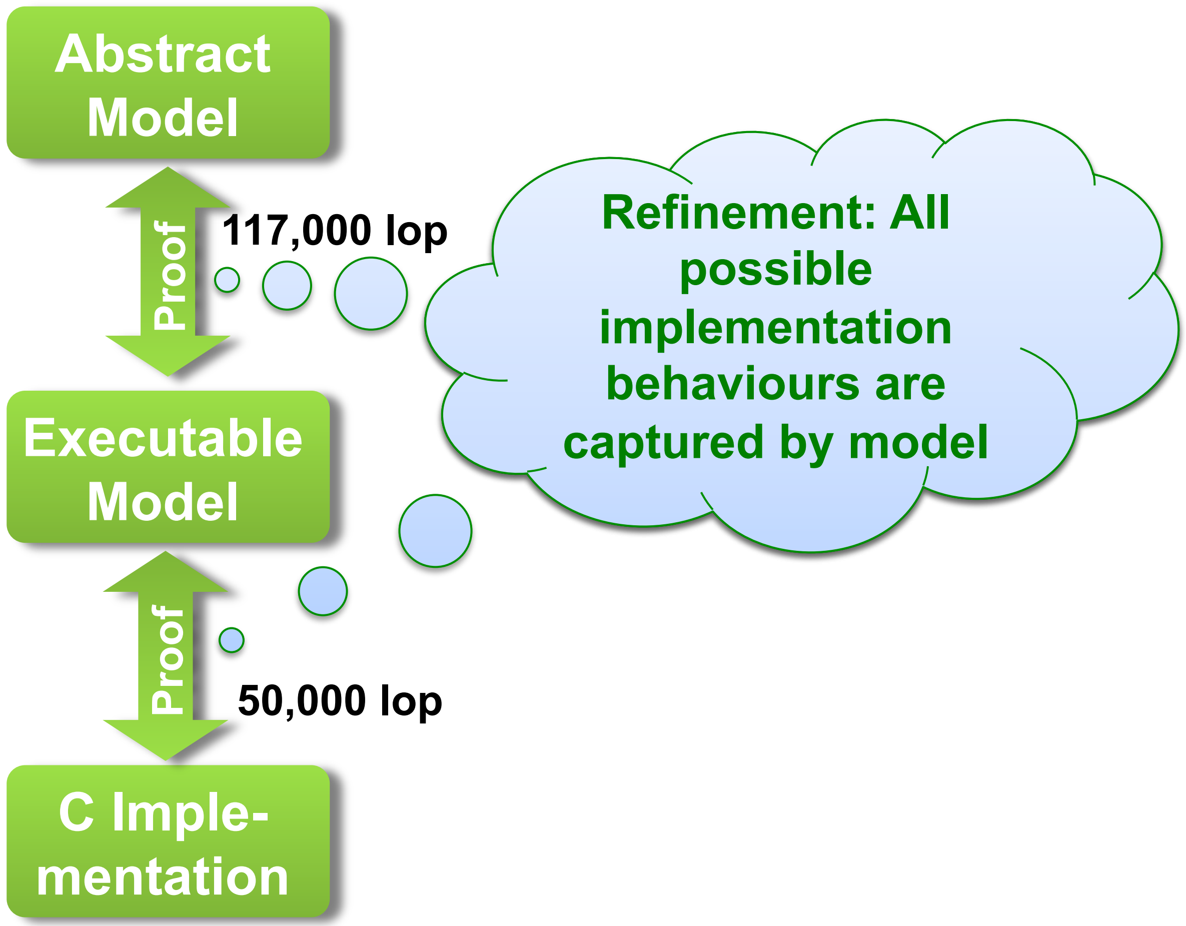
seL4 Provable Security and Safety



Exclusions (at present):

- Initialisation
- Privileged state & caches
- Multicore
- Covert *timing* channels

Proving Functional Correctness



Proving Functional Correctness

```
constdefs
  schedule :: "unit s_monad"
  "schedule ≡ do
     threads ← allActiveTCBs;
     thread ← select threads;
     do_machine_op flushCaches OR return ();
```

```
schedule :: Kernel ()
schedule = do
        action <- getSchedulerAction
        case action of
                                    rThread
                                    Slice curThread
                                    e == 0) chooseThread
```

```
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;
```

MIT Technology Review

10 BREAKTHROUGH TECHNOLOGIES 2011

Share

Crash-Proof Code

Making critical software safer

7 comments

WILLIAM BULKELEY

May/June 2011

Formal Verification Summary

Kinds of properties proved

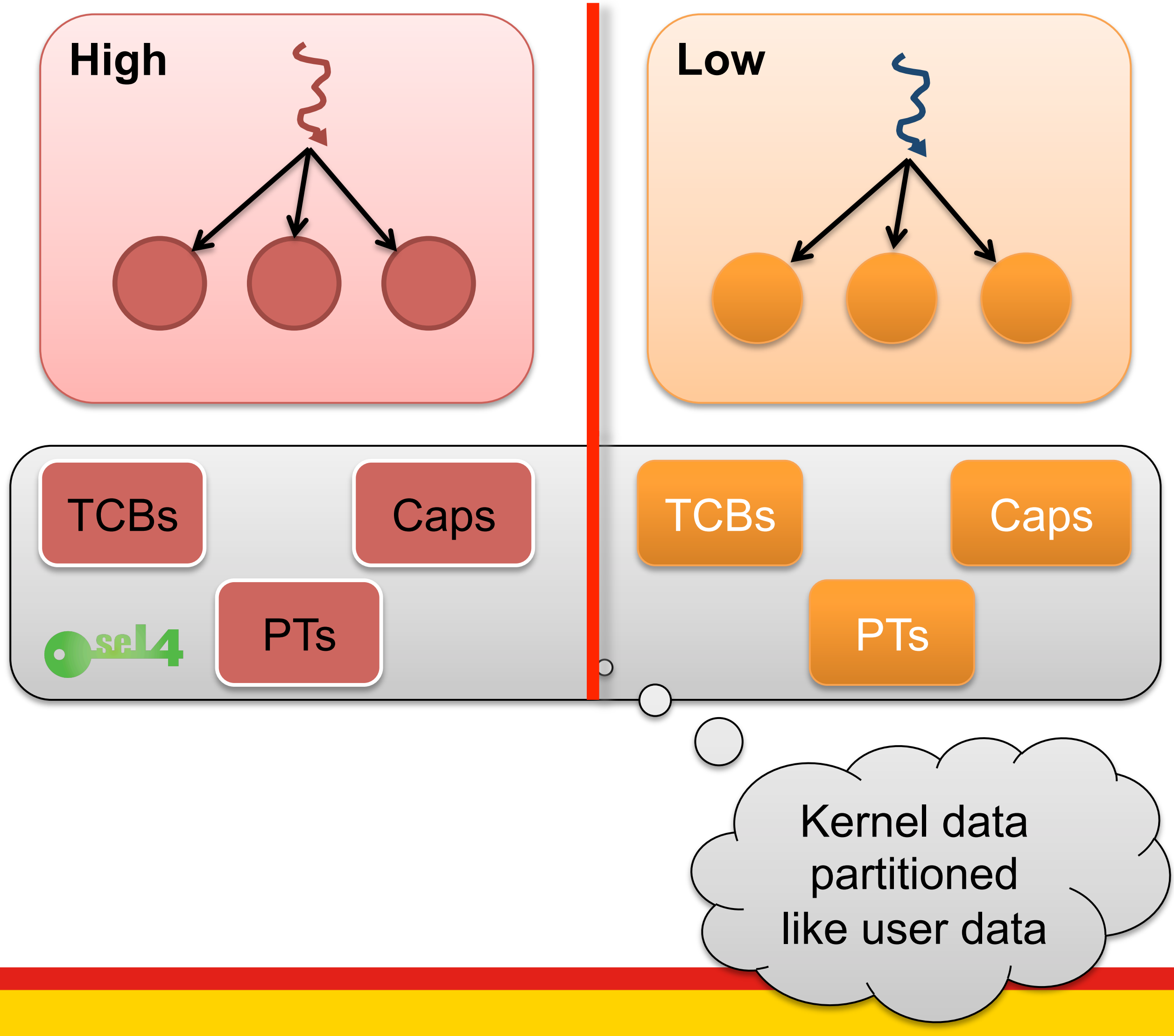
- Behaviour of C code is fully captured by abstract model
- Behaviour of C code is fully captured by executable model
- Kernel never fails, behaviour is always well-defined
  - assertions never fail
  - will never de-reference null pointer
  - cannot be subverted by misformed input
- All syscalls terminate,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

Can prove further properties on abstract level!

Did you find bugs?

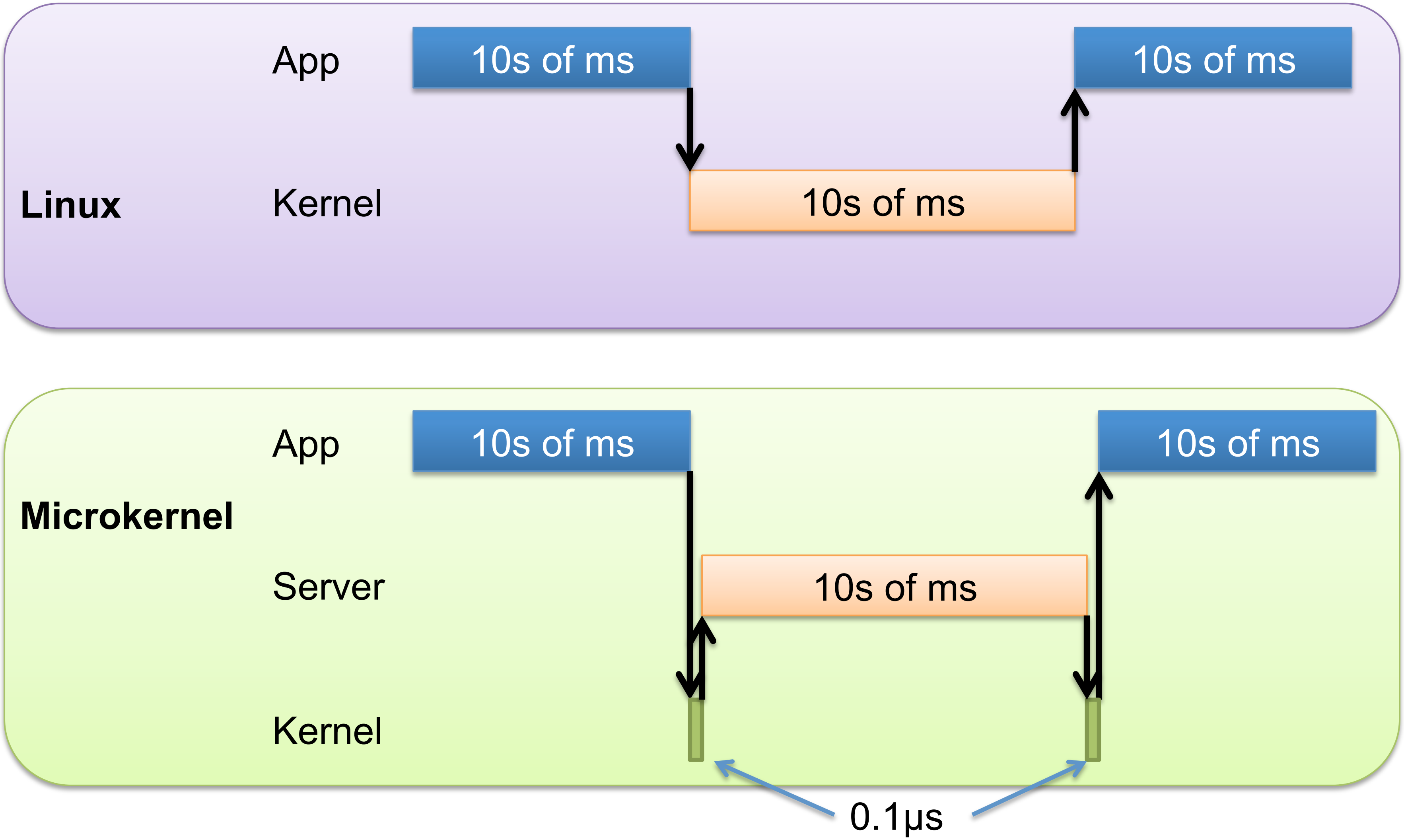
- During (very shallow) testing: 16
- During verification: 460
  - 160 in C, ~150 in design, ~150 in spec

Isolation Goes Deep

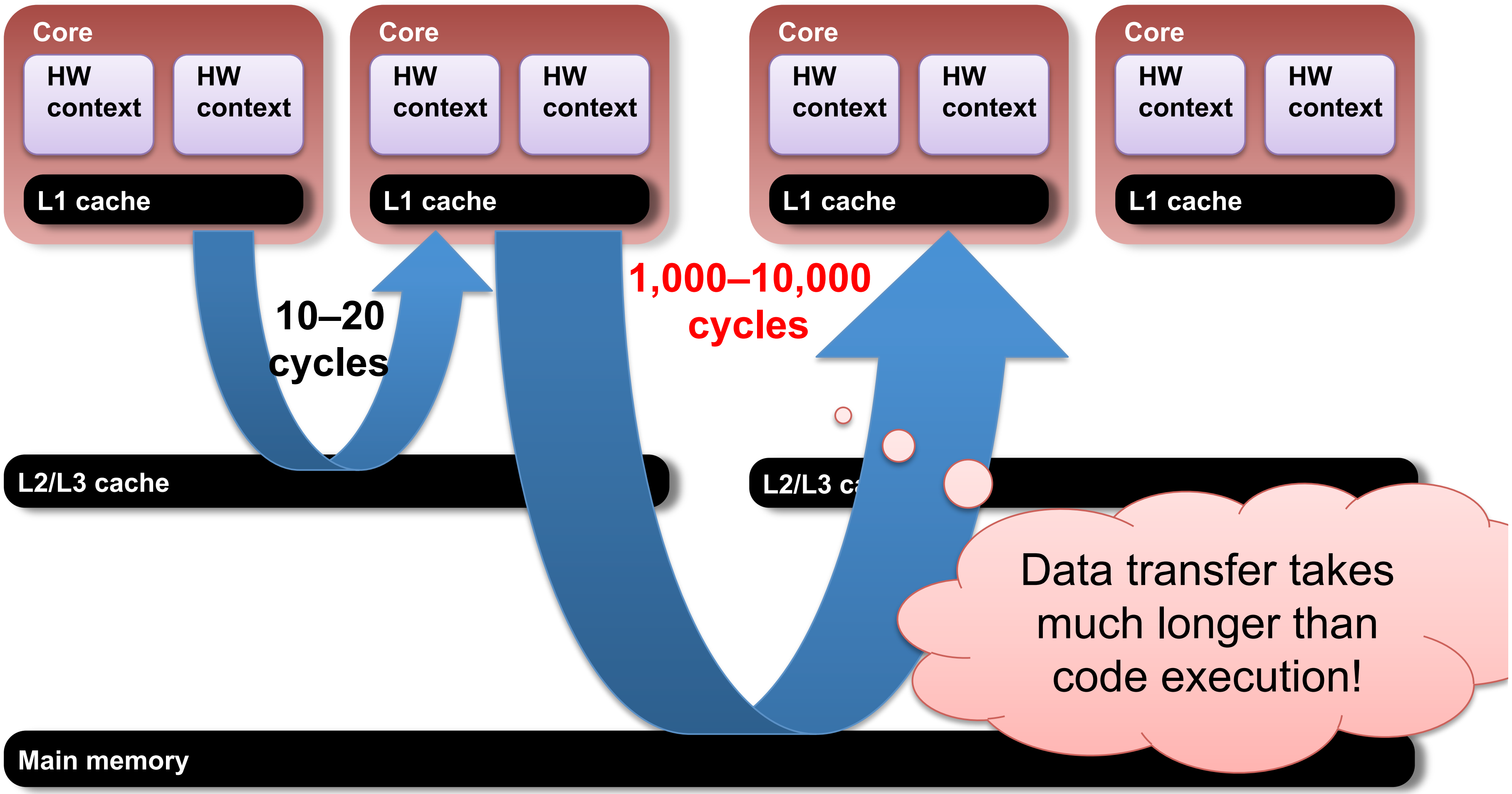


Multicore

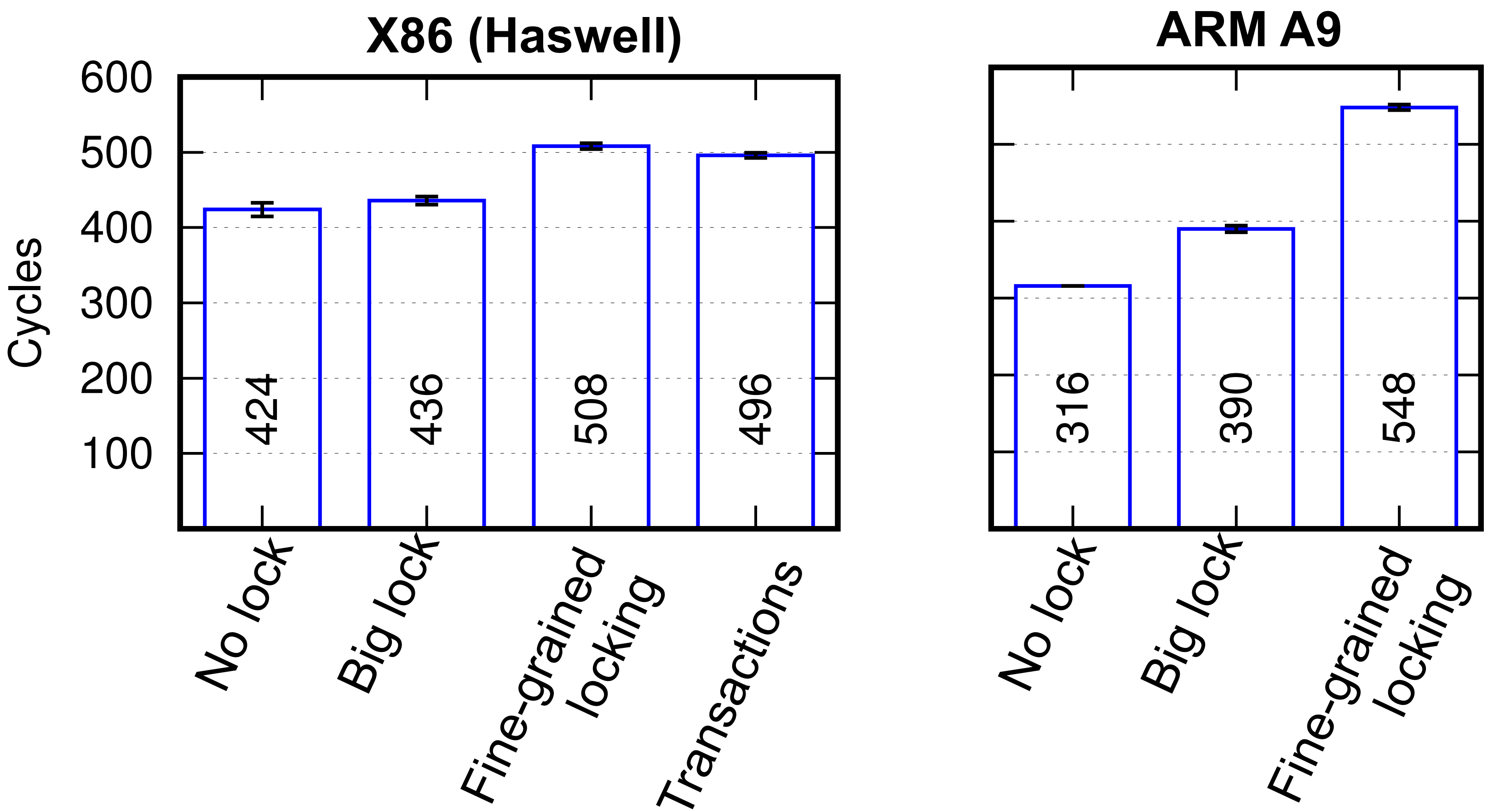
Microkernel vs Linux Execution



Cache Line Migration Latencies

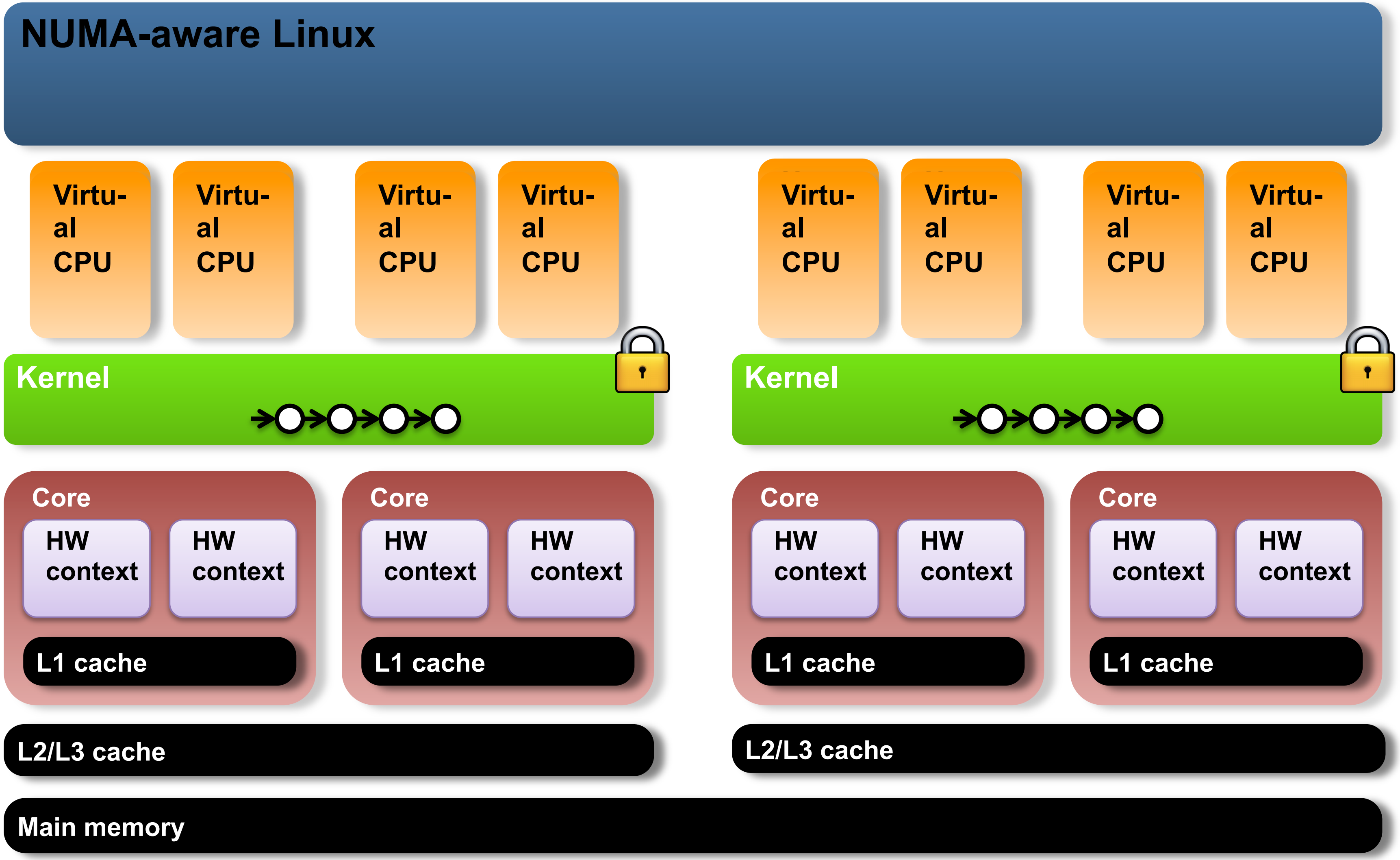


Cost of Locking

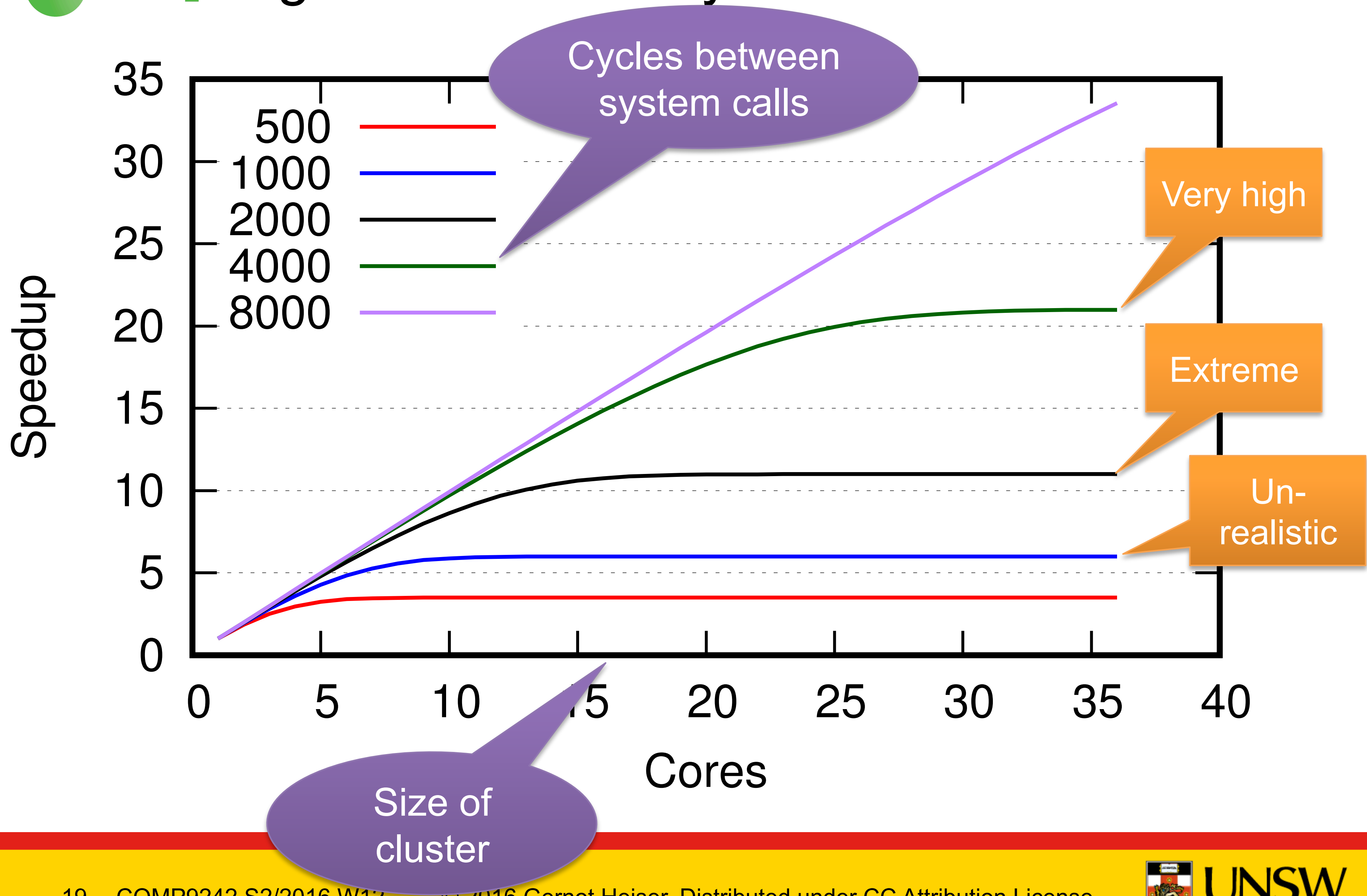


Locks have a cost –
significant in a fast microkernel!

Multicore Design: Clustered Multikernel

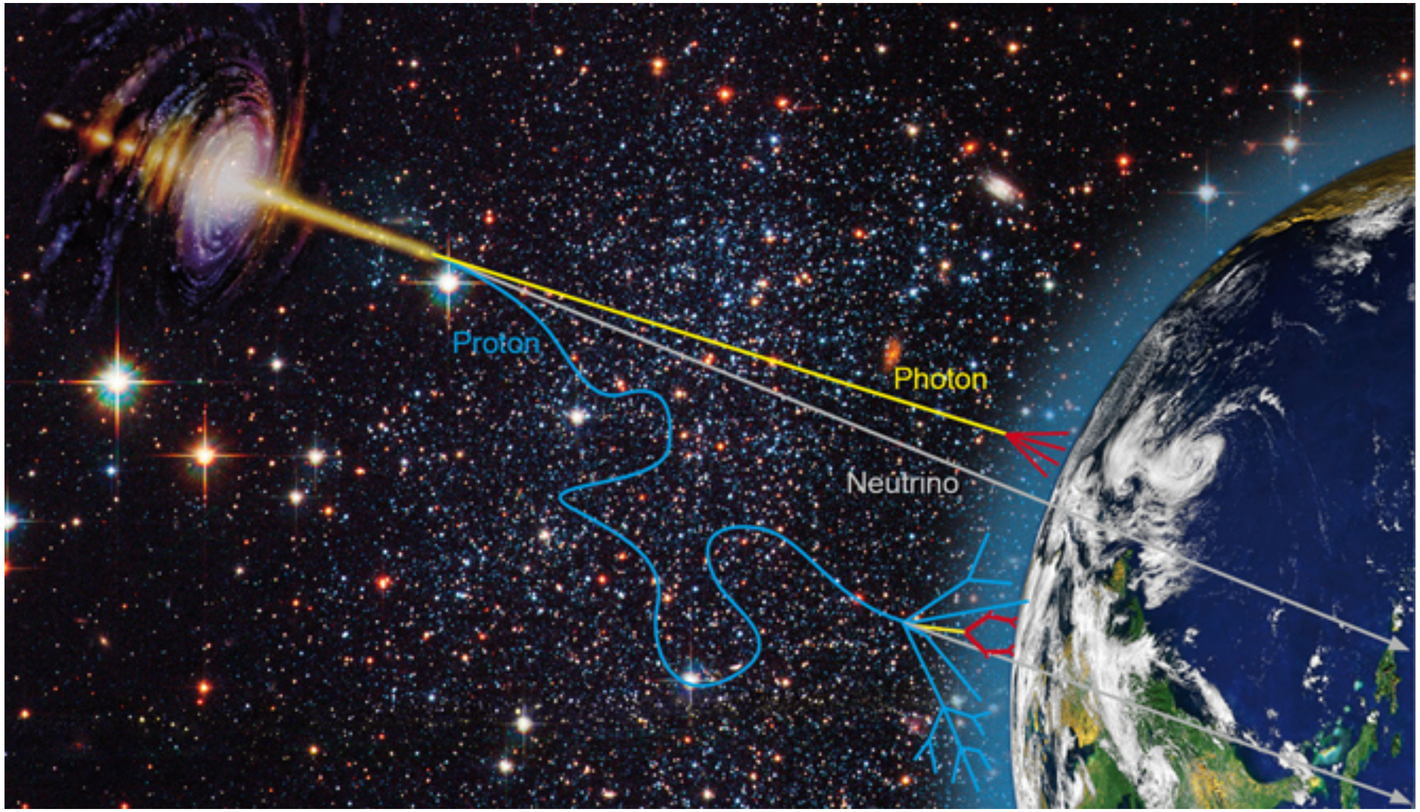


Big-Lock Scalability



Hardware Faults

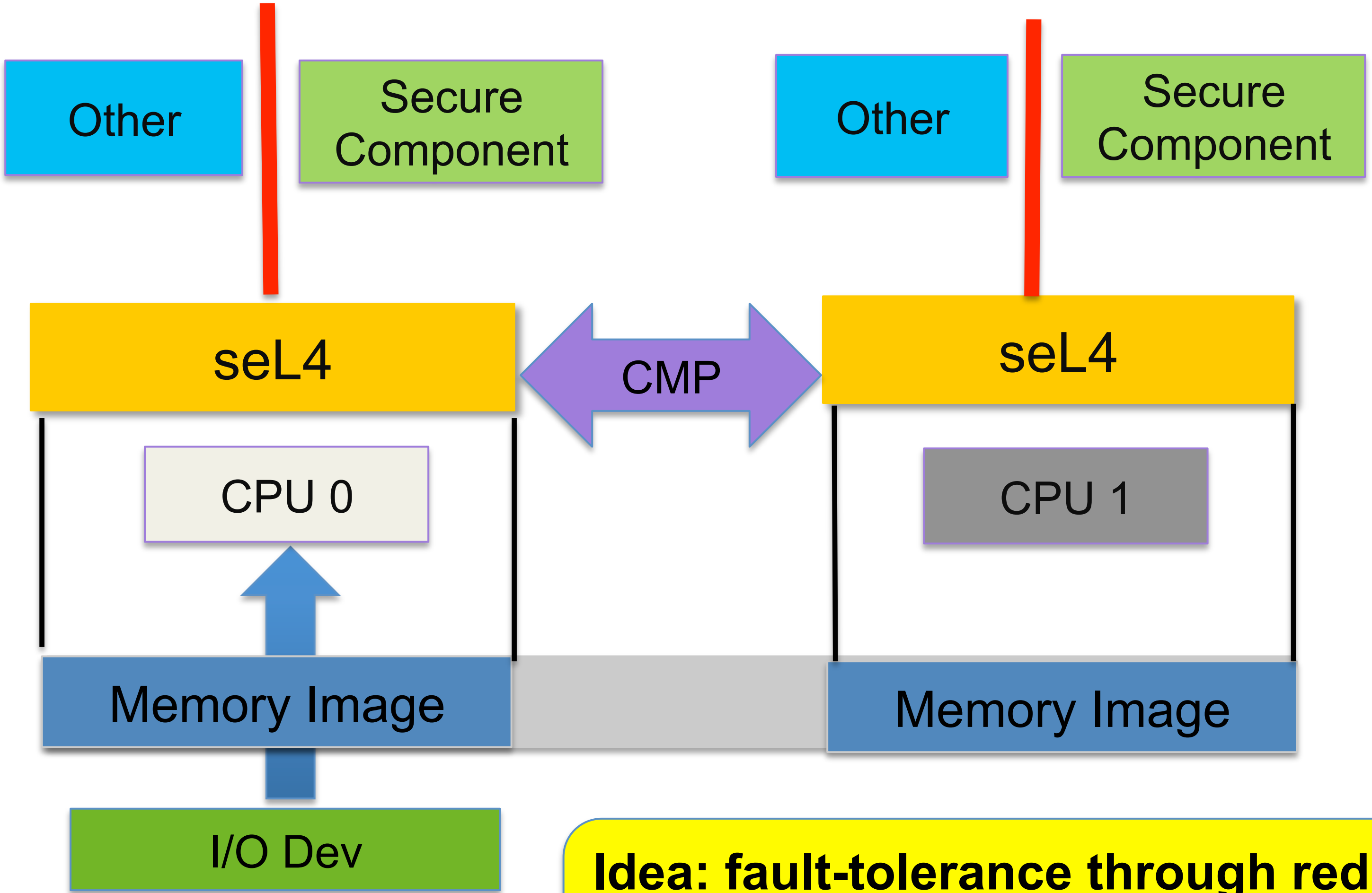
How About Hardware Faults?



- Single-event upset: Random (transient) bit-flips due to cosmic rays, natural radioactivity
- May break “proved” isolation

Courtesy Yanyan Shen

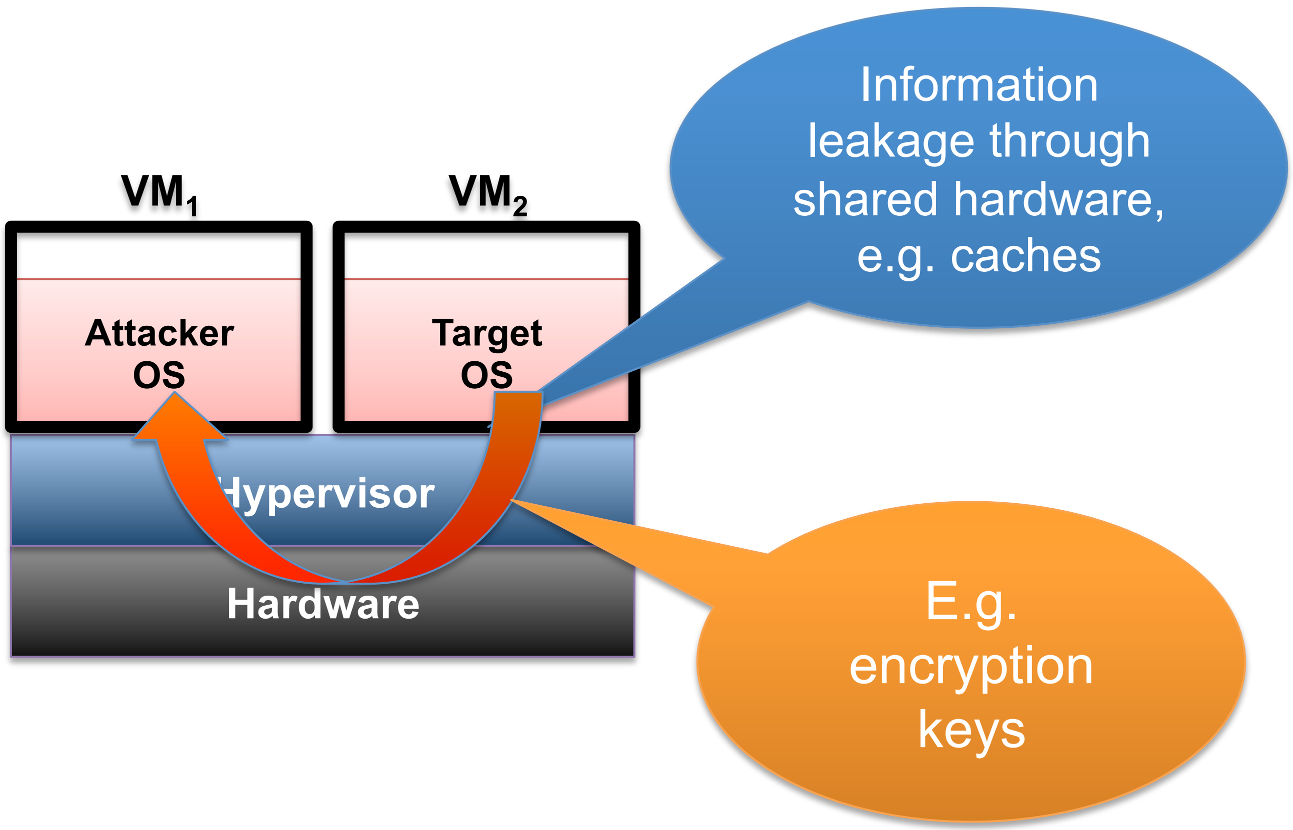
Redundant Execution



Idea: fault-tolerance through redundancy
- Compare & vote at kernel entry/exit
- Work in progress (Yanyan's PhD)

Side Channels

Side Channel Attacks



Types of Side Channels

Storage Channels

- Use some shared state
- Could be inside the OS/ hypervisor
  - Eg existence of a file
  - Eg accessibility of an object

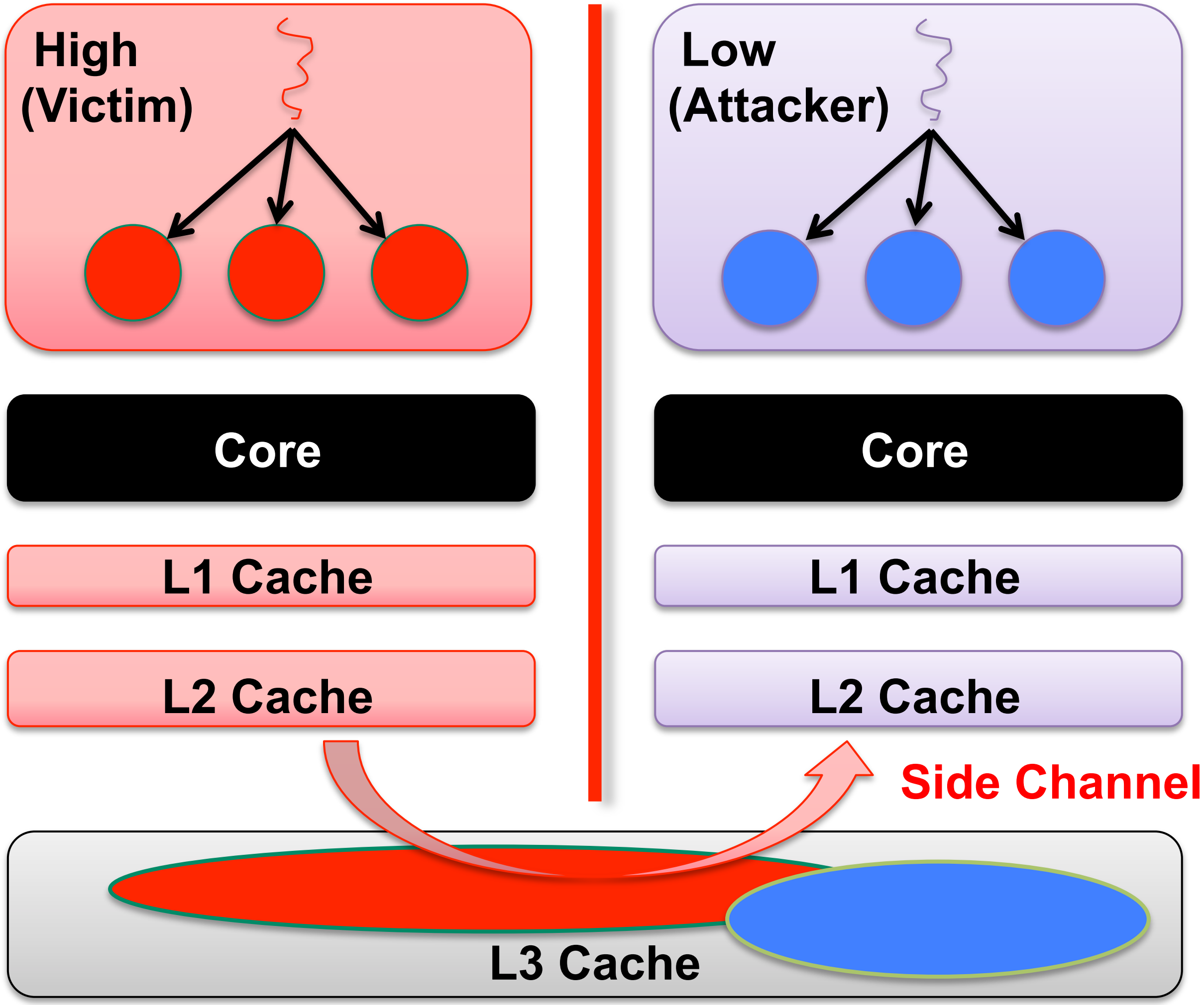
seL4: The world's only OS proved free of storage channels!

Timing Channels

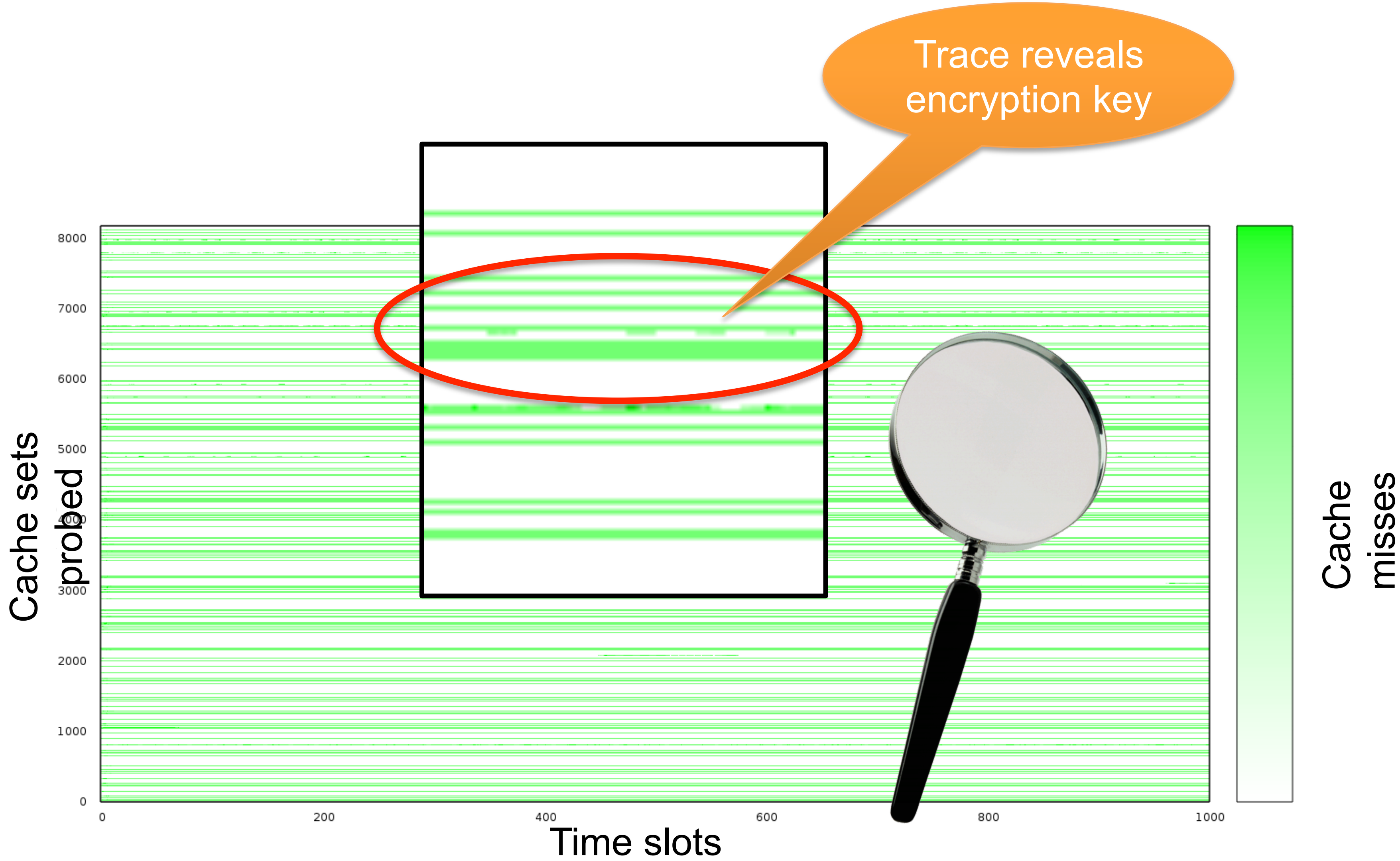
- Observe timing of events
- Eg memory access latency
  - Senses victim's cache footprint

How about timing channels?

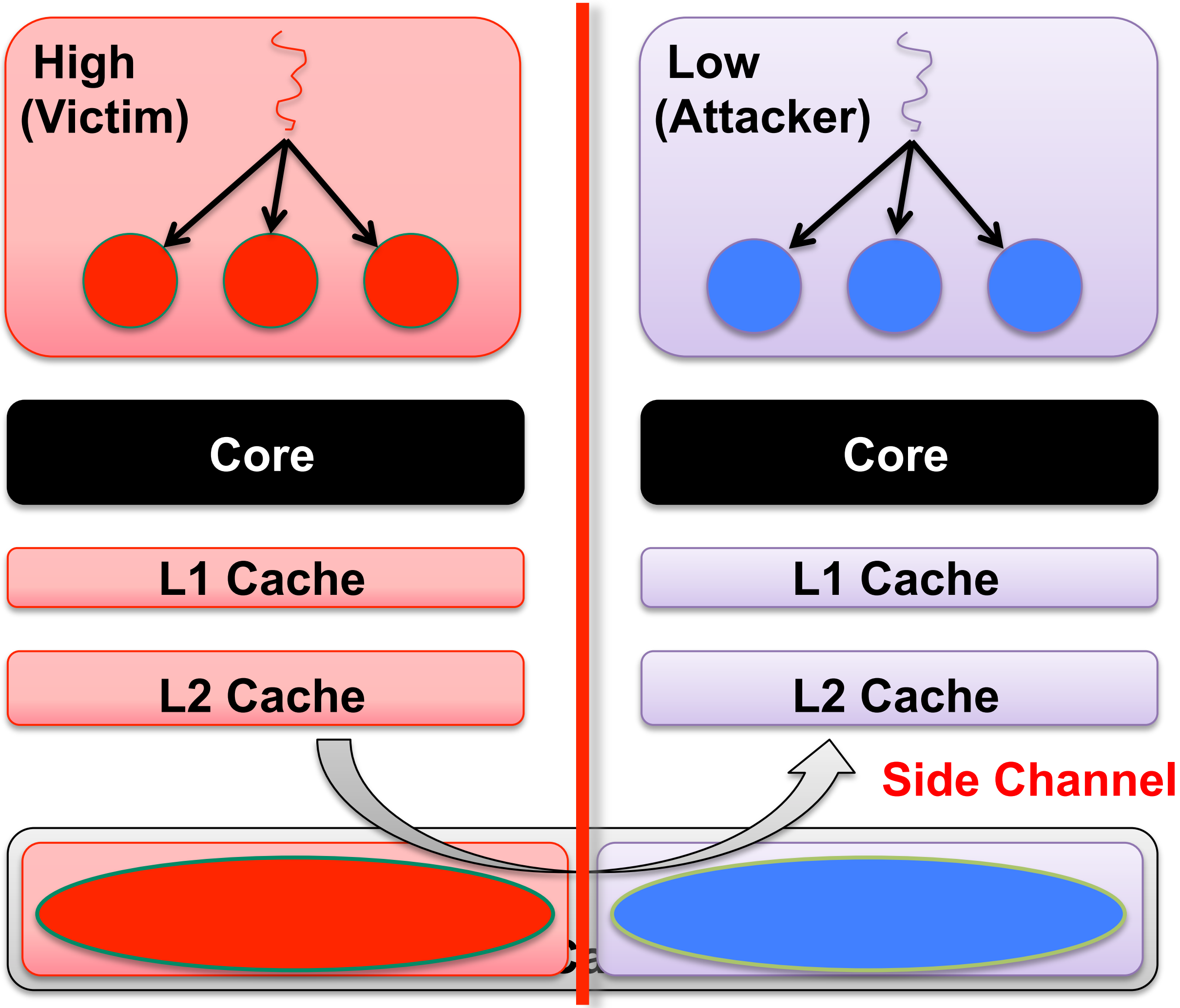
Timing Side-Channel Attack in Public Cloud



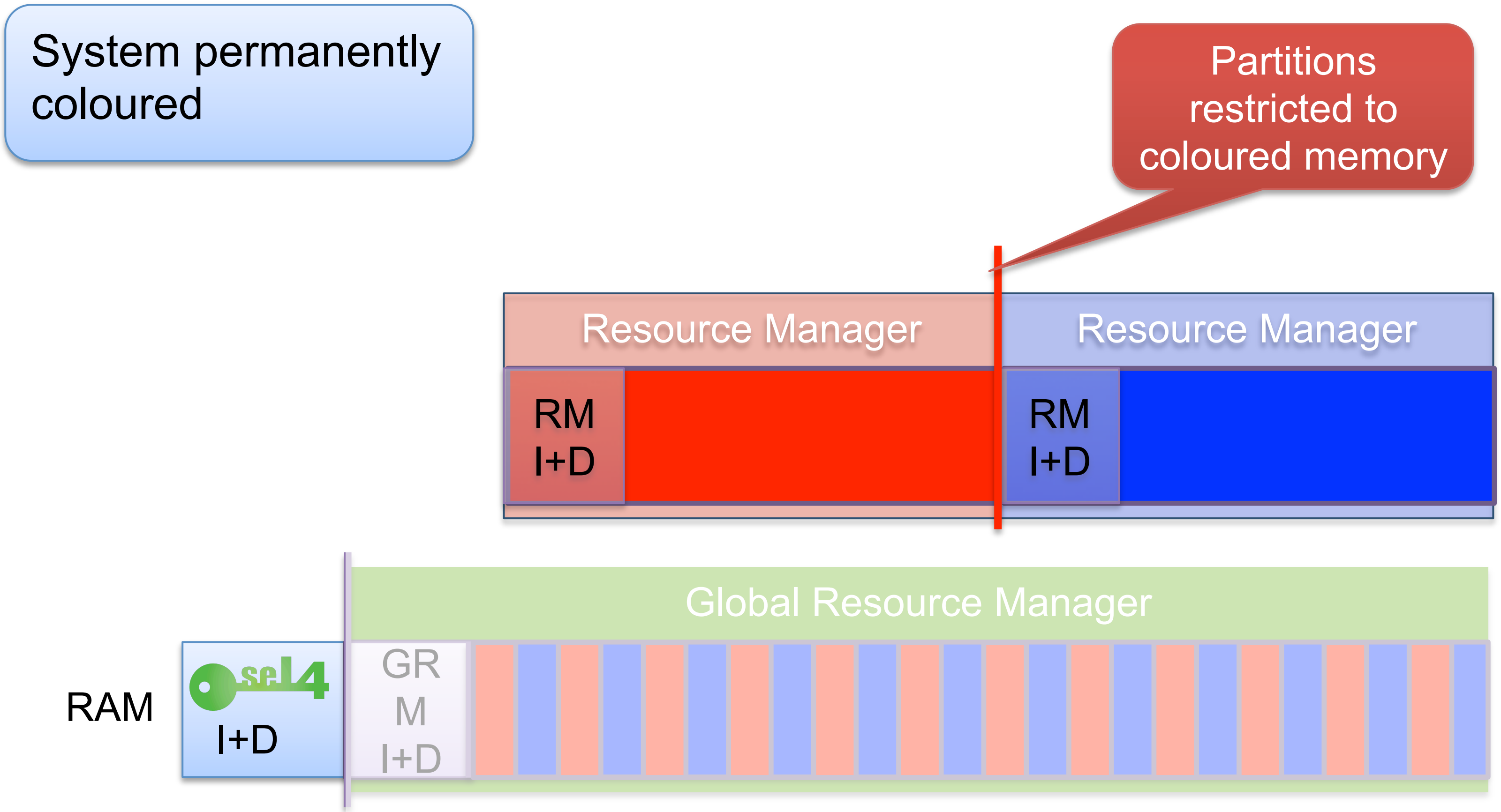
Analysing Memory Access Latency



Mitigation: Partition Cache (Colouring)

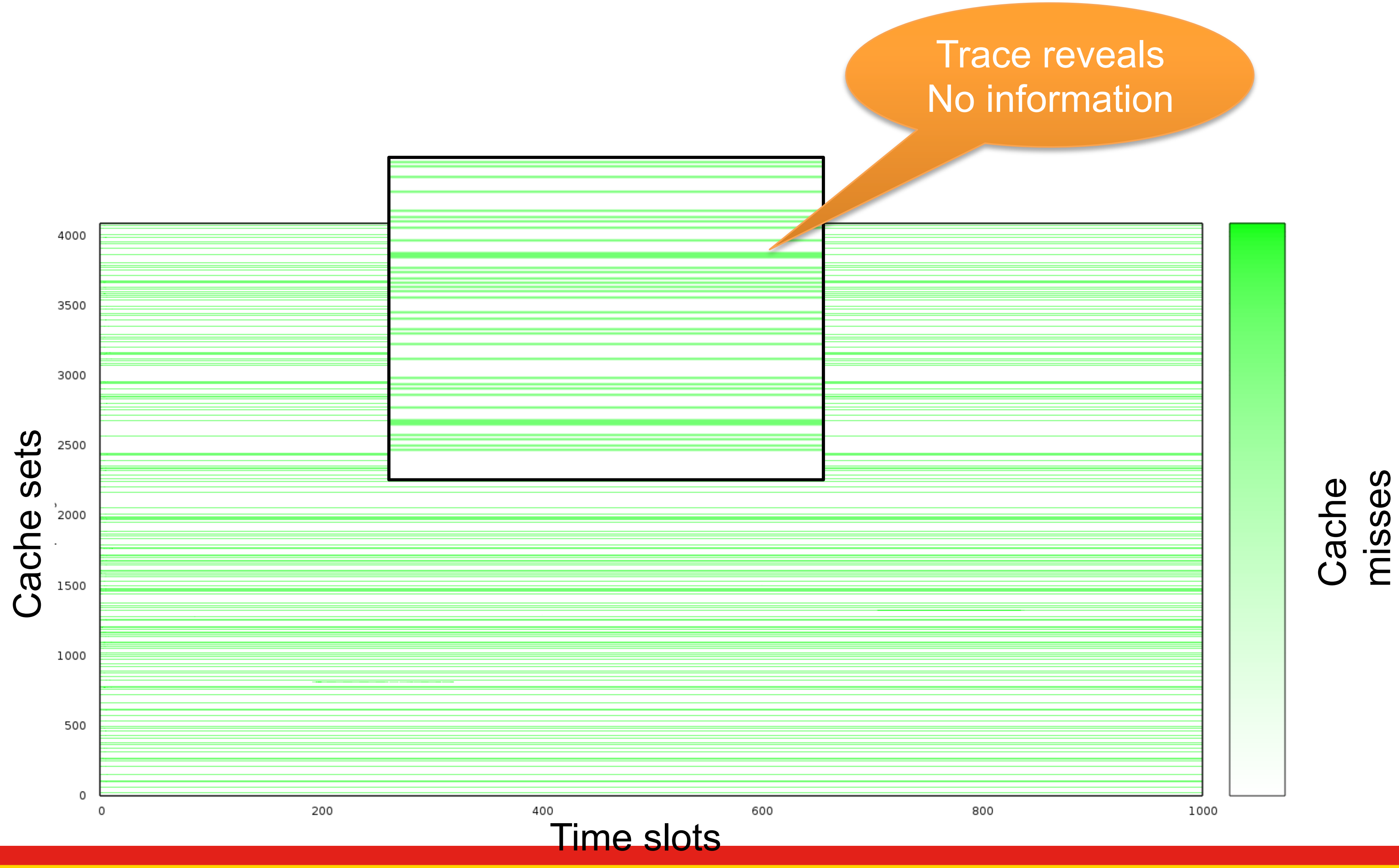


Colouring the System is Easy



Analysing Memory Access Latency

Coloured System



Timing Channel Through Kernel

High (Trojan)

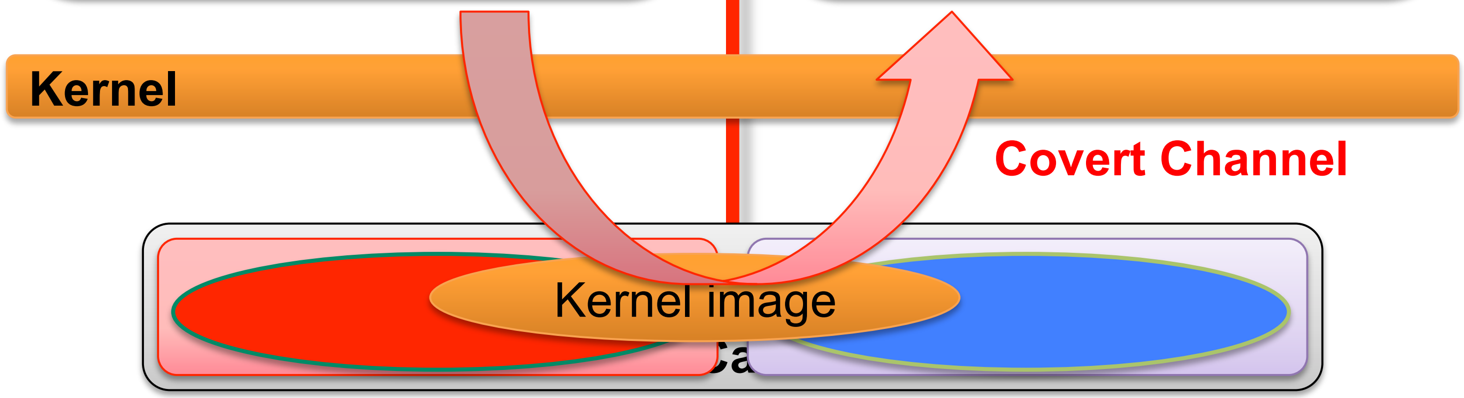
```
int count = 0;
for( ; ;) {

wait_for_new_system_tick( );
    if ((count %13) < 5)
        syscall(…);
    count++;
}
```

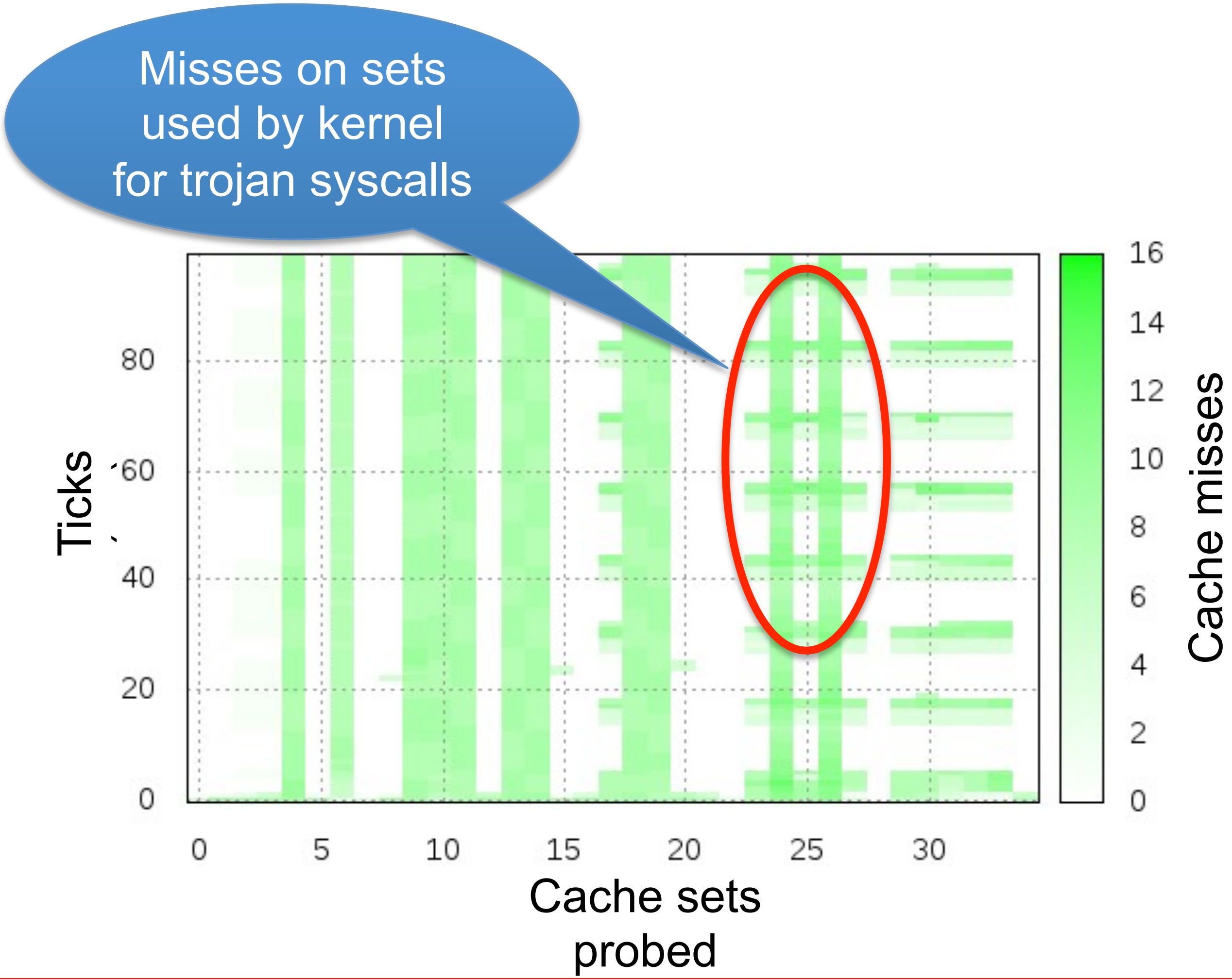
Low (Spy)

```
for( t = 0; t < 100 ; t++) {

wait_for_new_system_tick( );
    for (i = 0; i < prob_sets; i++)
        result[t][i] =
cache_probe(i)
}
```



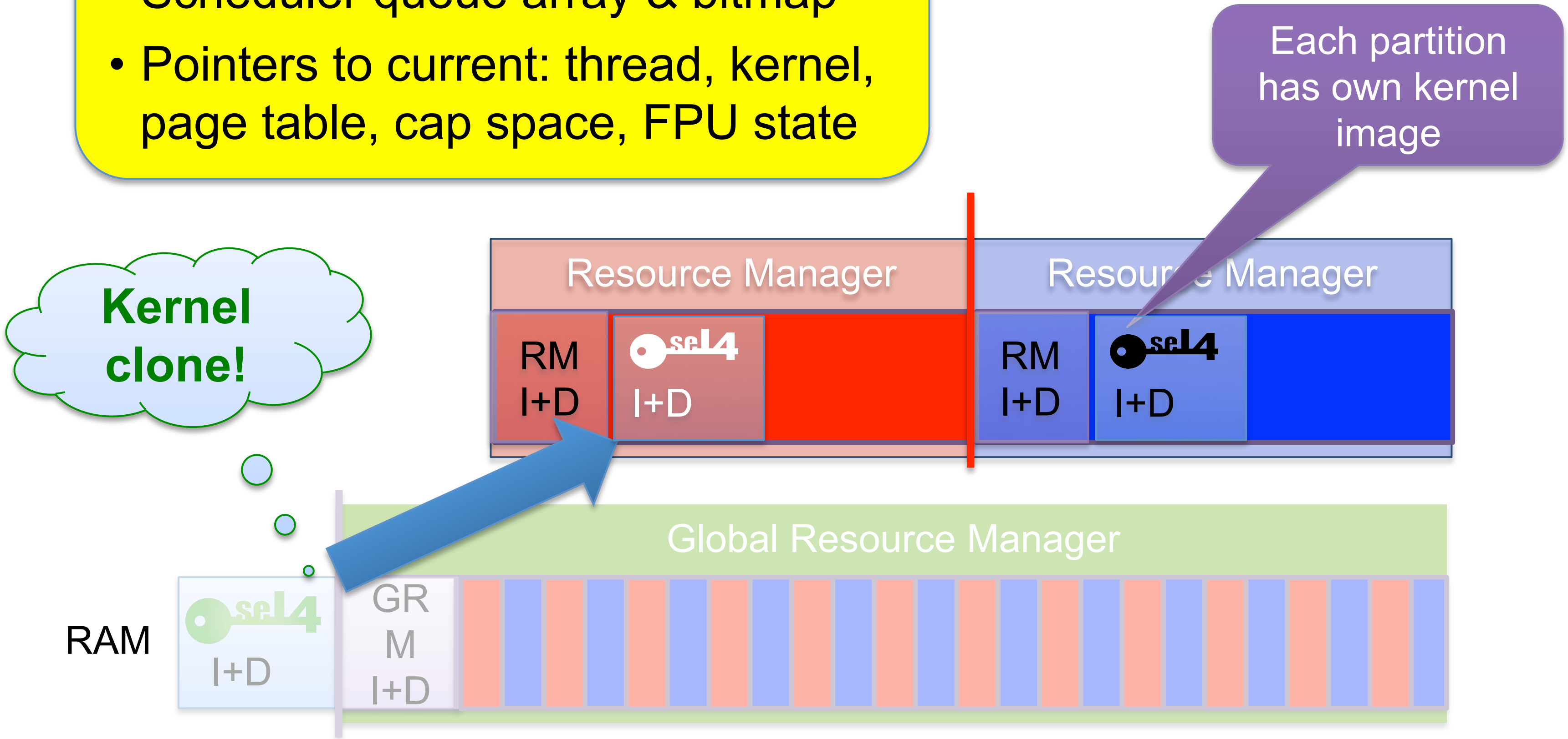
Cache Covert Channel Through Kernel
Spy observations



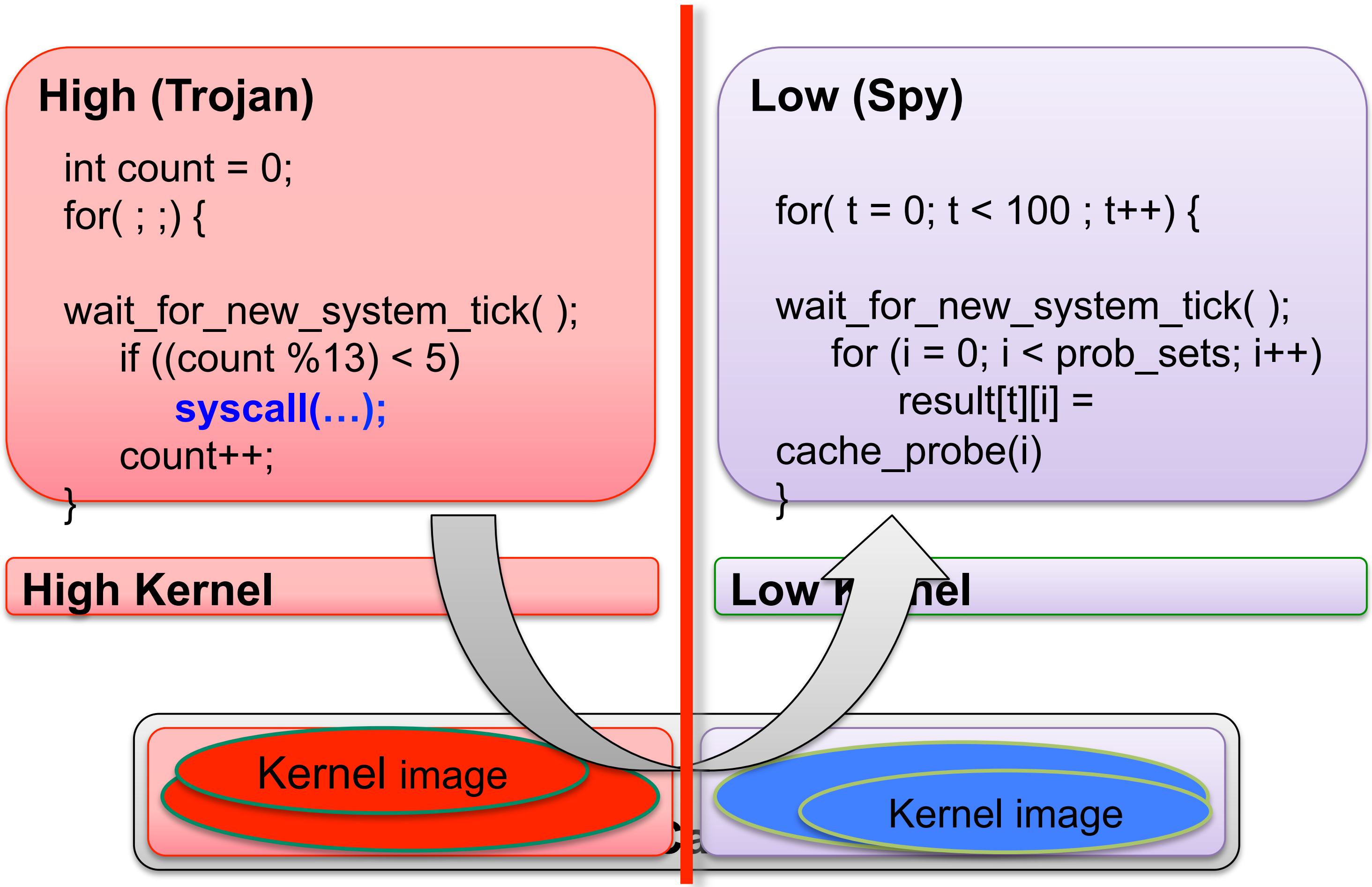
Colouring the Kernel

Only shared kernel data:

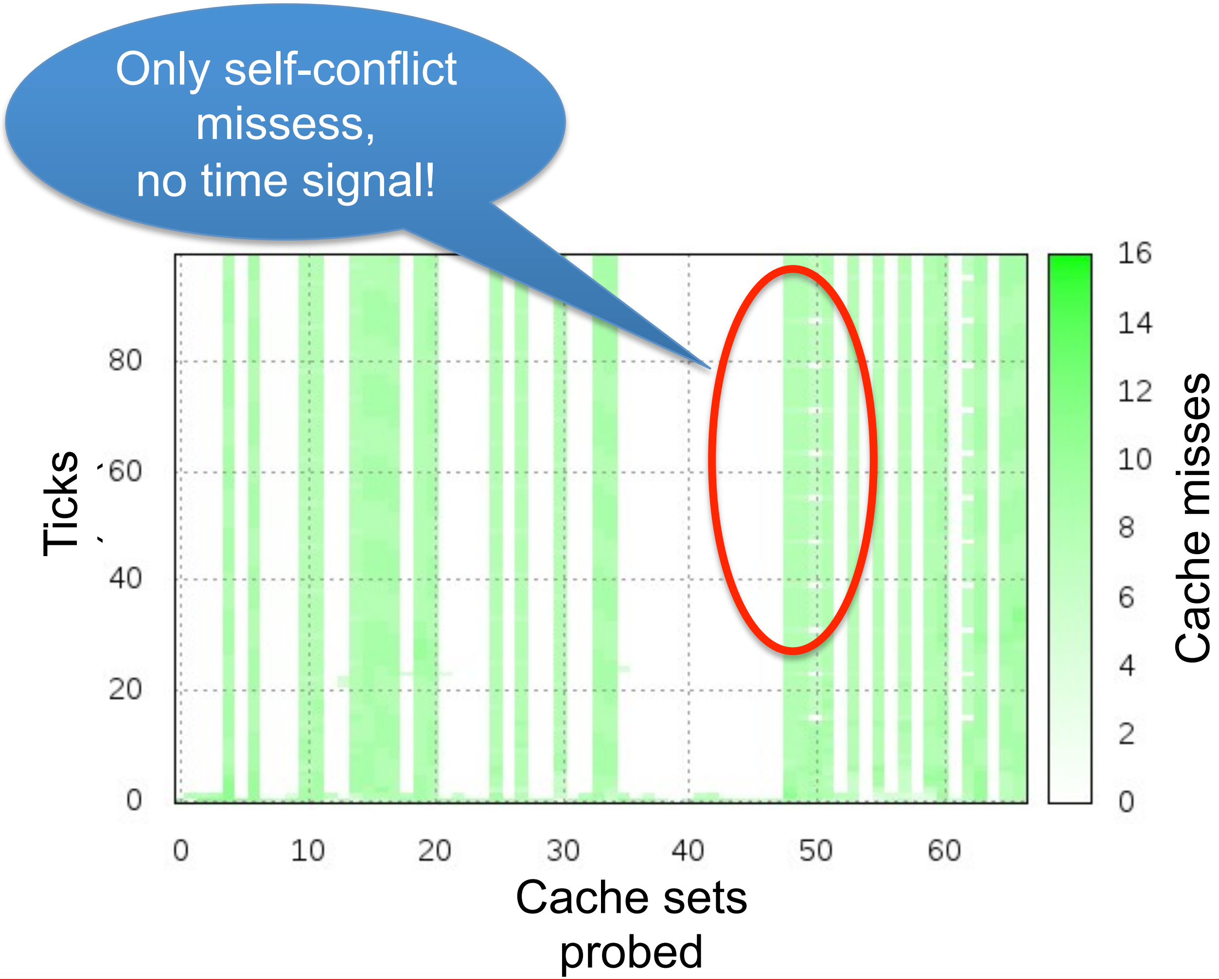
- Scheduler queue array & bitmap
- Pointers to current: thread, kernel, page table, cap space, FPU state



Timing Channel Through Kernel



Cache Covert Channel Through Kernel
Spy observations with coloured kernel

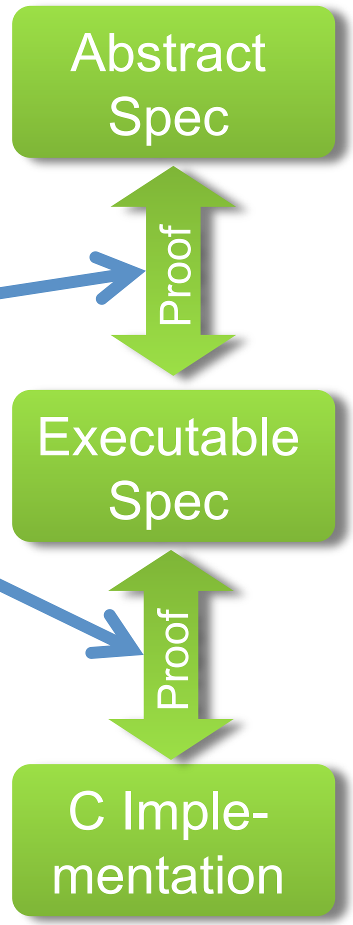


Tackling Verification Cost

seL4 Verification Cost Breakdown

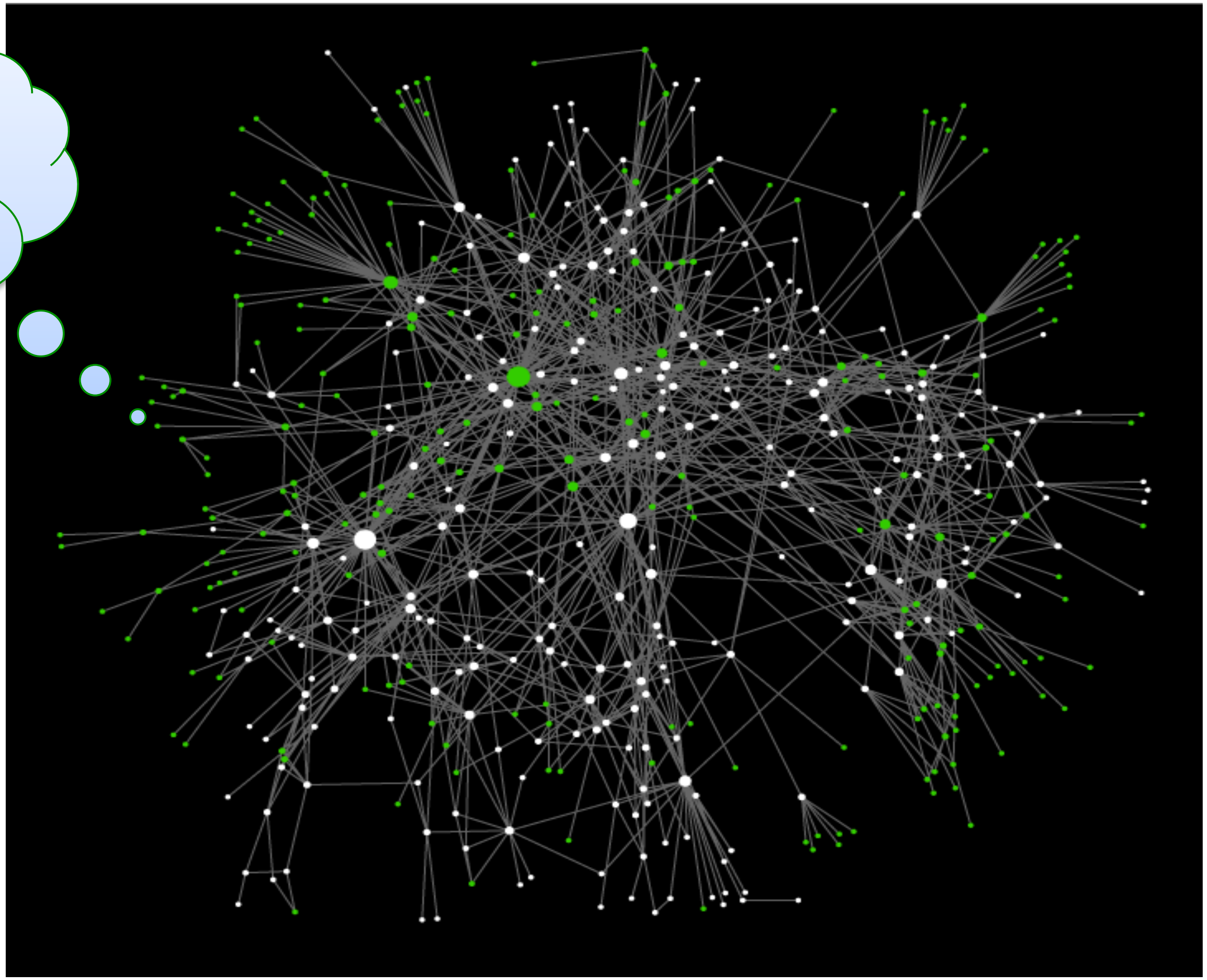
Haskell design	2 py
C implementation	2 months
Debugging/Testing	2 months
Abstract spec refinement	8 py
Executable spec refinement	3 py
Fastpath verification	5 months
Formal frameworks	9 py
Total	**24 py**
Repeat (estimated)	6 py
Traditional engineering	4–6 py

Reusable!

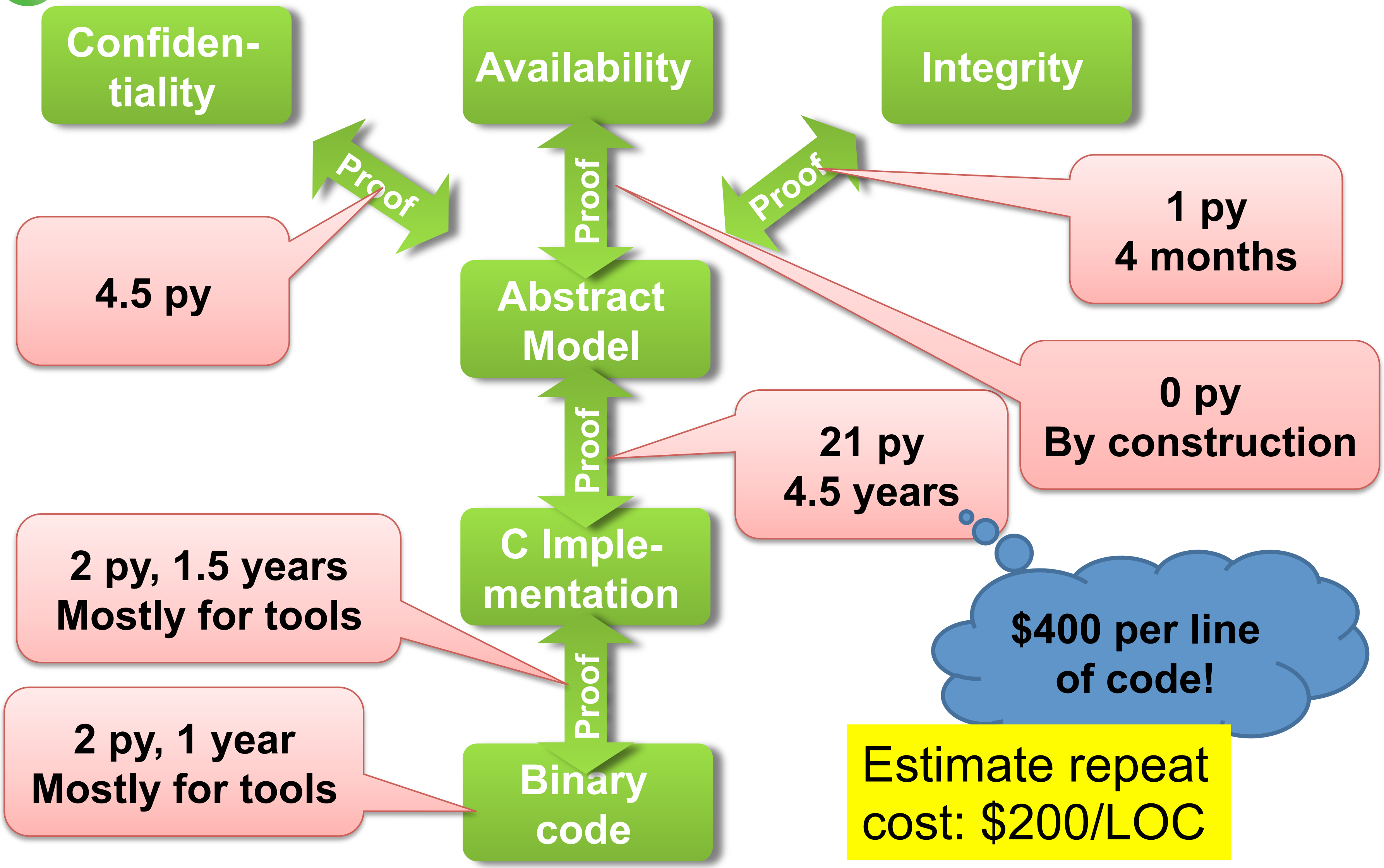


Why So Hard for 9,000 LOC?

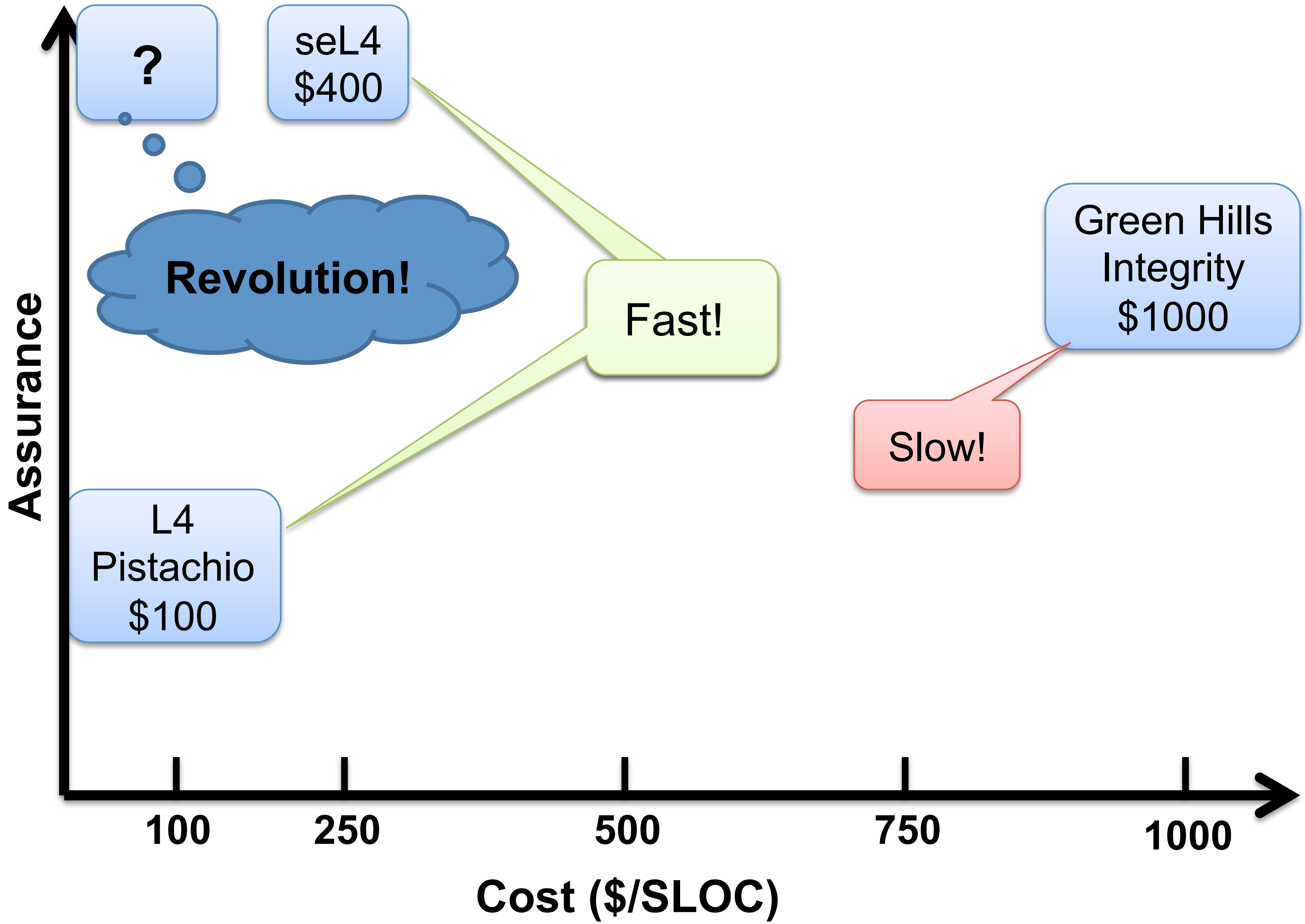
seL4 call graph



seL4 Cost of Assurance



Microkernel Life-Cycle Cost in Context



Cost of Assurance

Industry Best Practice:

- "High assurance": $1,000/LOC, no guarantees, *unoptimised*
- Low assurance: $100–200/LOC, 1–5 faults/kLOC, *optimised*

State of the Art – seL4:

  - $400/LOC, 0 faults/kLOC, *optimised*
- Estimate repeat would cost half
  - that's about twice the development cost of the predecessor Pistachio!
- Aggressive optimisation [APSys'12]
  - much faster than traditional high-assurance kernels
  - as fast as best-performing low-assurance kernels

What Have We Learnt?

Formal verification *probably* didn't produce a more *secure* kernel

- In reality, traditional separation kernels are *probably* secure

But:

- We now have certainty
- We did it *probably* at less cost

Real achievement:

- Cost-competitive at a scale where traditional approaches still work
- Foundation for scaling beyond: **2 × cheaper, 10 × bigger!**

How?

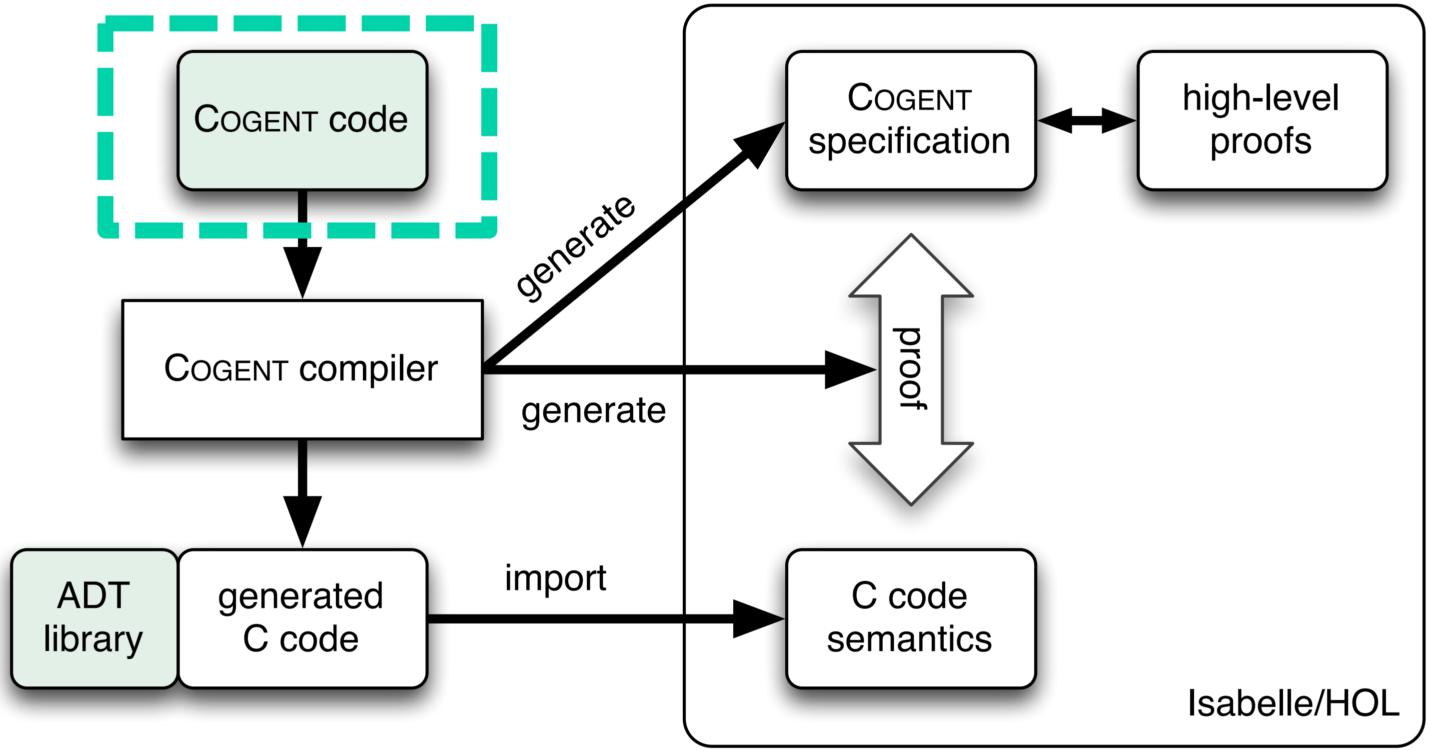
- Combine theorem proving with
  - synthesis
  - domain–specific languages (DSLs)

Our approach

- Cogent: code and proof co-generation
  - Implement FS in high-level functional language (and reason about it)
  - Generate efficient low-level code in C
  - Automatically prove correspondence between the two

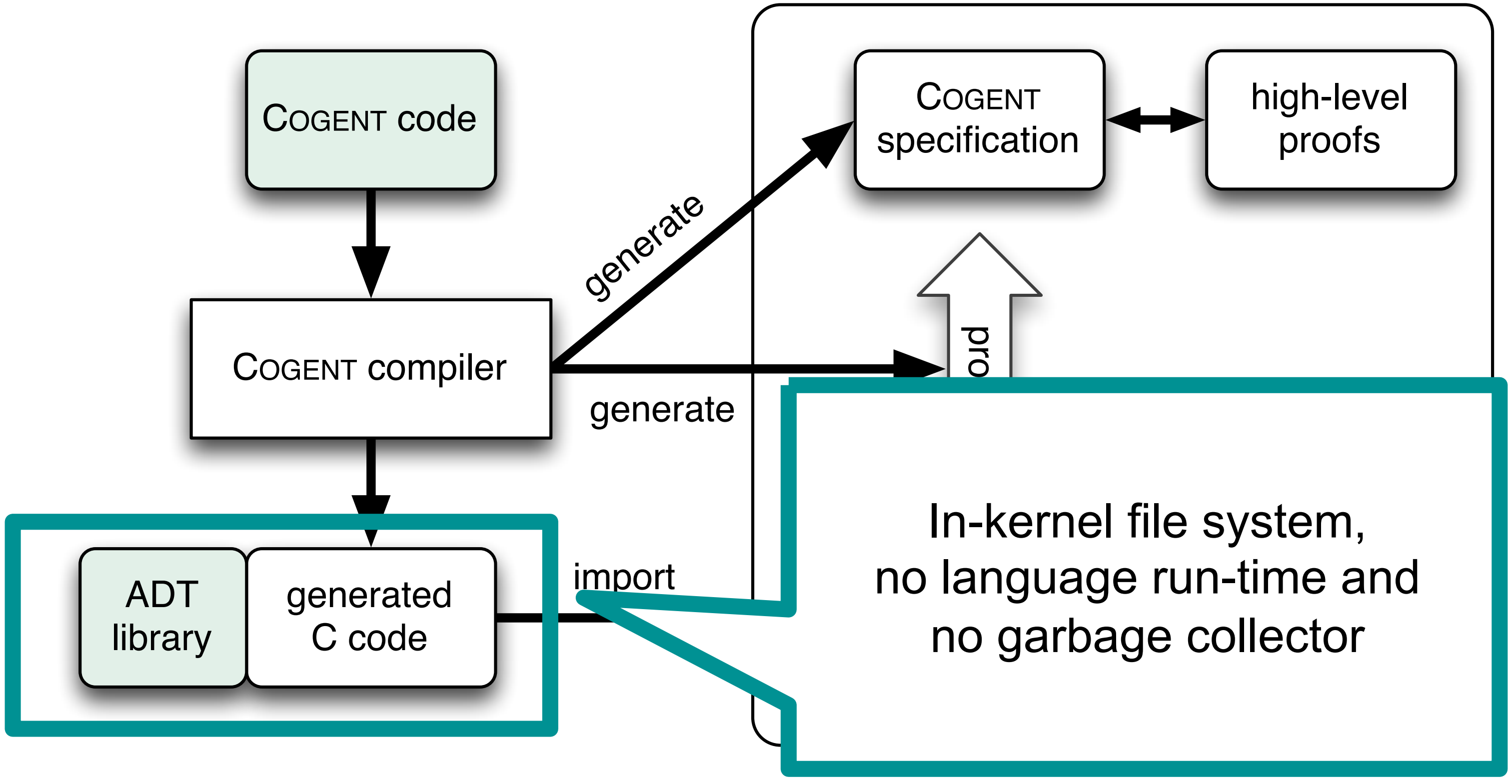
Cogent Workflow

- Cogent: purely functional memory-safe language



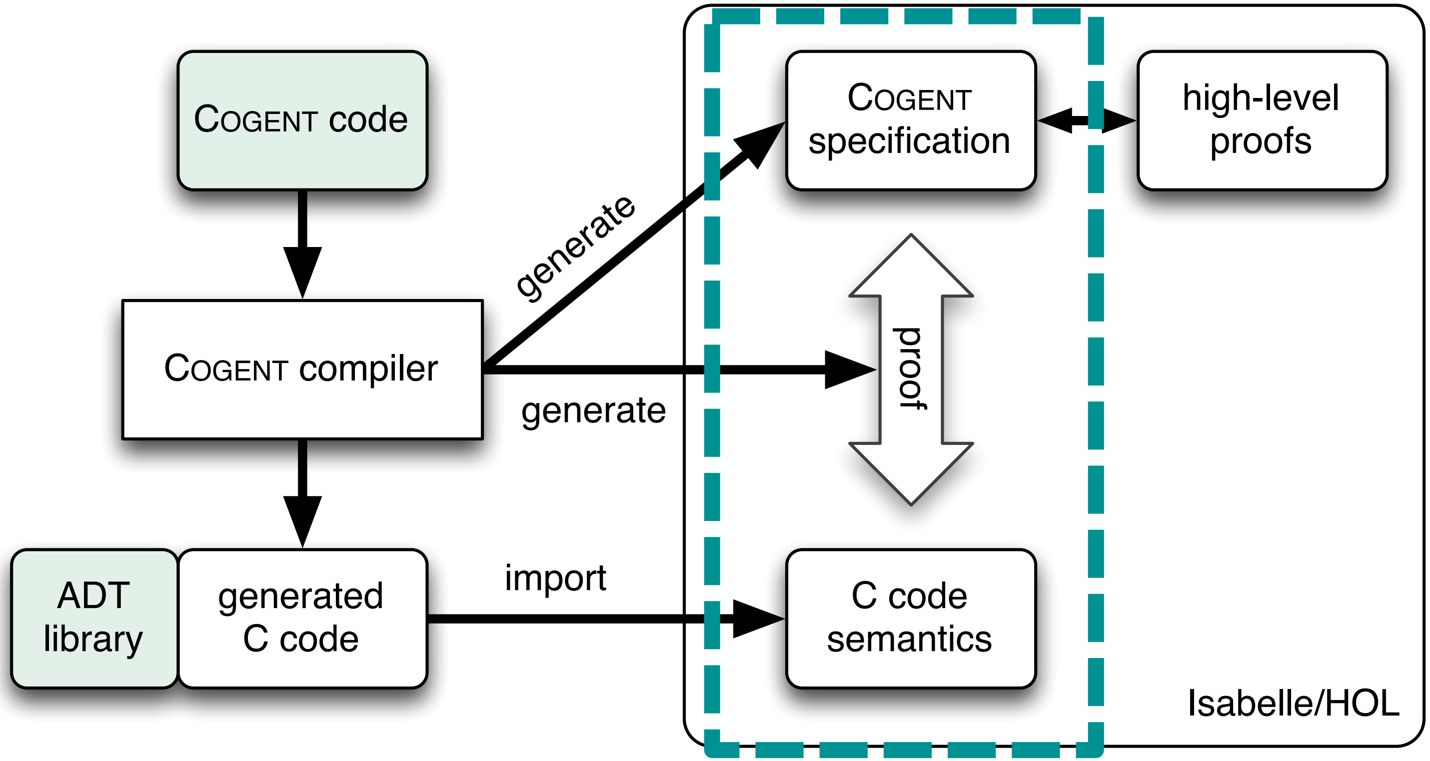
Cogent workflow

- Cogent's certifying compiler generates an C implementation



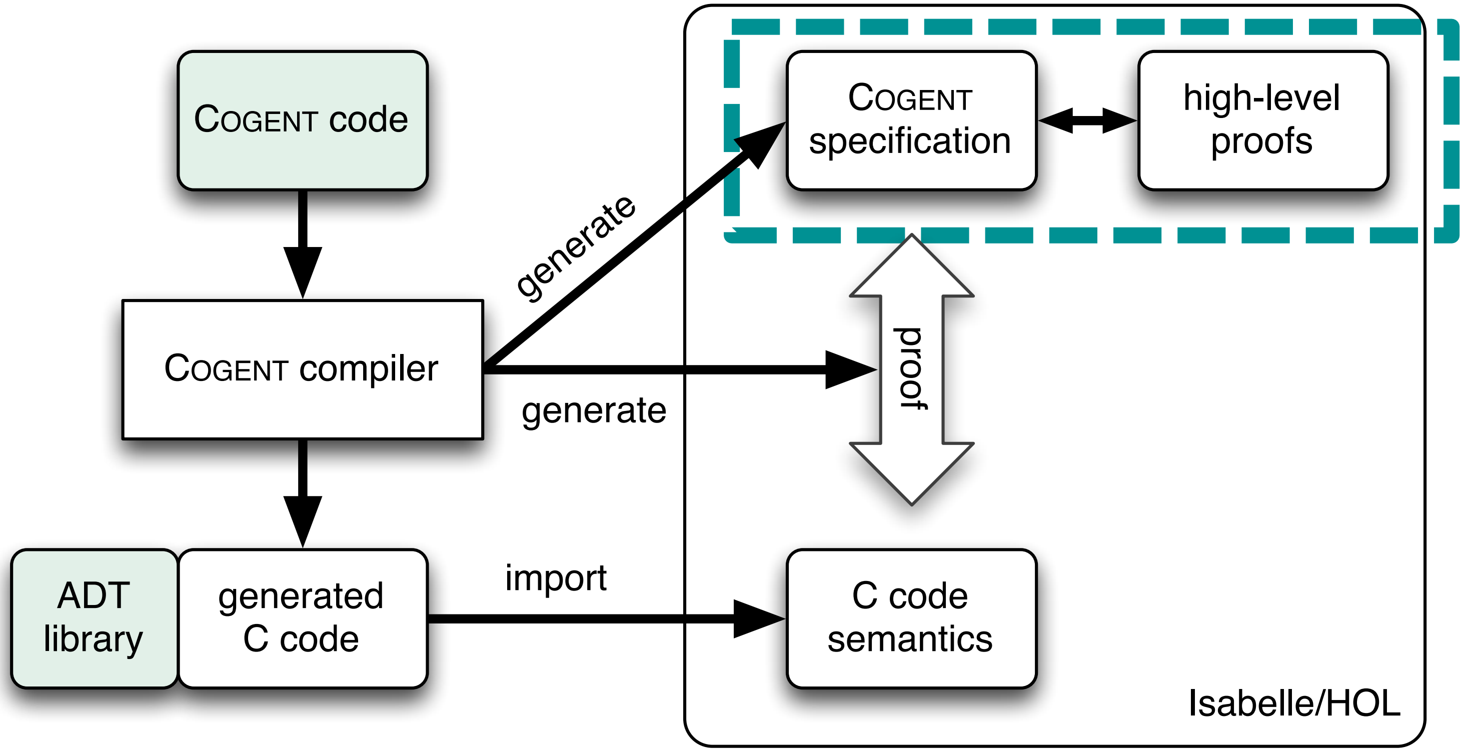
Cogent workflow

- Cogent generates a specification and a proof that links it to the C code



Cogent workflow

- Prove high-level properties about Cogent-generated specifications using a proof assistant

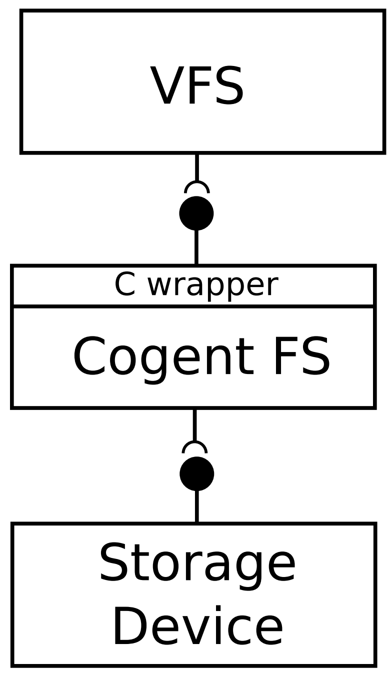


Cogent File Systems

- We implemented two Linux FSs:
  - Ext2: functionally complete original spec
    - No ACLs, symlinks
  - BilbyFs: custom flash file system

- Invoked from VFS via a small C wrapper, which:
  - Uses a global lock to prevent concurrent execution of FS operations
  - Handles VFS caches
  - Calls Cogent FS entry points

- FSs interface with the storage device via external ADT functions

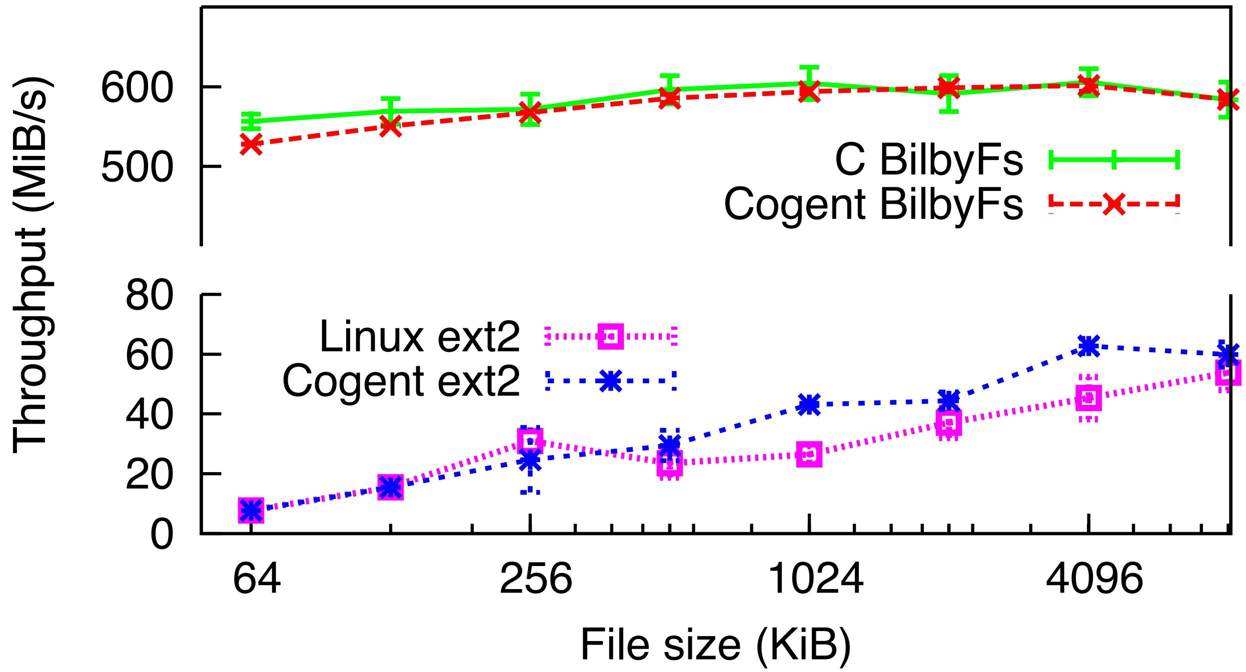


Evaluation

- Compare ext2 with Linux's native implementation
  - Hardware:
    - 4 core i7-6700 running at 3.1 GHz,
    - Samsung HD501JL 7200RPM 500G SATA disk

- Compare BilbyFs with handwritten C implementation
  - Hardware:
    - Mirabox development board
    - Marvell Armada 370 single-core 1.2 GHz ARMv7 processor
    - 1 GiB of NAND flash

IOZone random 4k writes



- 20% CPU load for Cogent BilbyFs vs 15% for C
- Both ext2 implementations have the same CPU load

Postmark on RAM-disk

System	Total time sec	creation files/sec	read rate kB/sec
C ext2	10	5025	248
COGENT ext2	21	2393	118
C BilbyFs	6	33375	431
COGENT BilbyFs	10	20025	259

- Degradation of a factor 2 for Cogent FSs

Postmark on RAM-disk

System	Total time sec	creation files/sec	read rate kB/sec
C ext2	10	5025	248
COGENT ext2	21	2393	118
C BilbyFs	6	33375	431
COGENT BilbyFs	10	20025	259

- Degradation of a factor 2 for Cogent FSs

- Overhead is due to two reasons:
  - extra copying involved when converting in-buffer directory entries into Cogent's internal data type
  - Cogent compiler is overly reliant on C compiler's optimiser to convert automatically C structs passed by copy to pointers

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Remember: Verification Cost Breakdown