School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2019 T2 Week 09a

Formal Verification and seL4

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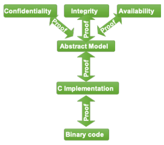

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Assurance and Verification

Refresher: Assurance and Formal Verification

- **Assurance**:
  - systematic evaluation and testing
  - essentially an intensive and onerous form of quality assurance
- **Formal verification**:
  - mathematical proof
- **Certification**: independent examination
  - confirming that the assurance or verification was done right

Assurance and formal verification aim to establish correctness of
- mechanism design
- mechanism implementation

Assurance: Substantiating Trust

- Specification
  - Unambiguous description of desired behaviour
- System design
  - Justification that it meets specification
- Implementation
  - Justification that it implements the design
- Maintenance
  - Justifies that system use meets assumptions

Informal (English) or formal (maths)

Compelling argument or formal proof

Code inspection, rigorous testing, proof

Common Criteria

- *Common Criteria for IT Security Evaluation* [ISO/IEC 15408, 99]
  - ISO standard, for general use
  - Evaluates QA used to ensure systems meet their requirements
  - Developed out of the famous US DOD "Orange Book": *Trusted Computer System Evaluation Criteria* [1985]
- Terminology:
  - *Target of evaluation* (TOE): Evaluated system
  - *Security target* (ST): Defines requirements
  - *Protection profile* (PP): Standardised ST template
  - *Evaluation assurance level* (EAL): Defines thoroughness of evaluation
    - PPs have maximum EAL they can be used for

CC: Evaluation Assurance Levels

Thoroughness, cost

Level	Requirements	Specification	Design	Implementation
EAL1	not evaluated	**Informal**	not eval	not evaluated
EAL2	not evaluated	**Informal**	**Informal**	not evaluated
EAL3	not evaluated	**Informal**	**Informal**	not evaluated
EAL4	not evaluated	**Informal**	**Informal**	not evaluated
EAL5	not evaluated	**Semi-Formal**	**Semi-Formal**	**Informal**
EAL6	**Formal**	**Semi-Formal**	**Semi-Formal**	**Informal**
EAL7	**Formal**	**Formal**	**Formal**	**Informal**

Common Criteria: Protection Profiles (PPs)

- *Controlled Access PP* (CAPP)
  - standard OS security, up to EAL3
- *Single Level Operating System PP*
  - superset of CAPP, up to EAL4+
- *Labelled Security PP* (LSPP)
  - MAC for COTS OSes
- *Multi-Level Operating System PP*
  - superset of CAPP, LSPP, up to EAL4+
- *Separation Kernel Protection Profile* (SKPP)
  - strict partitioning, for EAL6-7

COTS OS Certifications

- EAL3:
  - 2010 Mac OS X (10.6)
- EAL4:
  - 2003: Windows 2000
  - 2005: SuSE Enterprise Linux
  - 2006: Solaris 10 (EAL4+)
    - against CAPP (an EAL3 PP!)
  - 2007: Red Hat Linux (EAL4+)
- EAL6:
  - 2008: Green Hills INTEGRITY-178B (EAL6+)
    - against SKPP, relatively simple PPC-based hardware platform in TOE
- EAL7:
  - 2019: Prove & Run PROVENCORE

Get regularly hacked!

SKPP on Commodity Hardware

- SKPP: OS provides only separation
- One Box One Wire (OB1) Project
  - Use INTEGRITY-178B to isolate VMs on commodity desktop hardware
  - Leverage existing INTEGRITY certification
    - by "porting" it to commodity platform

NSA subsequently dis-endorsed SKPP, discontinued certifying ≥EAL5

Conclusion [NSA, March 2010]:
- SKPP validation for commodity hardware platforms infeasible due to their complexity
- SKPP has limited relevance for these platforms

Common Criteria Limitations

Effectively dead in 5-Eyes defence

- Very expensive
  - rule of thumb: EAL6+ costs $1K/LOC design-implementation-evaluation-certification
- Too much focus on development process
  - rather than the product that was delivered
- Lower EALs of little practical use for OSes
  - c.f. COTS OS EAL4 certifications
- Commercial Licensed Evaluation Facilities licenses rarely revoked
  - Leads to potential "race to the bottom" [Anderson & Fuloria, 2009]

Formal Verification

- Prove properties about a mathematical model of a system

Model checking / abstract interpretation:
- Cannot generally prove code correct
  - Proves specific properties
  - Has false positives or false negatives (unsoundness)
- Suffers state-space explosion
- May scale to large code bases

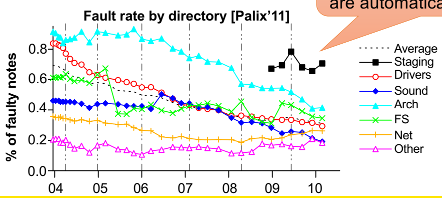
Theorem proving:
- Can deal with large (even infinite) state spaces
- Can prove functional correctness against a spec
- Very labour-intensive

Recent work automatically proved functional correctness of simple systems using SMT solvers [Hyperkernel, SOSP'17]

Model Checking and Linux: A Sad Story

- Static analysis of Linux source [Chou & al, 2001]
  - Found high density of bugs, especially in device drivers
- Re-analysis 10 years later [Palix & al, 2011]

Disappointing rate of improvement for bugs that are automatically detectable!



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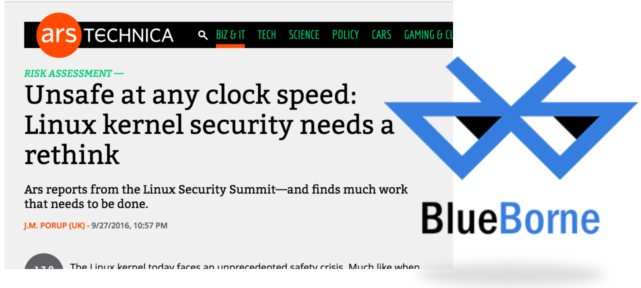
And the Result?



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seL4

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August 2009

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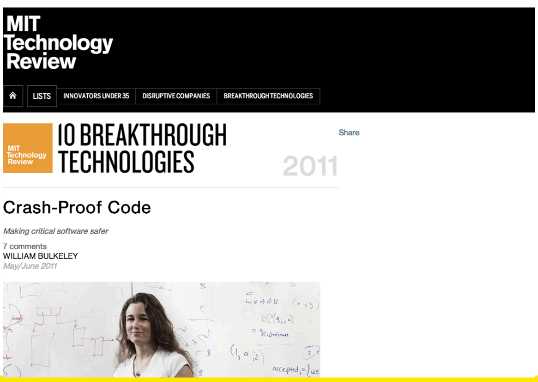

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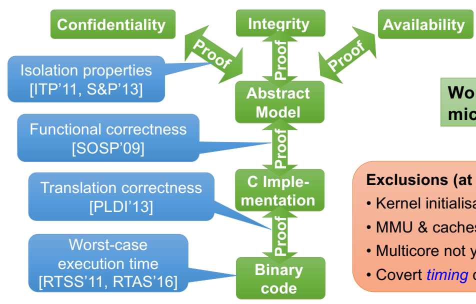
seL4 Proving Security and Safety



World's fastest microkernel!

Exclusions (at present):
- Kernel initialisation not yet verified
- MMU & caches modelled abstractly
- Multicore not yet verified
- Covert *timing* channels not precluded

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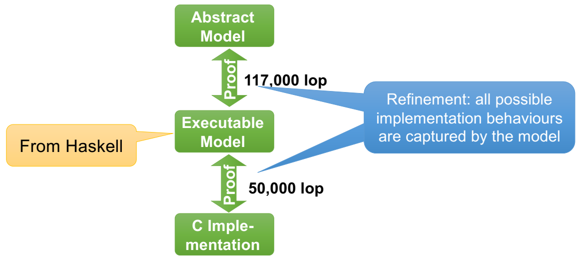
seL4 Proving Functional Correctness



seL4 Proving Functional Correctness

```
constdefs
  schedule :: "unit s_monad"
  "schedule ≡ do
     threads ← allActiveTCBs;
     thread ← select threads;
     do_machine_op flushCaches OR return ();
     modify (λs. s ⦇ cur_thread := thread ⦈)
   od"
```

```
schedule :: Kernel ()
schedule = do
        action <- getSchedulerAction
        case action of
            rmally -> do
            ead <- getCurThread
            le <- isRunnable curThread
            - threadGet tcbTimeSlice curThread
            not runnable || time == 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[o
        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;
```


seL4 Functional Correctness Summary

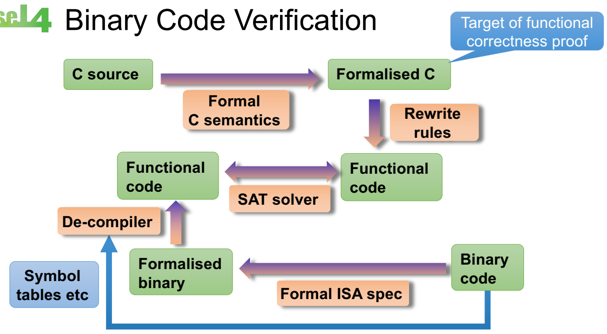
Kinds of properties proved

- 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
  - will never access array out of bounds
  - 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

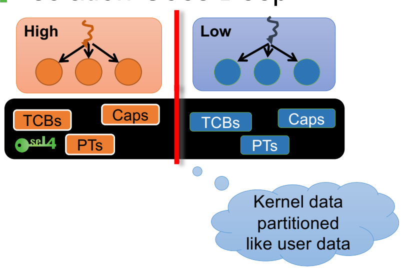
Can prove further properties on abstract level!

Bugs found:
- 16 in (shallow) testing
- 460 in verification
  - 160 in C,
  - 150 in design,
  - 150 in spec

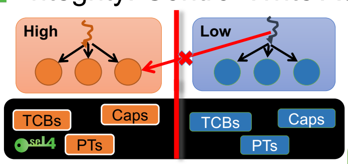
seL4 Binary Code Verification



seL4 Isolation Goes Deep



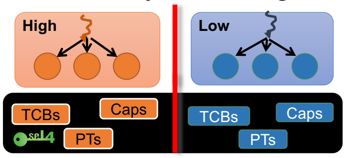
seL4 Integrity: Control Write Access



Event-based kernel always operates on behalf of well-defined user:
- Prove kernel only modifies data if presented write cap

To prove:
Low has no *write* capabilities to High objects
⇒ no action of Low will modify High state
Specifically, *kernel does not modify on Low's behalf!*

seL4 Availability: Ensuring Resource Access



Nothing to do, implied by other properties!

Strict separation of kernel resources
⇒ Low cannot deny High access to resources

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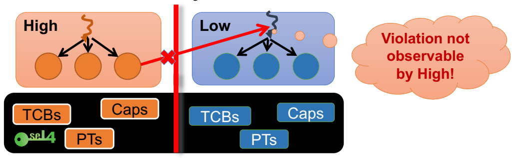
seL4 Confidentiality: Control Information Flow



Non-interference proof:
- Evolution of Low does not depend on High state
- Also shows absence of covert *storage channels*

To prove:
Low has no *read* capabilities to High objects
⇒ no action will reveal High state to Low

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seL4 Confidentiality Proof Challenge

Spec

```
bool a();

bool b() {
  int secret;
}
```

Idiotic but valid refinement

Implementation

```
bool a() {
  return !secret;
}
```

Non-determinism breaks confidentiality under refinement!

Solution:
- Remove non-determinism where it affects confidentiality
- Eg: scheduler strictly round-robin

Infoflow is very strong property, requiring restrictions rarely met in real world

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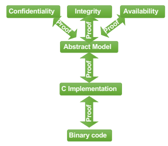
seL4 Verification Assumptions



1. Hardware behaves as expected
   - Formalised hardware-software contract (ISA)
   - Hardware implementation free of bugs, Trojans, …
2. Spec matches expectations
   - Can only prove “security” if specify what “security” means
   - Spec may not be what we think it is
3. Proof checker is correct
   - Isabel/HOL checking core that validates proofs against logic

With binary verification do **not** need to trust C compiler!

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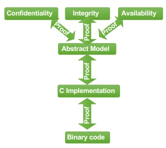
seL4 Present Verification Limitations



- Not verified boot code
  - **Assume** it leaves kernel in safe state
- Caches/MMU presently modeled at high level / axiomised

MMU model just finished

- Not proved any temporal properties
  - Presently not proved scheduler observes priorities, properties needed for RT
  - WCET analysis applies only to dated ARM11/A8 cores
  - No proofs about timing channels

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seL4 Common Criteria?

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EAL5	not evaluated	Semi-Formal	Semi-Formal	Informal
EAL6	Formal	Semi-Formal	Semi-Formal	Informal
EAL7	Formal	Formal	Formal	Informal
seL4	Formal	Formal	Formal	Formal

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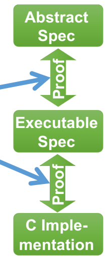
Cost of Verification

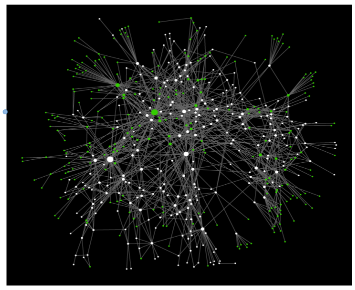
seL4 Verification Cost Breakdown

	Haskell design	2 py
	C implementation	2 months
Verification	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**
Reusable!	**Non-reusable verification**	**11.5 py**
	Traditional engineering	**4–6 py**

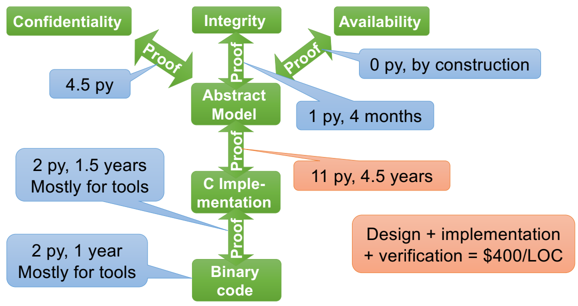


seL4 Why So Hard for 9,000 LOC?

seL4 call graph



seL4 Verification Cost



seL4 Microkernel Life-Cycle Cost in Context