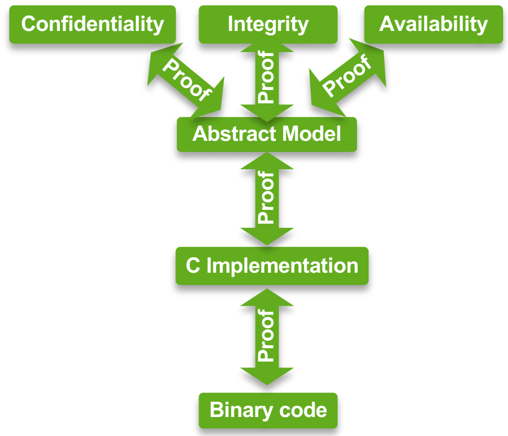
School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2022 T2 Week 10 Part 1

Formal Verification and seL4

@GernotHeiser



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Today's Lecture

- Assurance and verification
  - Common Criteria
  - Formal verification
- seL4
  - Functional correctness
  - Translation correctness
  - Security enforcement
  - Verification limitations
  - WCET analysis
  - Cost of verification
- Security impact of OS design

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

Informal (English) or formal (maths)

- System design
  - Justification that it meets specification

Compelling argument or formal proof

- Implementation
  - Justification that it implements the design

Code inspection, rigorous testing, proof

- Maintenance
  - Justifies that system use meets assumptions

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 [Green Hills] 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:

- **Systematic exploration of system state space**

❑ Cannot generally prove code correct
  - Proves specific properties

❑ Generally have to
  - over-approximate (false positives), or
  - under-approximate (false negatives, unsound)

❑ Suffers state-space explosion

✓ Automatic

✓ May scale to large code bases

Theorem proving:

- **Proofs about state spaces**

✓ Can deal with large (even infinite) state spaces

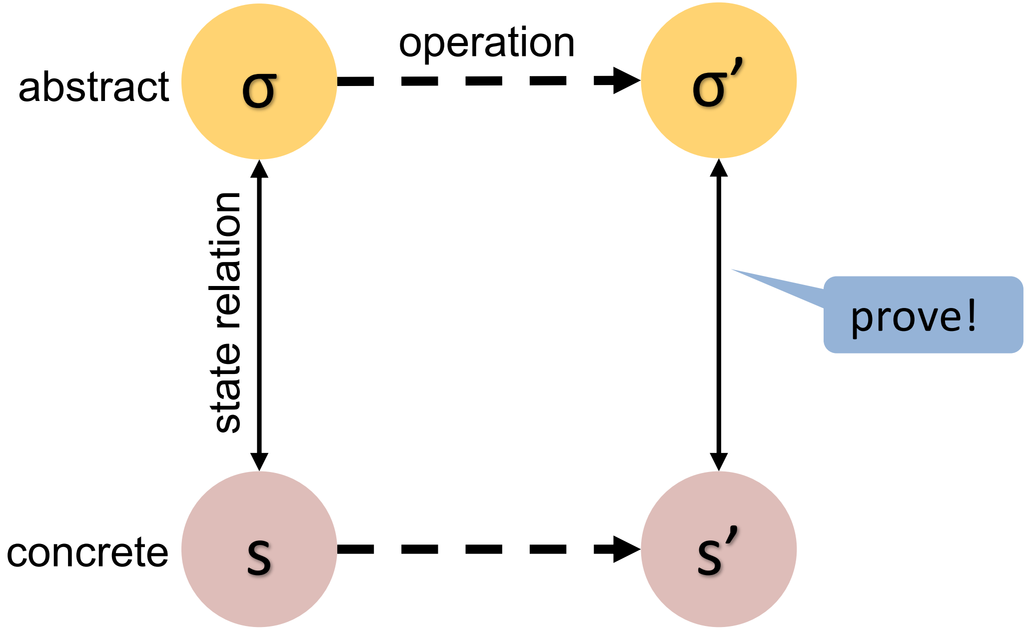
✓ Can prove functional correctness against a spec

❑ Very labour-intensive

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

Theorem Proving

"Forward simulation":
Prove state correspondence
of abstract and concrete levels

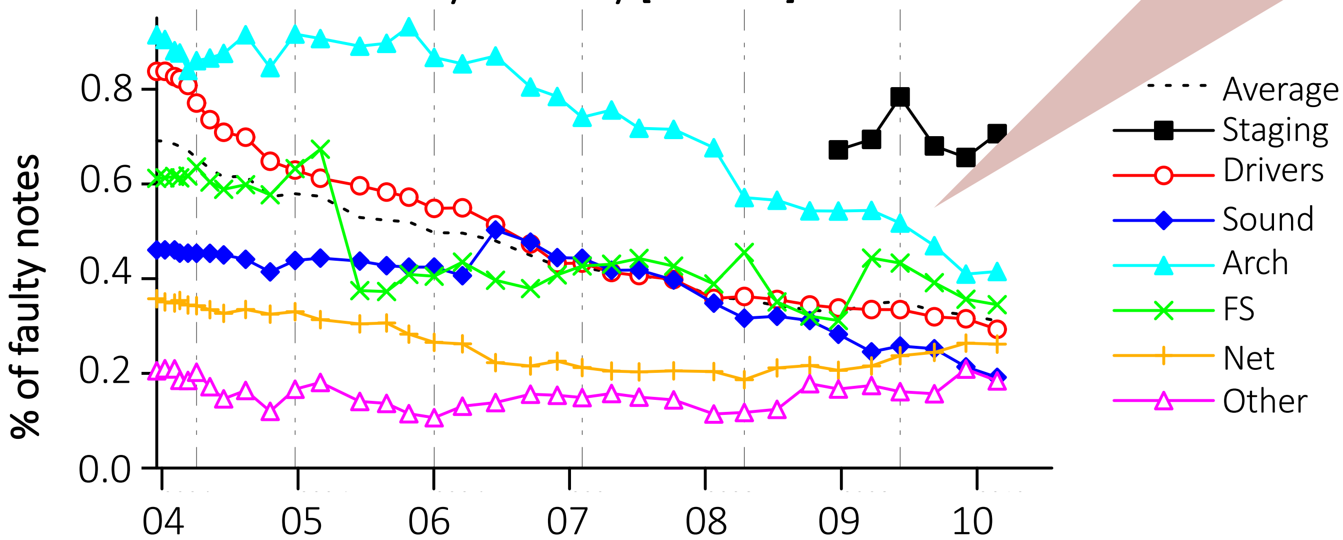


Model Checking and Linux: A Sad Story

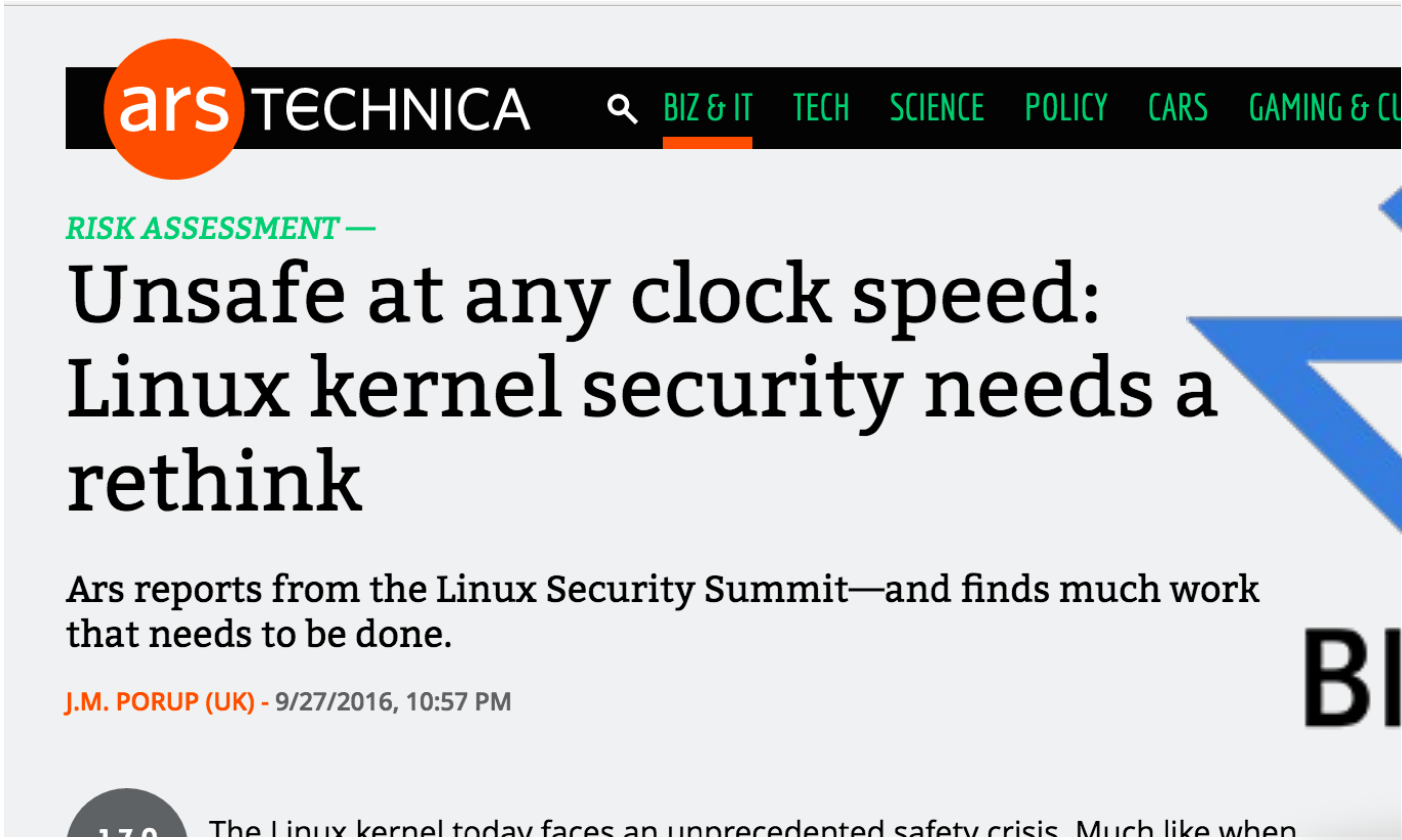
- Static analysis of Linux source [Chou & al, 2001]
  - Found high density of bugs, especially in device drivers
- Re-analysis 10 years later [Palix & al, 2011]

Disappointing rate of improvement for bugs that are automatically detectable!

Fault rate by directory [Palix'11]



And the Result?


ars TECHNICA BIZ & IT TECH SCIENCE POLICY CARS GAMING & CU

RISK ASSESSMENT —

Unsafe at any clock speed: Linux kernel security needs a rethink

Ars reports from the Linux Security Summit—and finds much work that needs to be done.

J.M. PORUP (UK) - 9/27/2016, 10:57 PM

The Linux kernel today faces an unprecedented safety crisis. Much like when

BlueBorne

seL4

August 2009

A NICTA bejelentette a világ első, formális módszerekkel igazolt,

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Technology: World's Firs

Posted by Soulskill on Thursday Aug
from the wait-for-it dept.

An anonymous reader writes

> "Operating systems usually have
> and so forth are known by almos
> to prove that a particular OS ker
> formally verified, and as such it
> researchers used an executable
> the Isabelle theorem prover to ge
> matches the executable and the

Does it run Linux? "We're pleased to say that it does. Presently, we have a para-virtualized ver

eredményeképpen pedig egy olyan megbízhatóságot kapnak a szoftvertől, amely e

New Scientist
Saturday 29/8/2009
Page: 21
Section: General News
Region: National
Type: Magazines Science / Technology
Size: 196.31 sq.cms.
Published: -----S-

The ultimate way to keep your computer safe from harm

FLAWS in the code, or "kernel", that sits at the heart of modern computers leave them prone to occasional malfunction and vulnerable to attack by worms and viruses. So the development of a secure general-purpose microkernel could pave the

just mathematics, and you can reason about them mathematically," says Klein.

His team formulated a model with more than 200,000 logical steps which allowed them to prove that the program would always behave as its

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Share

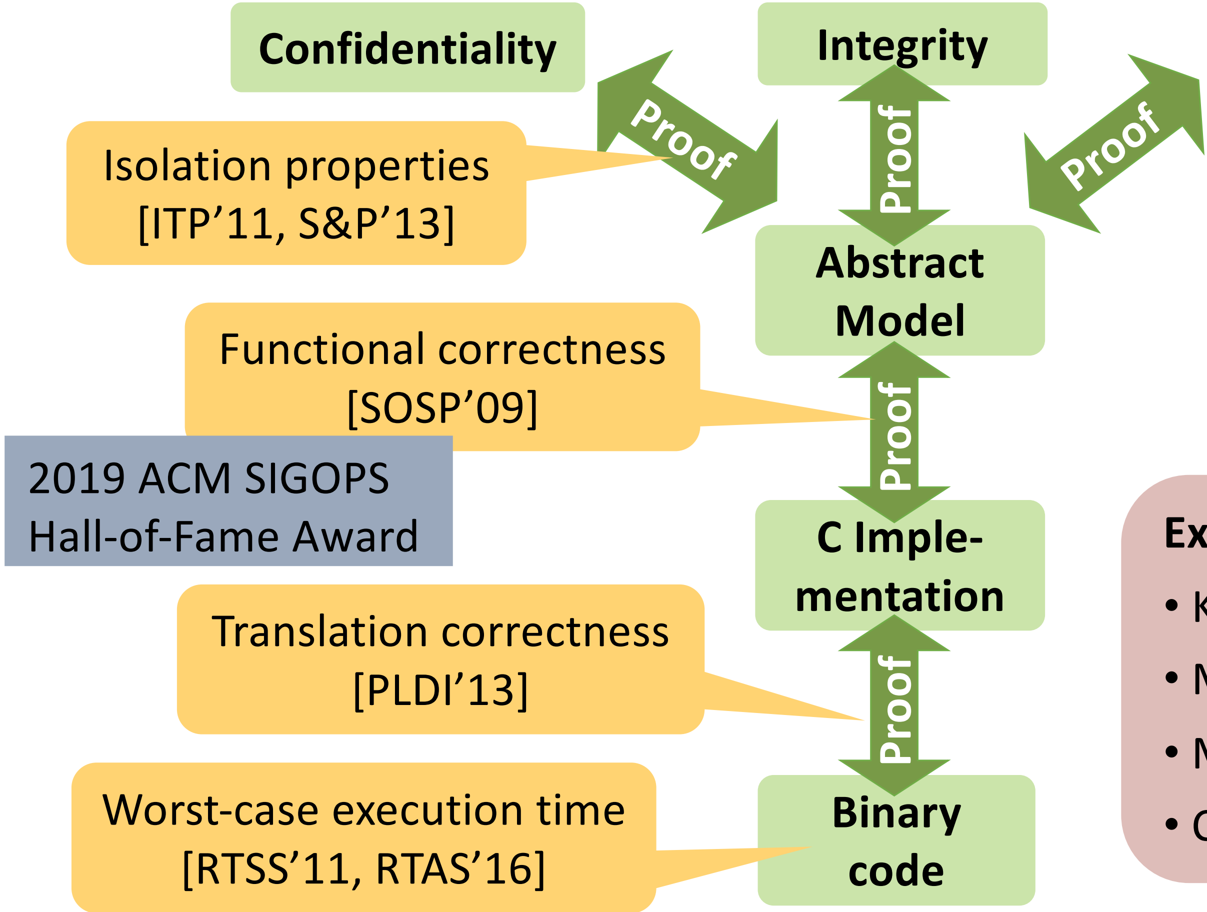
Crash-Proof Code

Making critical software safer

7 comments
WILLIAM BULKELEY
May/June 2011

UNSW SYDNEY

Proving Security and Safety (Armv6/7)



Still most compre-hensive verification

Still only verified capability-based OS

Exclusions (at present, Armv7):

- Kernel initialisation not yet verified
- MMU & caches modelled abstractly
- Multicore not yet verified
- Covert *timing* channels not precluded

Security Is No Excuse For Bad Performance!

World's fastest microkernel!

Latency (in cycles) of a round-trip cross-address-space IPC on x64

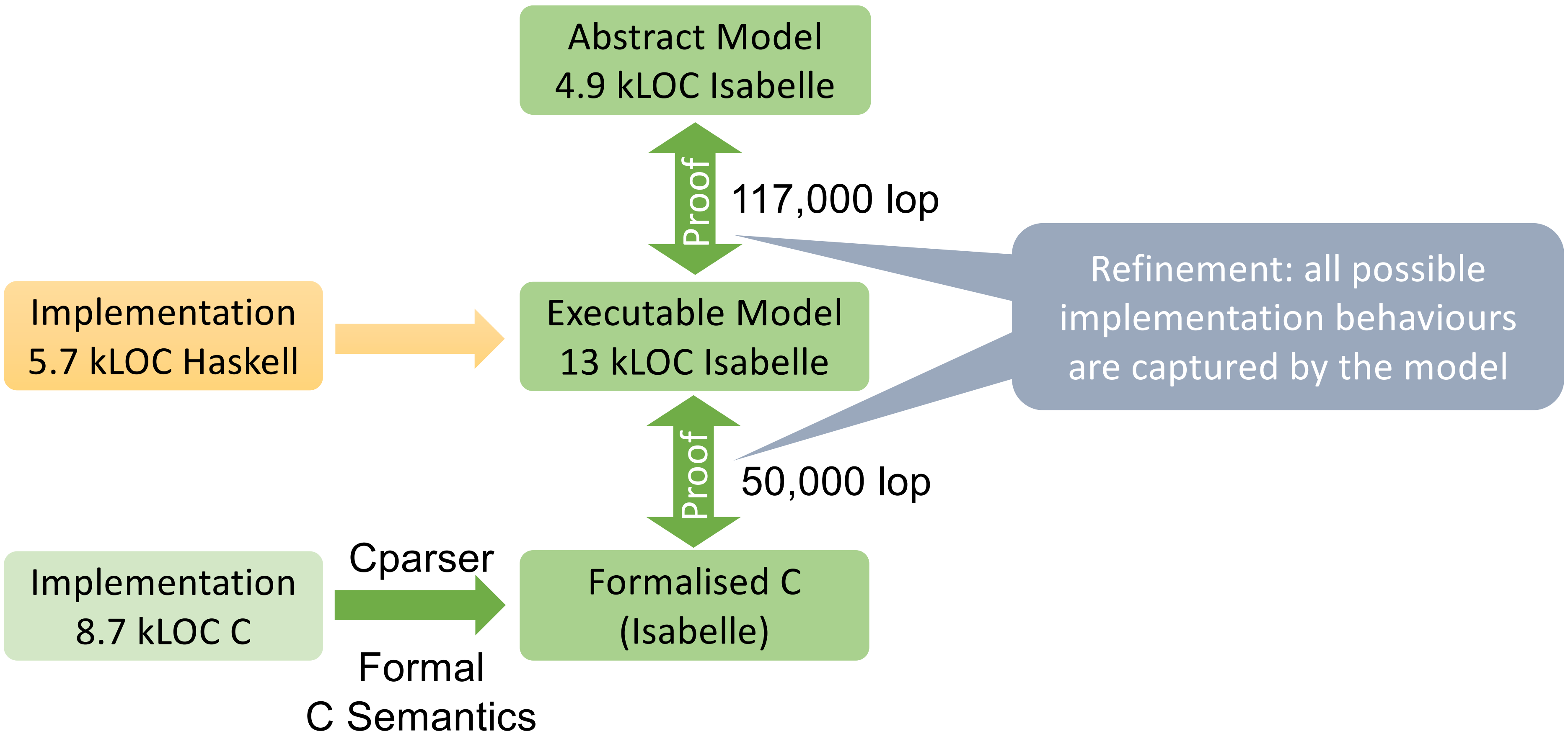
Source	seL4	Fiasco.OC	Zircon
Mi et al, 2019	986	2717	8157
seL4.systems, Jul'22	763	N/A	N/A

Within 10% of hardware limit!

Sources:
- Zeyu Mi, Dingji Li, Zihan Yang, Xinran Wang, Haibo Chen: "SkyBridge: Fast and Secure Inter-Process Communication for Microkernels", EuroSys, April 2020
- seL4 Performance, https://sel4.systems/About/Performance/, accessed 2022-07-31

Functional Correctness

Proving Functional Correctness



Functional Correctness Summary

Can prove further properties on abstract level!

Kinds of properties proved

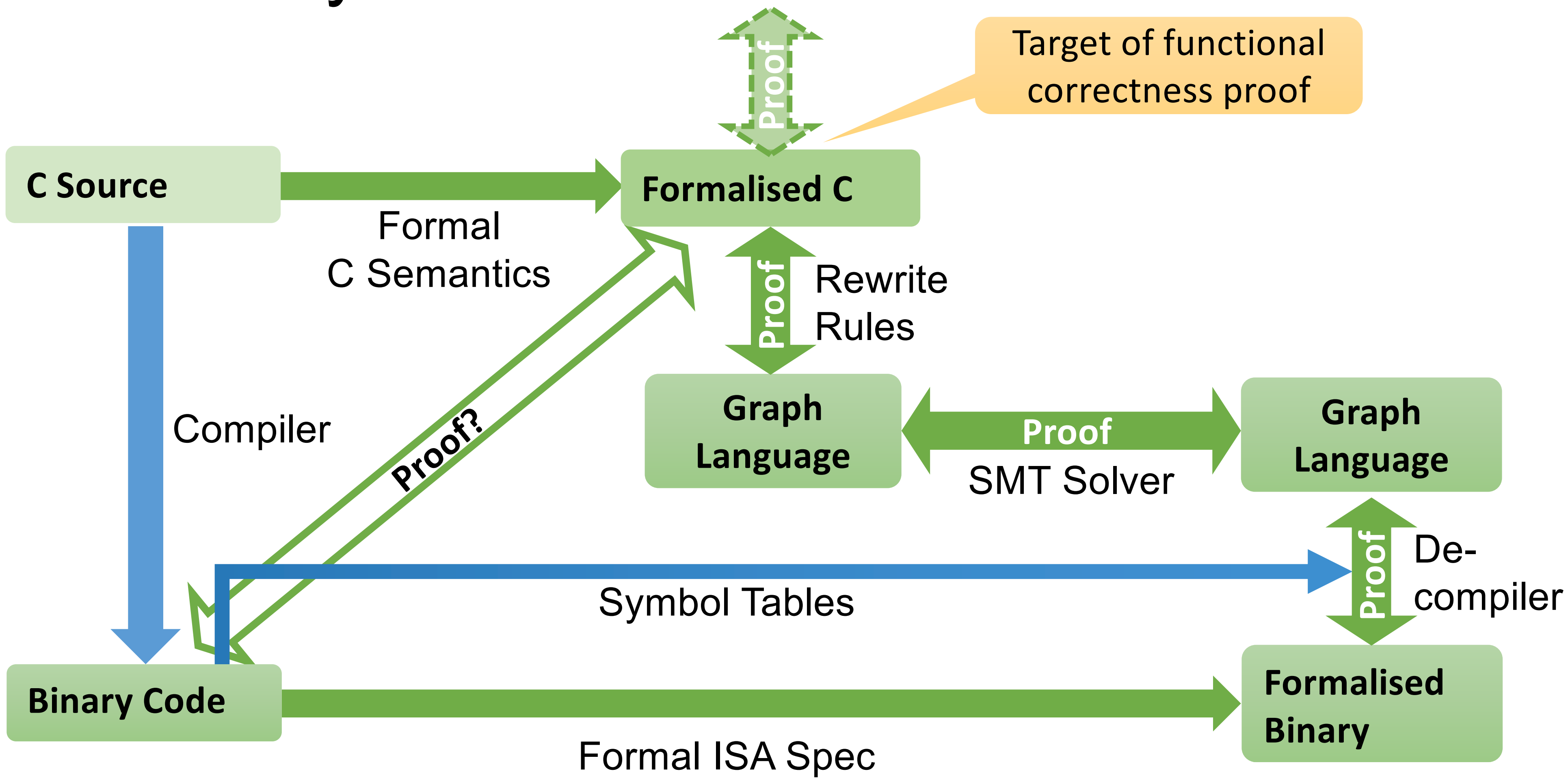
- Behaviour of C code is fully captured by abstract model
- Behaviour of C code is fully captured by executable model
- Kernel never fails, behaviour is always well-defined
  - assertions never fail
  - will never de-reference null pointer
  - will never access array out of bounds
  - cannot be subverted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

Bugs found:

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

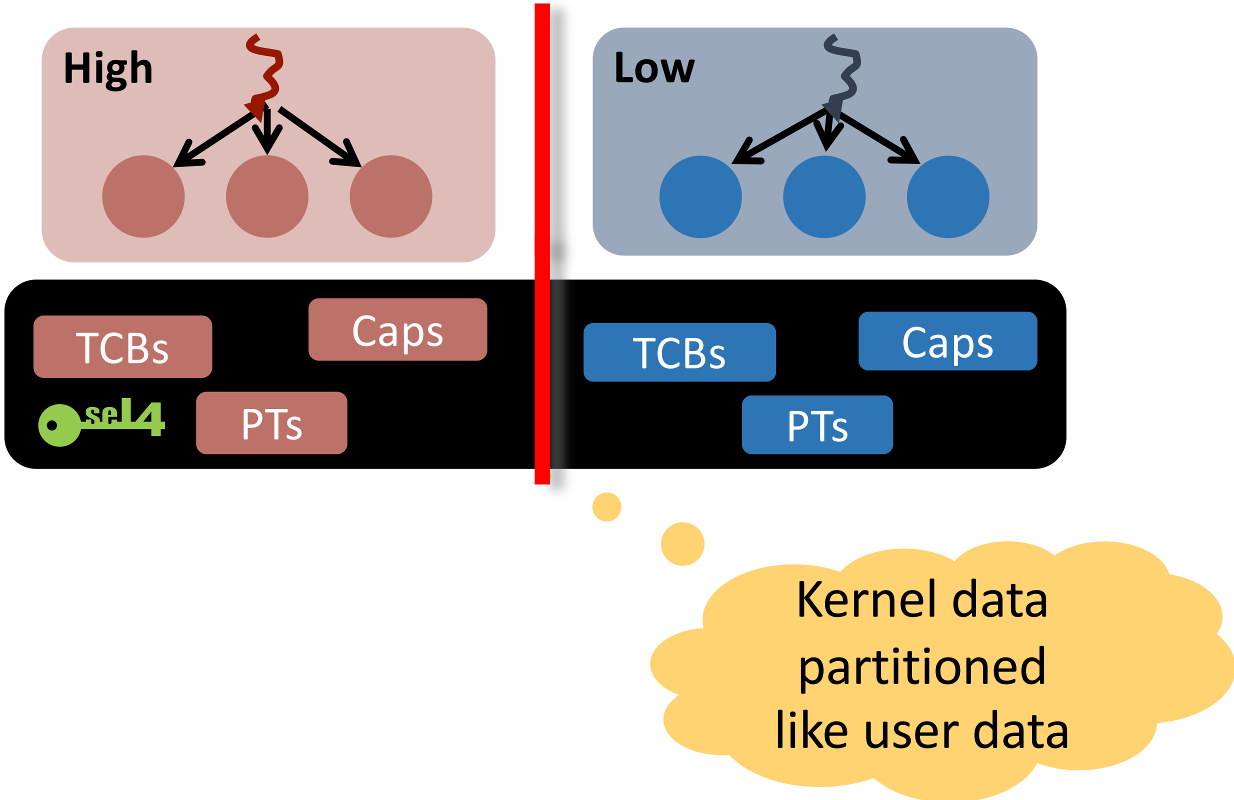
Translation Correctness

Binary Verification: Translation Validation

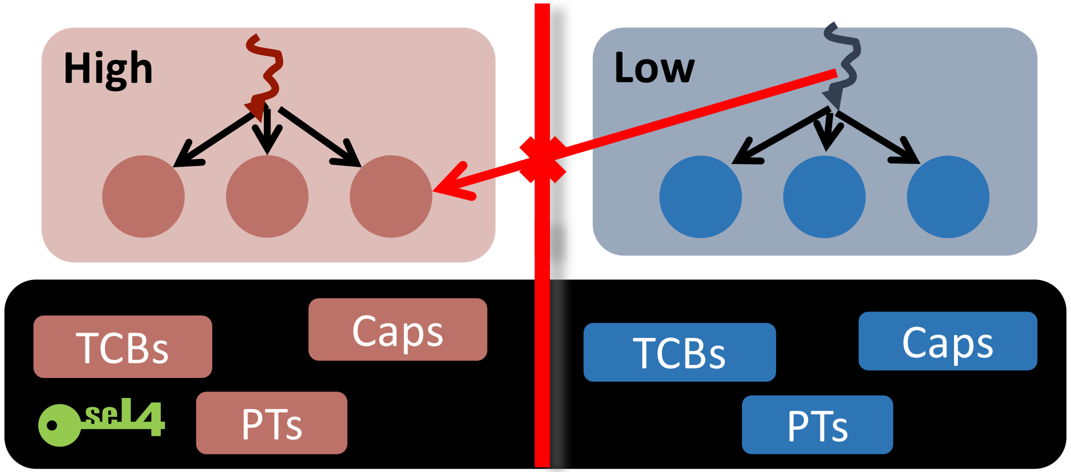


Security Enforcement

Isolation Goes Deep



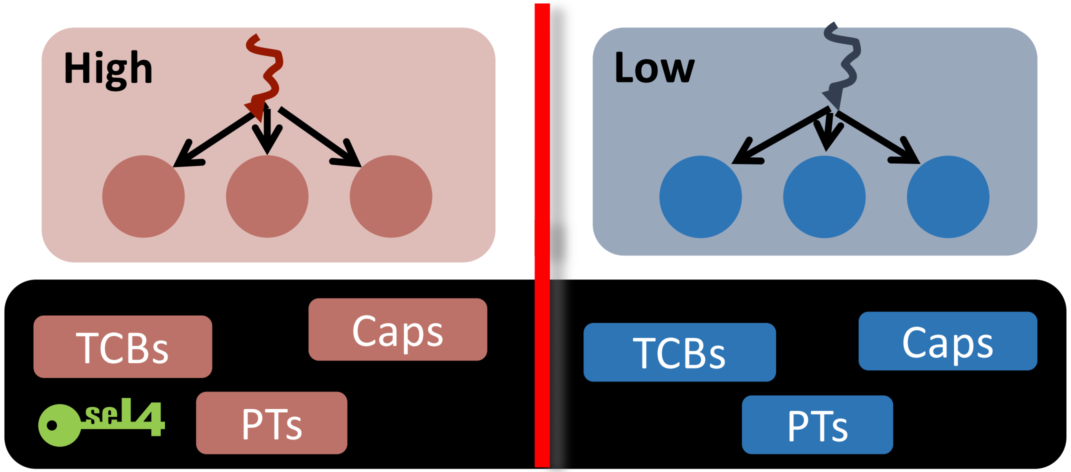
Integrity: Control Write Access



Event-based kernel always operates on be-half 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!*

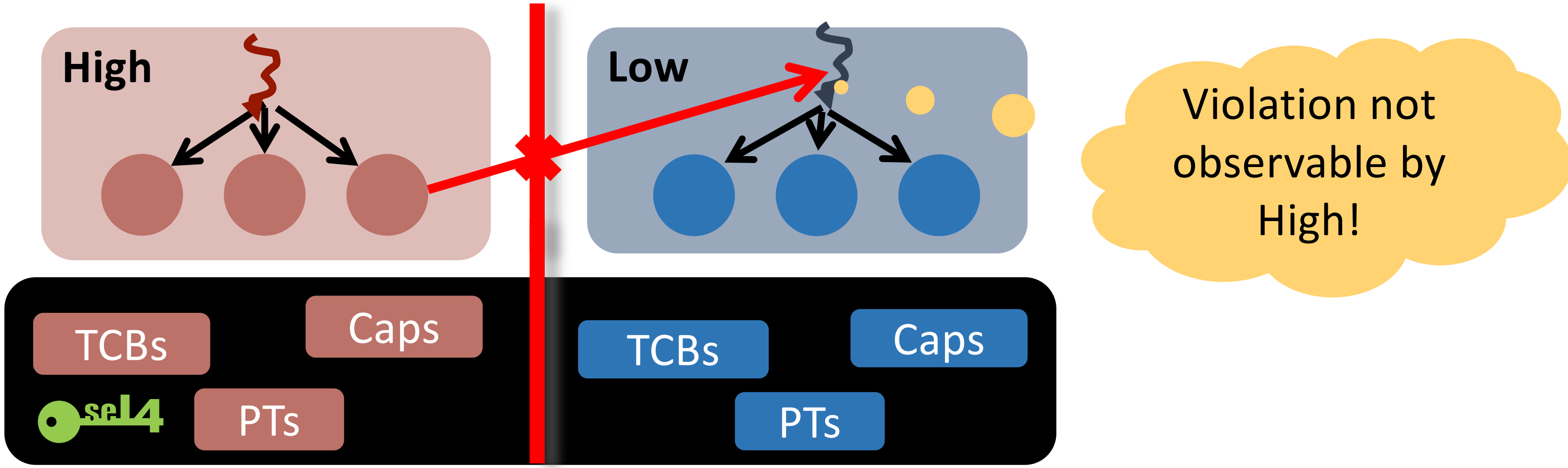
Availability: Ensuring Resource Access



Nothing to do, implied by other properties!

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

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

Confidentiality Proof Challenge

Spec

```
bool a();
```

Idiotic but valid refinement

Implementation

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

Non-determinism breaks confidentiality under refinement!

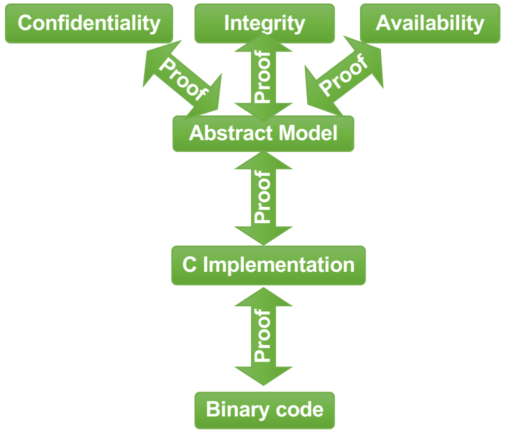
Solution:

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

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

Limitations

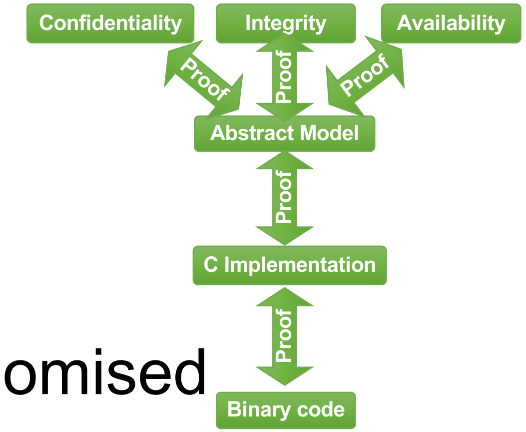
Verification Assumptions



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!

Present Verification Limitations



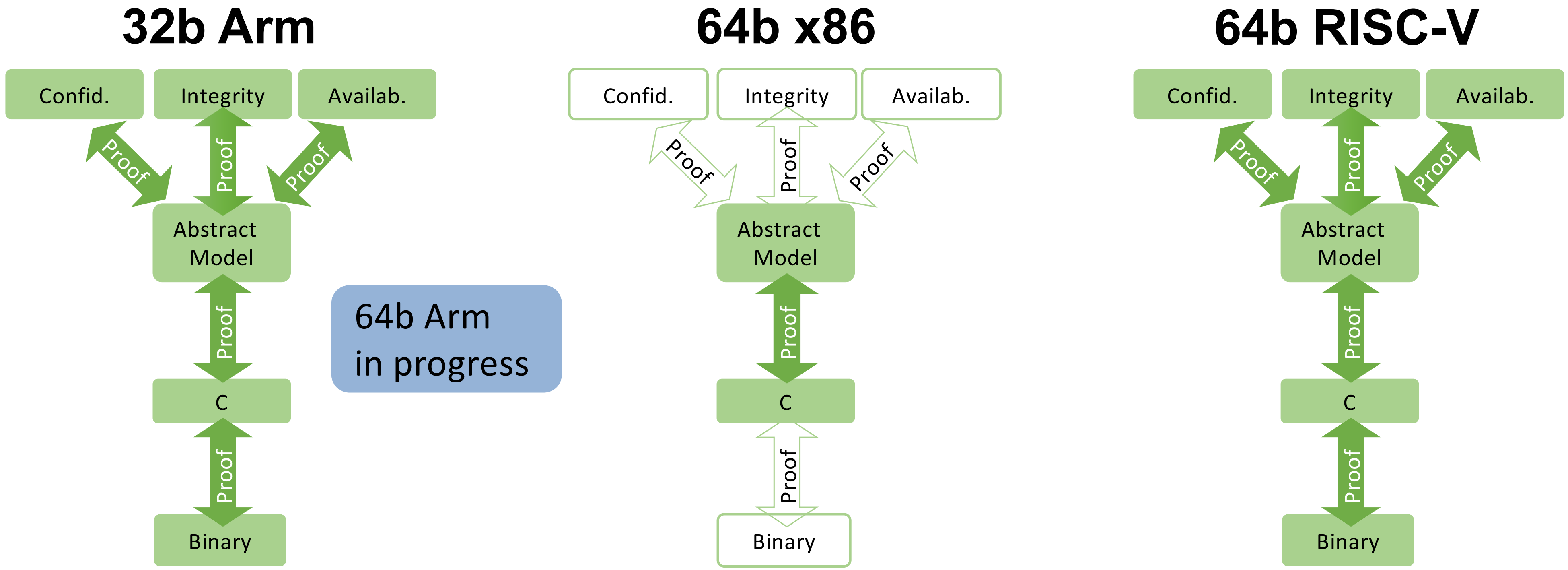
- Not verified boot code
  - **Assume** it leaves kernel in safe state
- Caches/MMU presently modeled at high level / axiomised

MMU model finished by recent PhD

- 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 (yet)

Present research!

Present Status



seL4 Common Criteria?

Level	Requirements	Specification	Design	Implementation
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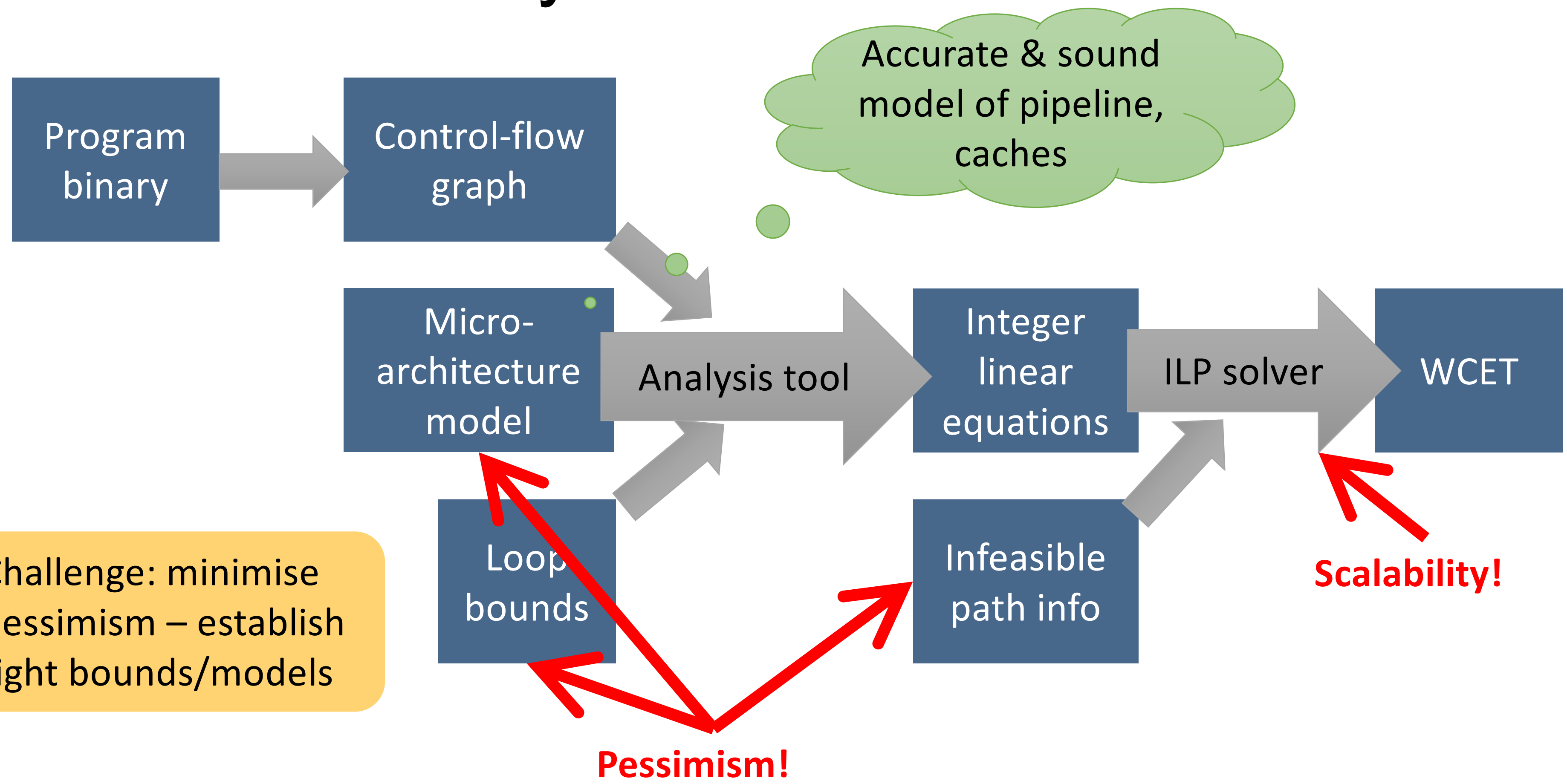
EAL7	**Formal**	**Formal**	**Formal**	**Informal**
seL4	**Formal**	**Formal**	**Formal**	**Formal**

WCET Analysis

WCET Analysis

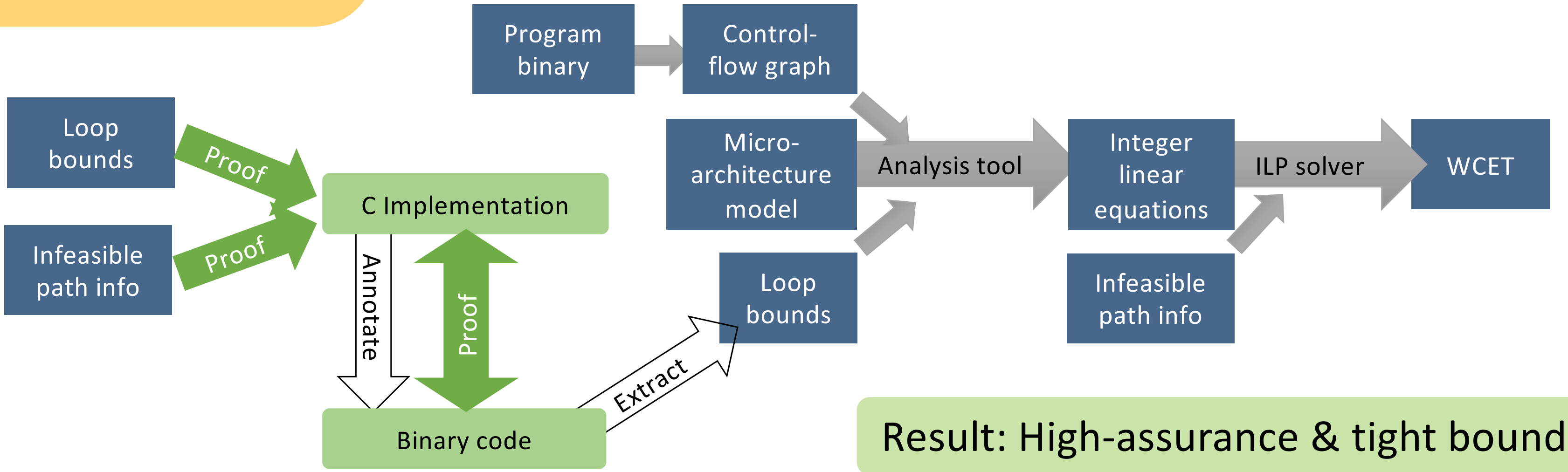


Challenge: minimise pessimism – establish tight bounds/models

Loop Bounds & Infeasible Paths

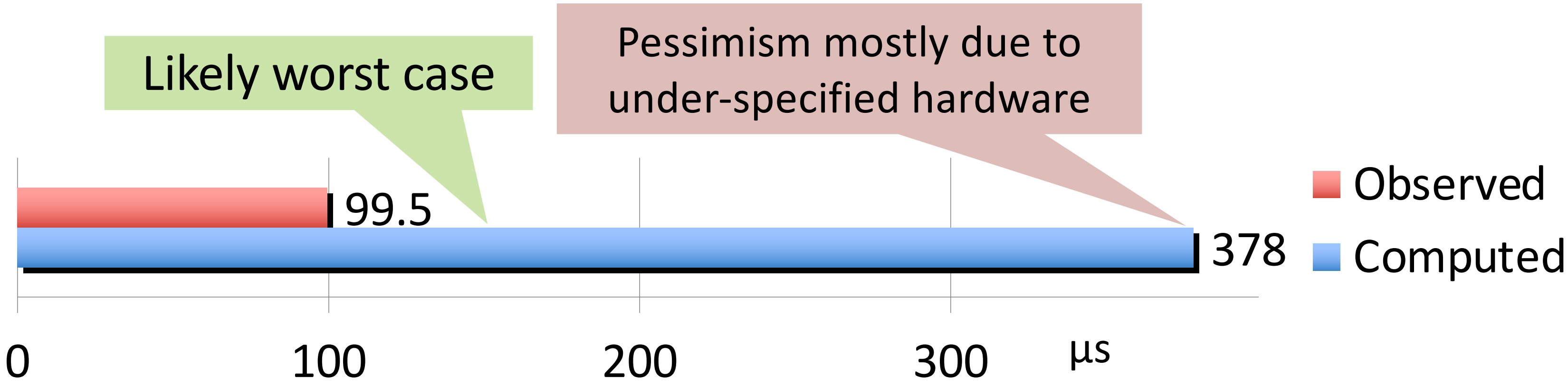
Tight loop bounds and infeasible path refutations infeasible to obtain from binary – lack of semantic information, especially pointer aliasing analysis.

Idea:
- prove on C level
- transfer to binary using translation-validation toolchain



Result: High-assurance & tight bounds!

WCET Analysis on ARM11



WCET presently limited by verification practicalities

- without regard to verification achieved 50 µs
- 10 µs seem achievable
- BCET ~ 1µs
- [Blackham'11, '12] [Sewell'16]

Problem: Latency information no longer published by Arm!

RISC-V

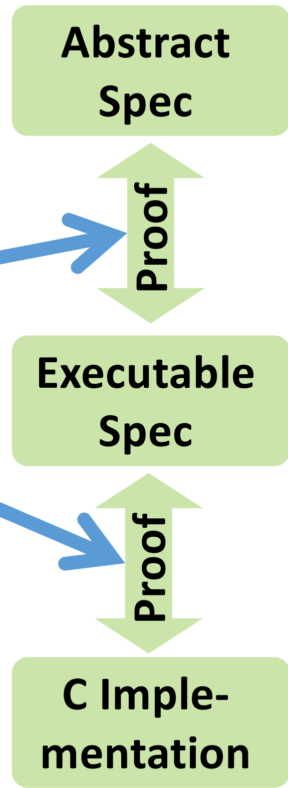
Cost of Verification

seL4 Verification Cost Breakdown

Haskell design	2 py
C implementation	0.15 py
Debugging/Testing	0.15 py
Abstract spec refinement	8 py
Executable spec refinement	3 py
Fastpath verification	0.4 py
Formal frameworks	9 py
Total	**24 py**
Non-reusable verification	**11.5 py**
Traditional engineering	**4–6 py**

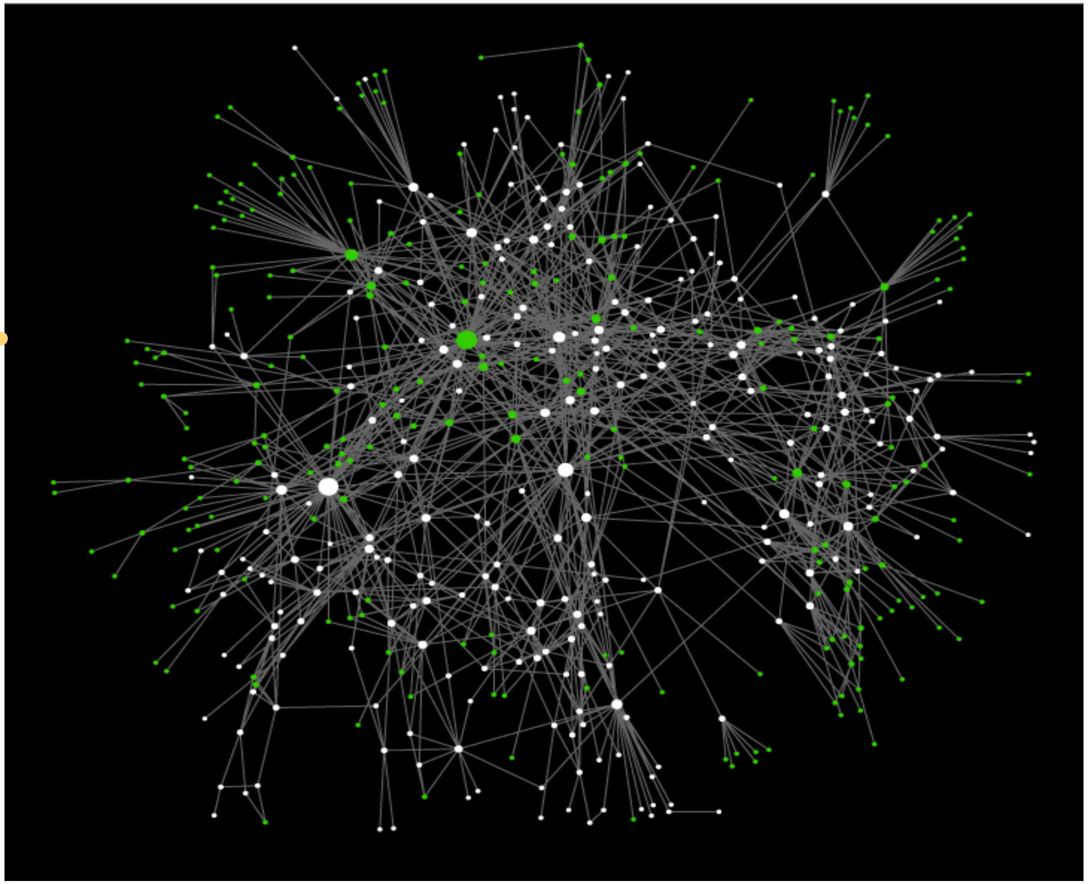
Verification

Reusable!

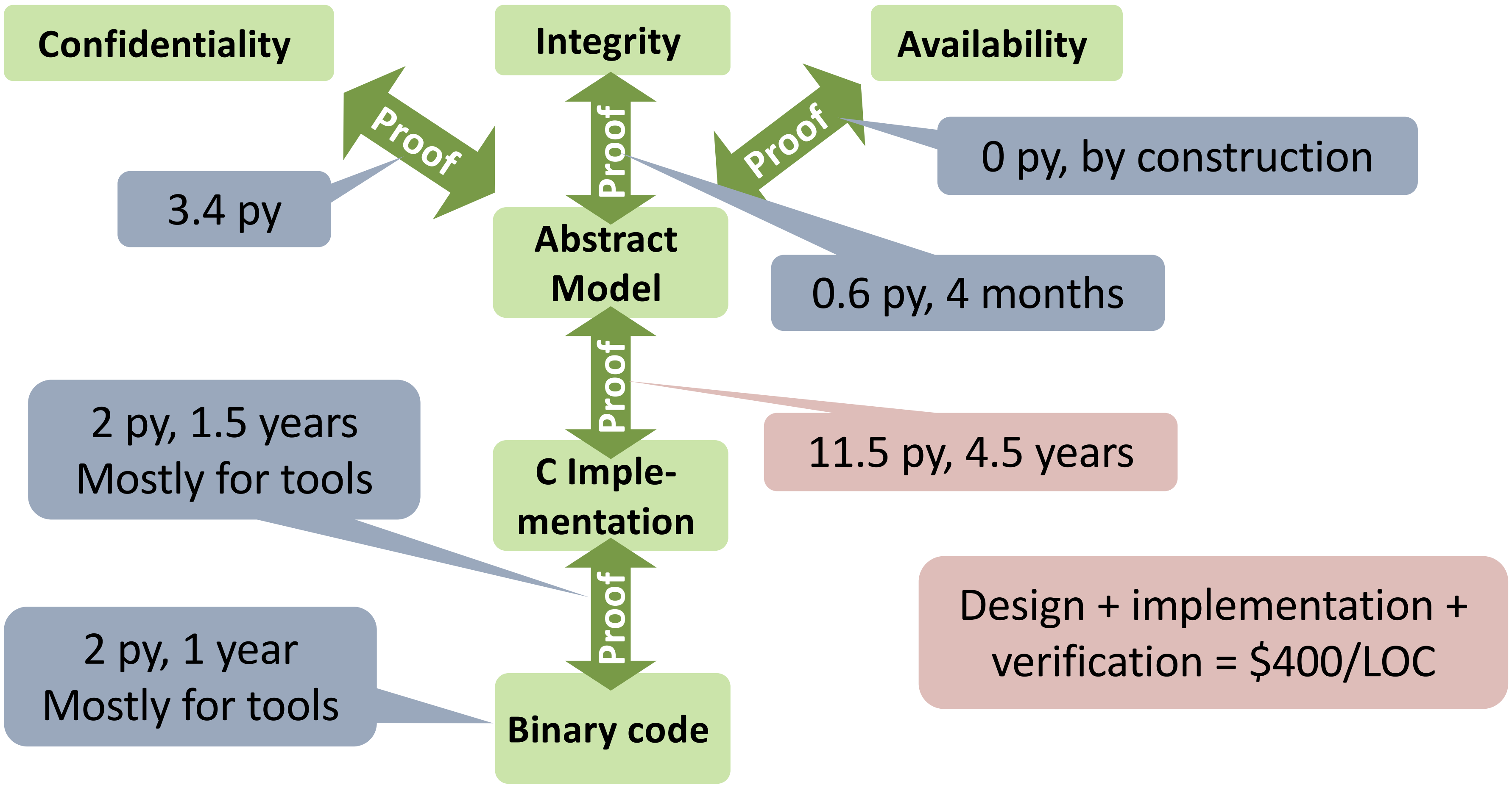


Why So Hard for 9,000 LOC?

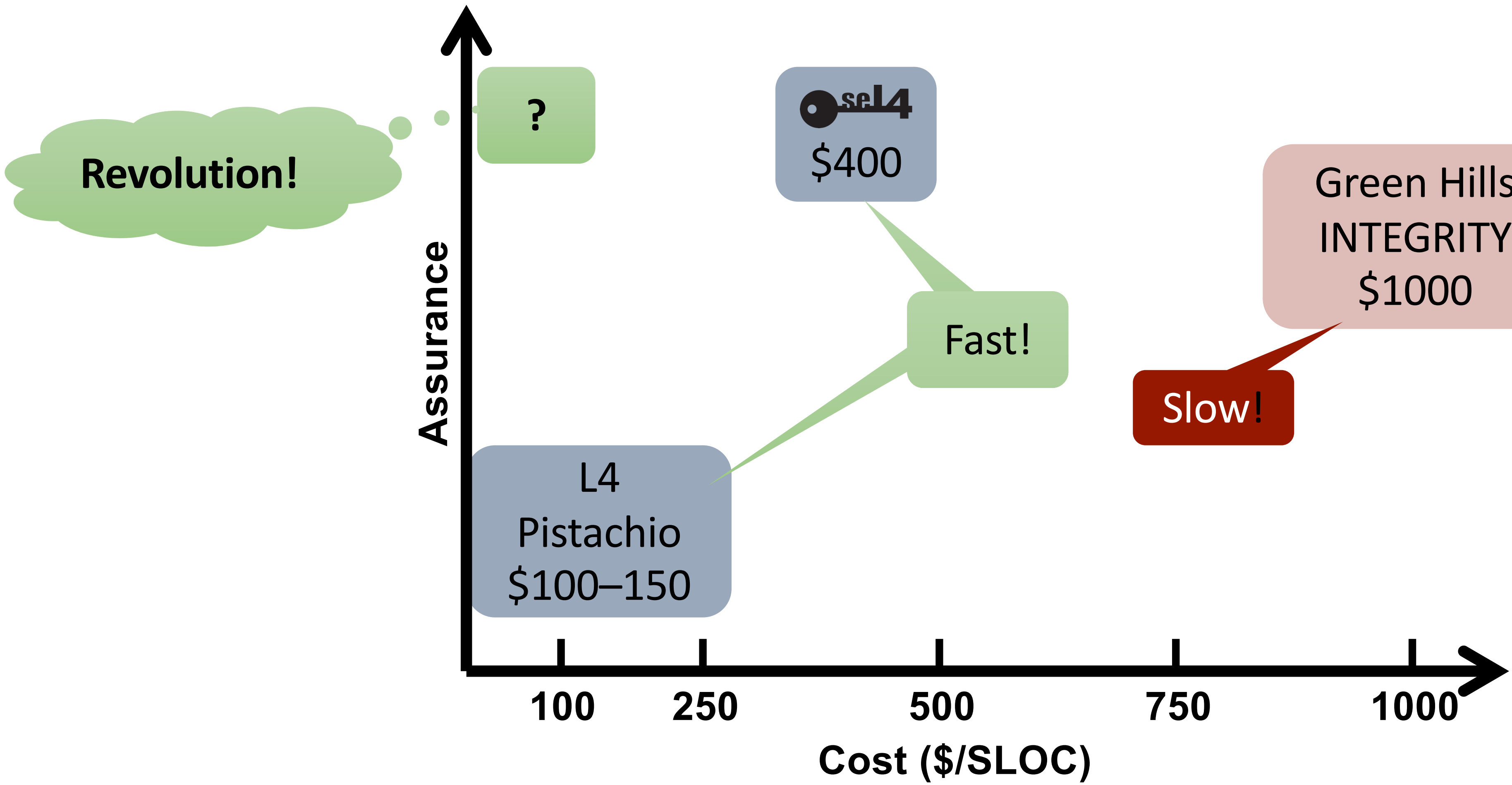
seL4 call graph



Verification Cost



Microkernel Life-Cycle Cost in Context



Security Impact of OS Design

Quantifying OS-Design Security Impact

Approach:

- Examine all ***critical*** Linux CVEs (vulnerabilities & exploits database)

  - easy to exploit
  - high impact
  - no defence available
  - confirmed

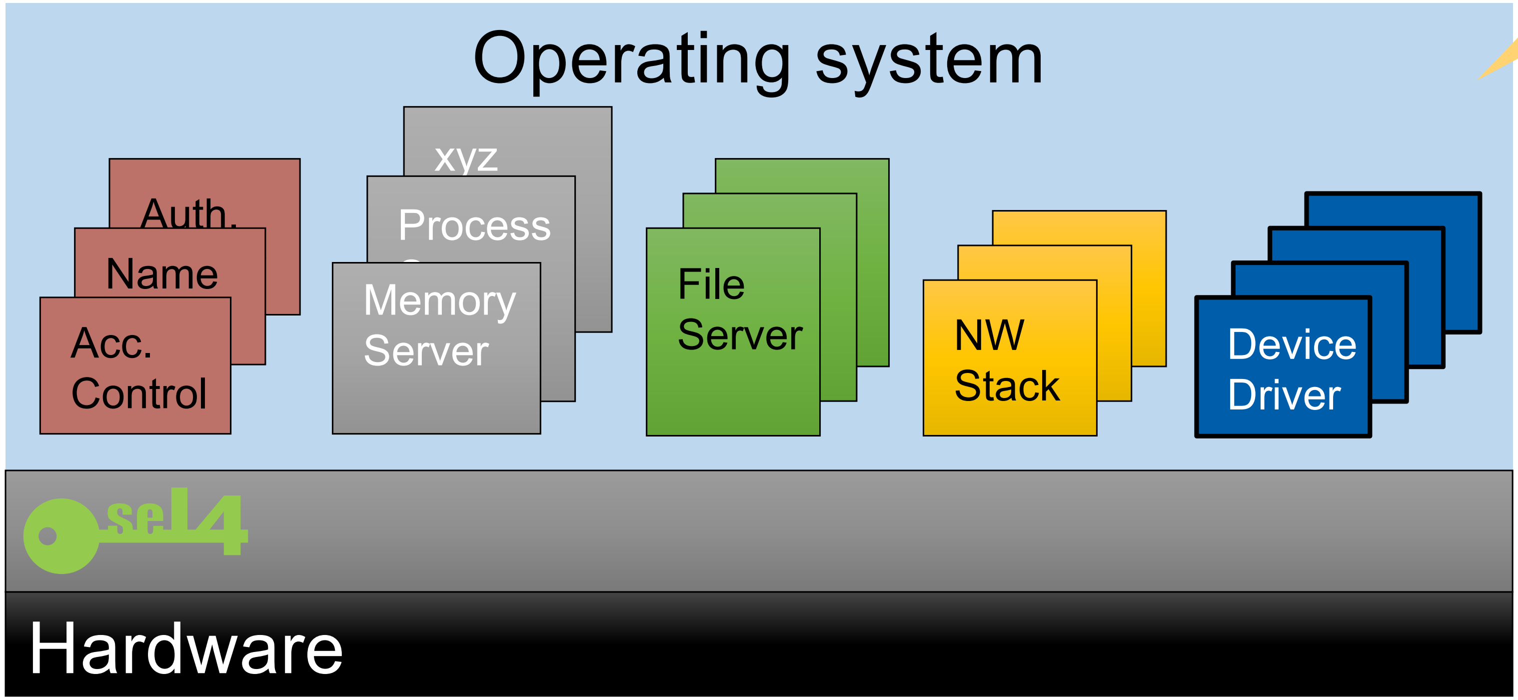
  115 critical Linux CVEs to Nov'17

- For each establish how microkernel-based design would change impact

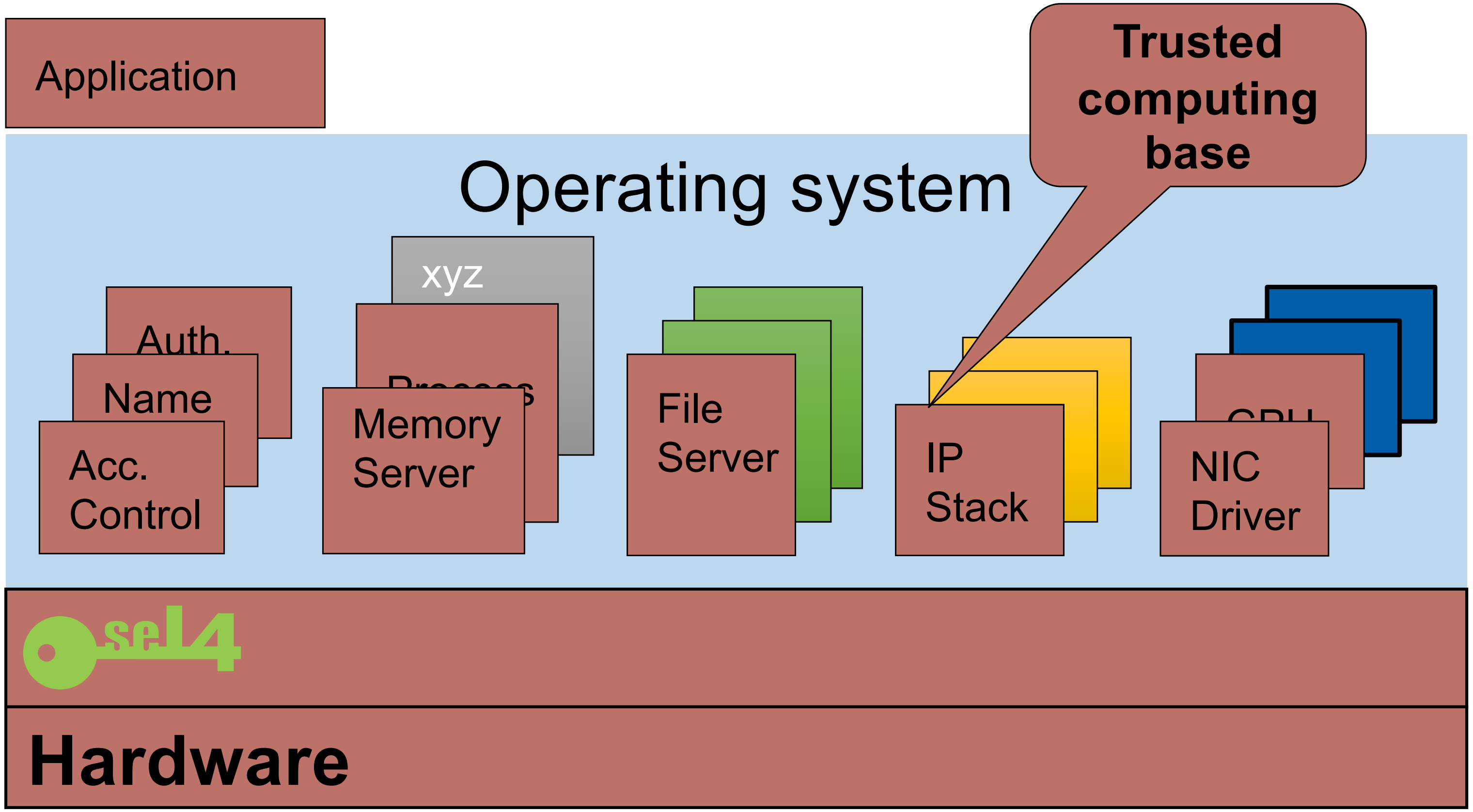
Hypothetical seL4-based OS

OS structured in *isolated* components, minimal inter-component dependencies, *least privilege*

Functionality comparable to Linux



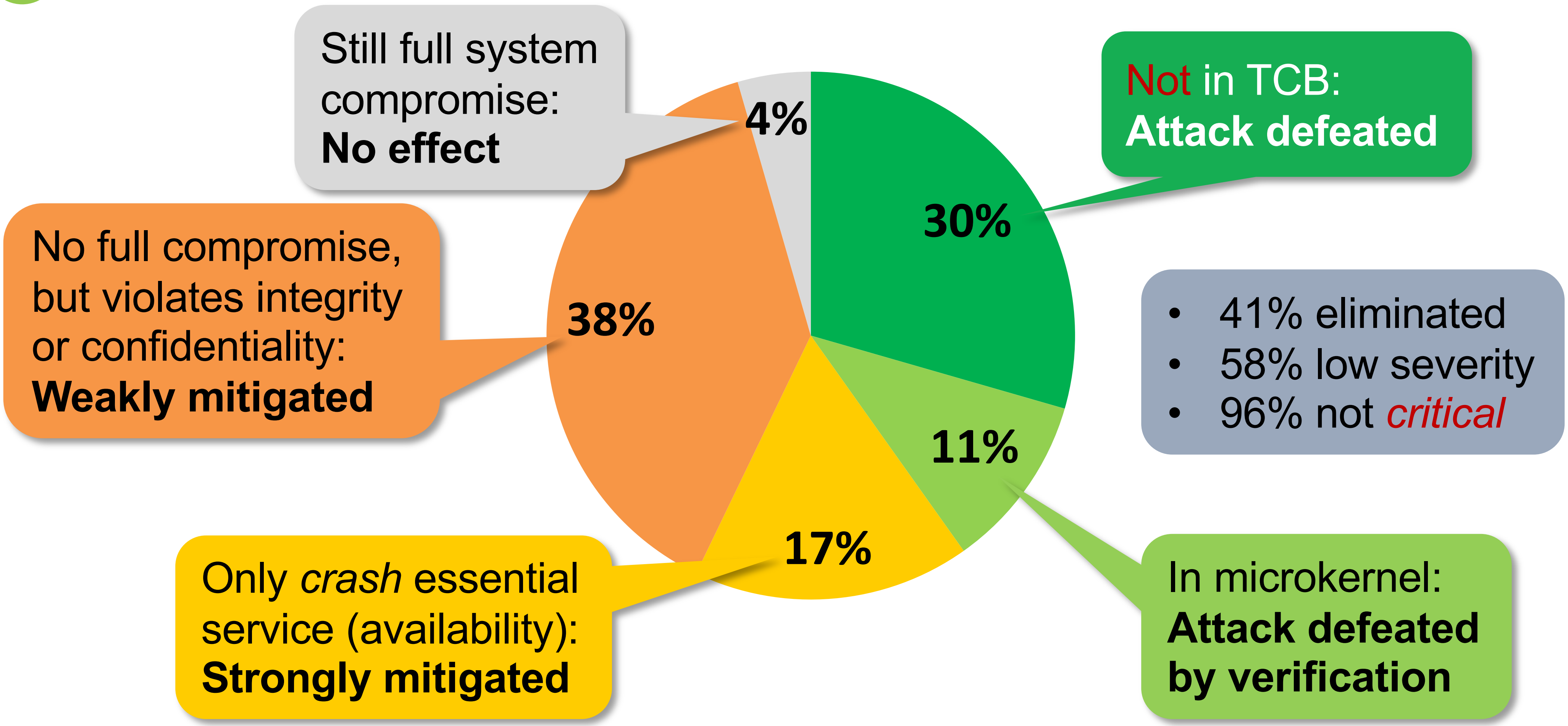
Hypothetical Security-Critical App



App requires:

- IP networking
- File storage
- Display output

All Critical Linux CVEs to 2017



Conclusion: OS Structure Matters

- Microkernels definitely improve security
- Microkernel verification improves further
- Monolithic OS design is *fundamentally flawed from security point of view*

[Biggs et al., APSys'18]

Use of a monolithic OS in security- or safety-critical scenarios is professional malpractice!