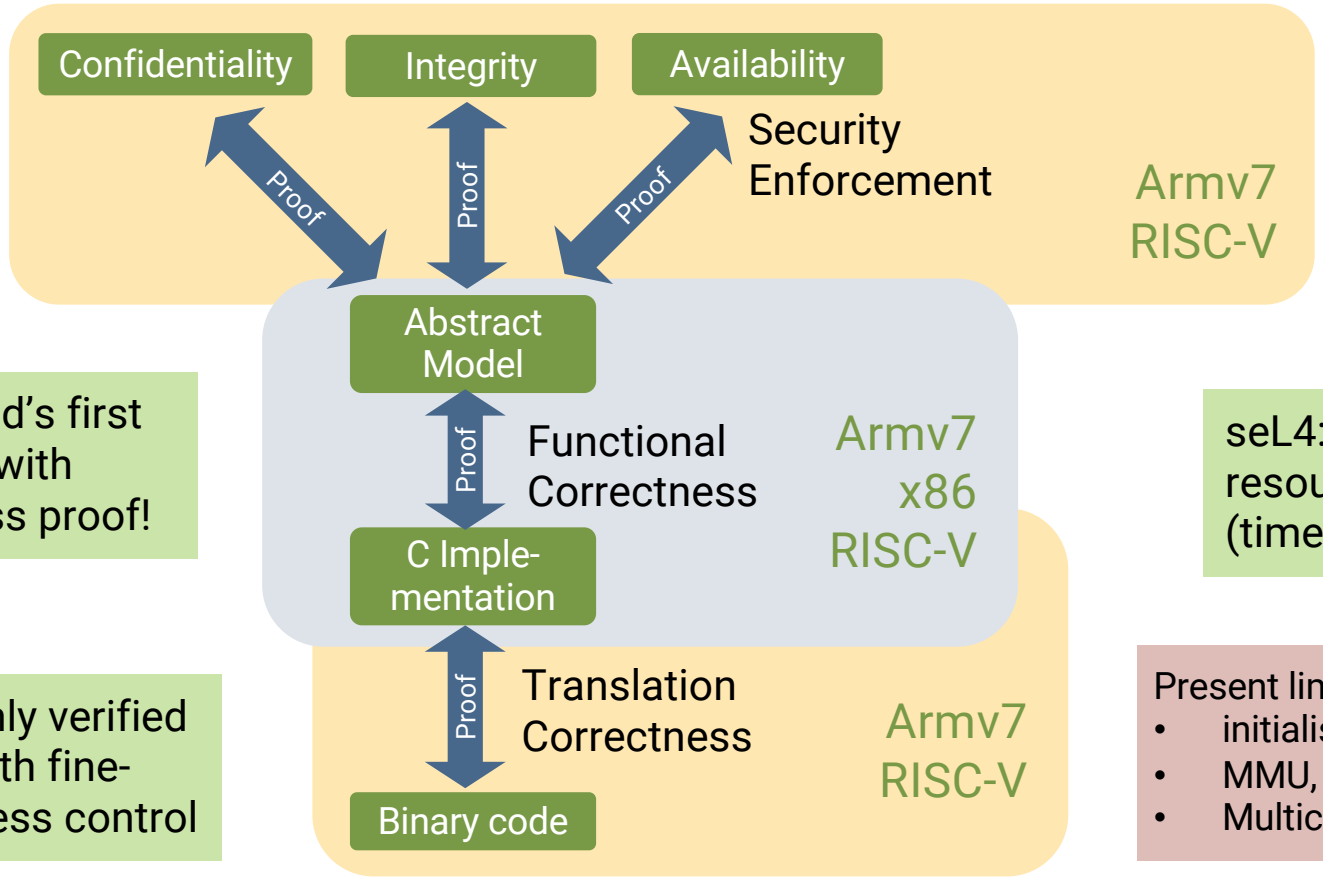
School of Computer Science & Engineering

Trustworthy Systems Group

State of seL4-related Research at Trustworthy Systems

Gernot Heiser
gernot@trustworthy.systems

Success Story – What's Next?



AArch64 in progress

seL4: World's first OS kernel with correctness proof!

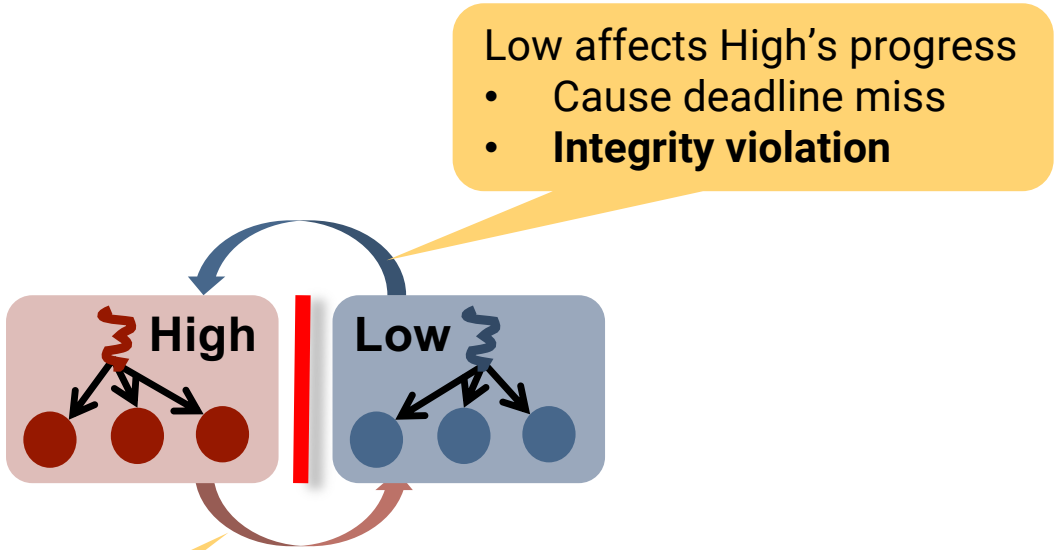
seL4: Unique, policy-free resource management (time and space)

seL4: Still only verified OS kernel with fine-grained access control

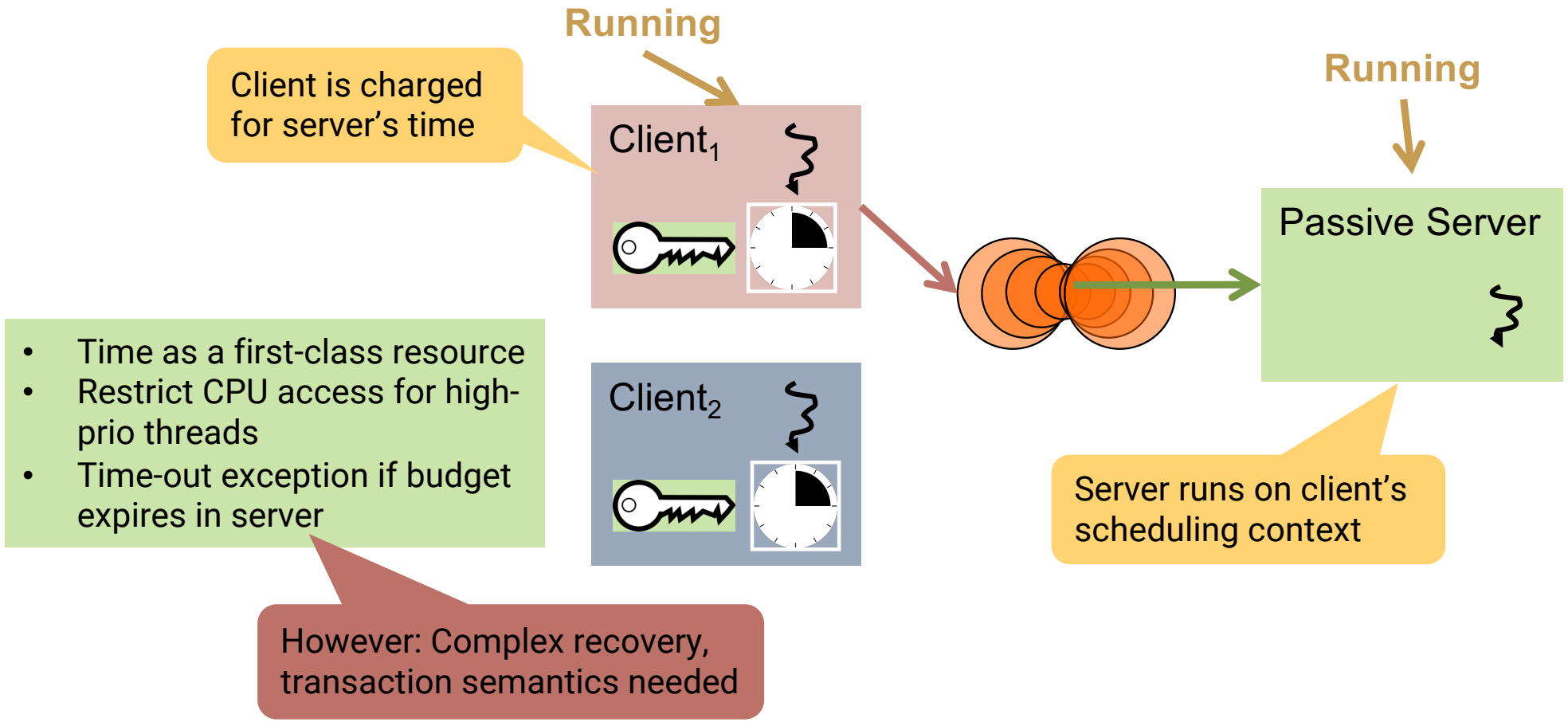
Present limitations
- initialisation code not verified
- MMU, caches modelled abstractly
- Multicore not yet verified

Time – The Final Frontier

Issues With Time



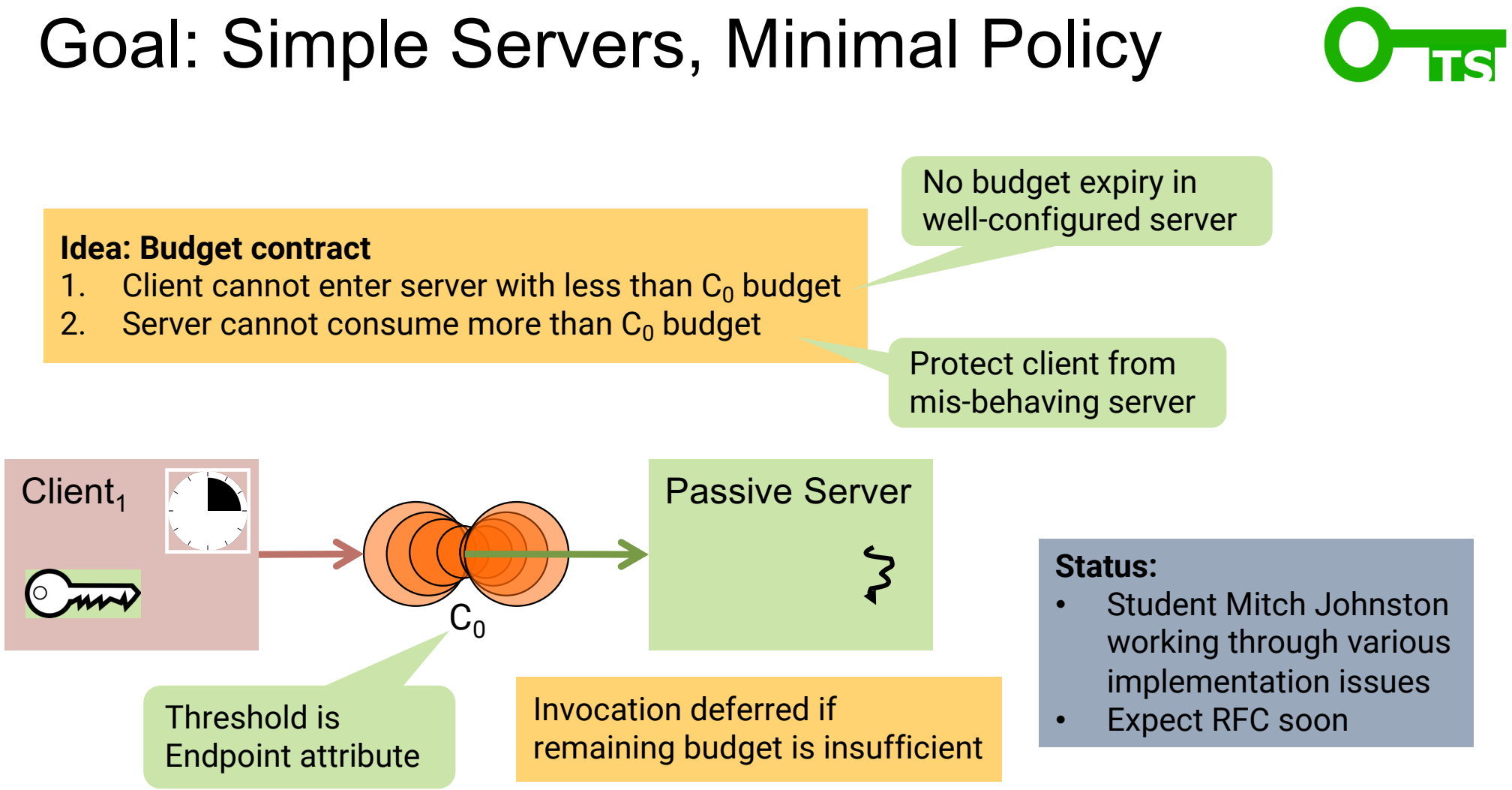
Temporal Integrity: MCS Kernel



- Time as a first-class resource
- Restrict CPU access for high-prio threads
- Time-out exception if budget expires in server

However: Complex recovery, transaction semantics needed

Goal: Simple Servers, Minimal Policy



Later: Formal Scheduling Analysis

Challenge: Prove timeliness of critical real-time components

- MCS provides mechanisms
- WCET analysis of kernel done (for old version on old HW 😢)
- In principle can reason about schedulability

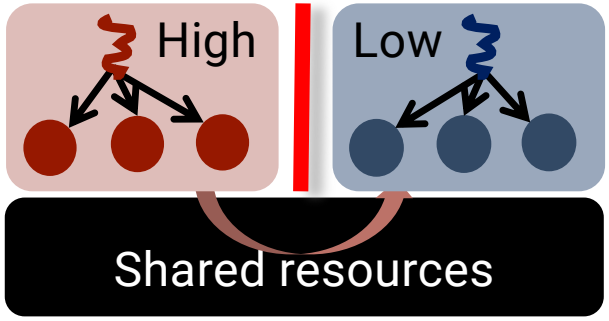
Reality:

- Need to resolve usability issues with MCS
- WCET analysis for old version on old HW 😢
- More theory work needed

Status:

- Not started yet
- Looking for good PhD student!

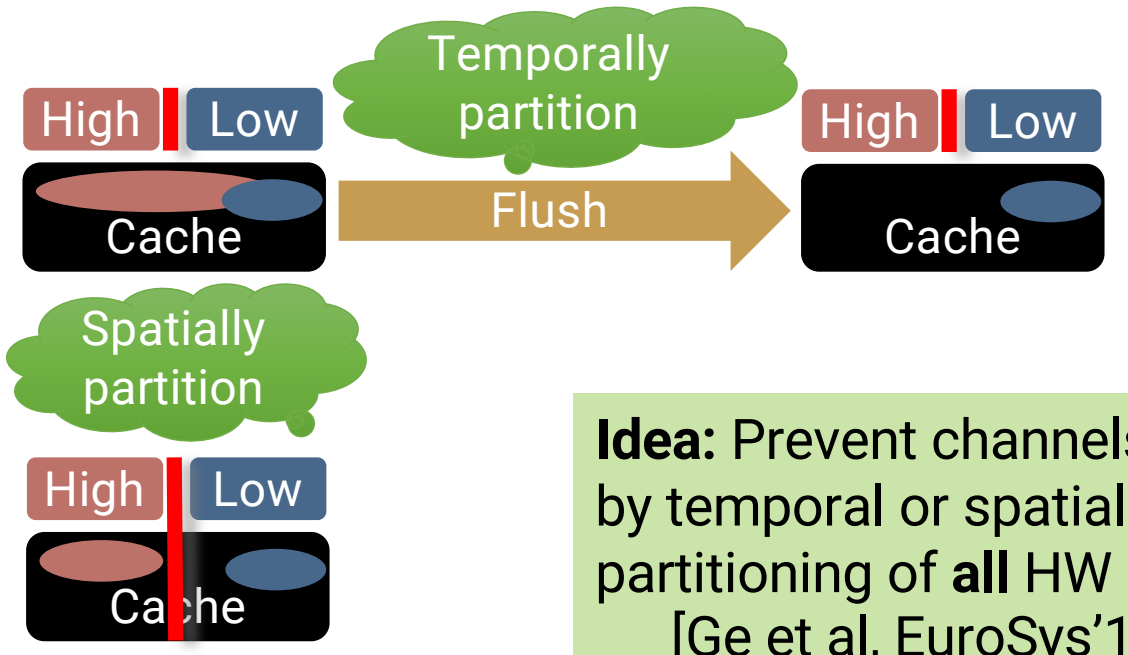
Confidentiality: Timing Channels



Microarchitectural timing channels:
Contention for shared hardware resources affects execution speed

Standard approach:
Patch & Pray

Time Protection: Principled Prevention



Aim: *Provably prevent* information flow through micro-architectural timing channels

Idea: Prevent channels by temporal or spatial partitioning of **all** HW
[Ge et al, EuroSys'19]

Temporal Partitioning: Flush on Switch

Must remove any history dependence!

1. T_0 = current_time()
2. Switch user context
3. Flush on-core state
4. while (T_0+WCET < current_time()) ;
5. Reprogram timer
6. return

Latency depends on prior execution!

Time padding to remove dependency

Proving Temporal Partitioning

Must remove any history dependence!

Prove: flush all non-partitioned HW
- Needs model of stateful HW
- Somewhat idealised on present HW … but matches RISC-V prototype
- **Functional property**

1. T_0 = current_time()
2. Switch user context
3. Flush on-core state
4. while (T_0+WCET < current_time()) ;
5. Reprogram timer
6. return

Prove: access to shared data is deterministic
- Each access sees same cache state
- Needs cache model
- **Functional property**

Prove: padding is correct

Padding: Use Minimal Clock Abstraction

Abstract clock = monotonically increasing counter
Operations:
- Add constant to clock value
- Compare clock values

To prove: padding loop terminates as soon as clock ≥ T0+WCET
- **Functional property!**

Time Protection Verification: Status

1. [Done] Specify isolation property
2. [Done] Prove enforcement on high-level model
3. [In progress] Connect to seL4 proofs
    1. [Done] Update seL4 abstract specification to account for memory accesses
    2. Prove these accesses are bounded according to security policy
    3. Connect 3.1-3.2 to high-level model to prove isolation property
    4. Prove preservation of 3.1-3.3 by refinement to lower-level seL4 specifications

Support:
- Australian Research Council
- USAF-AOARD
- NCSC (UK)

Hardware Support for Time Protection

1. T_0 = current_time()
2. Switch user context
3. Flush on-core state
4. while (T_0+WCET < current_time()) ;
5. Reprogram timer
6. return

Hardware Reality:
Mainstream processors do not allow resetting all history-dependent state!
[Ge et al., APSys'18]

RISC-V to the rescue!
- Add instruction to clean state
- Also help with padding
- **See talk by Nils Wistoff**

Multicore Performance

Getting Rid of the Big Kernel Lock?

Background:
- Multicore seL4 uses a single big lock
- Works because seL4 syscalls are short
- Makes sense as long cost of migrating cache line is small fraction of syscall cost

Aim:
Resolve locking issue before progressing with multicore verification

Issue:
- While not generally a performance issue, BKL leads to very pessimistic WCET
- Also large cross-core timing channels
- Removing take single-kernel image further

Getting Rid of the Big Kernel Lock?

Writer has to wait at most 1 reader's locking time to obtain lock

Idea:
- Bounded reader-writer lock
- Lock-free updates

Status:
- Done: Implementations for x86 and Arm
- Done: Proofs of desired properties
- In progress: Implementation in seL4

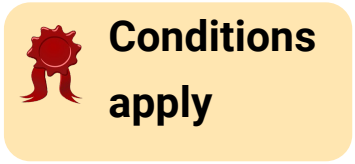
Support:
- NCSC (UK)

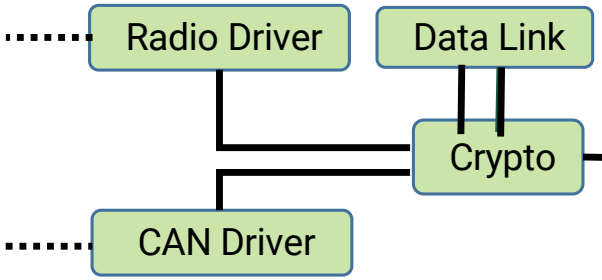
So, Why Isn’t seL4 Everywhere by Now?

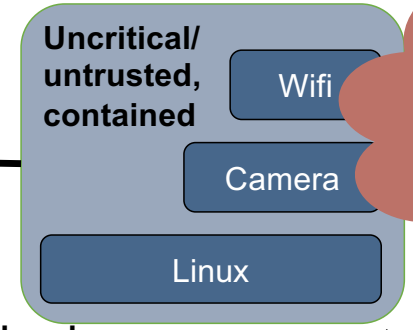
- Usability
- Functionality: Native services
- Trustworthiness: More than the kernel
- Applicability: Embedded vs general-purpose

Usability

Recommended Framework: CAmkES



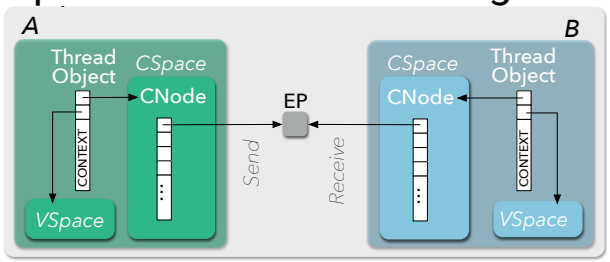


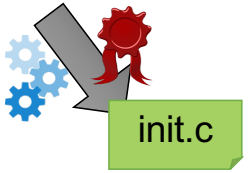


- Good for assurance
- Bad for usability & functionality

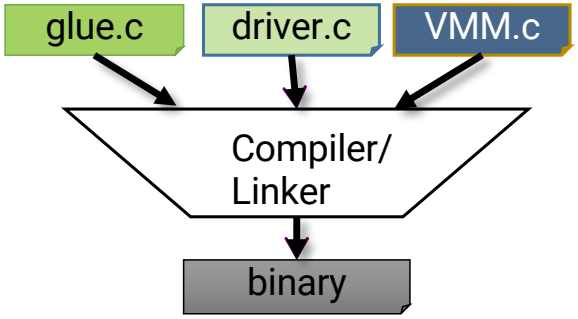
Architecture specification

CapDL: Low-level access rights





- Forces use of kernel build system on apps
- Fully static
- Hard to extend
- Significant overheads



New Framework: seL4 Core Platform

Small OS/SDK for IoT, cyber-physical and other embedded use cases

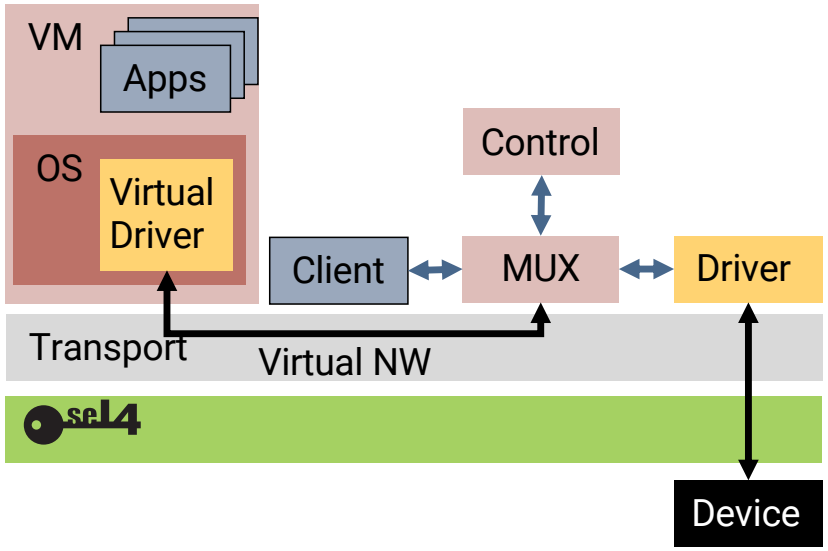
- Leverage seL4-enforced isolation for strong security/safety
- Lean, retain seL4's superior performance
- Retain near-minimal trusted computing base (TCB)
- Integrate with build system of your choice
- Support "correct" use of seL4 mechanisms by default
- Be amenable to formal verification of the TCB

Details in Zoltan Kocsis' talk

Support:
- NCSC (UK)

Functionality: Native Services

Key Component: Driver Framework



Aim:
- Simple model for robust drivers
- Secure, low-overhead sharing of devices between components
- Low overhead

Details in Lucy Parker's talk

Support:
- seL4 Foundation
- TII

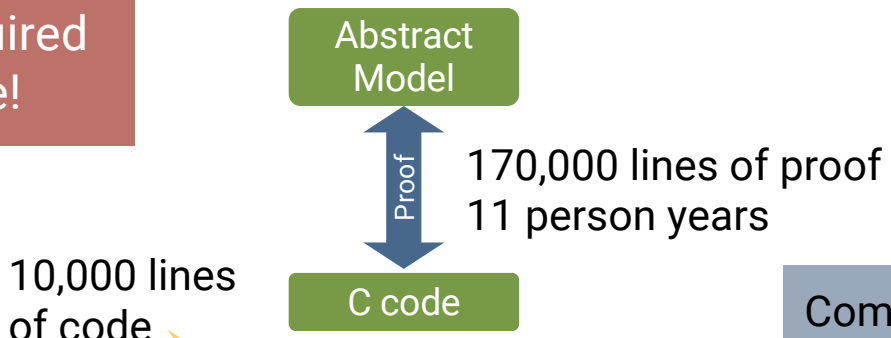
Approach:
- Zero-copy transport layer
- Standard interfaces, virtIO
- Re-use Linux drivers in per-device VM
- Investigate verifying MUX, Controller

Trustworthiness

More than the kernel

Cost of Verification?

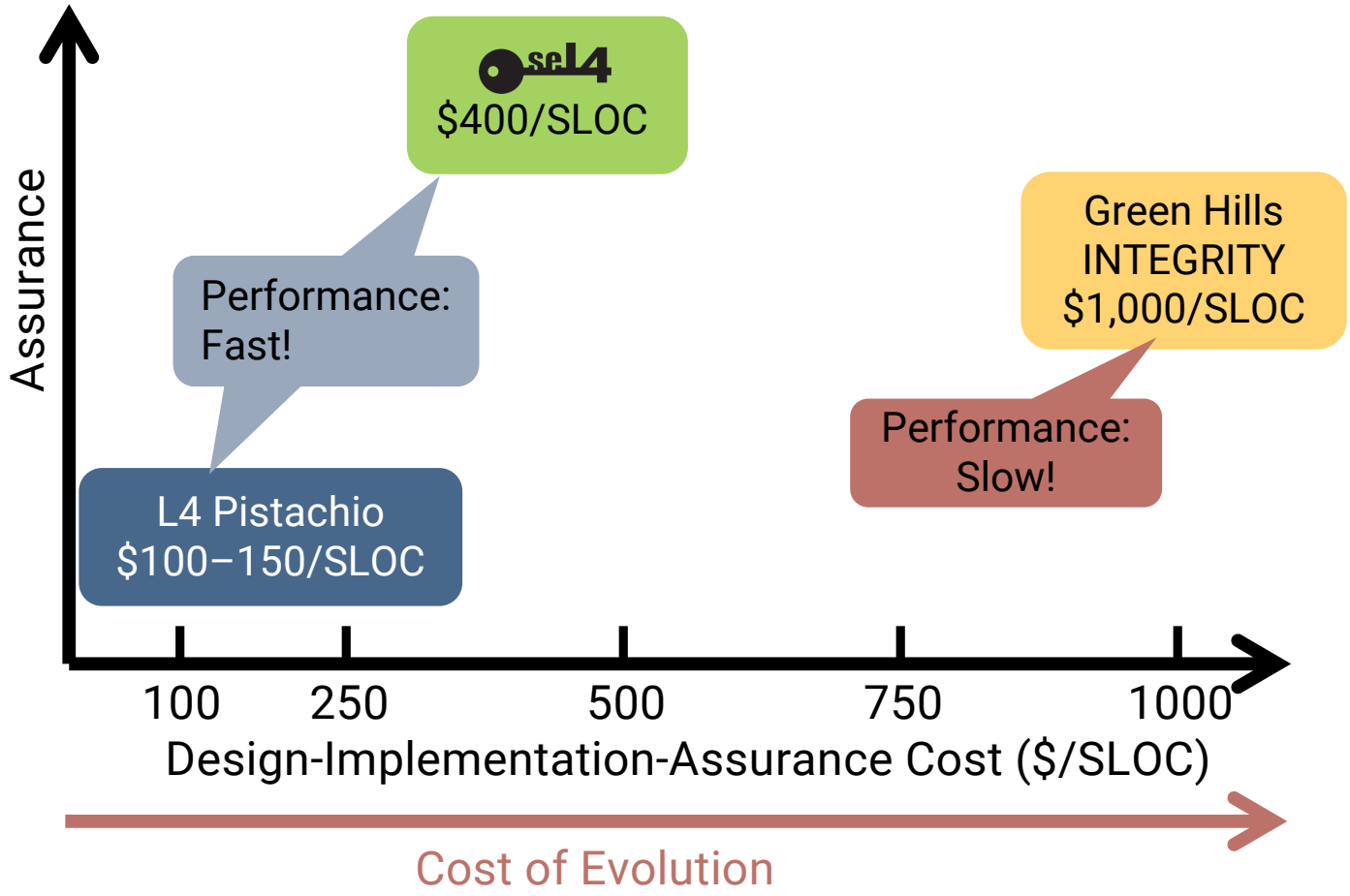
Verifying code not written for verification is infeasible, significant expertise required for writing verifiable code!



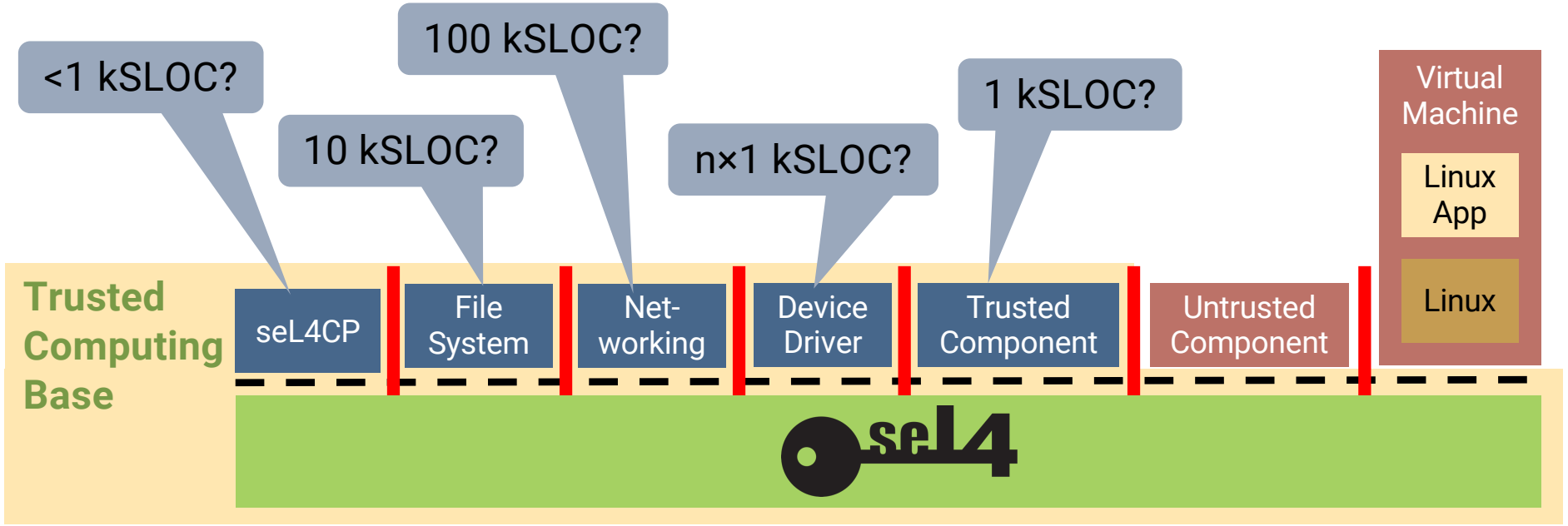
Designed and implemented for verification!

Complete seL4 proof base now ≫ 1,000,000 lines!

Verification Cost in Context

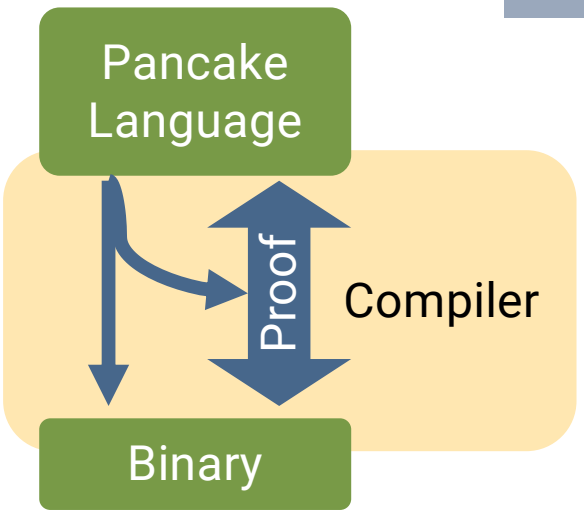


Beyond the Kernel



Reducing Cost of Verified Systems Code

Aim: Simplify verifying user-level OS components



Idea:

- Use low-level but safe systems language with certifying compiler
- Gives many proof obligations for free

Systems language:

- memory safe
- not managed (no garbage collector)
- low-level (obvious translation)
- interfacing to hardware
- no run-time system

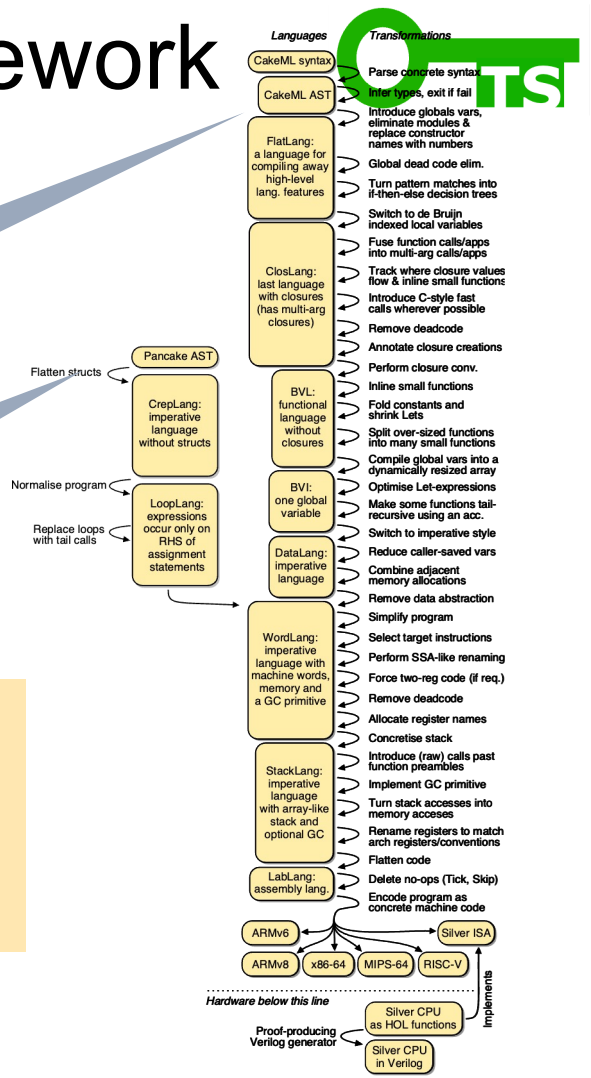
Approach: Re-Use CakeML Framework

CakeML:
- functional language
- type & memory safe
- managed (garbage collector)
- high-level, abstract machine
- verified run time
- verified compiler
- mature system
- active ecosystem

Great, but too high-level!

CakeML compiler

Pancake compiler



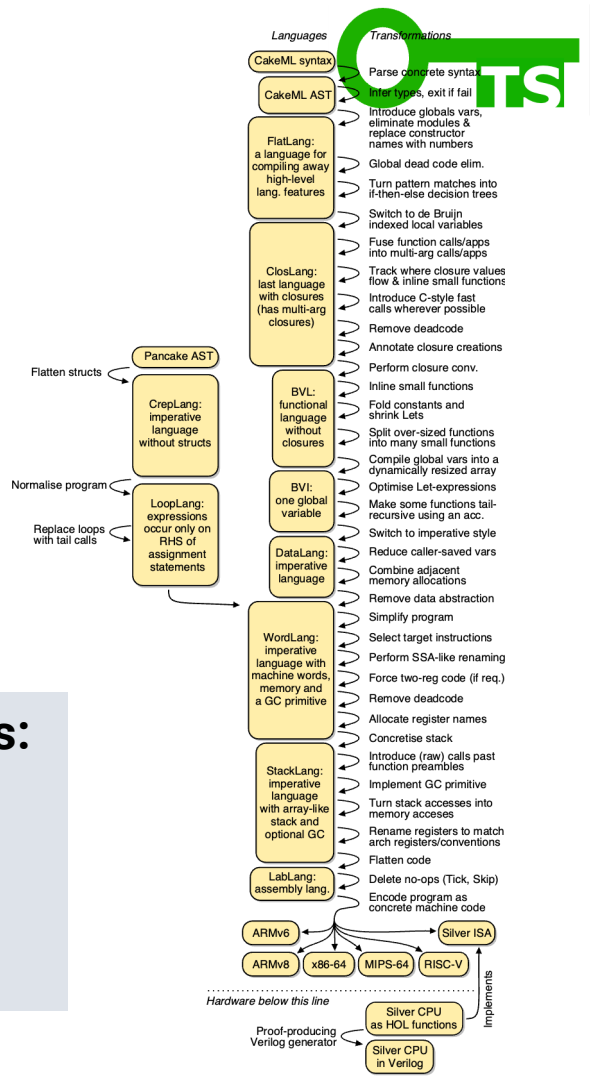
Approach:
Re-use lower part of CakeML compiler stack for imperative language

Verified Pancake Compiler

Pancake compiler is written in CakeML
⇒ can use CakeML compiler to produce verified Pancake compiler binary!

Status:

- Mostly done: Toy (serial) driver verification to explore semantics
- Prototype done: Parser
- Almost done: Verification of link to CakeML compiler:
- In progress: Binary compiler bootstrap
- Not started: Shared-memory driver-device, driver-client



Collaborators:

- ANU
- Chalmers

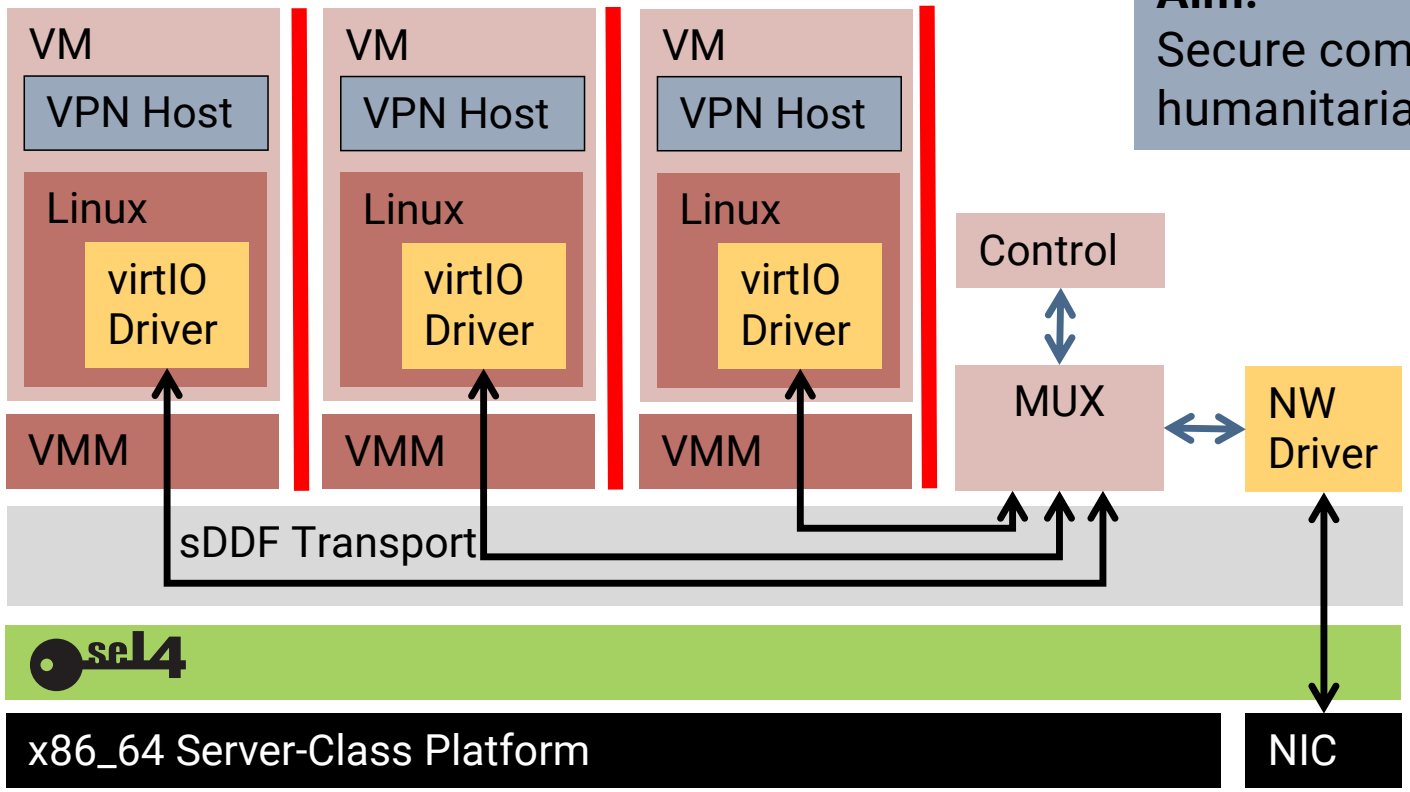
Support:

- TII

Applicability

Embedded vs General-Purpose

Makatea: Secure VPN Service



Aim:
Secure communications for humanitarian organisations

Requires:
- Support for server-class Intel platform
- Efficient network virtualisation

Client:
- Neutrality

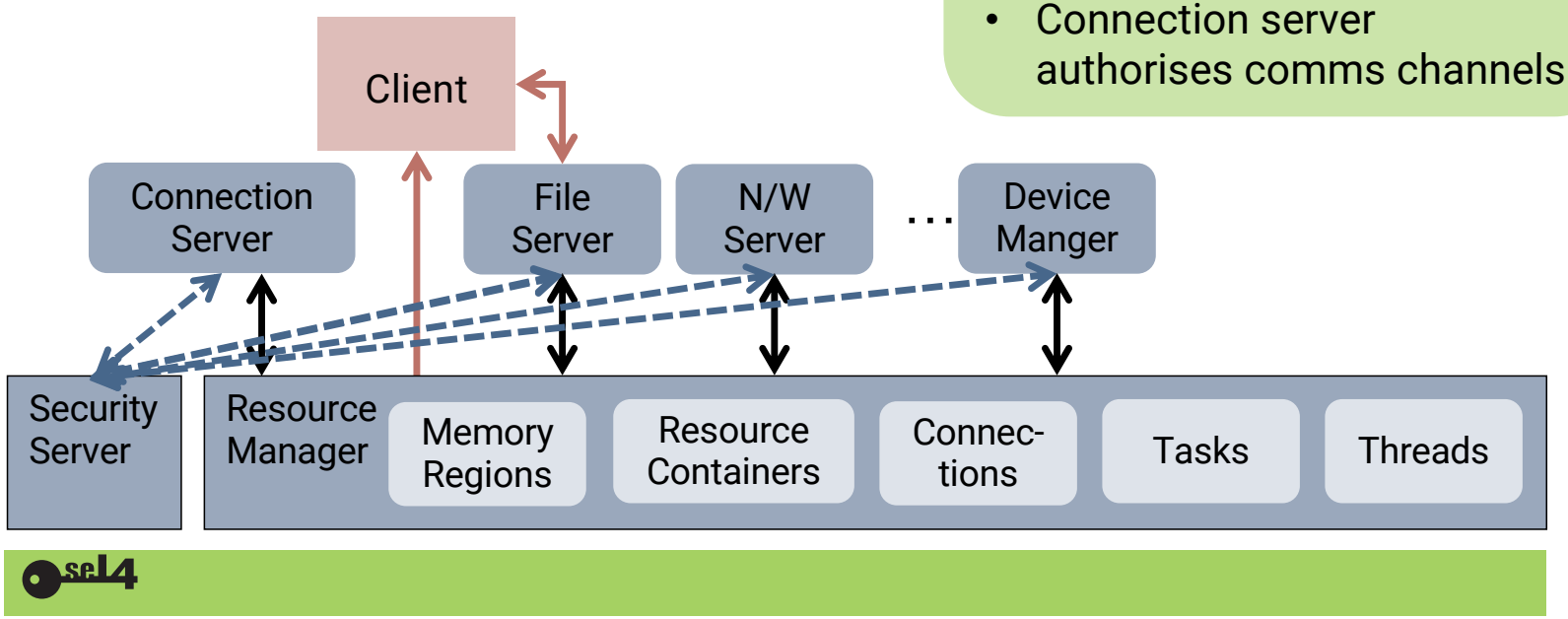
Support:
- NLnet

Provably Secure General-Purpose OS

Problem:
- GP-OS with security policy diversity
- Proof that policy is enforced
- Performance

Solution:
- Multi-server OS with policy isolated in security server
- Object servers provable to ensure complete mediation
- Connection server authorises comms channels

Status:
- prototyping core servers



Partners
Penn State

Support
NCSC

FAQ: If You Did It Again, What Would Be Different?

Major Issues?

Main issues with original seL4:
- Need protocols for establishing reply channel
- Naïve scheduling with no serious time management

Addressed by
- reply caps
- reply objects

Addressed by scheduling contexts (MCS)

Annoyances [1/2]: Map/Unmap Args

Issue:
- Mapping operates on frame, taking address space as argument:
  `frame_c.Map(AS_c, vaddr)`
- User view is that the the mapping is added to the AS, which is modified:
  `AS_c.Map(frame_c, vaddr)`

Cost:
- Mapping multiple frames requires one syscall per frame
- Same for Unmap

Multi-frame operations:
- Process creation
- Write-protecting/unprotecting for
  - copy-on-write
  - garbage collection

Better:
- `AS_c.Map(frame_c, vaddr, frame_c, vaddr, ...)`
- `AS_c.Unmap(vaddr, vaddr, ...)`

Status:
- SMOS, AutoOS will demonstrate costs

Annoyances [2/2]: Lazy FPU Switch

Present FPU context switching is lazy:

1. At context switch, disable FPU
2. Access causes fault
3. On fault, switch FPU state & enable

Issue:

- Compilers use FPU registers for string ops, etc
- Most app code uses FPU
- No benefit from lazy switching

Cost:

- Extra kernel entry
- For servers not using FPU:
  - wastes memory in thread control block
  - WCET must assume FPU switch!

Better:

- Principled resource management: make FPU access a right, provided by FPU object
- Switch FPU eagerly

Issues Under Investigation

Issue:

- Signal that unblocks thread moves it to front of scheduling queue
- ACKing IRQ requires a syscall
- Can we abort IPC by Signal?

Messes with scheduling analysis

Why not implicit in waiting on IRQ Notification?

- Would much simplify timeout implementation
- Idea is to have a mask that says which Signals may abort

Summary

- **seL4 is the best – but we can still improve it!**
  - Budget thresholds: simplify implementation of passive servers
  - Time protection: principled way for *preventing* timing channels
  - Improved locks: make multicore better
  - Hopefully get rid of some long-standing annoyances
- **seL4 is real-world capable – but we can make it easier!**
  - seL4 Core Platform: lean & easy to deploy
  - seL4 Device Driver Framework: ease driver writing
  - Pancake: towards verified device drivers
- **seL4 can own the embedded space – but we can take it further!**
  - seL4 on server platforms
  - General-purpose, provably-secure system

Defining the state of the art in trustworthy systems since 2009