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Formal OS Kernel Verification — Making Trusted Trustworthy

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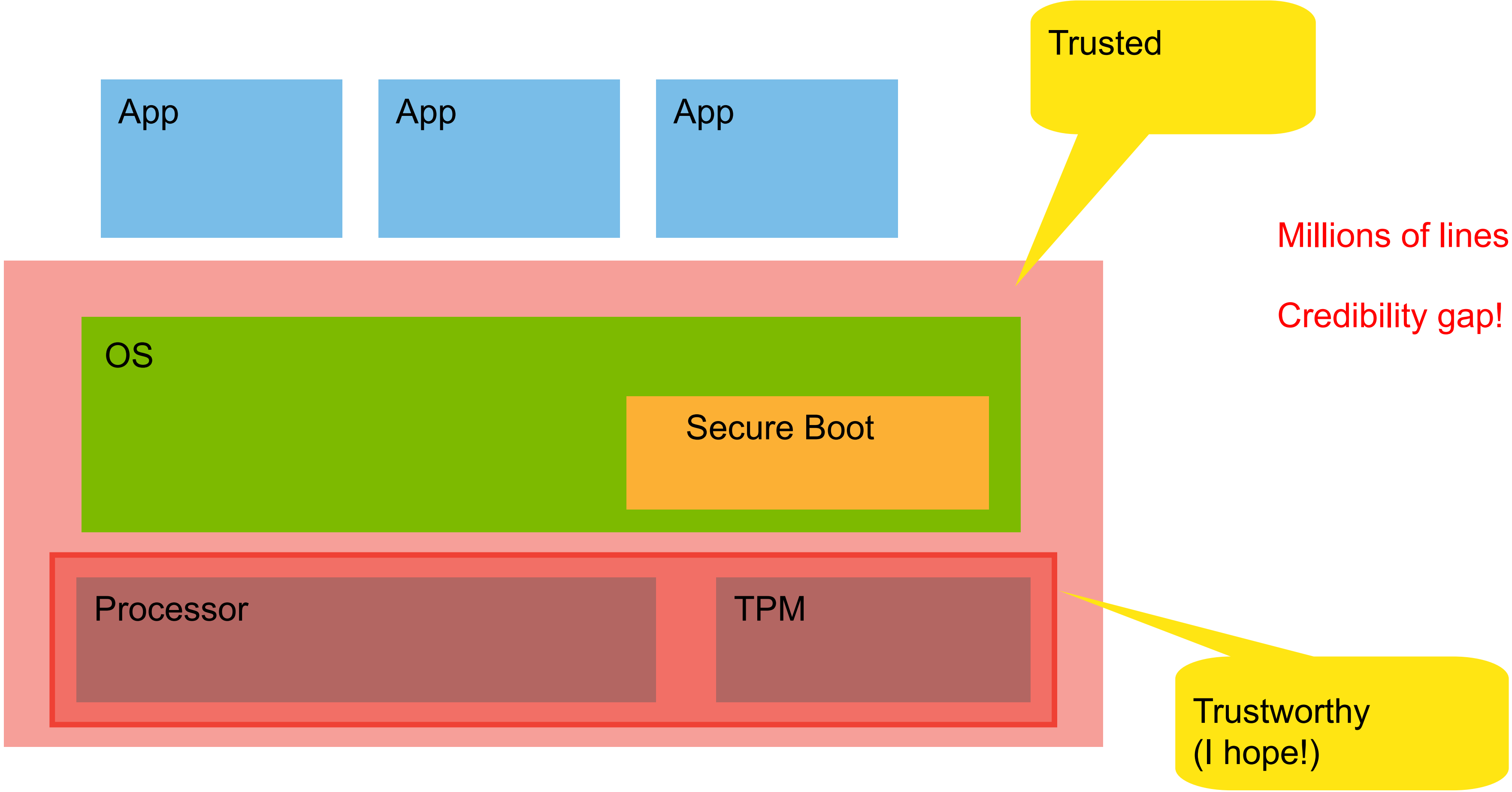
December, 2008

"Trusted Computing" a la TCG



Millions of lines of code!

Credibility gap!

Rehash of Yesterday

Operating systems are trusted, but not trustworthy

→ Millions of lines of code (LOC)

→ Thousands of bugs

→ Hundreds of security holes

→ Standard way out: minimise the *trusted computing base* (TCB)

- Microkernels are good
- Fewer LoC ⍰ fewer security-relevant bugs

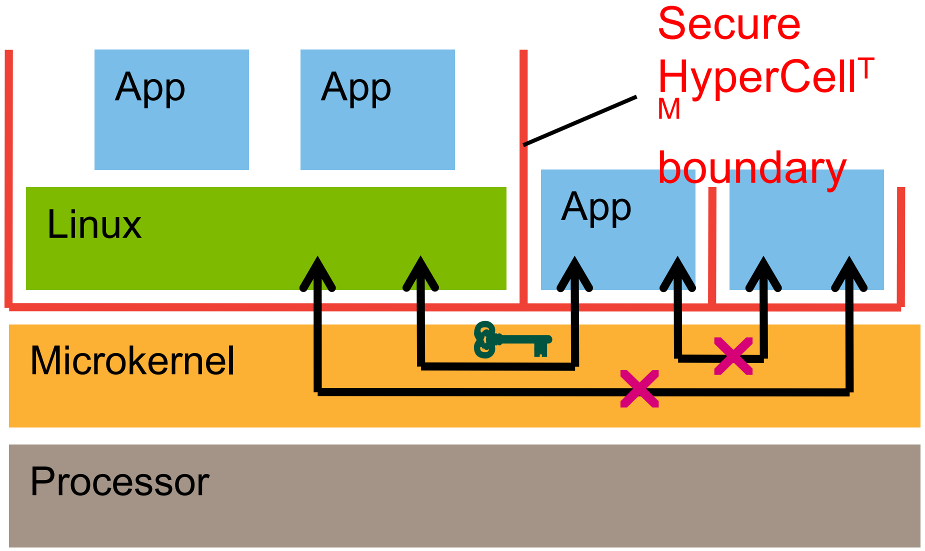
→ Not exactly a radical idea

- QNX selling a microkernel since early '90s
- Green Hills Integrity since 2000 or so
- OKL4 from Open Kernel Labs deployed in 250 million devices

Also Mentioned: Communication Control & MAC

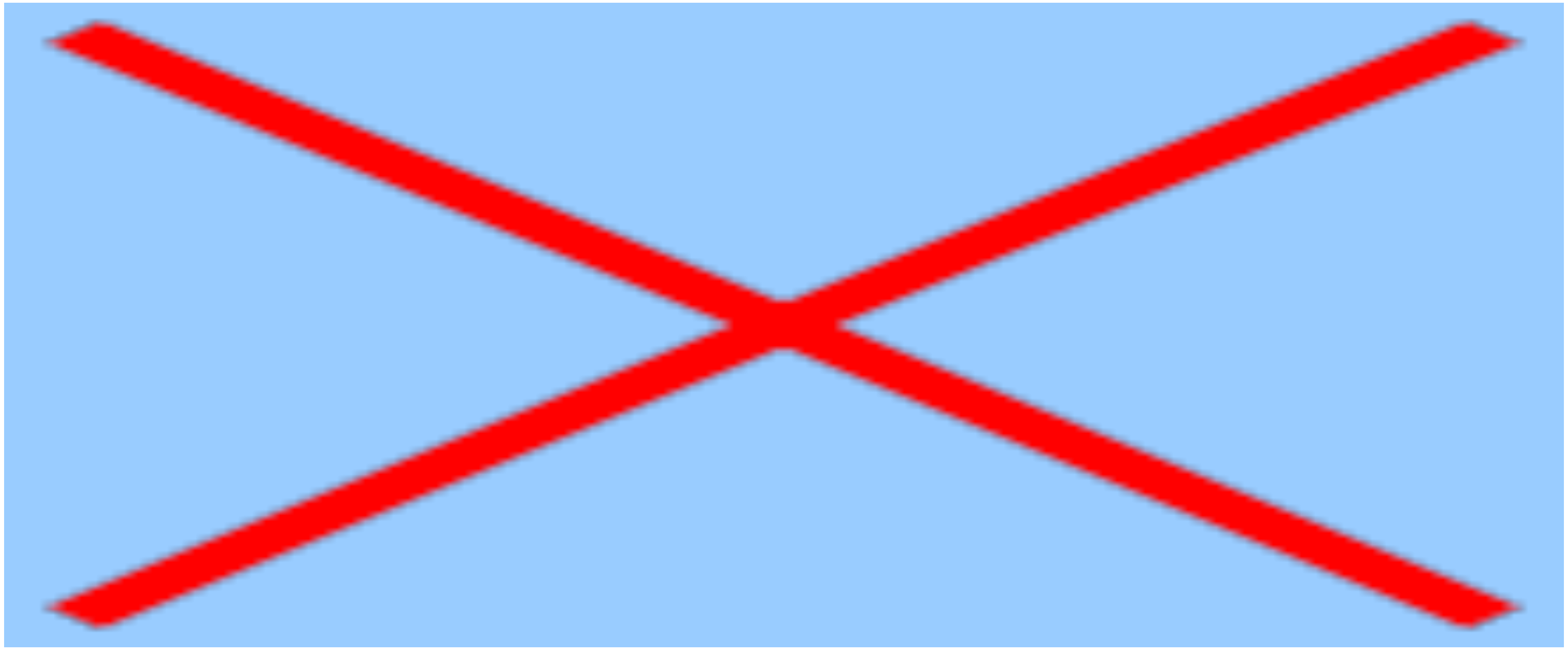
OKL4 has it:

- → Communication controlled by capabilities
  - Use of a communication channel requires a
- → Define isolation domains called *Secure HyperCells*
- → Impose mandatory communication control based on system-wide policy



How About Formal Verification?

- → Never done before — why?
- → E.g. Common Criteria:



- → One system is close: NICTA's seL4 microkenel

The seL4 Microkernel

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Goals

- → Formal specification of kernel and machine
- → High-performance implementation
- → Formal proof of security properties
- → Formal verification of implementation

Isabelle

Innovation over other L4 kernels:

- → All accesses mediated by capabilities
- → Kernel resource accounting
  - complete internal separation of memory held on behalf of ~~a~~ tables, con
  - memory explicitly provided to kernel
  - free from covert storage channels *by construction*
- → No significant performance penalty for new features
  - 15 cycles per syscall ok. Maybe.

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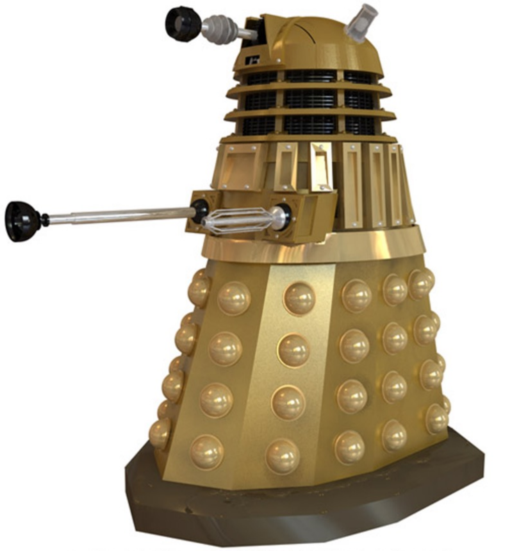
Two Teams

Formal Methods Practitioners
vs
Kernel Developers



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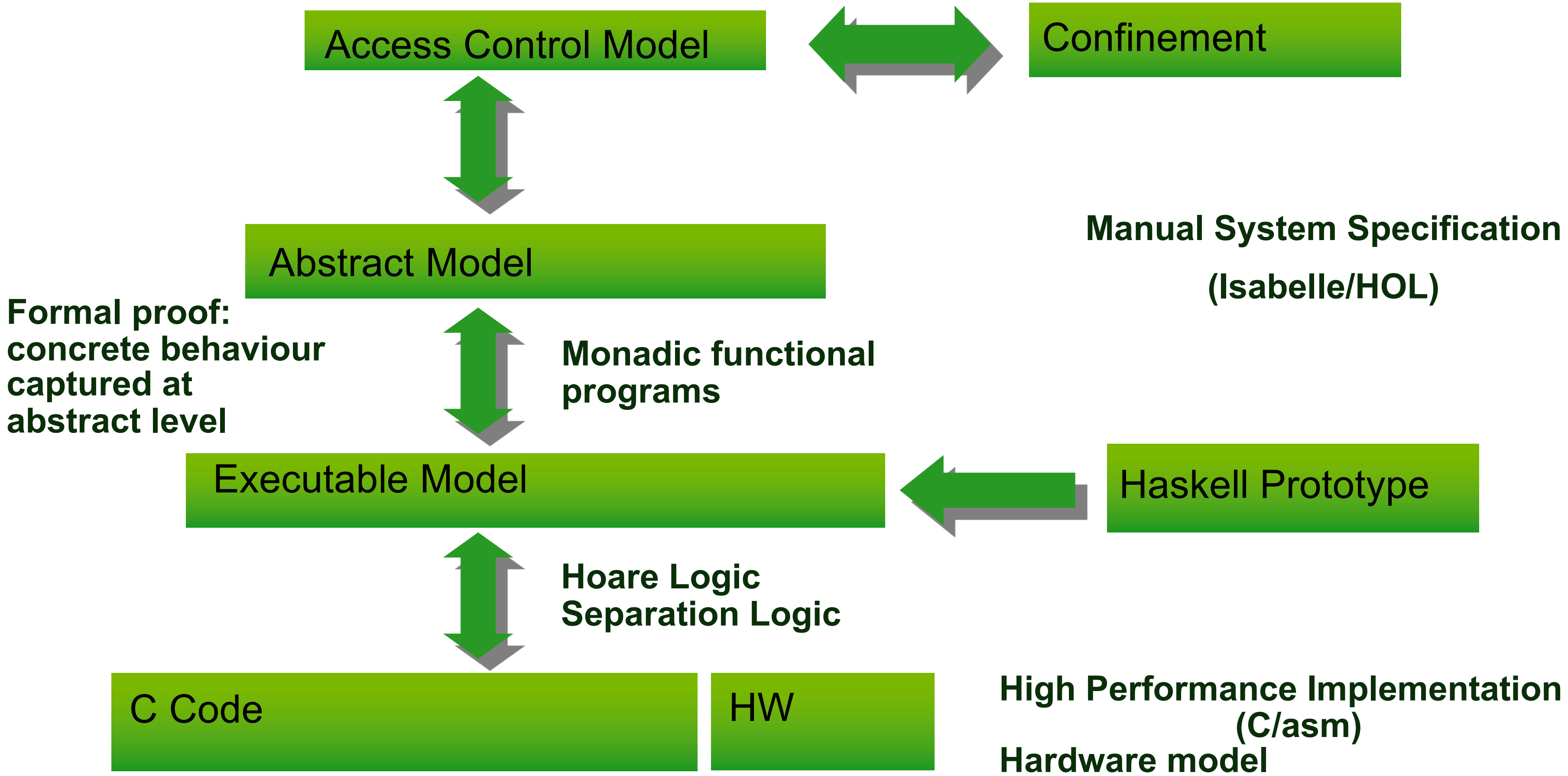
The Proof



Access Control Model

Confinement

Manual System Specification

(Isabelle/HOL)

Abstract Model

Formal proof:
concrete behaviour
captured at
abstract level

Monadic functional
programs

Executable Model

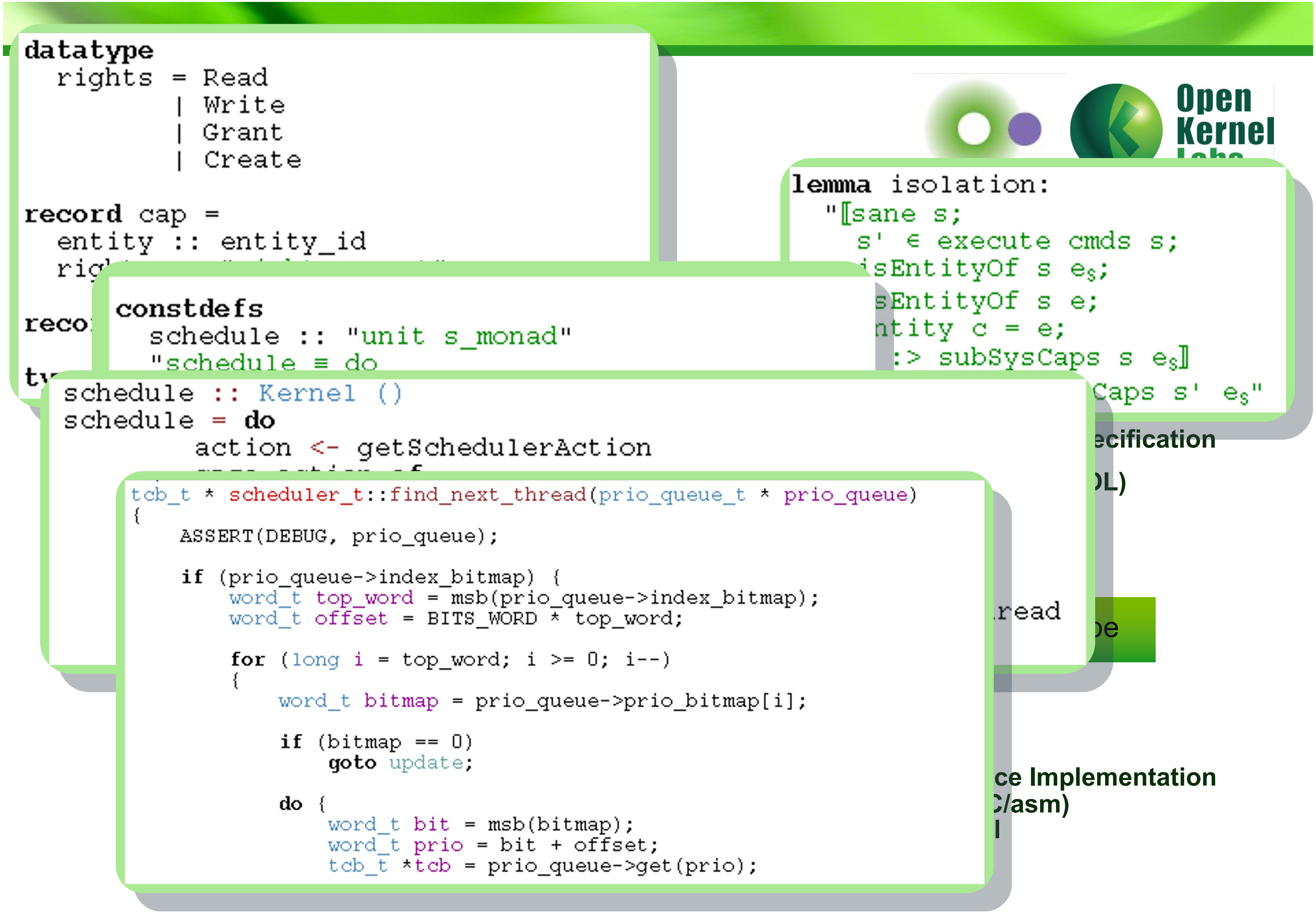
Haskell Prototype

Hoare Logic
Separation Logic

C Code

HW

High Performance Implementation
(C/asm)
Hardware model



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

record cap =
  entity :: entity_id
  rig

reco

ty
```

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

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

```
schedule :: Kernel ()
schedule = do
        action <- getSchedulerAction
                                                  read
```

```
tcb_t * scheduler_t::find_next_thread(prio_queue_t * prio_queue)
{
    ASSERT(DEBUG, prio_queue);

    if (prio_queue->index_bitmap) {
        word_t top_word = msb(prio_queue->index_bitmap);
        word_t offset = BITS_WORD * top_word;

        for (long i = top_word; i >= 0; i--)
        {
            word_t bitmap = prio_queue->prio_bitmap[i];

            if (bitmap == 0)
                goto update;

            do {
                word_t bit = msb(bitmap);
                word_t prio = bit + offset;
                tcb_t *tcb = prio_queue->get(prio);
```

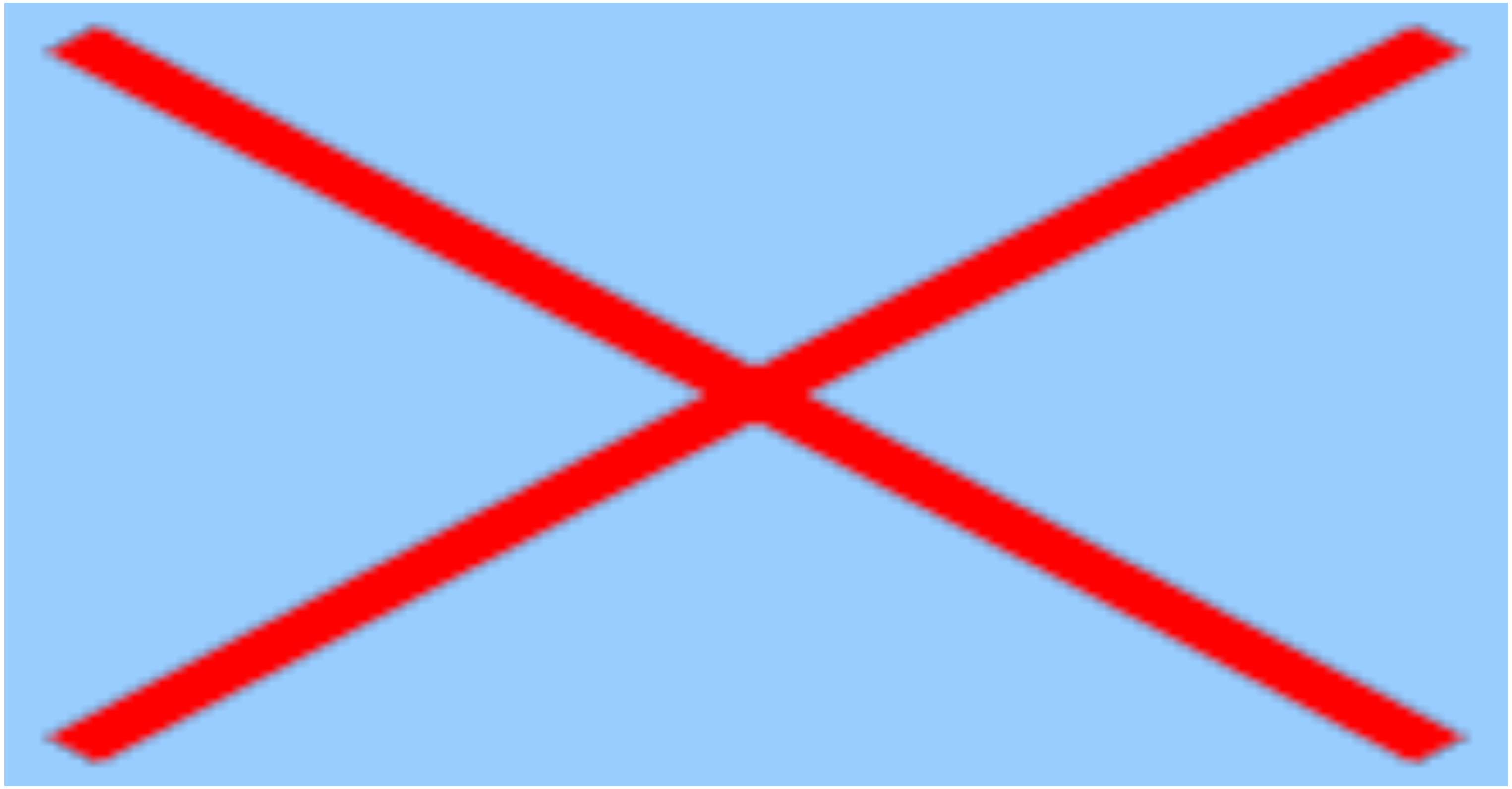
ecification

DL)

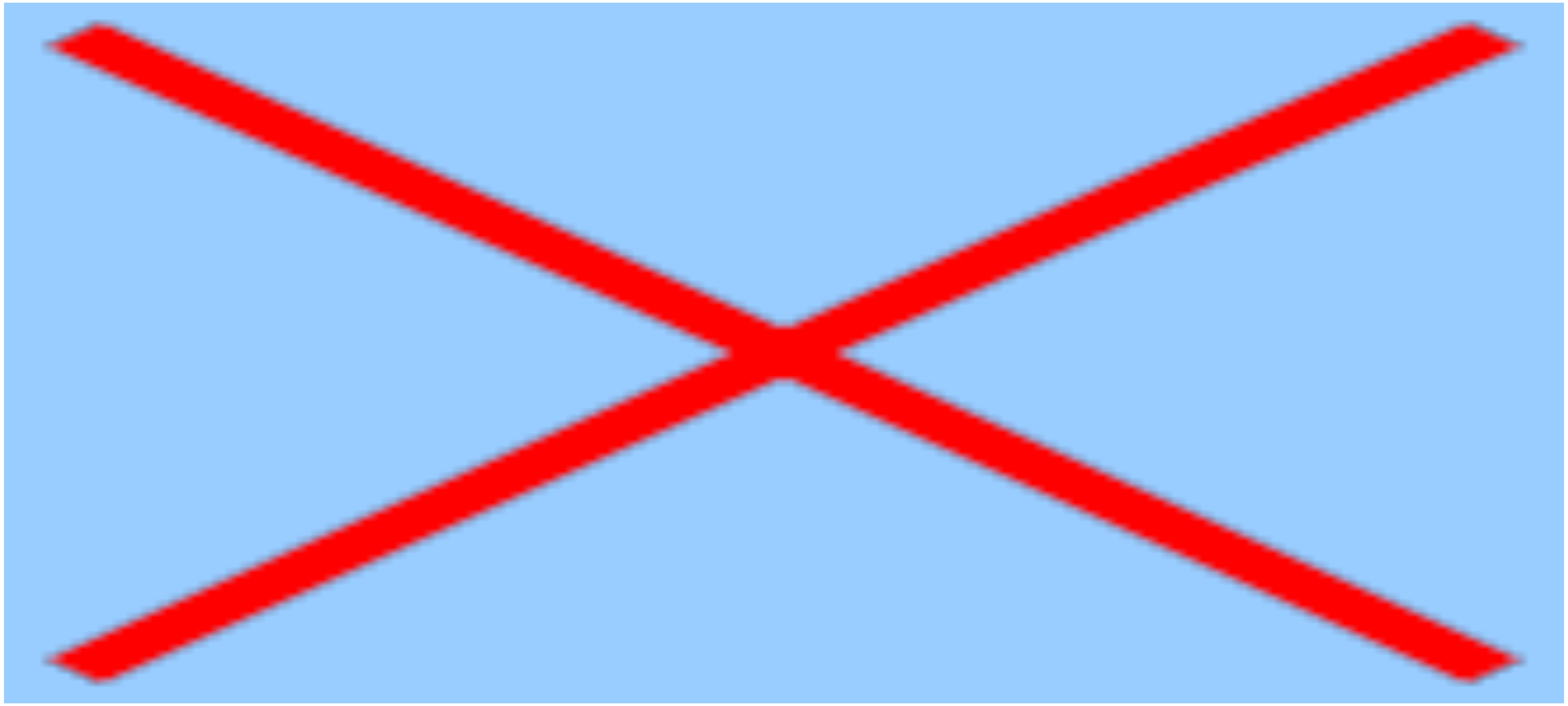
pe

ce Implementation
C/asm)
l

Common Criteria and seL4



Common Criteria and L4.verified



seL4 Summary

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Statistics

- 3.5k LoC abstract, 7kLoC concrete spec (about 3k Haskell)
- Abstract → Haskell: 100kLoP (more features coming)
- Haskell → C/asm: 80kLoP (estimated)
- Access control model + isolation proofs done (1kLoP)
- 109 patches to Haskell kernel, 132 to abstract spec
- Performance in line with other L4 kernels
- average 6 people over 5 years

Kinds of properties proved

- Well typed references, aligned objects, ..
- Well formed thread states, endpoint and scheduler queues, ...
- All syscalls terminate, reclaiming memory is safe, ...
- Authority is distributed by caps only
- Access control is decidable

Summary

seL4 verification status

- → Refinement to LLD complete
- → C level refinement in progress (due February)
- → Working on proving more security properties
- → Already most formally verified kernel ever
- → Performance comparable to other L4 kernels
- → Commercialization by Open Kernel Labs

Conclusion:

- → Verification of OS kernels is possible
- → ... but it ain't easy
  - limited to small kernels
  - but can leverage guarantees of verified kernel
  - however, doing this is an unsolved and highly non-trivial problem

How About Hardware?

- Hardware has the appearance of being more trustworthy
  - because it's unchangeable, people think more about it
- But: if it's broken in hardware, I can't fix it in software
  - hardware is too complex to be completely formally verified
  - putting more complexity into hardware is the wrong way to go
  - keep it simple, and let me control it by software
- What hardware should be like
  - sufficient for building secure software (doesn't need much!)
  - well-defined APIs (simplicity is a bonus)
  - correctly implemented
- Formally-verified kernel becomes more like hardware
  - it needs to be extremely well-designed
  - once verified, don't change it, as this will break your proofs!

A Final Word on Commercial Realities

Is it possible to commercialise a verified OS?

→ Formal verification can be less expensive than CC assurance

- ... but delivers more

→ seL4 is correct to a much higher degree than can be assured by CC EAL7

- ... but it won't even be acceptable where EAL4 is required

→ Problem with common criteria:

- too expensive
- no rewards for doing better

→ Unless this is changed, there is no business case for formal verification

- no business case ⍰ no commercial system will be verified
- no formal verification ⍰ no trustworthy systems

→ Requires leadership by governments (NSA, BSI, ...)

Thank You

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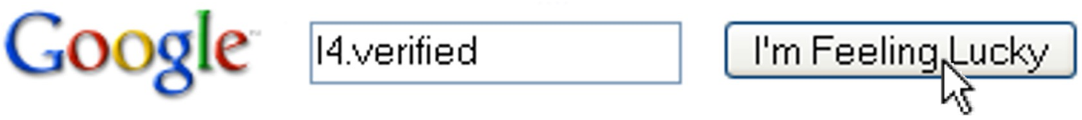
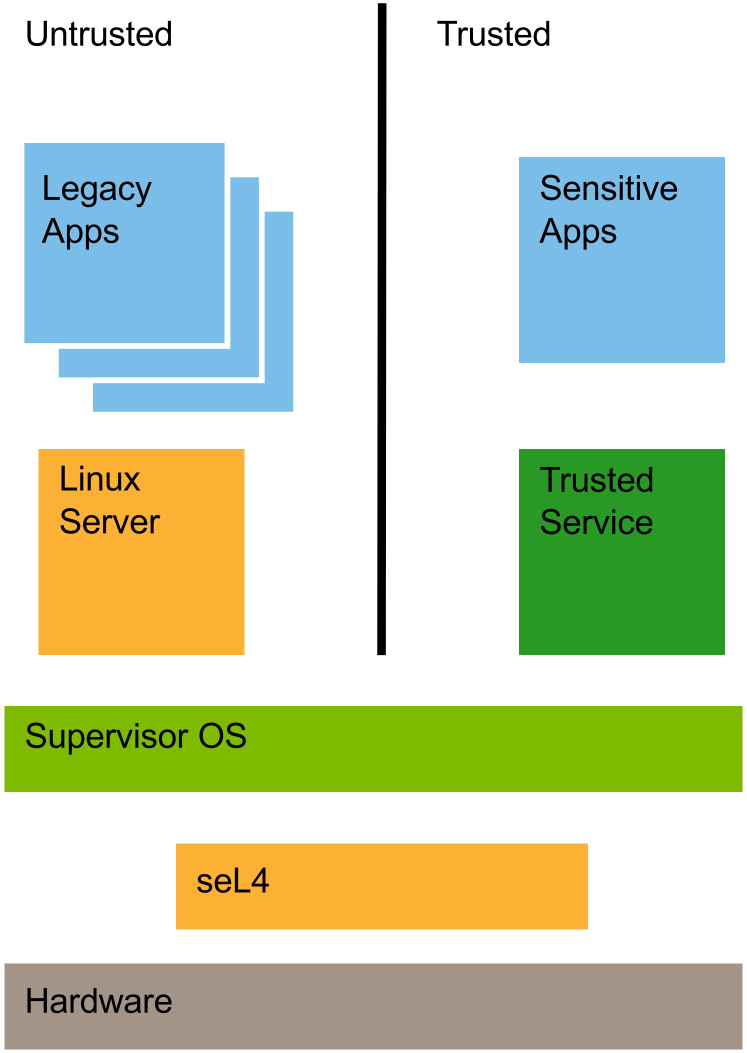


l4.verified

Small Kernels

- → Small trustworthy foundation
- → Hypervisor micro kernel, nano-kernel, virtual machine, separation kernel, exokernel ...
- → Applications:
  - Fault isolation
  - Fault identification
  - IP Protection
  - Modularity
  - ...
- → High assurance components in presence of other components

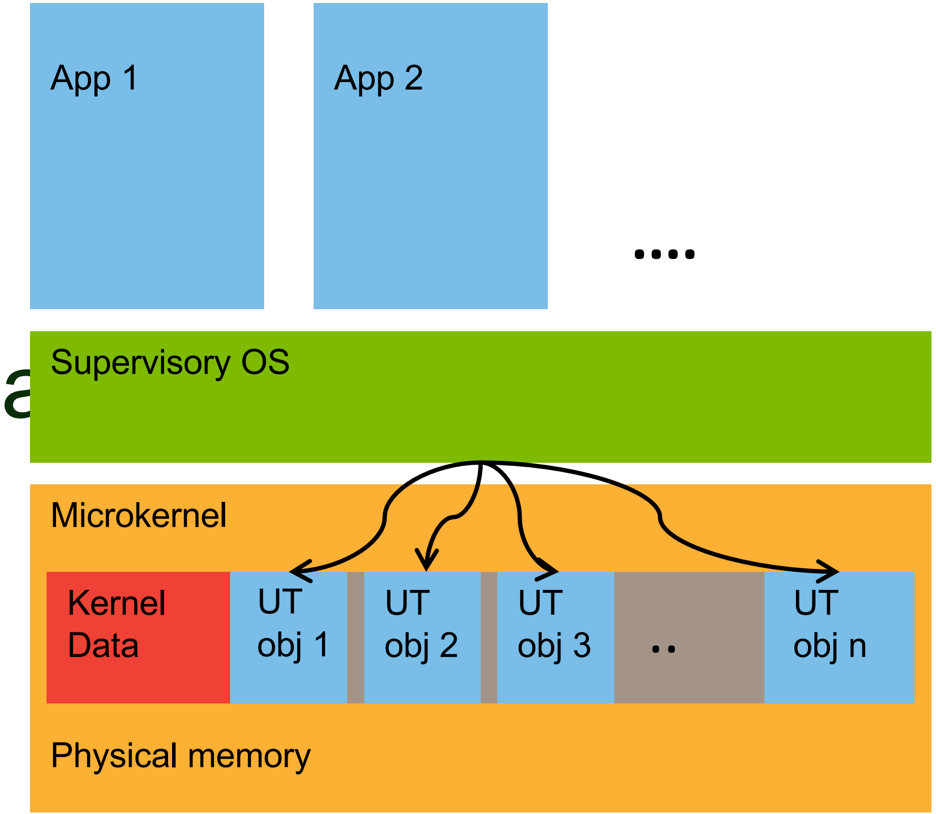


seL4 Physical Memory Management

Some kernel memory is statically allocated at boot time

Remainder is divided into untyped (UT) objects

- 2^n region of physica
- size aligned



Supervisor gets authority over these objects

- authority conferred by capabilities

Kernel never allocates dynamic memory

- user must provide memory for kernel objects

Refinement

- The old story
  - C refines A if all behaviours of C are contai
- Sufficient: forward simulation

$$\begin{tikzcd}
s \arrow[r, dotted, "A"] \arrow[d, leftrightarrow, "S"'] & t \arrow[d, dotted, leftrightarrow, "S"'] \\
s' \arrow[r, "C"'] & t'
\end{tikzcd}$$