The Clustered Multikernel:
An Approach to Formal Verification of Multiprocessor OS Kernels

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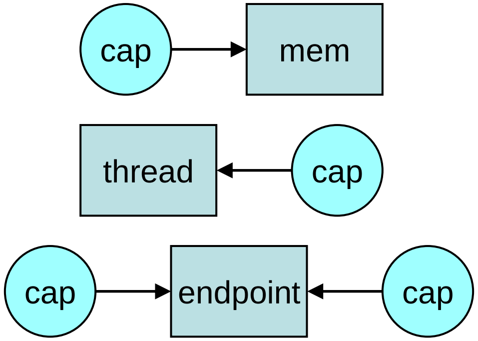
Introduction

- OS kernel is a critical software component in computer systems
- building secure, safe and reliable computer systems is facilitated by having strong kernel correctness guarantees

→ **formal verification** down to implementation level

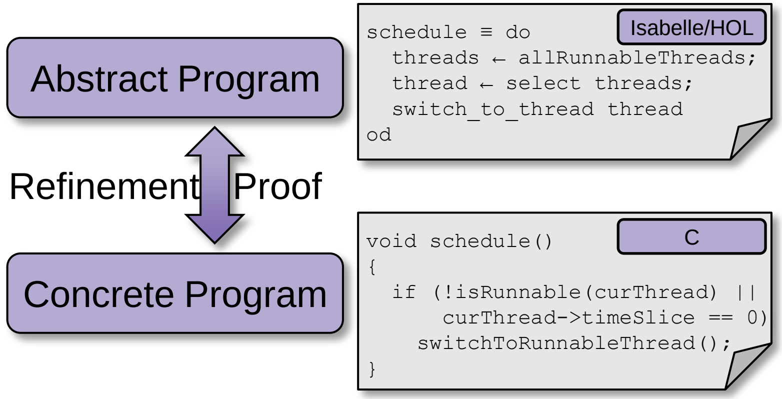
- **seL4** (secure embedded L4) **microkernel**:
  - provides strong isolation between components
  - allows fine-grained controlled communication and resource management via capabilities
  - C implementation is formally verified
  - property: **functional correctness**



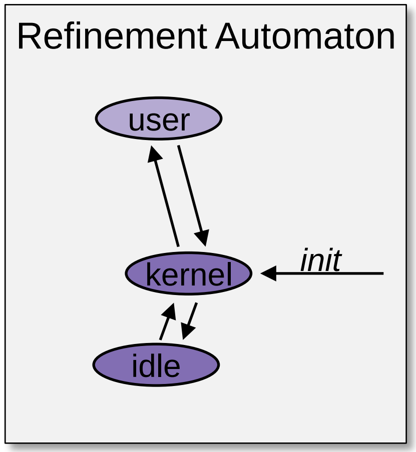
Refinement Background

Property: **functional correctness**

- proved by **refinement**
- **abstract**: specification
  - abstract program modifies abstract state
- **concrete**: implementation
  - concrete program modifies concrete state



- refinement automaton:
  - non-deterministic finite state automaton
  - **initialisation function** sets up initial state (corresponds to **bootstrapping phase** of kernel)
  - **events** trigger **transitions** between **states** (models the **runtime phase** of kernel)



- refinement proof:
  - consists of:
    1. **correspondence** proofs, which sometimes require
    2. **invariant** proofs
  - **transfers** theorems proved on the abstract level down to the concrete level → sufficient to prove theorems on abstract level

Motivation

- L4.verified approach has no concurrency in the model:
    1. able to avoid preemption-induced concurrency:
        - no preemption in kernel
        - except from two well-defined preemption points
        - instead of doing a stack switch, kernel saves state as continuation and exits
    2. able to avoid hardware concurrency:
        - device drivers outside the kernel (standard microkernel approach)
        - **only support uniprocessor systems**
- whole world is going **multicore** (even in embedded systems)

→ need for **verified multiprocessor kernels** arises

- aim: want to have a multiprocessor version of seL4 with the same **functional correctness** guarantees
- want to leverage as much of the uniprocessor proof as possible
    - L4.verified total effort: ~25py / 200 kLOC of proof

Challenges?

Verification Complexity

- we are hit with full concurrency of multiple CPUs
- proof needs to cover all possible "conceptual scenarios" which can arise from concurrent execution
- verification complexity depends on:
  - program complexity
  - **property** we want to prove
  - **state** we share (if concurrency is involved)

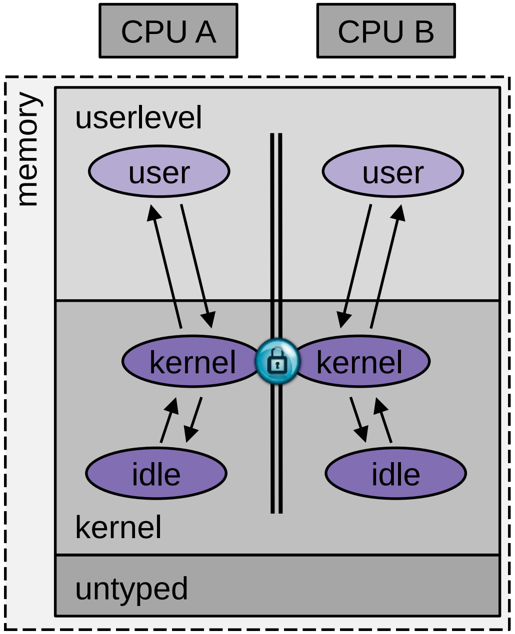
- mitigation techniques:
  - make proofs modular (e.g. rely-guarantee, ownership principle)
    - only works if modeled system can somehow be viewed in a modular way
  - make the system modular → componentise it
  - microkernels cannot be componentised

→ **approach**:
  - reduce the number of "conceptual scenarios" to a minimum
  - by avoiding *complexity potentially introduced by parallelism*

Multiprocessor Kernel Designs

There are two fundamental ways to avoid complexity potentially introduced by parallelism:

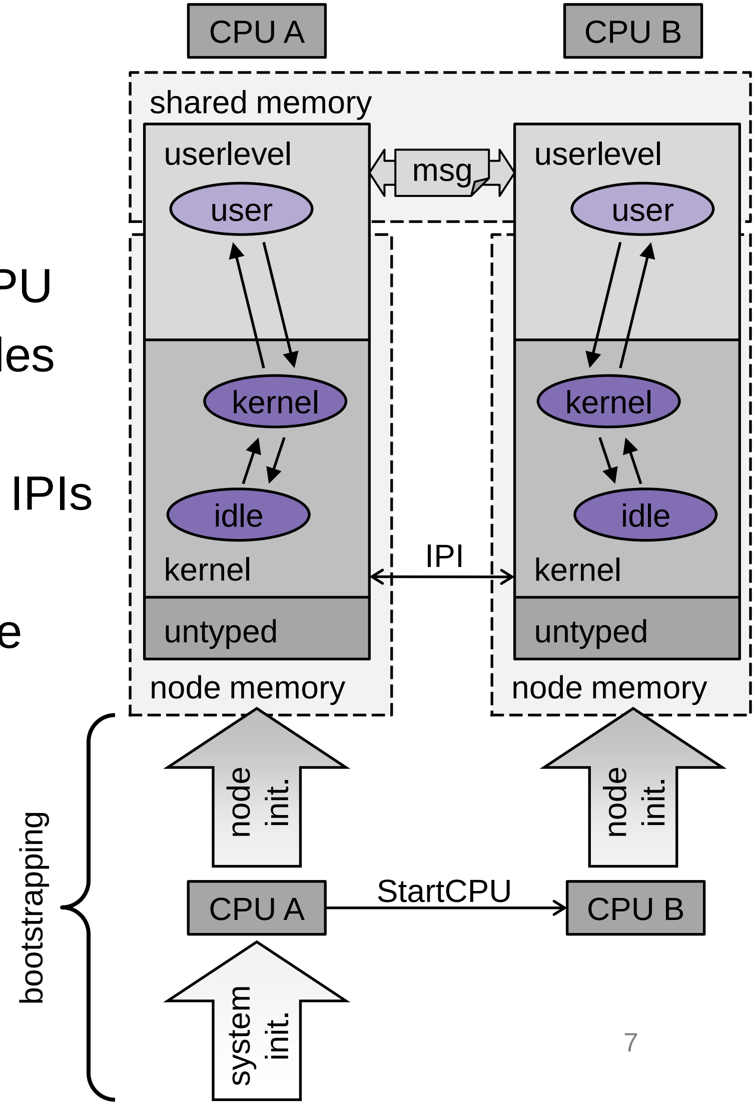
1. avoid parallelism itself (run things sequentially):
   - solution: ***big lock*** around the whole kernel
   - 👍 existing uniprocessor userlevel applications can be run unmodified and automatically benefit from the power of multiple CPUs
   - 👎 low scalability



Multiprocessor Kernel Designs

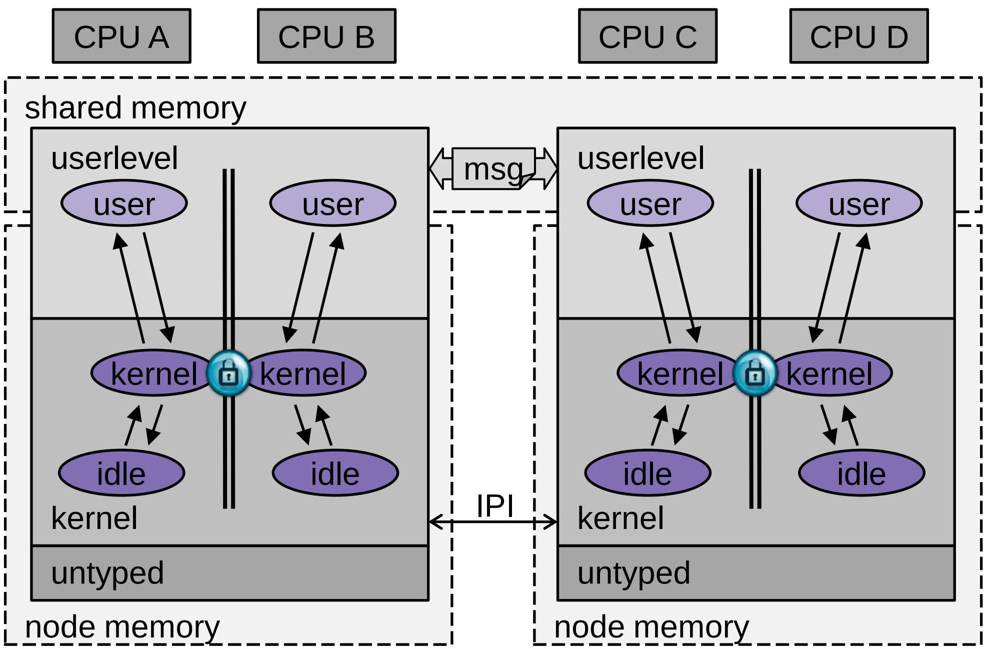
There are two fundamental ways to avoid complexity potentially introduced by parallelism:

2. establish independence (avoid sharing):
   - solution: restricted ***multikernel*** design
   - run one *node* of uniprocessor seL4 per CPU
   - kernel memory is partitioned between nodes
   - static region of shared userlevel memory
   - communication via userlevel memory and IPIs
   - high scalability
   - userlevel applications must be node-aware
   - no flexible kernel-memory usage between nodes



The Clustered Multikernel

- now we have two designs:
  - **big-lock kernel**: high flexibility, low scalability
  - **multikernel**: low flexibility, high scalability
- combine them: ***clustered multikernel***
  - like **multikernel**, but a node can span more than one CPU
  - within a node, kernel data is protected by a **big lock**
  - CPUs can be freely assigned to nodes



performance-optimisation opportunities:
- cluster of cores within a CPU
- NUMA-aligned clusters
- clustering for systems with “islands of cache coherence”
- clustering along performance-isolation boundaries

implementation: **seL4::CMK**

Lifting seL4's Refinement Proofs

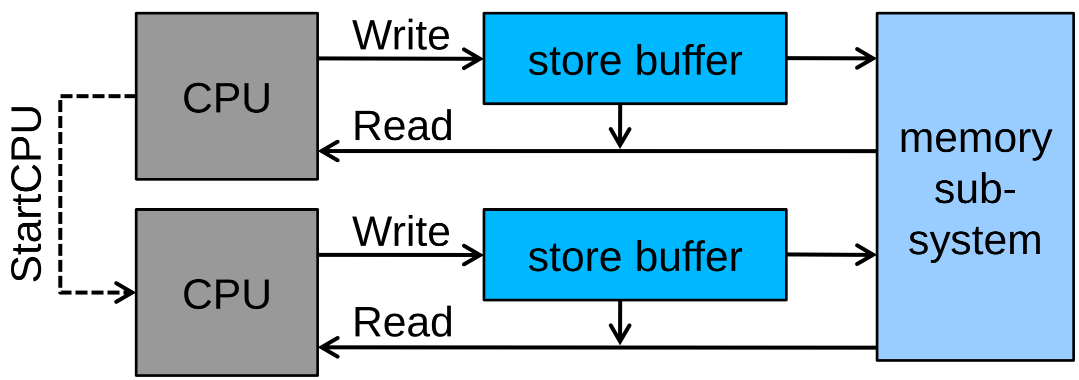
- lifting proofs = reusing proved theorems in a more generic context
  - e.g., a proved hoare triple over a kernel-internal function can be directly reused in the clustered-multikernel proof if we prove that this particular function is not exposed to concurrency

- refinement lifting proof consists of:
  - abstract specification of seL4::CMK's code
  - model of a total-store-order (TSO) multiprocessor architecture
    - deal with weak memory ordering, memory fences
    - needed for inherently concurrent **bootstrapping phase** of the kernel
  - node-isolation proof
    - want to be able to reason about each node in isolation
    - show: for seL4::CMK, refinement holds for each node in isolation
  - within each node:
    - refinement automaton represents **runtime phase** of the kernel
    - lifting of the refinement automaton into a **parallel composition** of itself

- specifications and proofs are machine-checked in Isabelle/HOL

TSO Multiprocessor Model

- challenges:
  - weak memory ordering and fences
  - in presence of CPUs starting up other CPUs (also nested)
  - integratable into L4.verified verification framework
- model:
  - operational model, inspired by the Cambridge x86-TSO model
  - 4 *high-level instructions*: Read, Write, MFENCE, StartCPU
- proof:
  - generic *sequential-semantics theorem* (MFENCEs, starting seq.)

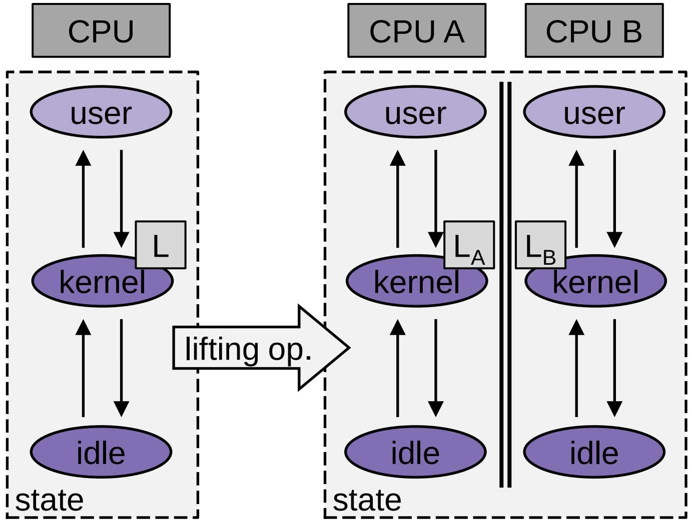


program order preserved	
R,R	✓
W,W	✓
R,W	✓
W,R	✗

Lifting into Parallel Composition

- lifting operation:
  – converts an arbitrary refinement automaton into parallel composition

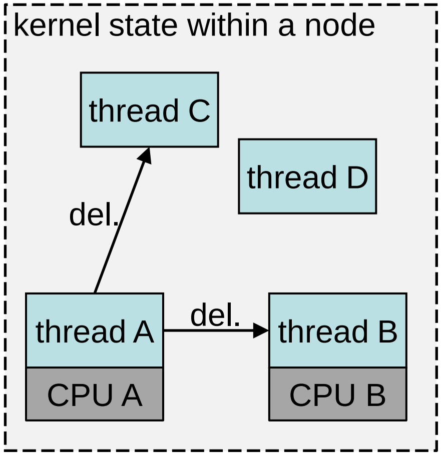
- lifting theorem:
  – “When applying the lifting operation to the refinement automata of both abstract and concrete levels of an arbitrary refinement proof:
    the **concrete parallel** refinement automaton
    refines the **abstract parallel** refinement automaton
    if the **original concrete** refinement automaton
    refines the **original abstract** refinement automaton.”



- transitions are interleaved non-det.
- original state is **shared** between CPUs
  – except for small subset which is **local**, i.e. duplicated for each CPU (L_A, L_B)
  – each CPU can modify the shared state and its own local state
- precondition:
  – original invariants need to be **splittable**
  – **unsplittable** ones proved manually
    - in seL4: valid pointer to currently running thread

Thread-Deletion Problem

- could not prove seL4's **unsplittable** invariants (did not hold)
- thread-deletion problem:
  - formally: CPU B's pointer to the currently running thread is not valid anymore if thread B is deleted by thread A running on CPU A
  - could not happen in uniprocessor case: only one thread currently running



- fix (add necessary coordination):
  - 2 new thread states ("current", "current req. inactive")
  - 8 new preemption points (before del./mod. of threads)
  - reason: event-based structure of seL4
    - specifically: no kernel-thread blocking allowed
  - changes small but invasive

  → increased proof complexity considerably

summary:

- specific to seL4, but likely to occur in other kernels as well
- a good example in showing the bug-finding abilities of theorem proving in general, and the lifting theorem in particular

Related Work

- Barrelfish:
  - **multikernel** OS designed for heterogeneous multiprocessing
  - follows a distributed-system approach by keeping kernel data structures local to a CPU or replicated on other CPUs
  - communication between nodes message-based, on userlevel

clustered kernels in the early 90s:

- Hurricane:
  - used clustering to improve data locality on large-scale NUMA machines
- Hive:
  - aimed at fault isolation between clusters

→ performed well for certain kinds of applications, but suffered from high complexity and unpredictable performance in general

- probably because they tried to hide clustering from userlevel and provide a single-system image

Conclusion and Future Work

Conclusion:

- implementation effort for seL4::CMK (diff. to seL4): ~**0.5 kLOC**
- the proof effort was ~**9 kLOC** (*conditions apply)
- not aware of a successful refinement proof of a multiprocessor kernel
- given a verified uniprocessor kernel, the clustered multikernel offers a way to achieve this with *relatively* low effort
  - compare **~0.5 kLOC** to seL4's code size of **~8.7 kLOC**
  - compare **~9 kLOC** to L4.verified's overall proof size of ~**200 kLOC**

Future Work:

- performance/scalability evaluation showing that the clustered multikernel is a "viable alternative" to a classical MP kernel:
  - a classical MP kernel (fine-grained locks/lock-free) would give us:
    1. good scalability, **and at the same time**
    2. flexible kernel-memory usage across CPUs
  - but for verification reasons, we restrict ourselves to a clustered multikernel where we only get a static tradeoff between (1) and (2)

  → want to show (benchmarks) that this is NOT a serious restriction

Questions?