Verifying the seL4 Microkernel

Formal Proof in Mathematics and Computer Science

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Outline

1. What is a μ-kernel?
2. Design process of seL4
3. Formal methods of the correctness proof
4. Layers of the correctness proof
5. Conclusion

What is a μ-kernel?

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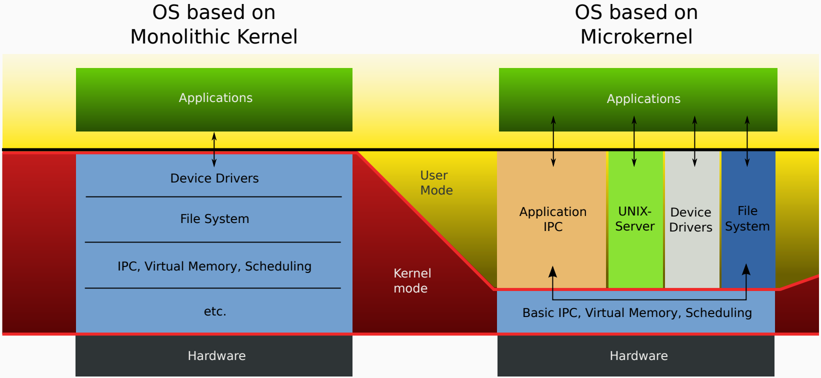
$\Rightarrow$ **Bugs are potentially fatal**

Definition: Microkernel

A concept is tolerated inside the μ-kernel only if moving it outside the kernel, i.e. permitting competing implementations, would prevent the implementation of the system's required functionality.

— Jochen Liedtke

Monolithic kernels and μ-kernels



The seL4 μ-kernel

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Design process of seL4

Design process for verification

Requirements

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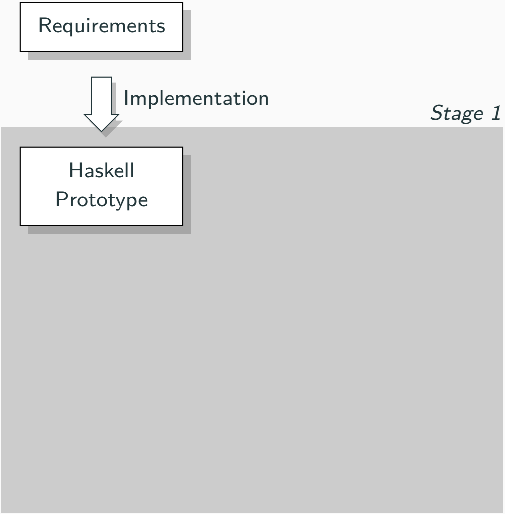
Stage 1

Design process for verification



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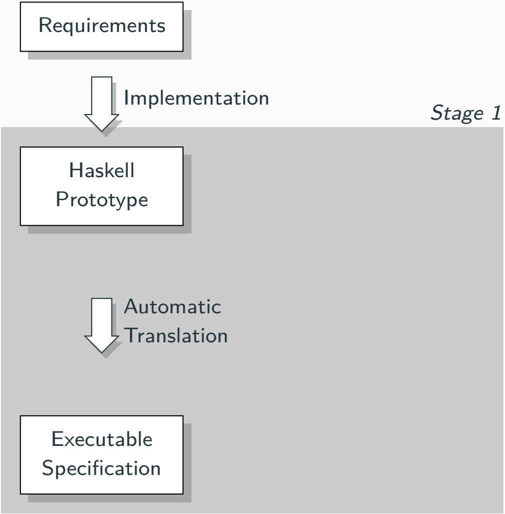

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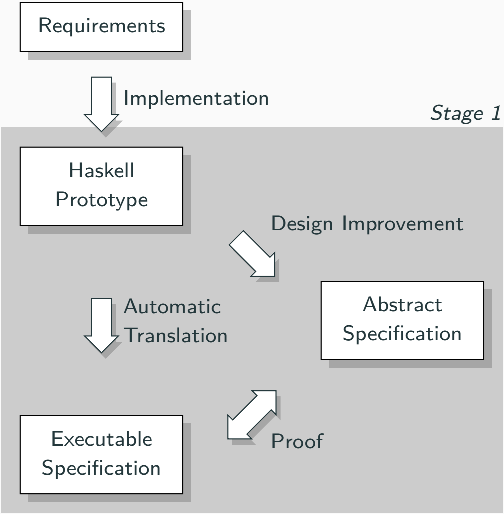

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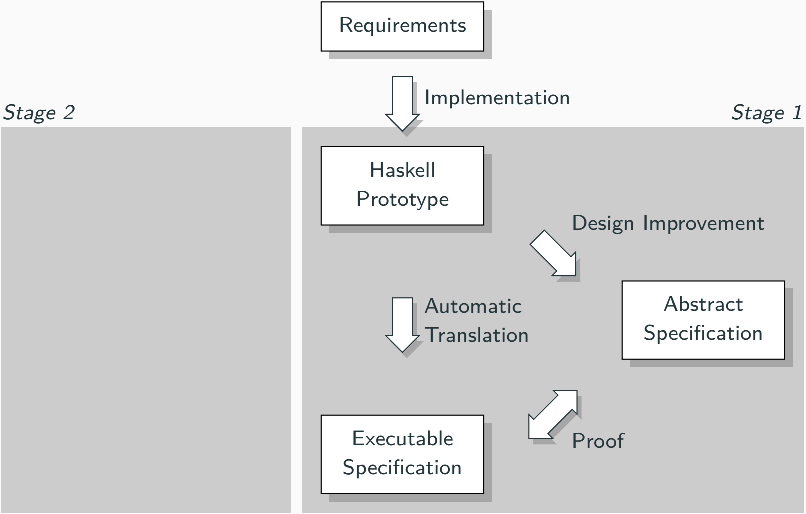

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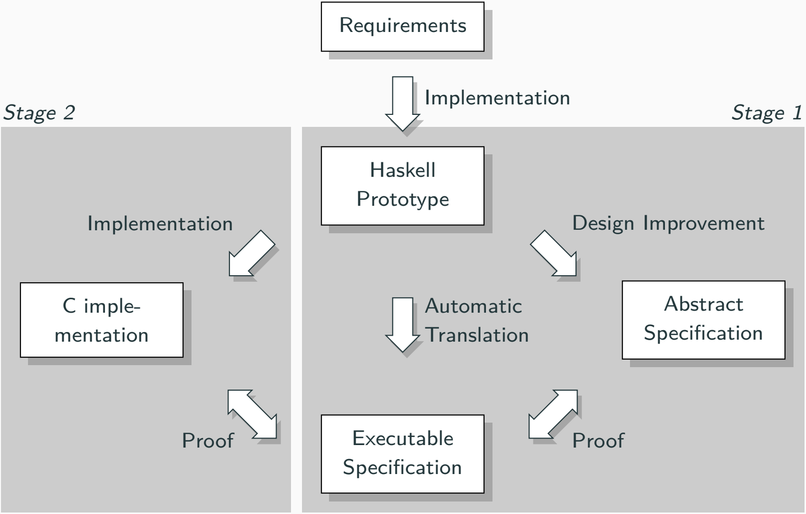


Formal methods of the correctness proof

Hoare logic

$$\overbrace{\{x = 1\}}^{P} \quad \overbrace{x := x + 1}^{C} \quad \overbrace{\{x = 2\}}^{Q}$$

More Hoare logic

$$\{x = 0 \land x = 1\} \quad y := 2 * x \quad \{ \qquad\qquad\qquad\qquad \}$$

More Hoare logic

$$\{x \text{ is even}\} \quad y := 2 * x \quad \{ \qquad\qquad\qquad\qquad \}$$

More Hoare logic

$$\{x \text{ is even}\} \quad y := 2 * x \quad \{x \text{ and } y \text{ are even}\}$$

Partial correctness of Hoare logic

$\{\quad\}$ `WHILE true DO c` $\{\quad\}$

Data refinement

Data refinement

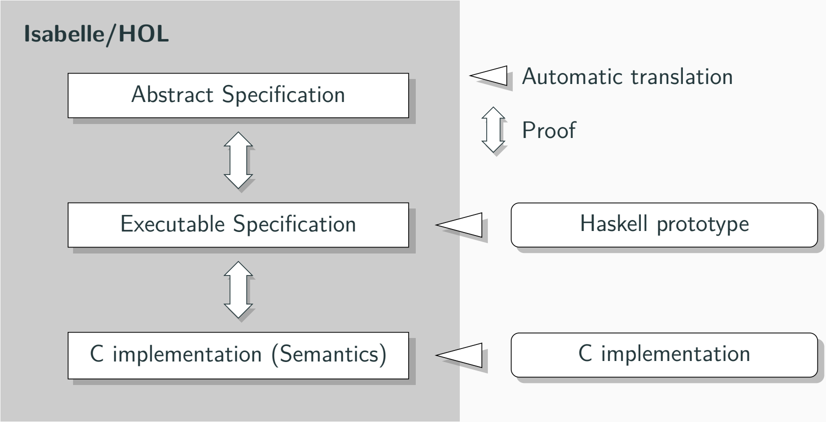
A concrete system C refines an abstract specification A if the behaviour of C is contained in that of A.

Data refinement: Examples

- The scheduler selects runnable threads
- System calls return non-zero values on error

Layers of the correctness proof

Proof structure



Abstract specification

The abstract specification is the most high-level layer still fully encapturing the behaviour of the kernel.

Scheduler on the abstract level

```
schedule ≡ do
    threads ← all_active_tcbs;
    thread ← select threads;
    switch_to_thread thread
od OR switch_to_idle_thread
```

Executable specification

Fill in the details left open by the abstract specification.

Haskell implementation of the scheduler

```
schedule = do
    action <- getSchedulerAction
    case action of
        ChooseNewThread -> do
            chooseThread
            setSchedulerAction ResumeCurrentThread
            ...

chooseThread = do
    r <- findM chooseThread' (reverse [minBound .. maxBound])
    when (r == Nothing) $ switchToIdleThread

chooseThread' prio = do
    q <- getQueue prio
    liftM isJust $ findM chooseThread'' q

chooseThread'' thread = do
    runnable <- isRunnable thread
    if not runnable then do
        tcbSchedDequeue thread
        return False
    else do
        switchToThread thread
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Get runnable thread with highest priority using `chooseThread'` or schedule idle thread.

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Call chooseThread to select next thread.

Get runnable thread with highest priority using `chooseThread'` or schedule idle thread.

Try to find runnable thread in Queue.

Check if thread is runnable and act accordingly.

C implementation

Translate the Haskell implementation to C.

Machine Model

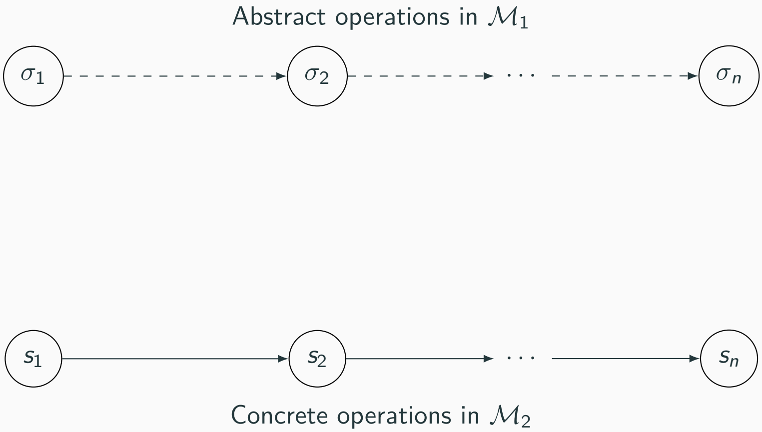
```
invalidateTLB :: unit machine_m => unit machine_m

invalidateCacheRange ::
    unit machine_m => word => word => unit machine_m
```

Data refinement for state machines

Concrete operations in $\mathcal{M}_2$

Data refinement for state machines



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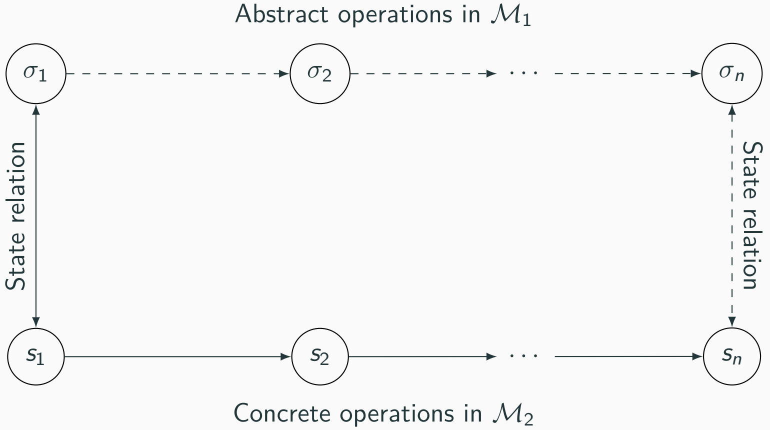

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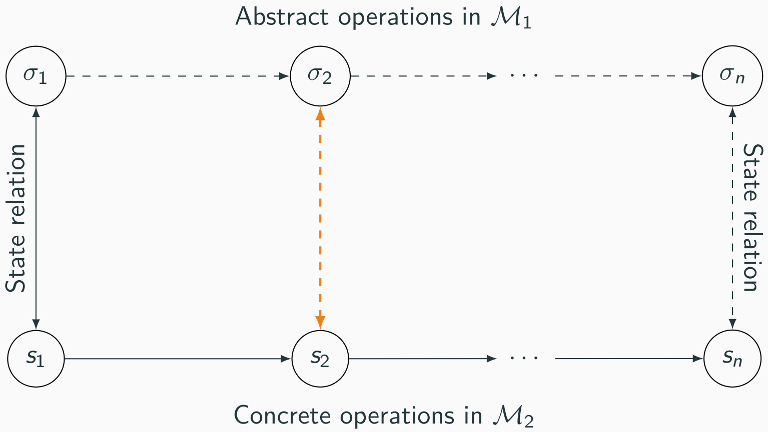
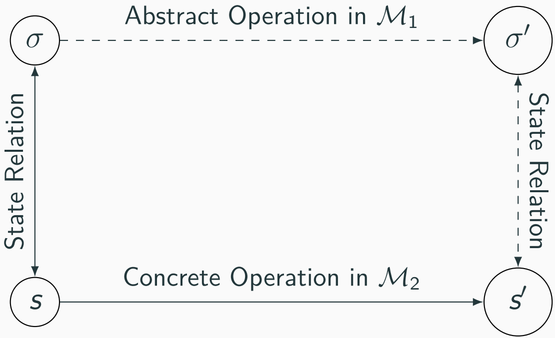


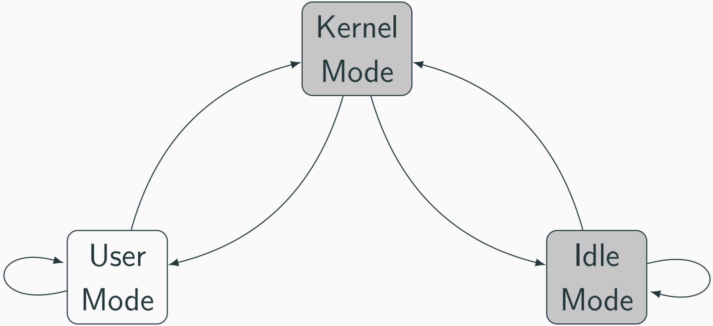
Refinement by forward simulation



Example for forward simulation

On the Board

Types of state transitions



Main result

$$\mathcal{M}_A$$

$$\mathcal{M}_E$$

$$\mathcal{M}_C$$

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$$\begin{tikzcd} \mathcal{M}_A \\ \mathcal{M}_E \arrow[u, "\text{refines}"'] \\ \mathcal{M}_C \arrow[u, "\text{refines}"'] \end{tikzcd}$$

Main result

$$
\begin{tikzcd}
\mathcal{M}_A \\
\mathcal{M}_E \arrow[u, "\text{refines}"'] \\
\mathcal{M}_C \arrow[u, "\text{refines}"'] \arrow[uu, bend left=60, "\text{refines}"]
\end{tikzcd}
$$

Conclusion

Expenditure of time

Artefact	Effort (py)	Total (py)
Haskell impl.	2.0	2.2
C impl.	0.2	
Generic framework	9.0	20.5
Abstract spec.	0.3	
Executable spec.	0.2	
Refinement $\mathcal{M}_A \leftrightarrow \mathcal{M}_E$	8.0	
Refinement $\mathcal{M}_E \leftrightarrow \mathcal{M}_C$	3.0	

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- EAL7: 1000\$/LOC $\leftrightarrow$ seL4: 370\$/LOC

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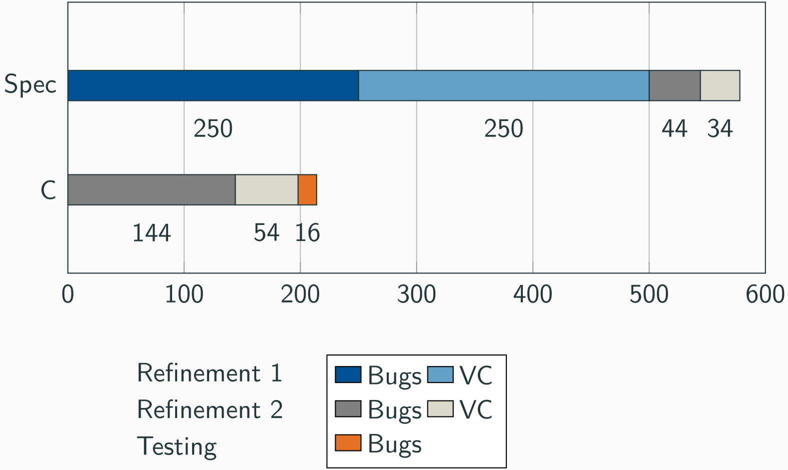
- L4 Pistachio kernel: 6 py $\leftrightarrow$ seL4 kernel: 2.2 py

Changes due to verification



What was achieved?

- Correctness proof down to binary level
- Trust in hardware

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- **What about Spectre and Meltdown?**

The future of seL4

- More architectures
- Multicore support

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- Multicore support
- Exclude timing-channel attacks

Questions?