seL4

Formal Verification of an OS Kernel

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NICTA
L4. Verified

1 microkernel
8,700 lines of C
0 bugs*

qed

*conditions apply
An exception 06 has occurred at 0028:C11B3ADC in VxD DiskTSD(03) + 00001660. This was called from 0028:C11B40C8 in VxD voltrack(04) + 00000000. It may be possible to continue normally.

* Press any key to attempt to continue.
* Press CTRL+ALT+RESET to restart your computer. You will lose any unsaved information in all applications.

Press any key to continue
The Problem
Small trustworthy foundation

- hypervisor, microkernel, nano-kernel, virtual machine, separation kernel, exokernel ...
- High assurance components in presence of other components

seL4 API:
- IPC
- Threads
- VM
- IRQ
- Capabilities
Small Kernels

Small trustworthy foundation

- hypervisor, microkernel, nano-kernel, virtual machine, separation kernel, exokernel ...
- High assurance components in presence of other components

seL4 API:
- IPC
- Threads
- VM
- IRQ
- Capabilities

Untrusted
- Legacy Apps
- Linux Server

Trusted
- Sensitive App
- Trusted Service

seL4

Hardware
The Proof
The Proof
Functional Correctness

Proof

Specification

Code
**Functional Correctness**

What

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Proof

Code

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**22 Threads and TCBs**

```plaintext
constdefs
switch_to_thread :: thread_ptr ⇒ unit s_monad
switch_to_thread t ≡
do state ← get;
assert yget_tcb t state ≠ None;
arch_switch_to_thread t;
modify y λ s. s ( cur_thread := t )
od

constdefs
switch_to_idle_thread :: unit s_monad
switch_to_idle_thread ≡
do thread ← gets idle_thread;
arch_switch_to_idle_thread;
modify y λ s. s ( cur_thread := thread )
do

definition
schedule :: unit s_monad
where
schedule ≡ do
threads ← allActiveTCBs;
thread ← select threads;
switch_to_thread thread
do
OR switch_to_idle_thread
end
```

```c
void schedule(void) {
    switch ((word_t)ksSchedulerAction) {
        case (word_t)SchedulerAction_ResumeCurrentThread:
            break;

        case (word_t)SchedulerAction_PauseCurrentThread:
            ksSchedulerAction = SchedulerAction_PauseCurrentThread;
            break;

        default: /* SwitchToThread */
            switchToThread(ksSchedulerAction);
            ksSchedulerAction = SchedulerAction_ResumeCurrentThread;
            break;
    }
}

void
chooseThread(void) {
    prio_t prio;
tcb_t *thread, *next;
```
*conditions apply
*conditions apply

Specification

Proof

Code

Assumptions
*conditions apply
Assume correct:
- compiler + linker (wrt. C op-sem)
- assembly code (600 loc)
- hardware (ARMv6)
- cache and TLB management
- boot code (1,200 loc)
Implications

Execution always defined:

- no null pointer de-reference
- no buffer overflows
- no code injection
- no memory leaks/out of kernel memory
- no div by zero, no undefined shift
- no undefined execution
- no infinite loops/recursion

Not implied:

- “secure” (define secure)
- zero bugs from expectation to physical world
- covert channel analysis
Proof Architecture

- Specification
- Proof
- C Code
Proof Architecture

- Specification
  - Design
    - C Code
Proof Architecture

Access Control Spec

Specification

Design

C Code

Confinement
22 Threads and TCBs

theory Tcb_A imports CSpace_A ArchVSpace_A Schedule_A Ipc_decls_A begin

constdefs
set_thread_state :: obj_ref \Rightarrow thread_state \Rightarrow unit s_monad
set_thread_state ref ts ≡ do
tcb ← assert_opt_get t get_tcb ref;
set_object ref yTCB ytcb (tcb_state := ts) zz od

defs
suspend_def: suspend lazy thread ≡ do
ipc_cancel thread;
set_thread_state thread Inactive od

constdefs
restart :: obj_ref \Rightarrow unit s_monad
restart thread ≡ do
state ← get_thread_state thread;
when y ¬ runnable state t do
ipc_cancel thread;
OR switch_to_idle_thread od
end
Proof Architecture

Access Control Spec

Specification

Design

C Code

Confinement

**C Code**

```haskell
schedule :: Kernel ()
schedule = do
  action <- getScheduledAction
  case action of
    ResumeCurrentThread -> return ()
    ChooseNewThread -> do
      chooseThread
      setSchedulerAction ResumeCurrentThread
    SwitchToThread t -> do
      switchToThread t
      setSchedulerAction ResumeCurrentThread

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

**Haskell**

Prototype

**Access Control Spec**

Specification

Design

C Code

Confinement

Proof Architecture

© NICTA 2009
Proof Architecture

Access Control Spec

Specification

Design

C Code

Confinement

void schedule(void) {
    switch ((word_t)ksSchedulerAction) {
        case (word_t)SchedulerAction_ResumeCurrentThread:
            break;

        case (word_t)SchedulerAction_ChOOSENEWTHREAD:
            chooseThread();
            ksSchedulerAction = SchedulerAction_ResumeCurrentThread;
            break;

        default: /* SwitchToThread */
            switchToThread(ksSchedulerAction);
            ksSchedulerAction = SchedulerAction_ResumeCurrentThread;
            break;
    }
}

void chooseThread(void) {
    prio_t prio;
    tcb_t *thread, *next;
System Model

States:
User, Kernel, Idle

Events:
Syscall, Exception, IRQ, VM Fault
System Model

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User, Kernel, Idle

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States:
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Kernel Design for Verification
Kernel Design for Verification
Two Teams

Formal Methods Practitioners

Kernel Developers
Two Teams

Formal Methods Practitioners

Kernel Developers

The Power of Abstraction

(Liskov 09)

Exterminate All OS Abstractions!

(Engler 95)
Iterative Design and Formalisation

Whiteboard

Haskell Prototype

Formal Design

Formal Specification

C Code
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Design for Verification

Reducing Complexity

Hardware
• drivers outside kernel

Concurrency
• event based kernel
• limit preemption

Code
• derive from functional representation
C subset

Everything from C standard

- **including:**
  - pointers, casts, pointer arithmetic
  - data types
  - structs, padding
  - pointers into structs
  - precise finite integer arithmetic

- **minus:**
  - goto, switch fall-through
  - reference to local variable
  - side-effects in expressions
  - function pointers (restricted)
  - unions

- **plus** compiler assumptions on:
  - data layout, encoding, endianess
Did you find any Bugs?

Bugs found

during testing: 16

during verification:
  • in C: 160
  • in design: ~150
  • in spec: ~150

460 bugs

Effort

<table>
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<th>Effort</th>
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<tr>
<td>Haskell design</td>
<td>2 py</td>
</tr>
<tr>
<td>First C impl.</td>
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<tr>
<td>Debugging/Testing</td>
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Cost

- Common Criteria EAL6: $87M
- L4.verified: $6M
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Effort

- Haskell design: 2 py
- First C impl.: 2 weeks
- Debugging/Testing: 2 months
- Kernel verification: 12 py
- Formal frameworks: 10 py
- Total: 25 py

Cost

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Summary

Formal proof all the way from spec to C.

- 200kloc handwritten, machine-checked proof
- ~460 bugs (160 in C)
- Verification on code, design, and spec
- Hard in the proof → Hard in the implementation

Formal Code Verification up to 10kloc:

It works.
It’s feasible.  (It’s fun, too.
It’s cheaper.  And we’re hiring..)
Thank You