seL4

Formal Verification of an OS Kernel

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NICTA

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Department of Communications, Information Technology and the Arts
Australian Research Council

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The University of Sydney
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Griffith University
QUT
The University Of Queensland

L4Verified

1 microkernel

8,700 lines of C

0 bugs*

qed

*conditions apply

Windows

An exception 06 has occured 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 Kernels

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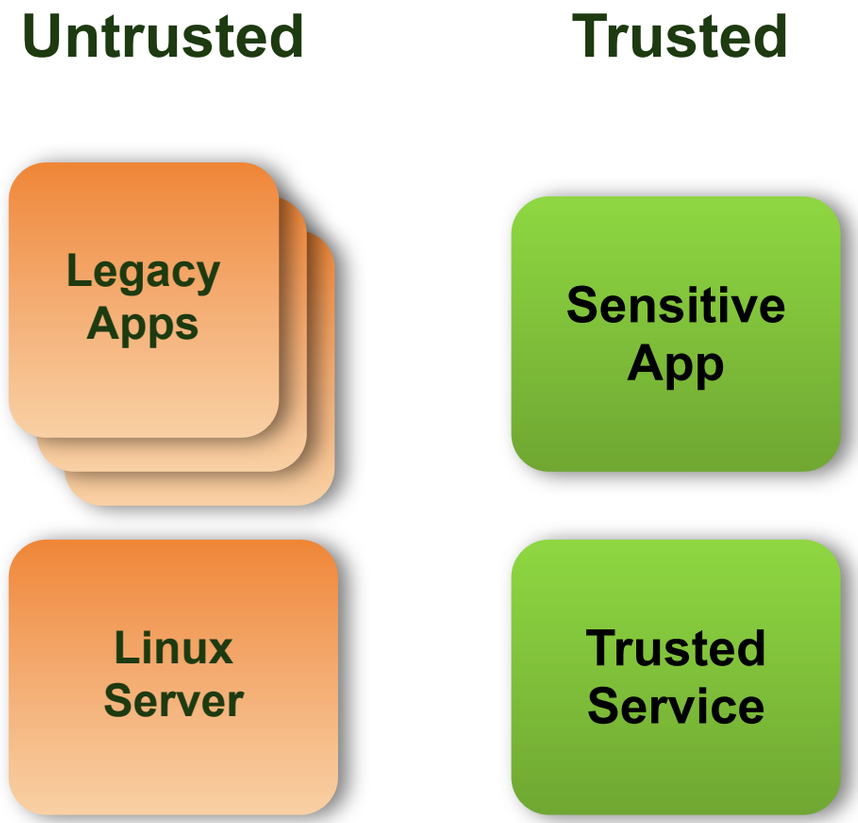
Small trustworthy foundation

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



seL4 API:

- IPC
- Threads
- VM
- IRQ
- Capabilities

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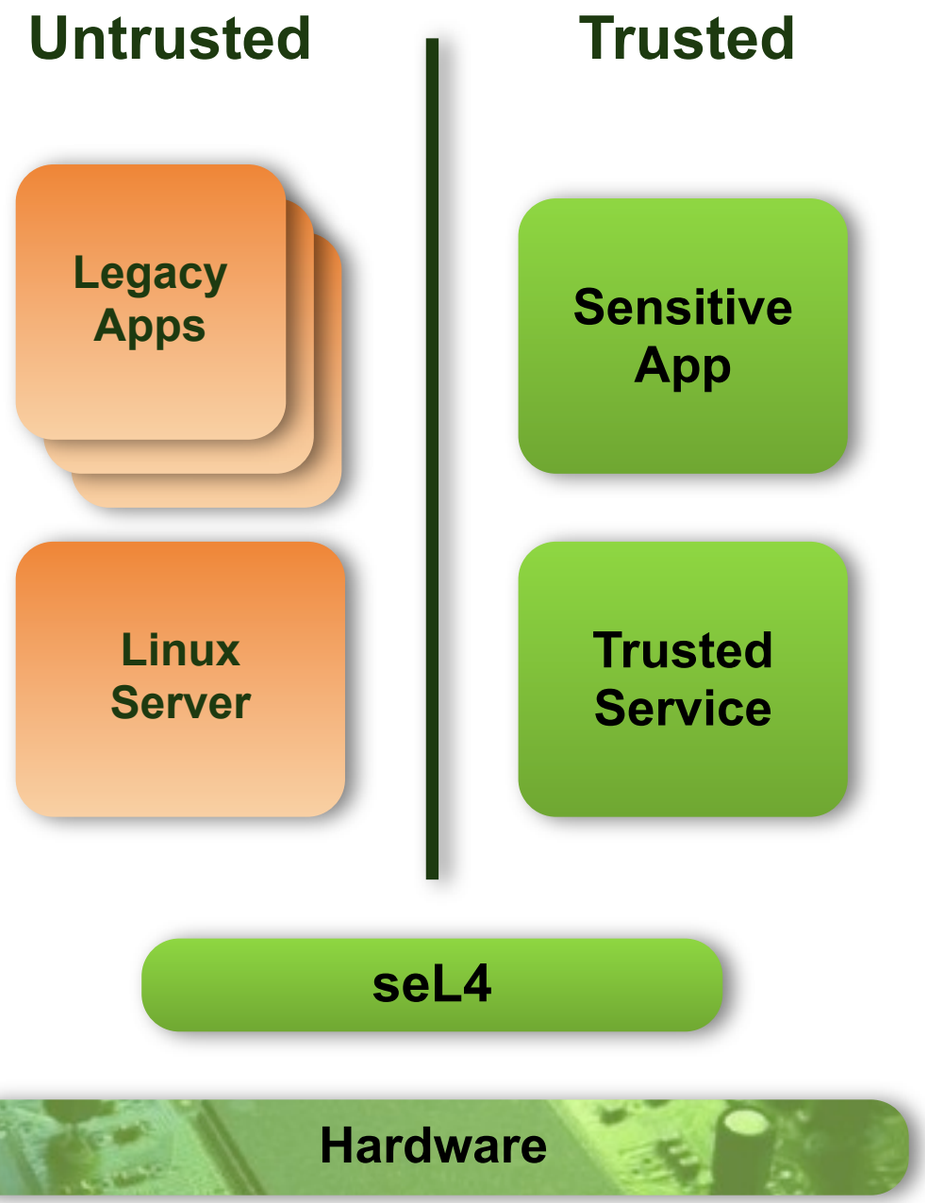

seL4 API:

- IPC
- Threads
- VM
- IRQ
- Capabilities

The Proof

The Proof

Functional Correctness

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Specification

Proof

Code

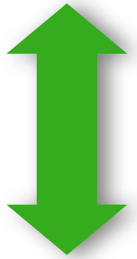
Functional Correctness

What

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

Specification

Proof



Code

Functional Correctness

NICTA

What

Proof

How

Specification

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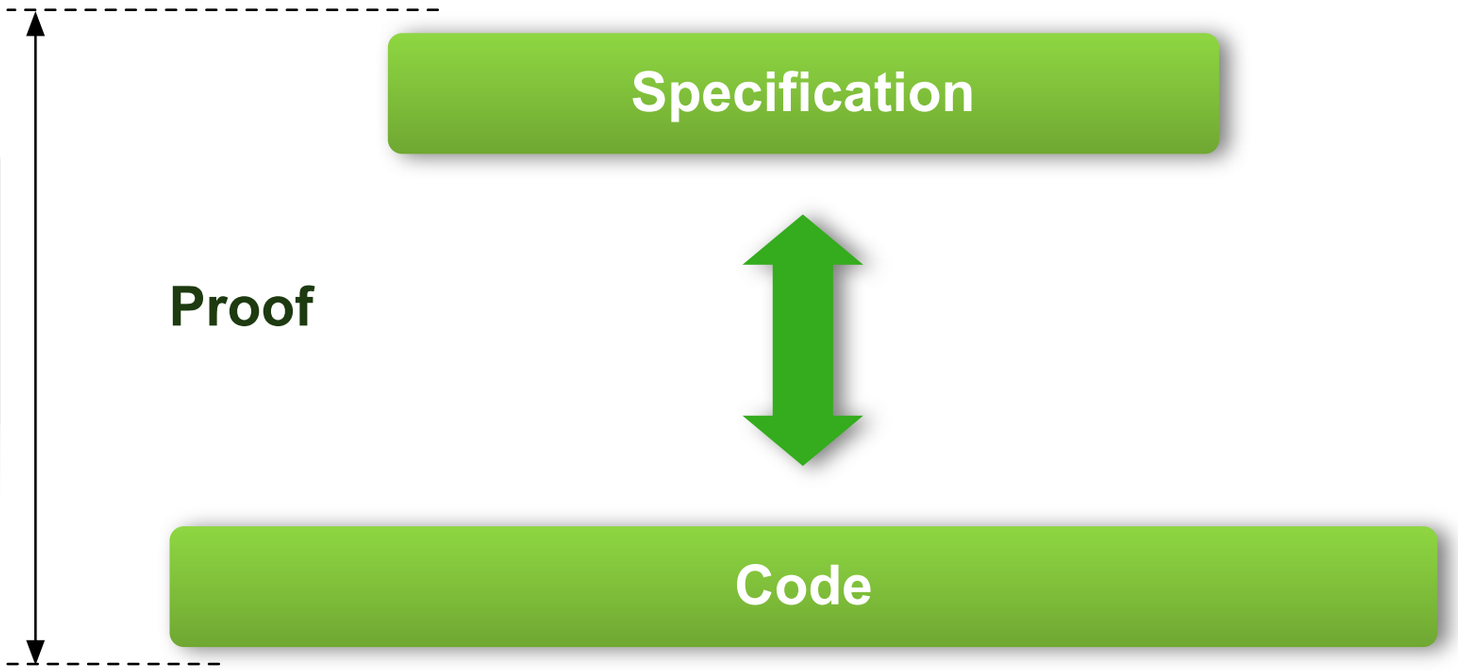
*conditions apply



*conditions apply

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Specification

Proof

Code

Assumptions

*conditions apply

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Expectation

Specification

Proof

Code

Assumptions

*conditions apply

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Assume correct:

- compiler + linker (wrt. C op-sem)
- assembly code (600 loc)
- hardware (ARMv6)
- cache and TLB management
- boot code (1,200 loc)

Specificati

Proof

Code

Assumptions

Implications

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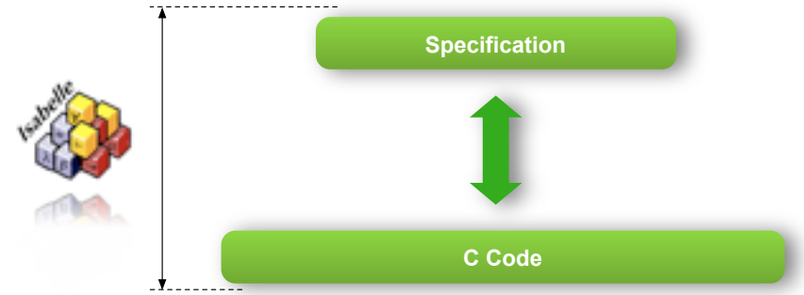
Execution always defined:

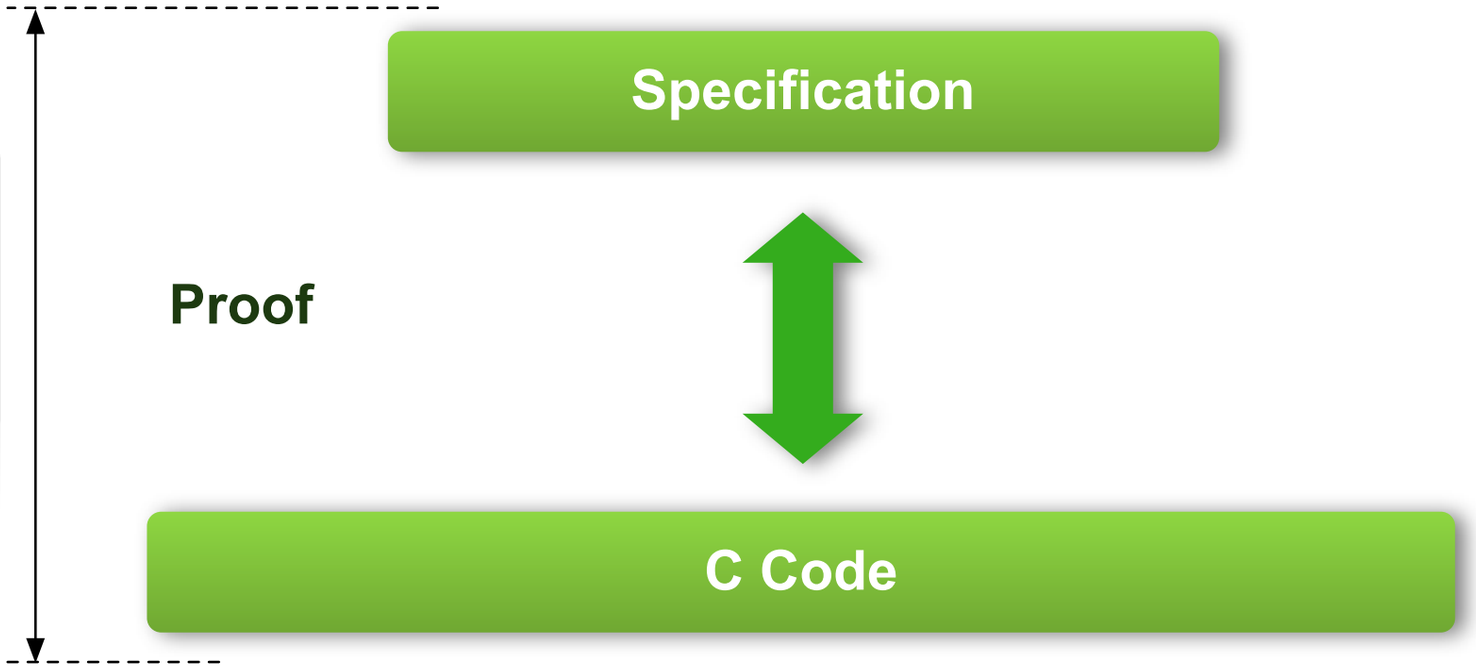
- no null pointer de-reference
- no buffer overflows
- no code injection
- no memory leaks/out of kernel memory
- no div by zero, no undefined shift
- no undefined execution
- no infinite loops/recursion



Not implied:

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

Proof Architecture



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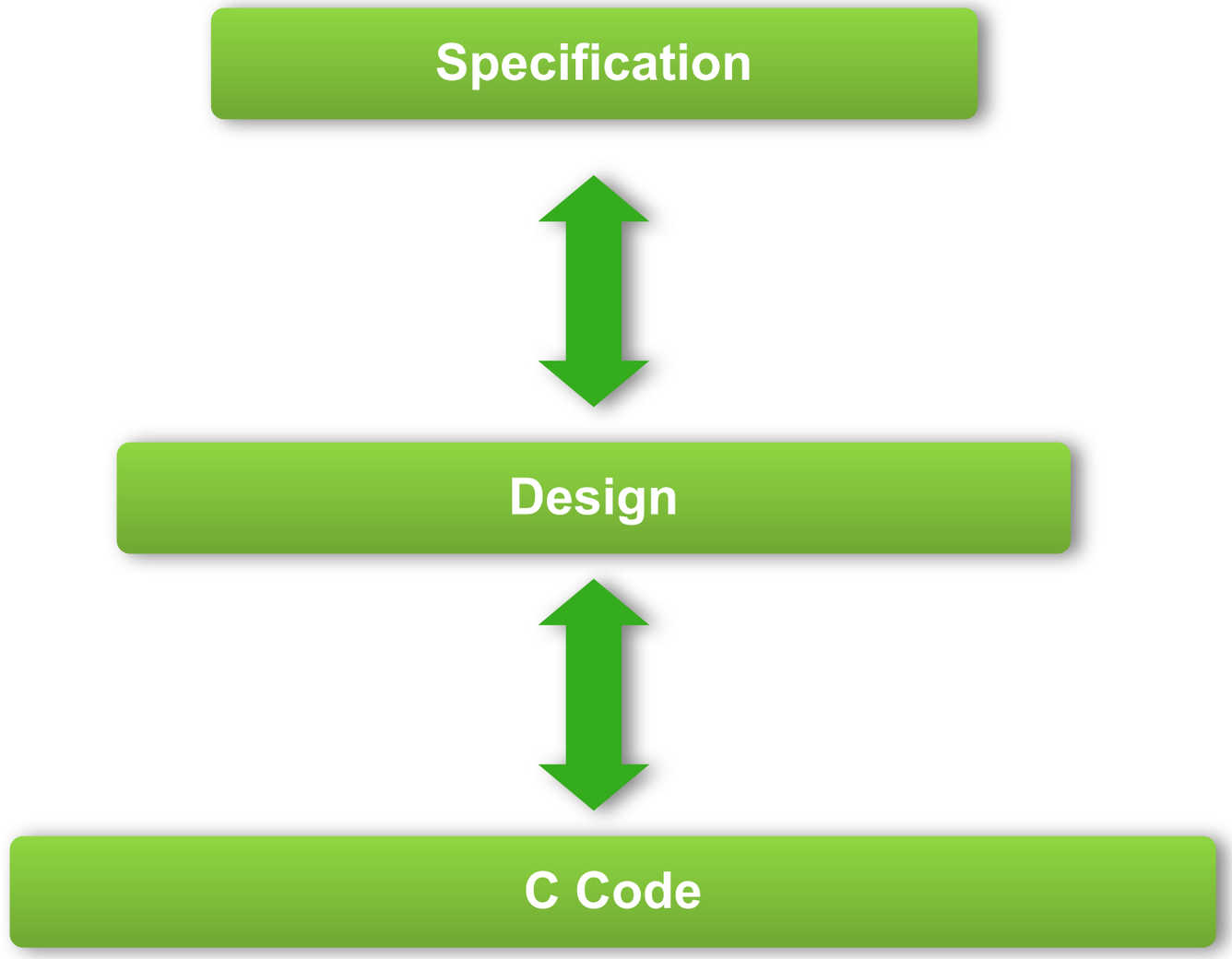

Proof Architecture

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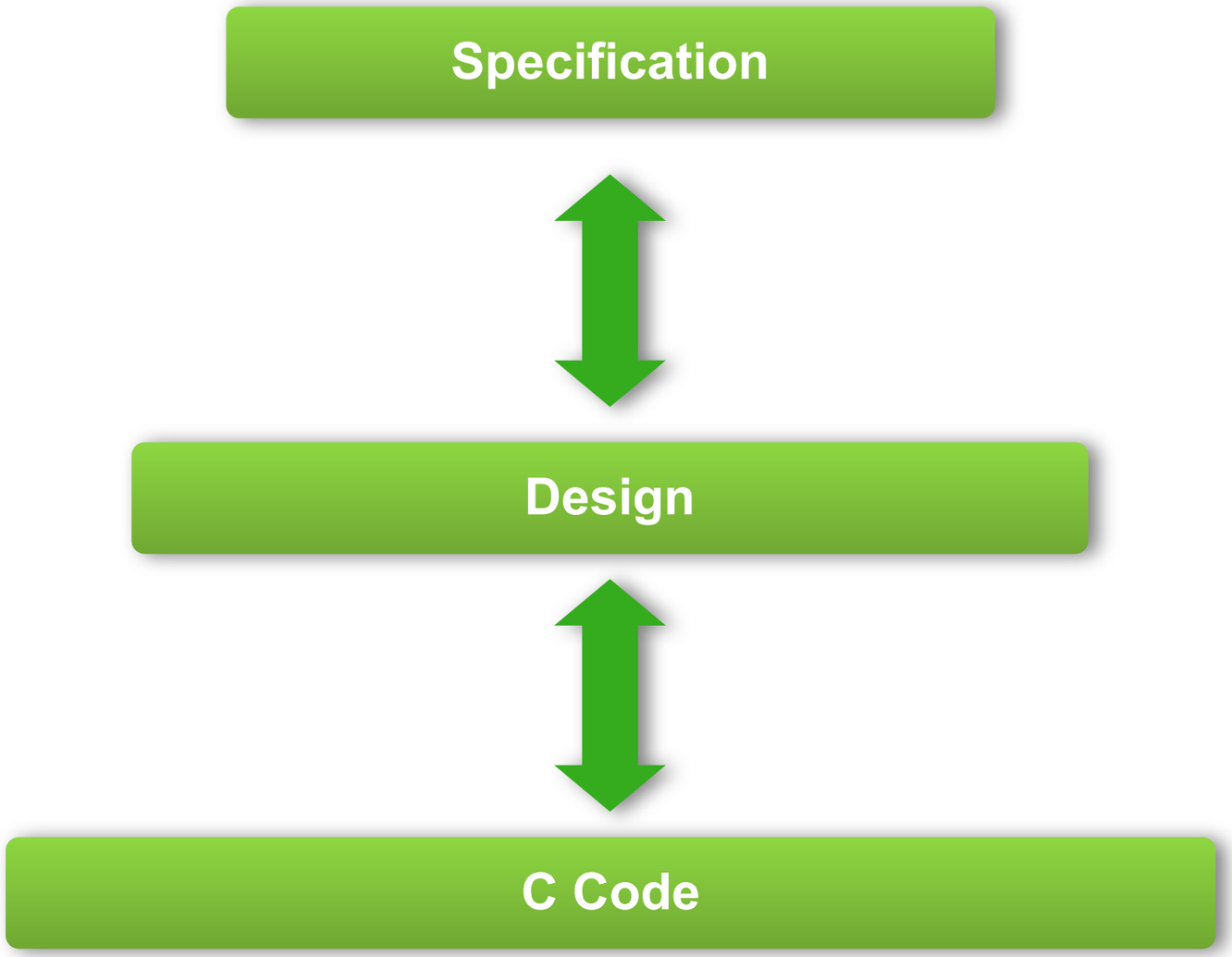

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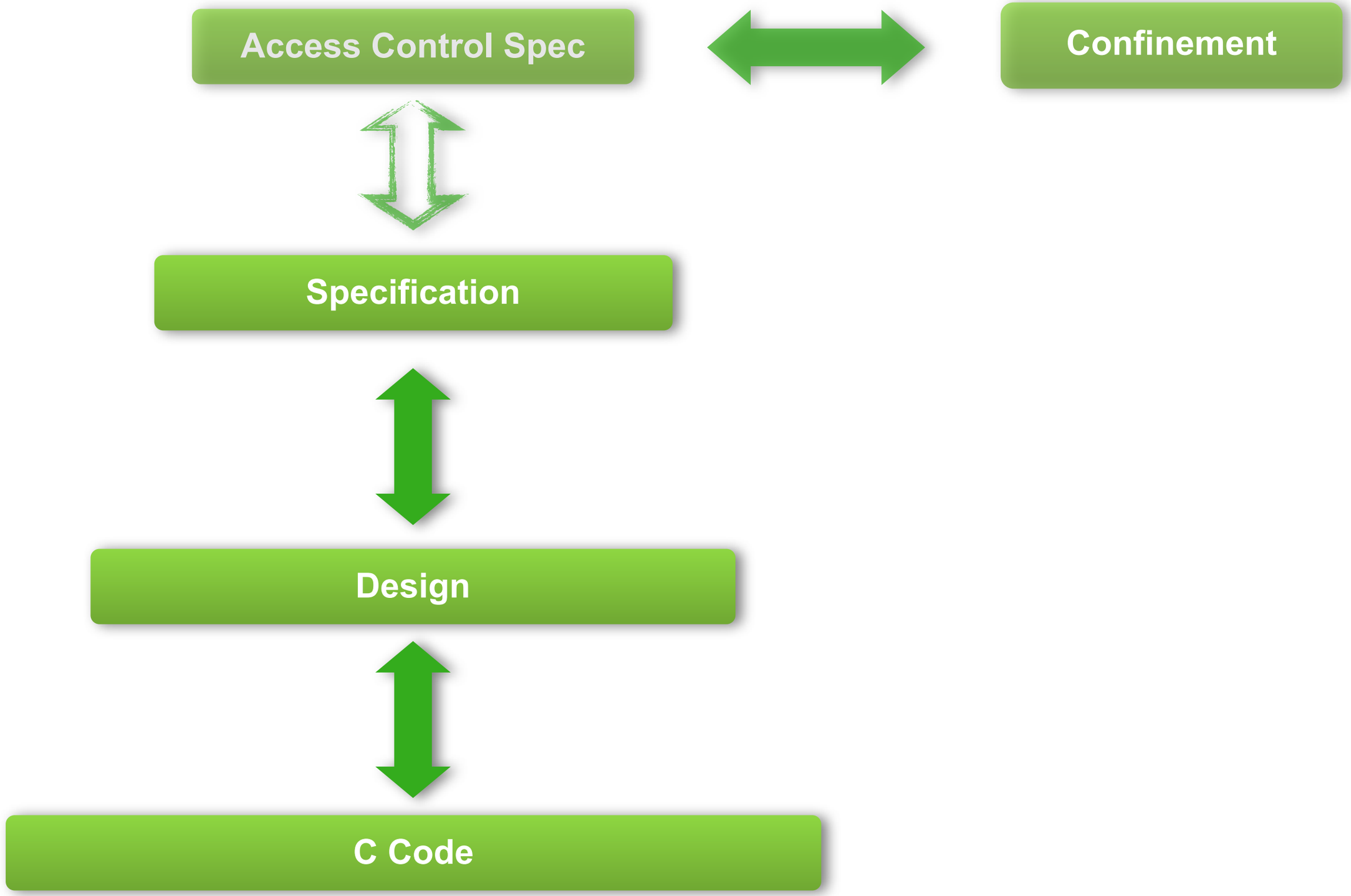

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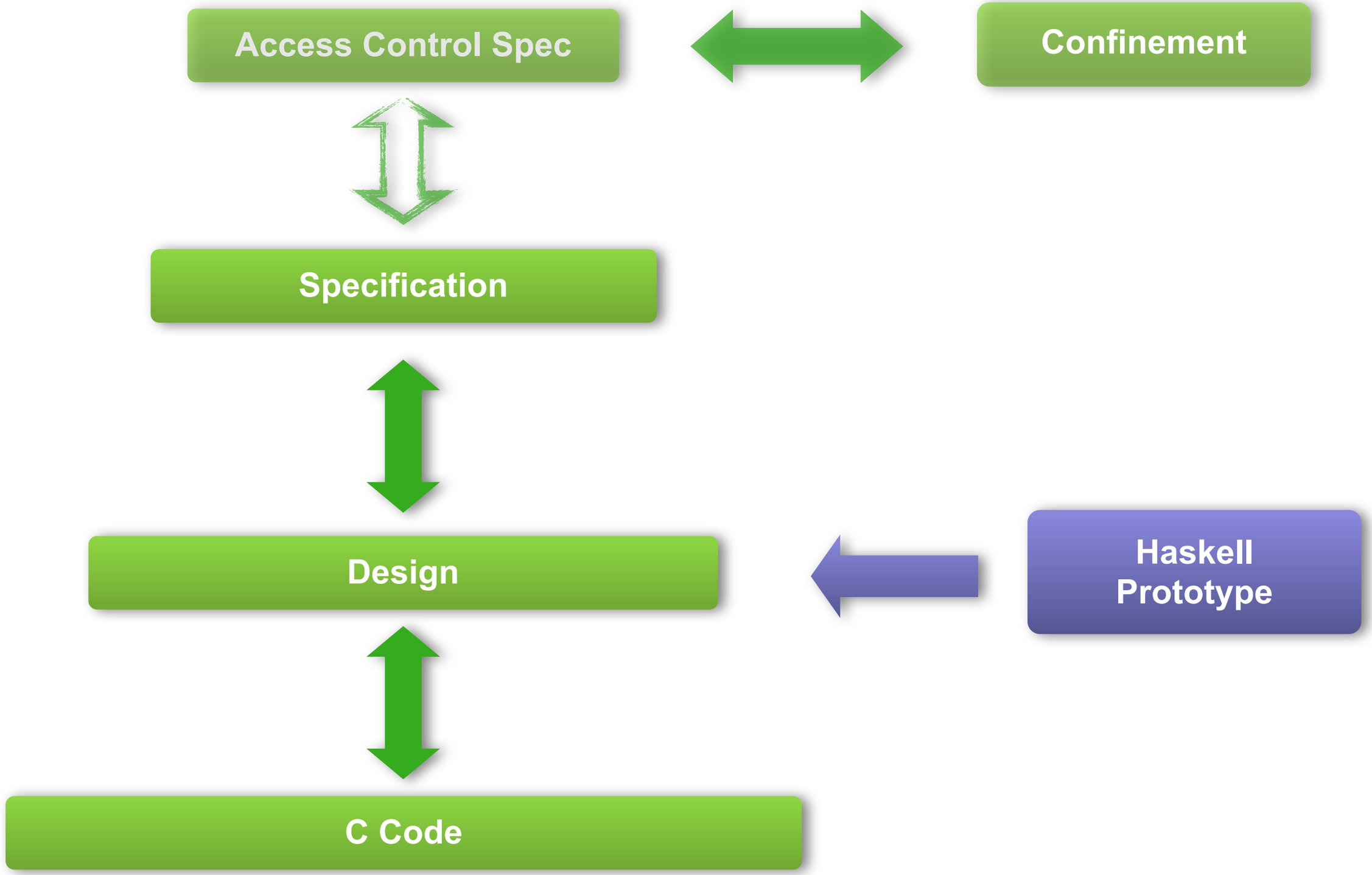

Proof Architecture

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Access Control Spec

Confinement

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definition
  schedule :: unit s_monad where
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Specification

Design

Haskell Prototype

C Code

Proof Architecture

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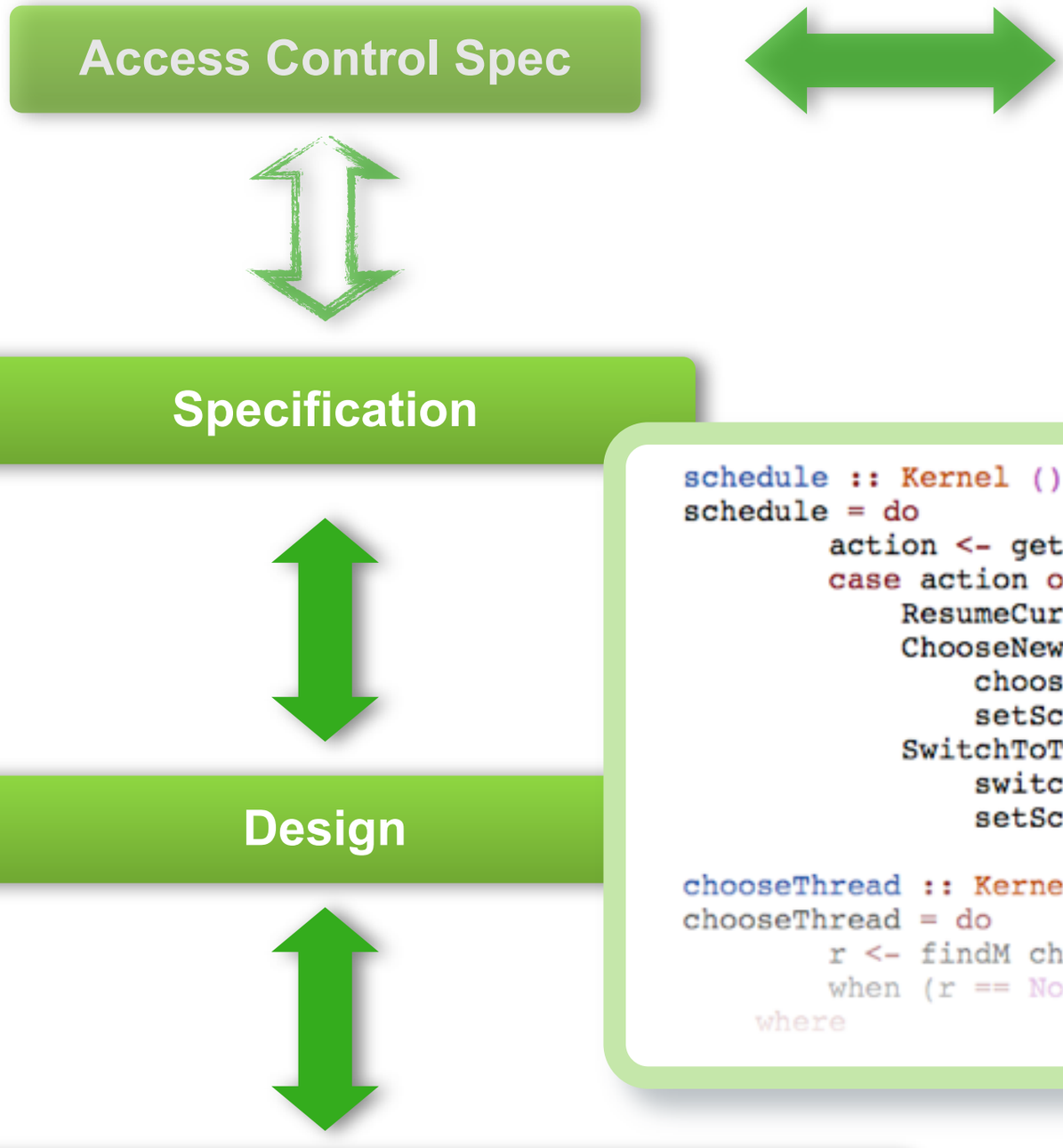


```
schedule :: Kernel ()
schedule = do
        action <- getSchedulerAction
        case action of
            ResumeCurrentThread -> return ()
            ChooseNewThread -> do
                chooseThread
                setSchedulerAction ResumeCurrentThread
            SwitchToThread t -> do
  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

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

Proof Architecture

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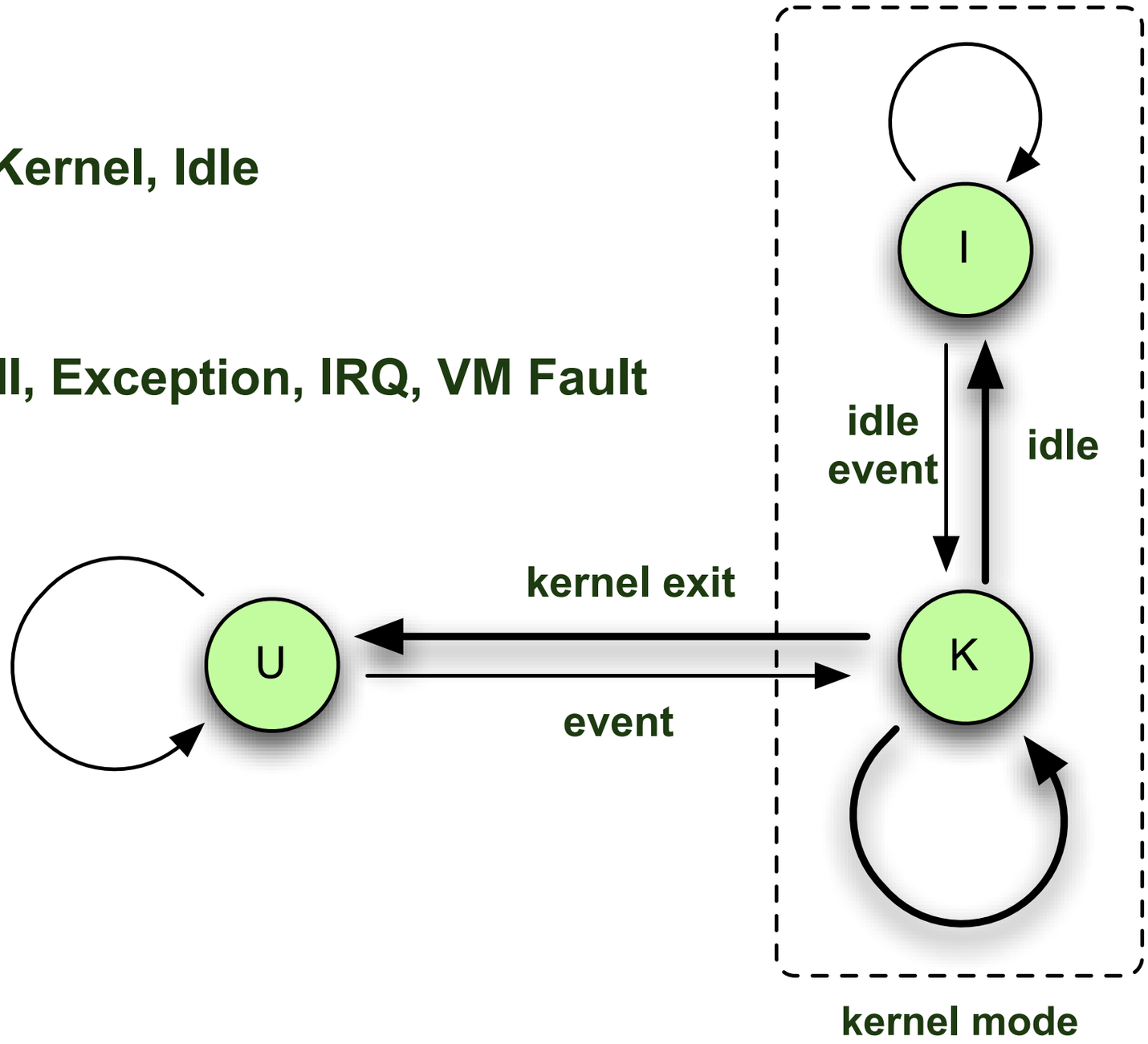
System Model

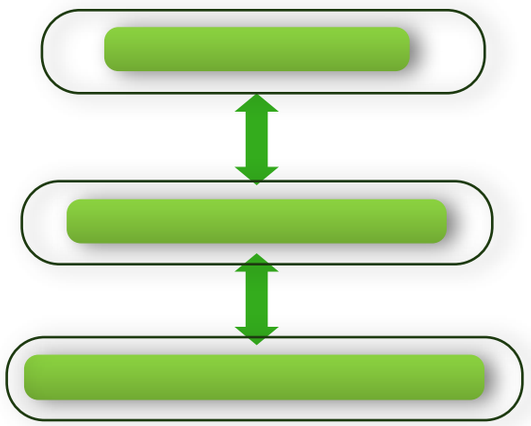
States:

User, Kernel, Idle

Events:

Syscall, Exception, IRQ, VM Fault





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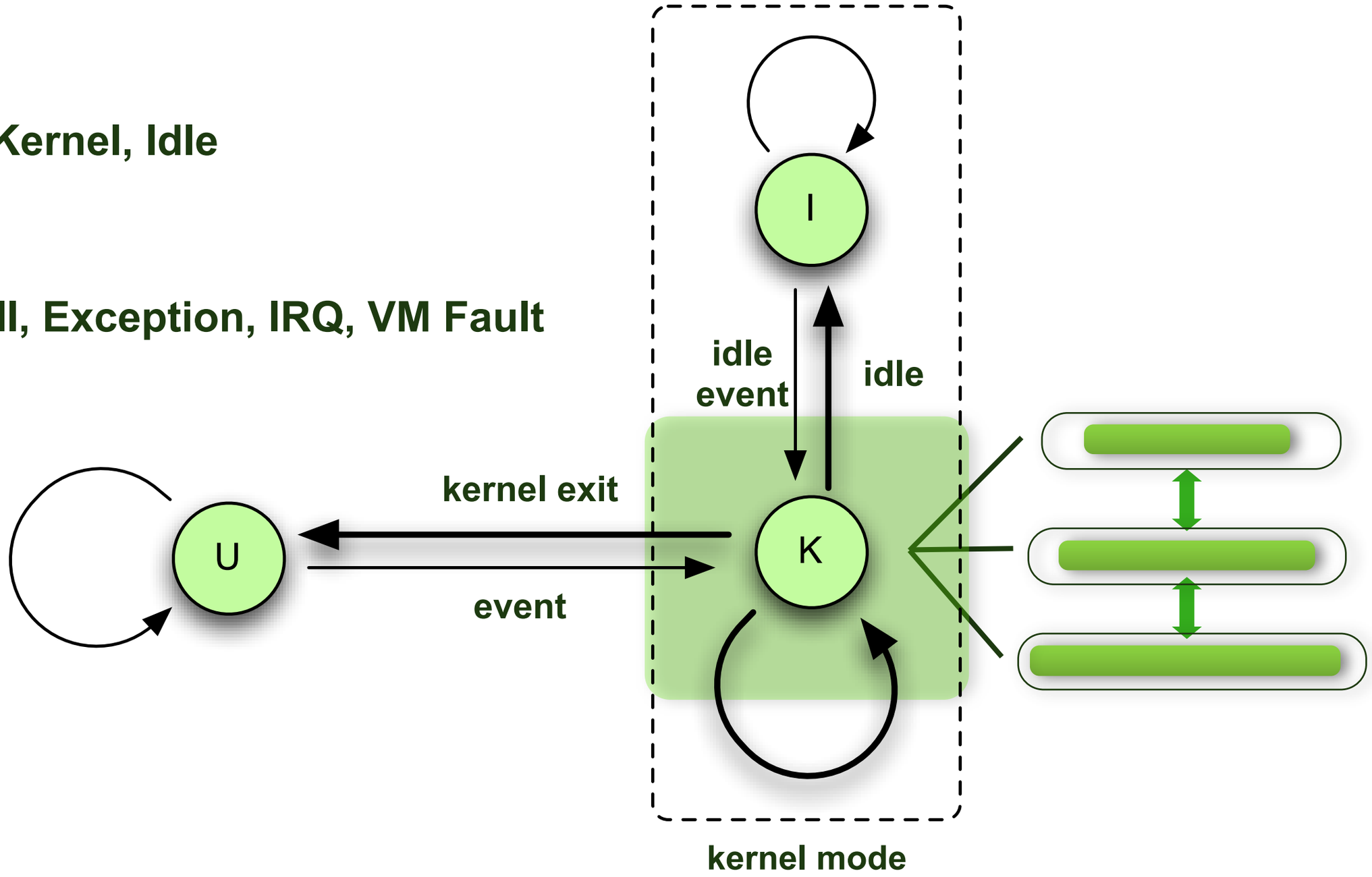
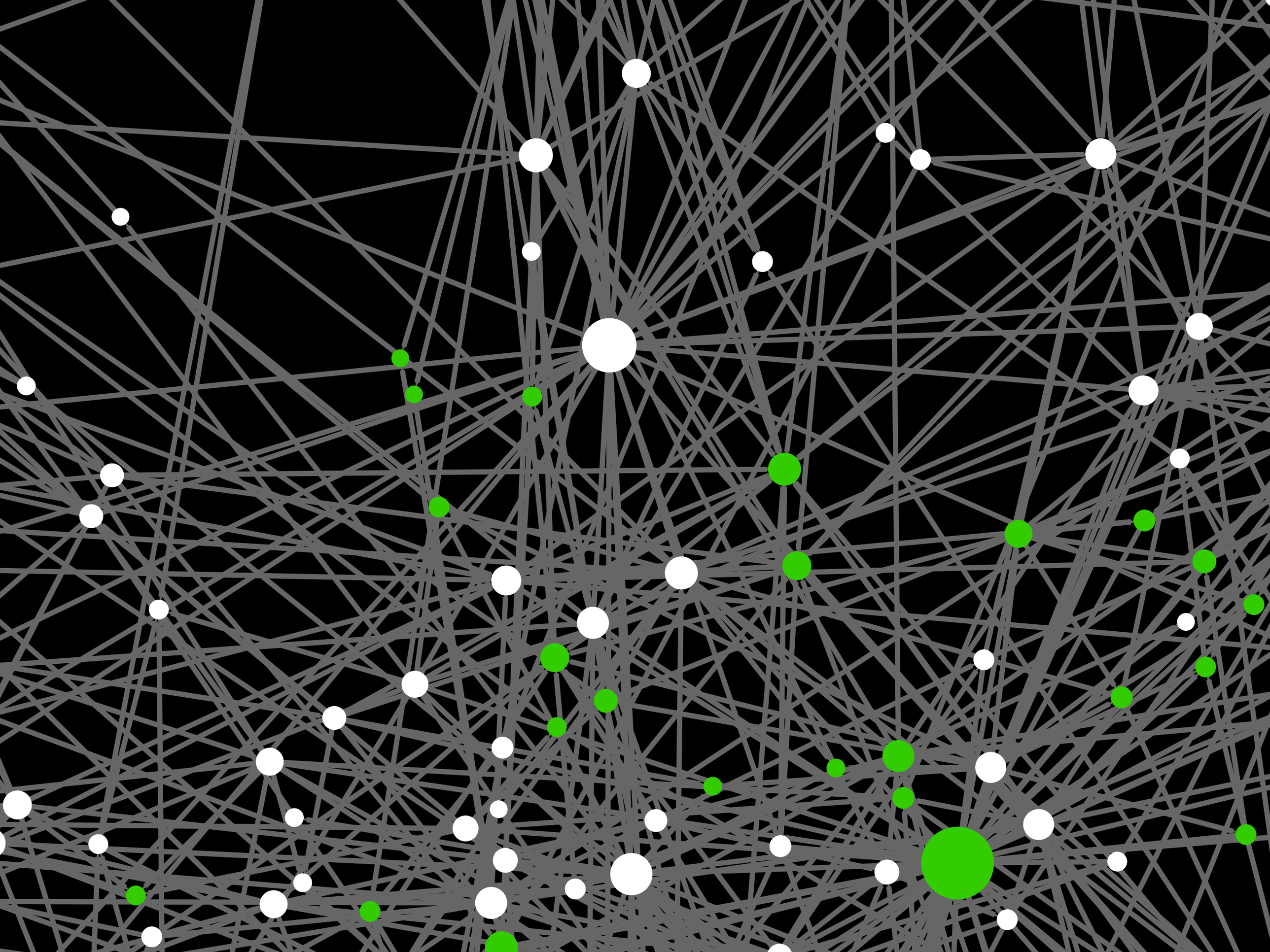
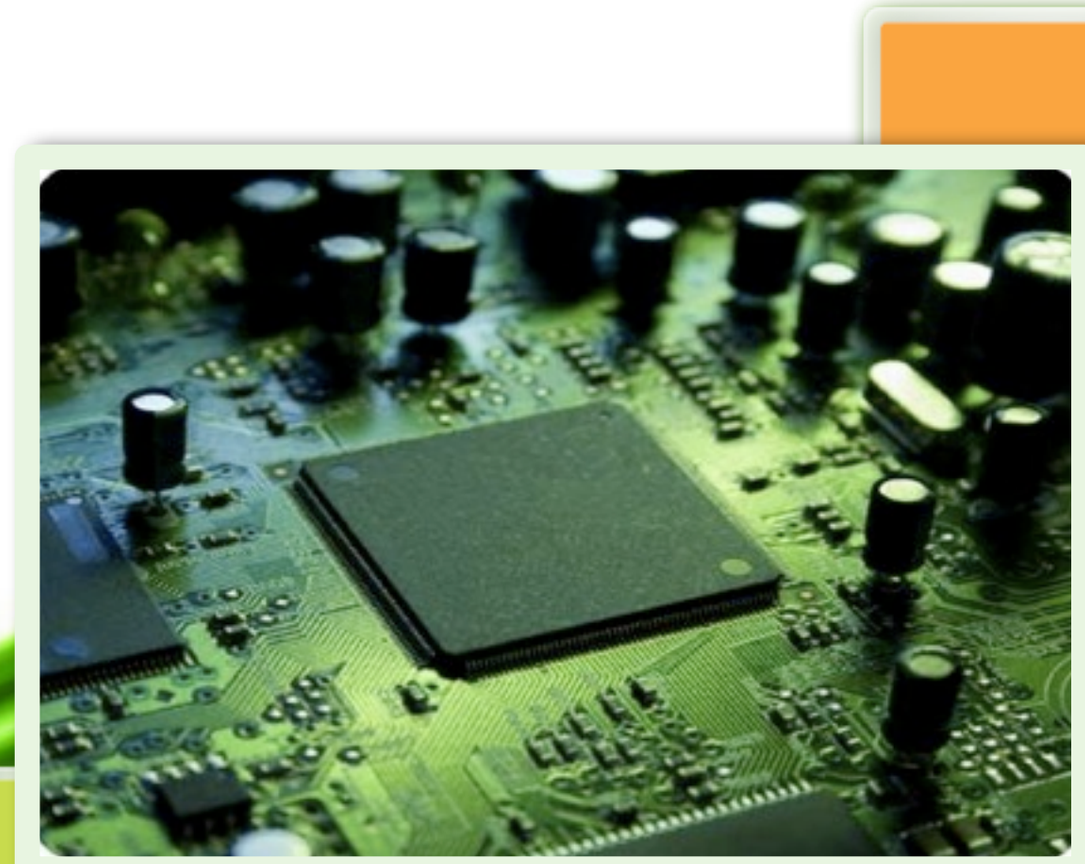





seL4

Kernel Design for Verification

Kernel Design for Verification



Two Teams

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Formal Methods Practitioners

Kernel Developers

Two Teams

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Formal Methods Practitioners

The Power of Abstraction

(Liskov 09)

Kernel Developers

Exterminate All OS Abstractions!

(Engler 95)

Iterative Design and Formalisation

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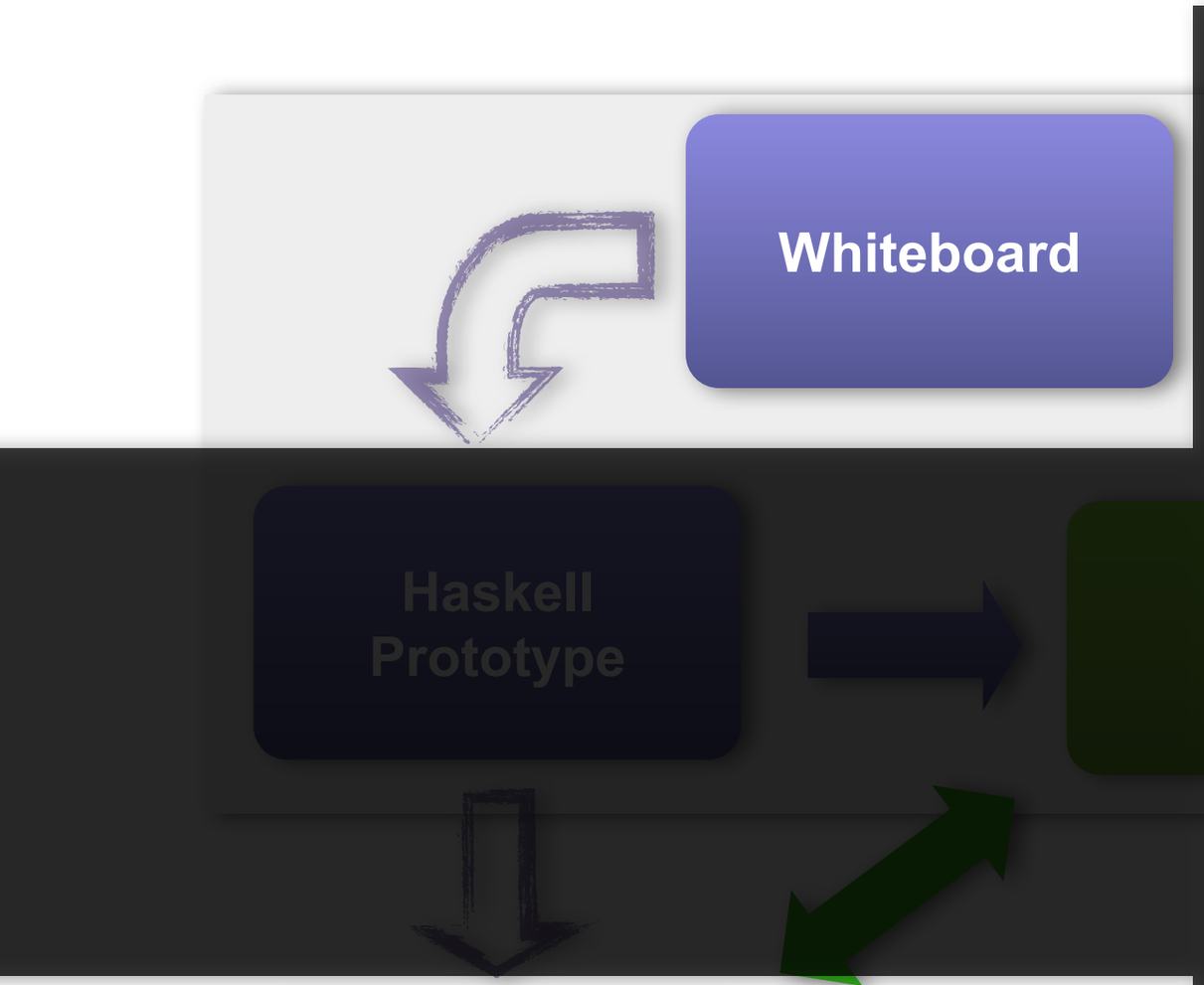

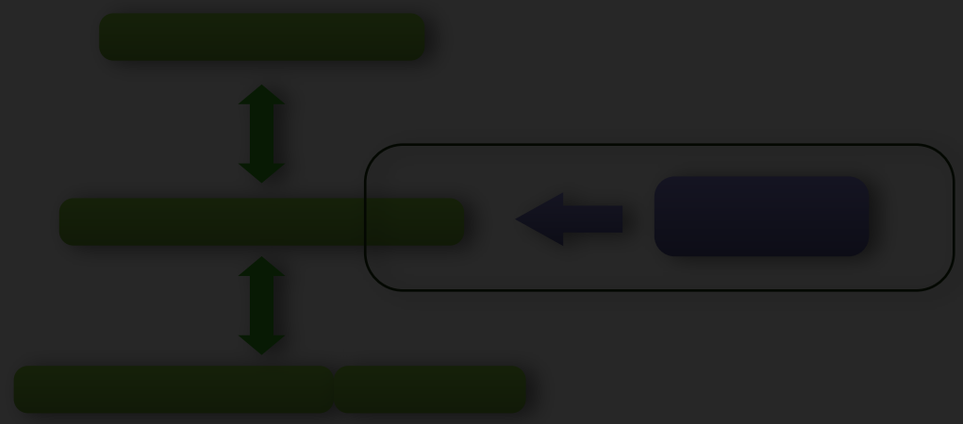

Iterative Design and Formalisation

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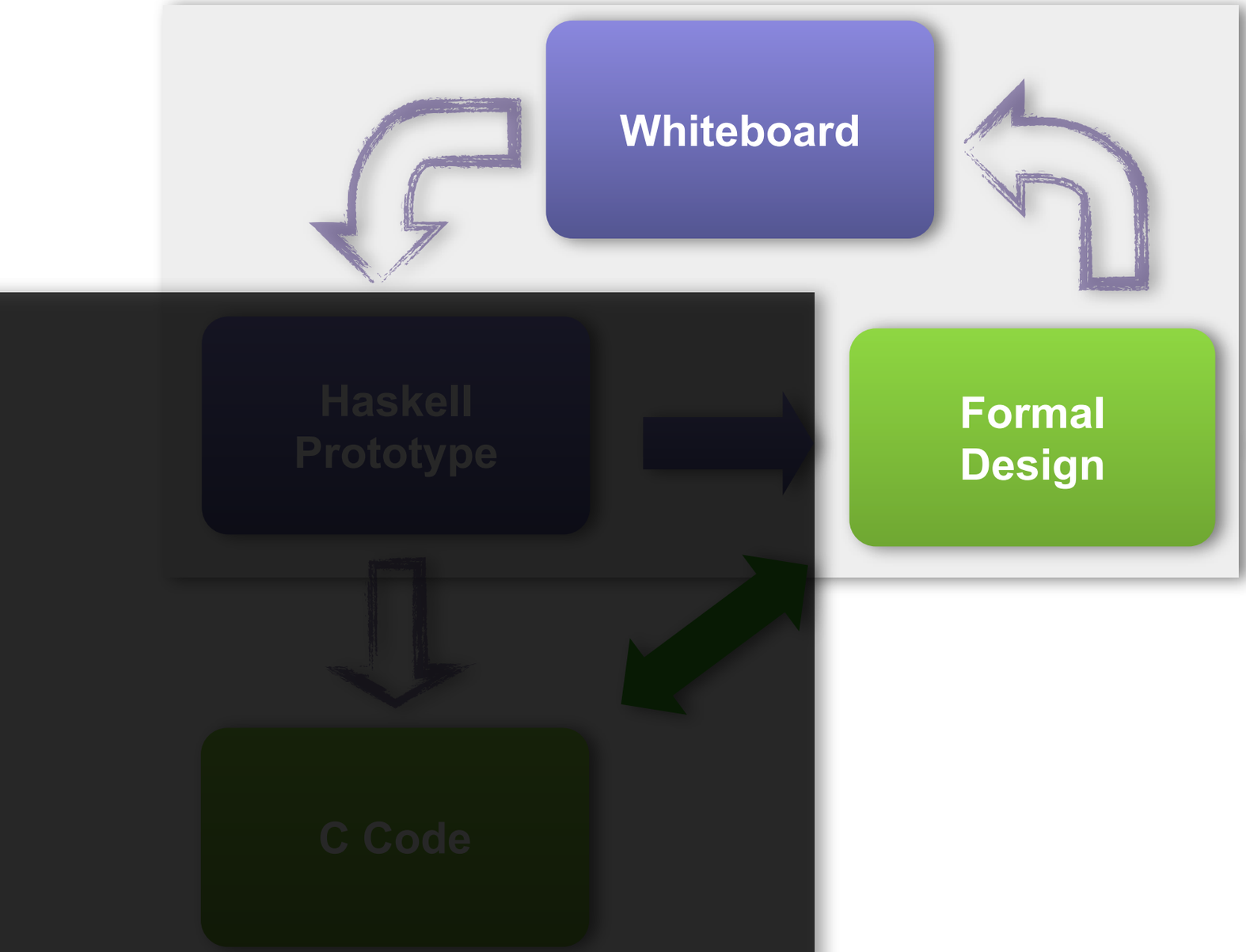

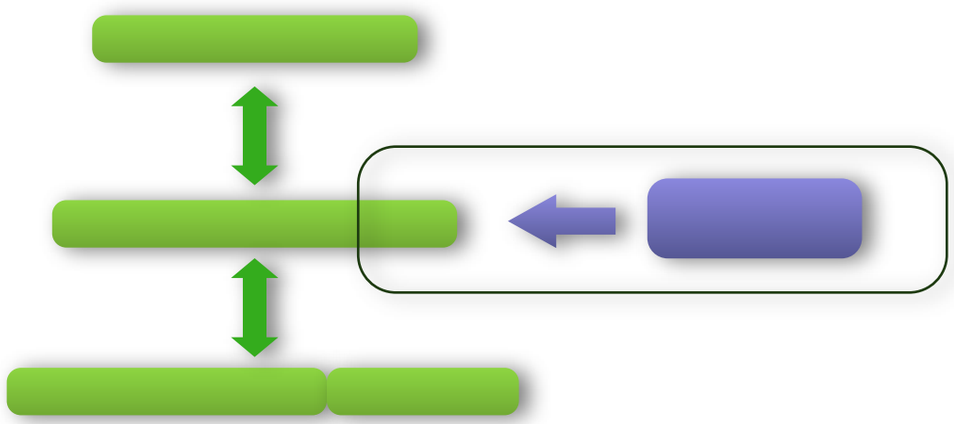

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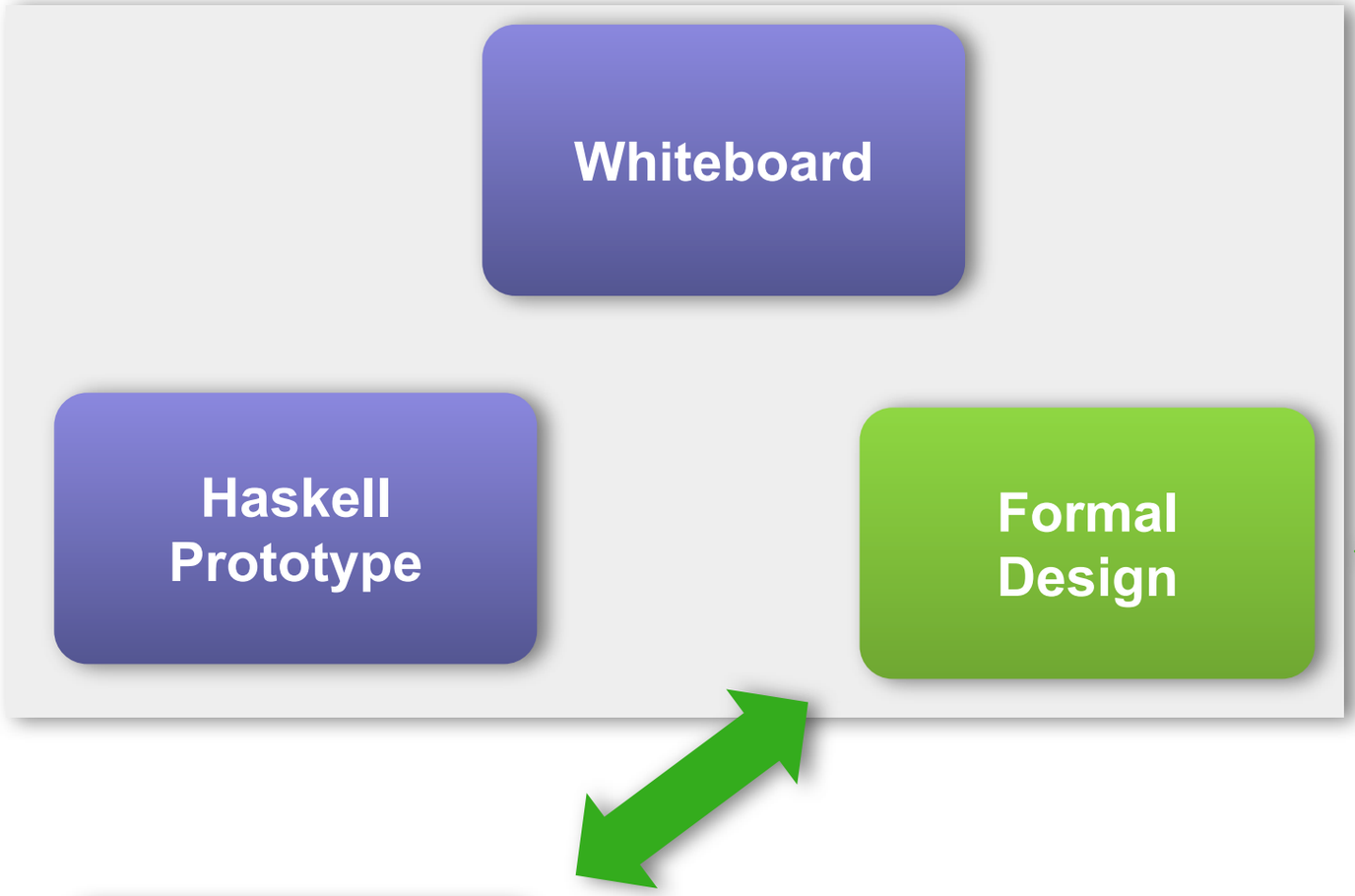

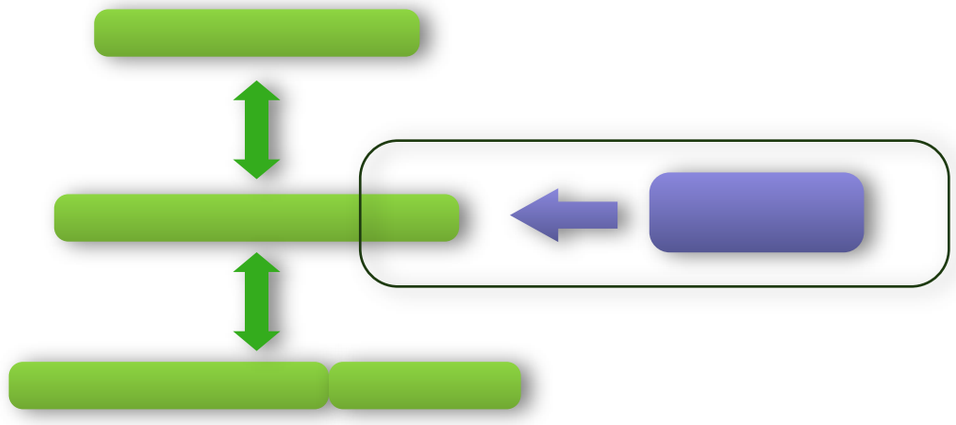

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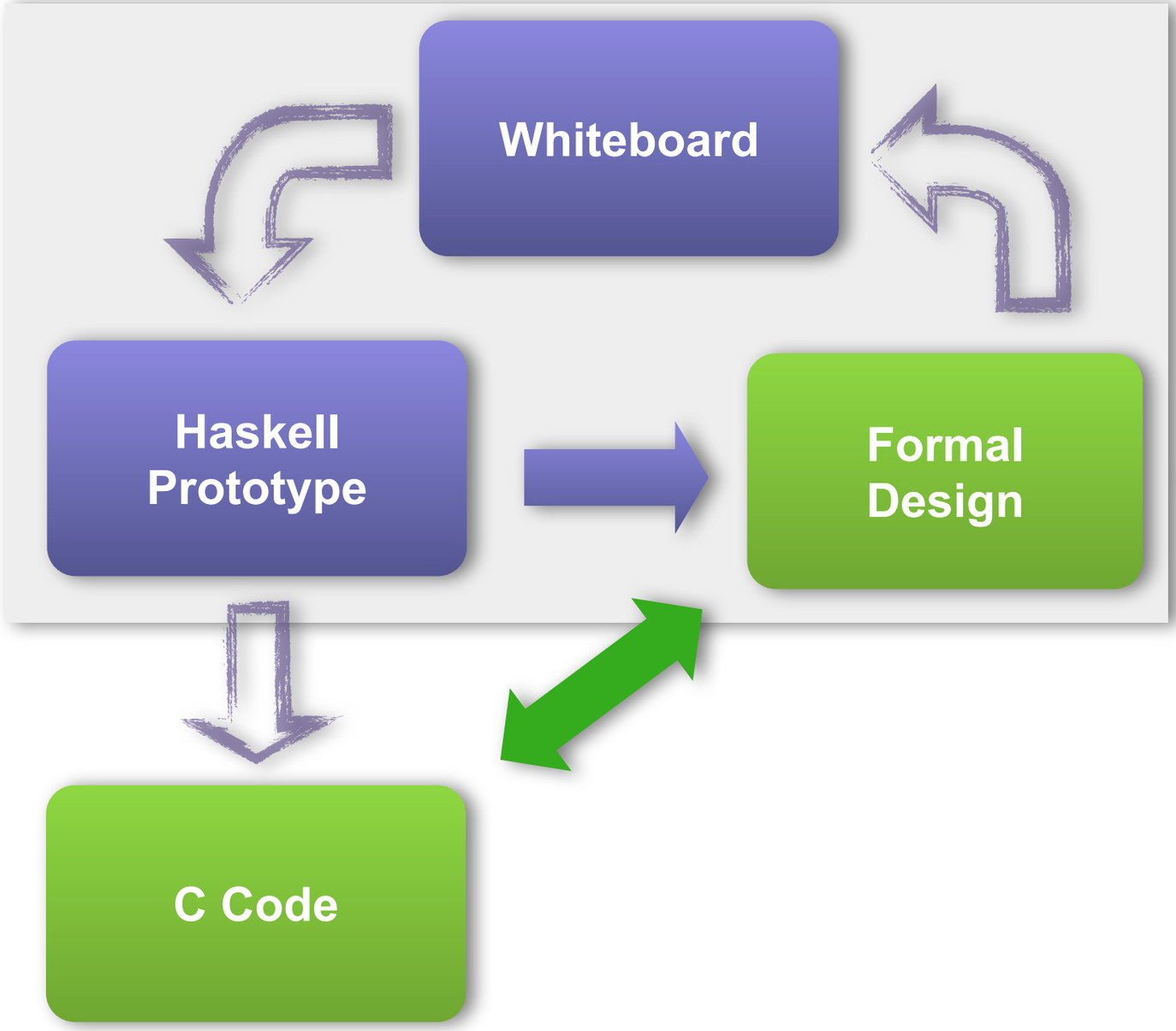

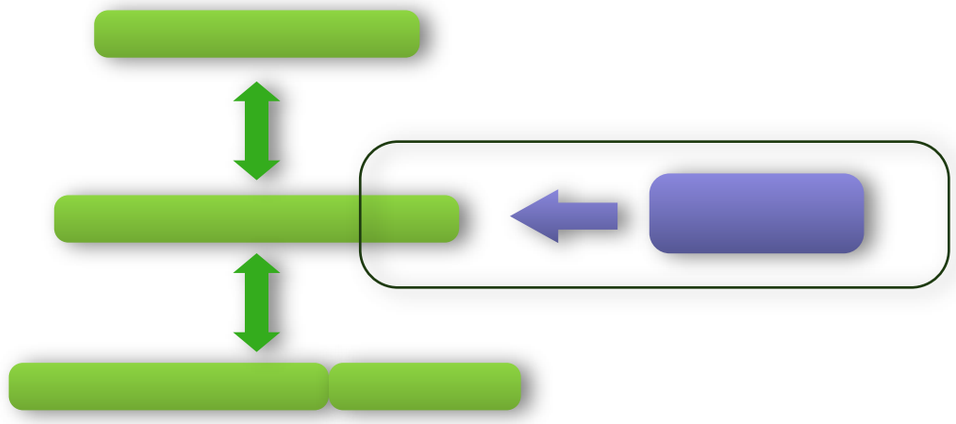

Design for Verification

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Reducing Complexity

Hardware

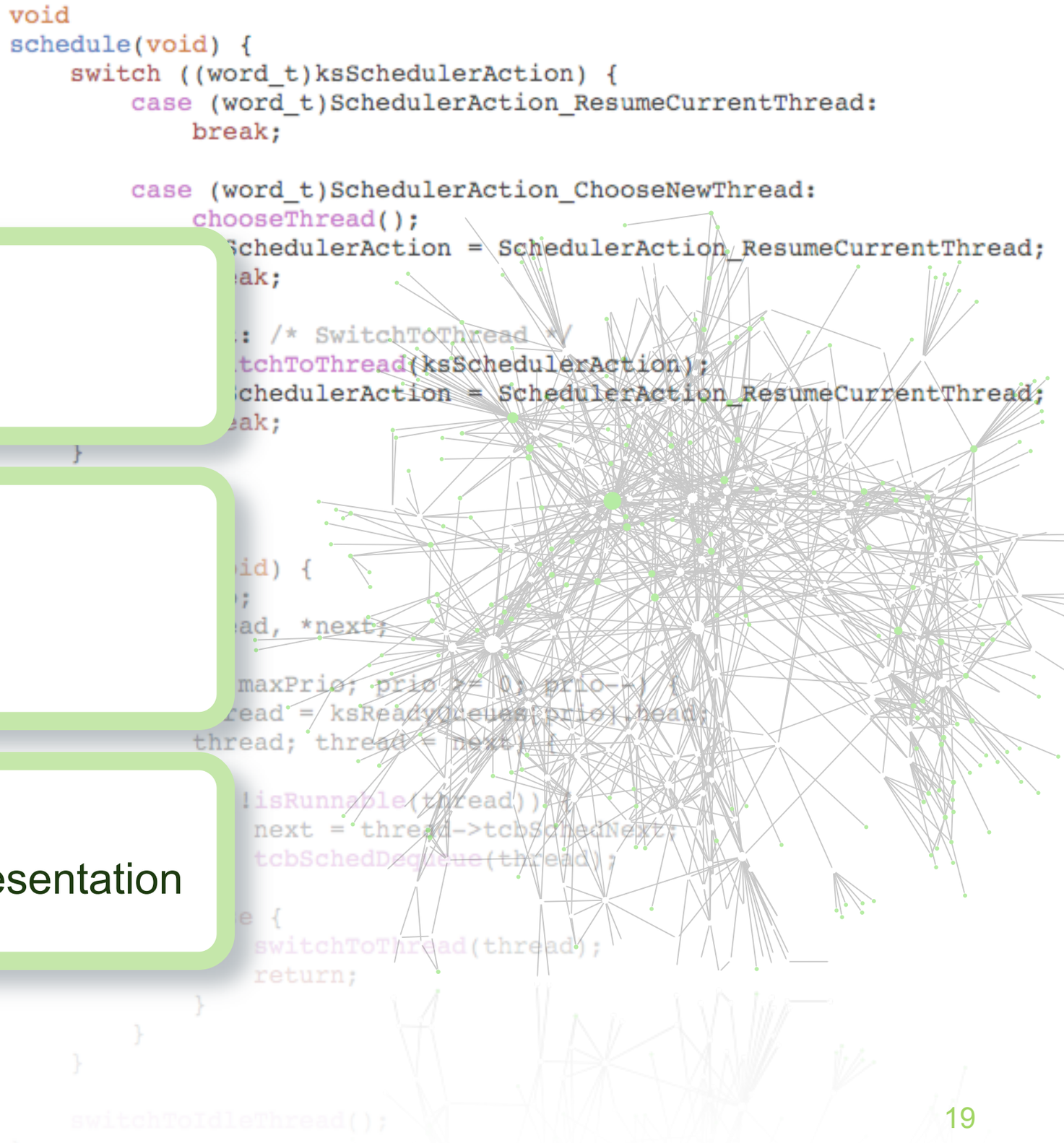
- drivers outside kernel

Concurrency

- event based kernel
- limit preemption

Code

- derive from functional representation



C subset

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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?

NICTA

Bugs found

during testing: 16

during verification:

- in C: 160
- in design: ~150
- in spec: ~150

460 bugs

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

Common Criteria EAL6:	**$87M**
L4.verified:	**$6M**

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Summary

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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 cheaper.

(It's fun, too.
And we're hiring..)

Thank You

Thank You