NICTA

L4.verified: An Overview

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The L4.verified project aims to formally verify the functional correctness of the seL4 microkernel …

Gerwin Klein, Kevin Elphinstone, Gernot Heiser, June Andronick, David Cock, Philip Derrin, Dhammika Elkaduwe, Kai Engelhardt, Michael Norrish, Rafal Kolanski, Thomas Sewell, Harvey Tuch and Simon Winwood. **seL4: Formal verification of an OS Kernel.** In 22nd SOSP 2009.

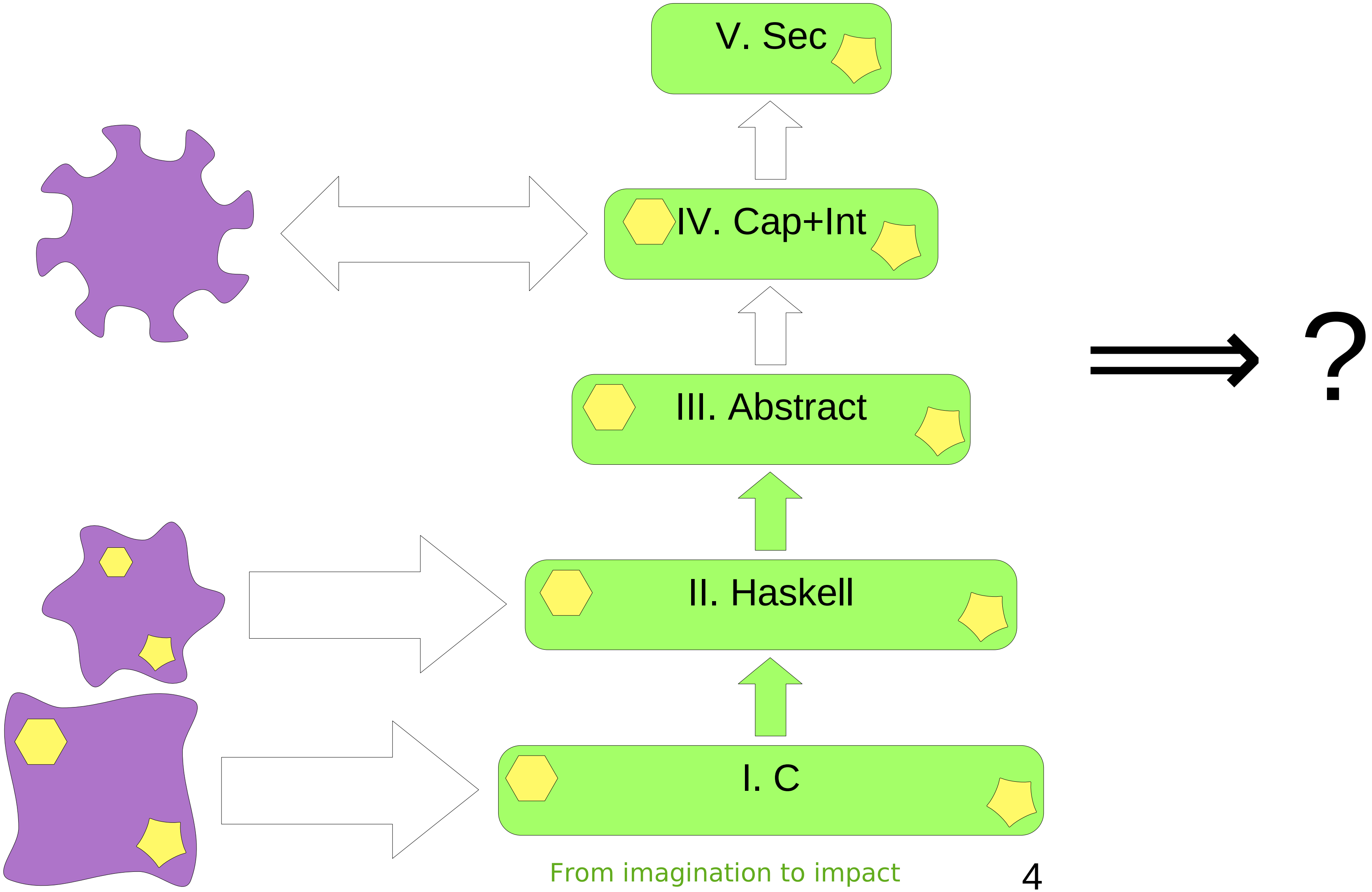
Klein et al. **seL4: Formal verification of an Operating-System Kernel.** In CACM 2010 No. 6.

seL4

NICTA

- Microkernel developed at UNSW/NICTA
- L4-style IPC
- Capability-based access control
- Capability-based control of kernel memory layout

Refinement



What do we want to show?

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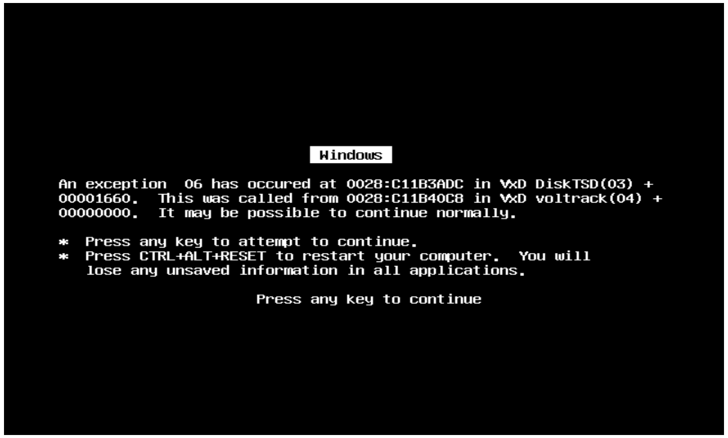
$$\Longrightarrow ?$$

- We want to develop an OS that can't crash.

- We want to address old frustrations about security & reliability.



What do we want to show?

$$\Longrightarrow ?$$

- seL4 has explicit memory management
  - Guaranteed to provide a level of service
  - Few shared global objects
  - Service is provided to capability holders

Refinement

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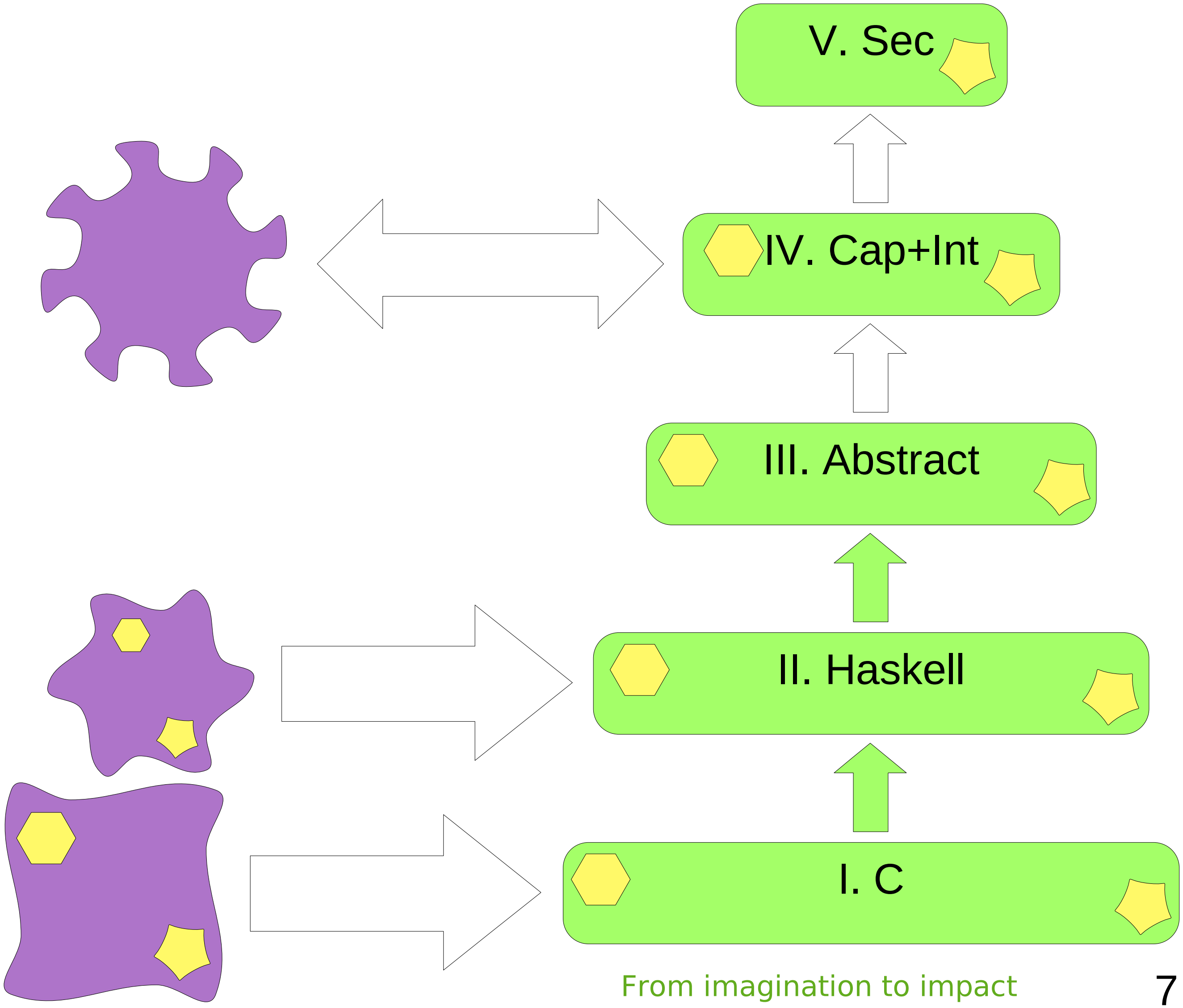
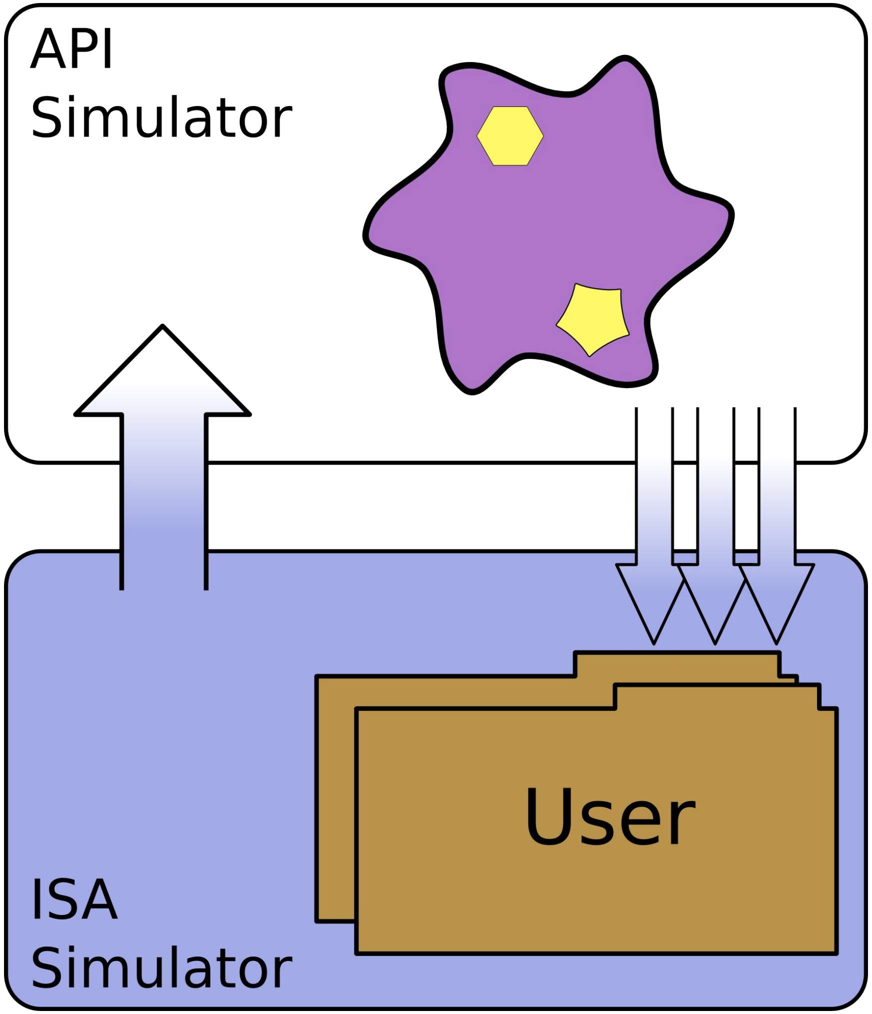
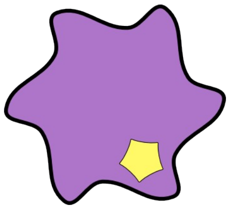


Haskell Prototype

- Predates L4.verified
- Written as a prototype
- Allowed the API to be exercised while still incomplete



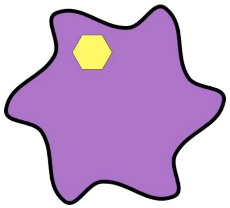
Haskell Prototype



- Written in Haskell
- Written as an implementation guide
- Simulates C with:
  - pointers
  - state
  - early return
- Has capabilities (caps)
- Full of details
  - including doubly linked lists

```
emptySlot :: PPtr CTE -> Maybe IRQ -> Kernel ()
emptySlot slot irq = do
    newCTE <- getCTE slot
    let mdbNode = cteMDBNode newCTE
    let prev = mdbPrev mdbNode
    let next = mdbNext mdbNode

    case (cteCap newCTE) of
        NullCap   -> return ()
        _         -> do
            updateMDB prev (\mdb -> mdb { mdbNext = next })
            updateMDB next (\mdb -> mdb {
                    mdbPrev = prev,
                    mdbFirstBadged = mdbFirstBadged mdb
                      || mdbFirstBadged mdbNode })
            updateCap slot NullCap
            updateMDB slot (const nullMDBNode)

            case irq of
                Just irq  -> deletedIRQHandler irq
                Nothing   -> return ()
```

Haskell Prototype



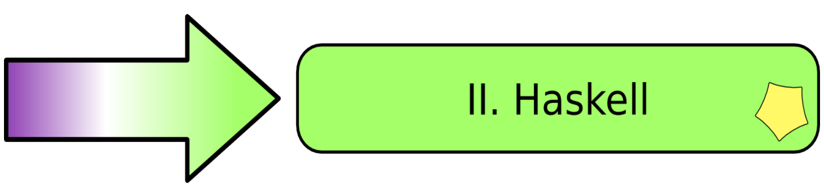
- Haskell lists and list operations are used for thread queues
  - Size at any address is not bounded
- Explicit recursion is usually avoided

```
chooseThread :: Kernel ()
chooseThread = do
        r <- findM chooseThread' (reverse [minBound ..
maxBound])
        when (r == Nothing) $ switchToIdleThread
    where
        chooseThread'' :: PPtr TCB -> Kernel Bool
        chooseThread'' thread = do
            runnable <- isRunnable thread
            if not runnable
                then do
                    tcbSchedDequeue thread
                    return False
                else do
                    switchToThread thread
                    return True
        chooseThread' :: Priority -> Kernel Bool
        chooseThread' prio = do
            q <- getQueue prio
            liftM isJust $ findM chooseThread'' q
```

Haskell Specification

- Isabelle translation of Haskell specification
  - Similar to the Haskabelle approach
  - Not a faithful representation of the semantics of Haskell.

```
defs emptySlot_def:
"emptySlot slot irq≡ (do
   newCTE ← getCTE slot;
   mdbNode ← return ( cteMDBNode newCTE);
   prev ← return ( mdbPrev mdbNode);
   next ← return ( mdbNext mdbNode);
   (case (cteCap newCTE) of
        NullCap ⇒   return ()
      | _ ⇒   (do
          updateMDB prev (λ mdb. mdb (| mdbNext := next |) );
          updateMDB next (λ mdb. mdb (|
                mdbPrev := prev,
                mdbFirstBadged :=
                   mdbFirstBadged mdb ∨ mdbFirstBadged mdbNode |) );
          updateCap slot NullCap;
          updateMDB slot (const nullMDBNode);
          (case irq of
               Some irq ⇒   deletedIRQHandler irq
             | None ⇒   return ()
             )
      od)
   )
od)"
```

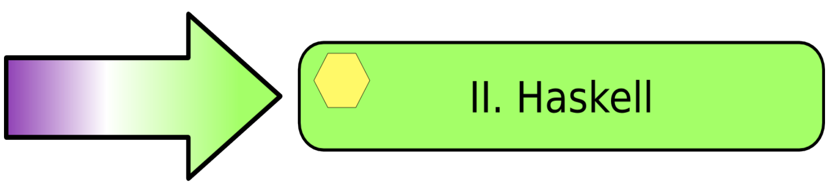


Haskell Specification

NICTA

- Isabelle translation of Haskell specification
  - Similar to the Haskabelle approach
  - Not a faithful representation of the semantics of Haskell.

```
defs chooseThread_def:
"chooseThread ≡
  let
    chooseThread'' = (λ  thread. (do
      runnable ← isRunnable thread;
      if Not runnable
        then (do
          tcbSchedDequeue thread;
          return False
        od)
        else (do
          switchToThread thread;
          return True
        od)
    od));
    chooseThread' = (λ  prio. (do
      q ← getQueue prio;
      liftM isJust $ findM chooseThread'' q
    od))
  in
            (do
    r ← findM chooseThread' (reverse [minBound  .e.  maxBound]);
    when (r = Nothing) $ switchToIdleThread
            od)"
```

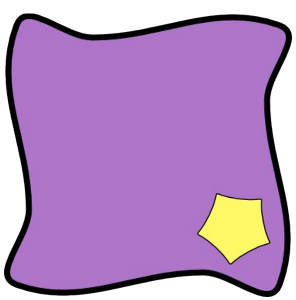


C Implementation

NICTA

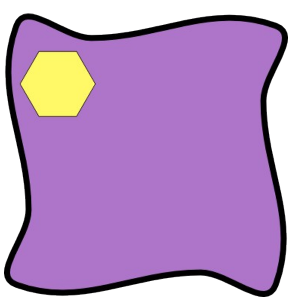
- Implementation of seL4 in C
- Written with the Haskell prototype as an implementation guide.
- Uses custom bitfield implementation rather than unions

```
static void
emptySlot(cte_t *slot, irq_t irq) {
    if(cap_get_capType(slot->cap) != cap_null_cap) {
        mdb_node_t mdbNode;
        cte_t *prev, *next;

        mdbNode = slot->cteMDBNode;
        prev = CTE_PTR(mdb_node_get_mdbPrev(mdbNode));
        next = CTE_PTR(mdb_node_get_mdbNext(mdbNode));

        if(prev)
            mdb_node_ptr_set_mdbNext(&prev->cteMDBNode,
                CTE_REF(next));
        if(next)
            mdb_node_ptr_set_mdbPrev(&next->cteMDBNode,
                CTE_REF(prev));
        if(next)
            mdb_node_ptr_set_mdbFirstBadged(&next->cteMDBNode,
                    mdb_node_get_mdbFirstBadged(next->cteMDBNode) ||
                    mdb_node_get_mdbFirstBadged(mdbNode));
        slot->cap = cap_null_cap_new();
        slot->cteMDBNode = nullMDBNode;

        if(irq != irqInvalid) deletedIRQHandler(irq);
    }
}
```



C Implementation

- Implementation of seL4 in C
- Written with the Haskell prototype as an implementation guide.
- Frequently more compact than the Haskell code.



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

    for(prio = maxPrio; prio >= 0; prio--) {
        for(thread = ksReadyQueues[prio].head;
            thread; thread = next) {

            if(!isRunnable(thread)) {
                next = thread->tcbSchedNext;
                tcbSchedDequeue(thread);
            }
            else {
                switchToThread(thread);
                return;
            }
        }
    }

    switchToIdleThread();
}
```

Haskell vs C

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- Haskell was written as a prototype and implementation guide by OS team
- Aimed to capture C behaviour
- Abstracted some details:
  - datatypes not tagged unions
  - lambdas not field updates
  - list operations not loops
- Ideal formal abstraction of C code

```
newCTE <- getCTE slot
let mdbNode = cteMDBNode newCTE
let prev = mdbPrev mdbNode
let next = mdbNext mdbNode

updateMDB prev (\mdb -> mdb { mdbNext = next })
```

```
mdbNode = slot->cteMDBNode;
prev = CTE_PTR(mdb_node_get_mdbPrev(mdbNode));
next = CTE_PTR(mdb_node_get_mdbNext(mdbNode));

if(prev)
    mdb_node_ptr_set_mdbNext(&prev->cteMDBNode,
        CTE_REF(next));
```

C Specification

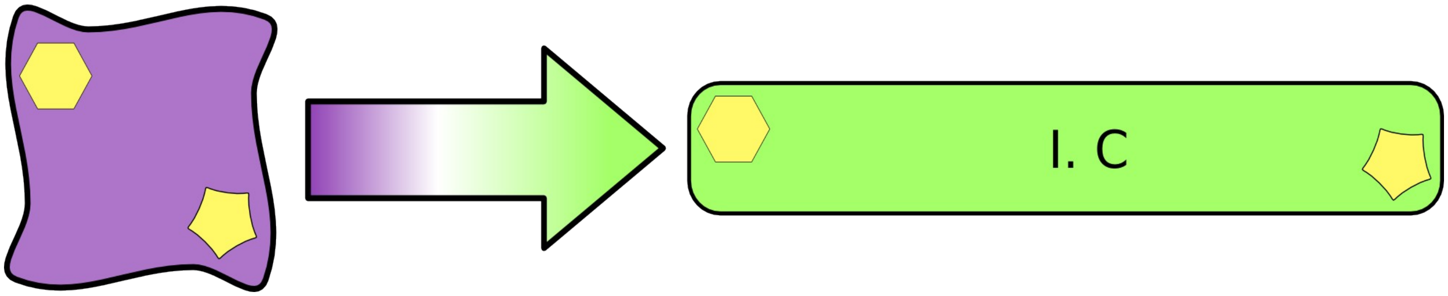
- Import of C code into Isabelle/HOL
- Parser is written in ML by Michael Norrish.
- Uses Norbert Schirmer's SimpL language framework.
- Uses Harvey Tuch's C memory semantics

```
theory Kernel_C imports ARMMachineTypes CTranslation

begin

install_C_file packed "c/kernel_all.c_pp"
  [machinety=machine_state]

end
```



C Specification

- Import of C code into Isabelle/HOL
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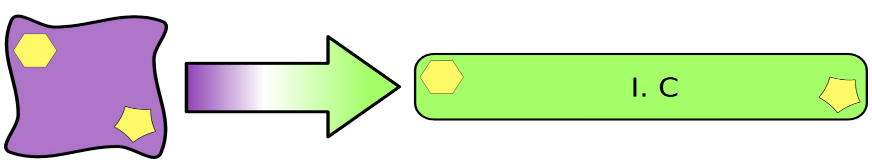
- Conservative
- Detailed




```
emptySlot_body ==
TRY
  Guard C_Guard {|c_guard (Ptr &(´slot→["cap_C"]))|}
   (´ret__unsigned_long :== CALL cap_get_capType_'proc(h_val
                          (hrs_mem ´t_hrs)
                          (Ptr &(´slot→["cap_C"]))));;
  IF ´ret__unsigned_long ~= cap_null_cap THEN
    ´mdbNode :== arbitrary;;
    ´prev :== arbitrary;;
    ´next__ptr_to_struct_cte_C :== arbitrary;;
    Guard C_Guard
     {|c_guard (Ptr &(´slot→["cteMDBNode_C"]))|}
     (´mdbNode :==
        h_val (hrs_mem ´t_hrs)
         (Ptr &(´slot→["cteMDBNode_C"])));;
    ´ret__unsigned_long :== CALL mdb_node_get_mdbPrev_'proc(´mdbNode);;
    ´prev :== Ptr (ucast ´ret__unsigned_long);;
    ´ret__unsigned_long :== CALL mdb_node_get_mdbNext_'proc(´mdbNode);;
    ´next__ptr_to_struct_cte_C :==
      Ptr (ucast ´ret__unsigned_long);;
    IF ´prev ~= NULL THEN
      Guard C_Guard
       {|c_guard (Ptr &(´prev→["cteMDBNode_C"]))|}
       (CALL mdb_node_ptr_set_mdbNext_'proc(Ptr
       &(´prev→["cteMDBNode_C"]),
         ucast (ptr_val ´next__ptr_to_struct_cte_C)))
    FI;;

   ...
```

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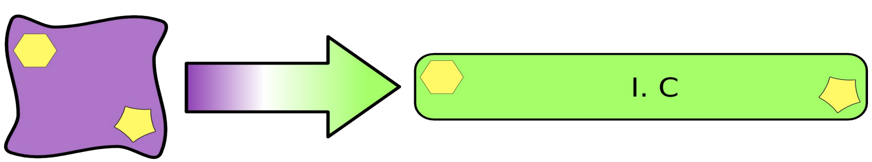


```
IF ´next__ptr_to_struct_cte_C ~= NULL THEN
  Guard C_Guard
   {|c_guard
      (Ptr &(´next__ptr_to_struct_cte_C→["cteMDBNode_C"]))|}
   (CALL mdb_node_ptr_set_mdbPrev_'proc(Ptr
   &(´next__ptr_to_struct_cte_C→["cteMDBNode_C"]),
    ucast (ptr_val ´prev)))
FI;;
IF ´next__ptr_to_struct_cte_C ~= NULL THEN
  Guard C_Guard
   {|c_guard
      (Ptr &(´next__ptr_to_struct_cte_C→["cteMDBNode_C"]))|}
   (´ret__unsigned_long :== CALL mdb_node_get_mdbFirstBadged_'proc(h_val
(hrs_mem ´t_hrs)
(Ptr &(´next__ptr_to_struct_cte_C→["cteMDBNode_C"]))));;
 ´ret__int :==
    (if ´ret__unsigned_long ~= 0 then 1 else 0);;
  IF ´ret__int ~= 0 THEN
    SKIP
  ELSE
    ´ret__unsigned_long :== CALL mdb_node_get_mdbFirstBadged_'proc(´mdbNode);;
    ´ret__int :==
      (if ´ret__unsigned_long ~= 0 then 1 else 0)
  FI;;
  Guard C_Guard
   {|c_guard
      (Ptr &(´next__ptr_to_struct_cte_C→["cteMDBNode_C"]))|}
   (CALL mdb_node_ptr_set_mdbFirstBadged_'proc(Ptr
        &(´next__ptr_to_struct_cte_C→["cteMDBNode_C"]),
    ucast ´ret__int))
FI;;
´ret__struct_cap_C :== CALL cap_null_cap_new_'proc();;
Guard C_Guard
 {|c_guard (Ptr &(´slot→["cap_C"]))|}
 (´globals :==
    t_hrs_'_update
     (hrs_mem_update
       (heap_update (Ptr &(´slot→["cap_C"]))
         ´ret__struct_cap_C)));;
´ret__struct_mdb_node_C :== CALL mdb_node_new_'proc(ucast 0,
ucast false,ucast false,ucast 0);;
Guard C_Guard
 {|c_guard (Ptr &(´slot→["cteMDBNode_C"]))|}
 (´globals :==
    t_hrs_'_update
     (hrs_mem_update
       (heap_update
         (Ptr &(´slot→["cteMDBNode_C"]))
         ´ret__struct_mdb_node_C)));;
IF ucast ´irq ~= irqInvalid THEN
  CALL deletedIRQHandler_'proc(´irq)
FI
FI
CATCH SKIP
END
```

C Specification

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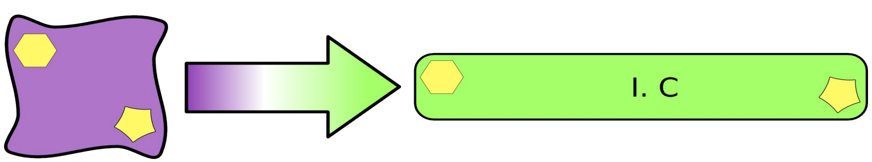


```
chooseThread_body ==
TRY
 ´prio :== arbitrary;;
 ´thread :== arbitrary;;
 ´next :== arbitrary;;
 ´prio :== scast maxPrio;;
 WHILE 0 <=s ´prio INV {|arbitrary|} VAR arbitrary DO
  ´thread :==
   head_C (index ´ksReadyQueues (unat ´prio));;
  WHILE ´thread ~= NULL INV {|arbitrary|} VAR arbitrary DO
   ´ret__enum__bool :== CALL isRunnable_'proc(´thread);;
   IF ~ ´ret__enum__bool ~= 0 THEN
    Guard C_Guard
     {|c_guard
        (Ptr &(´thread→["tcbSchedNext_C"]))|}
     (´next :==
        h_val (hrs_mem ´t_hrs)
         (Ptr &(´thread→["tcbSchedNext_C"])));;
    CALL tcbSchedDequeue_'proc(´thread)
   ELSE
    CALL switchToThread_'proc(´thread);;
    creturn_void global_exn_var_'_update
   FI;;
   ´thread :== ´next
  OD;;
  ´prio :== ´prio - 1
 OD;;
 CALL switchToIdleThread_'proc()
CATCH SKIP
END
```

HOL Specification

NICTA

- Written directly in Isabelle/HOL
- Not executable
- Captures the intent of computations declaratively
- Abstracts data structures
  - doubly linked MDB replaced with CDT map
- Also monadic
- Also has details
  - semantic details

```
definition
  empty_slot :: "cslot_ptr ⇒ irq option ⇒ unit s_monad"
where
 "empty_slot slot free_irq ≡ do
     cap ← get_cap slot;
     if cap = NullCap then
       return ()
     else do
       cdt ← gets cdt;
       parent ← return $ cdt slot;
       set_cdt ((λp. if cdt p = Some slot
                  then parent
                  else cdt p) (slot := None));
       set_revokable slot False;
       set_cap NullCap slot;

       case free_irq of Some irq ⇒ deleted_irq_handler irq
          | None ⇒ return ()
     od
  od"
```

III. Abstract

HOL Specification

NICTA

- Written directly in Isabelle/HOL
- Not executable
- Captures the intent of computations declaratively

```
"schedule = do
     cur ← gets cur_thread;
     threads ← allActiveTCBs;
     thread ← select threads;
     if thread = cur then
       return () OR switch_to_thread thread
     else switch_to_thread thread
 od OR switch_to_idle_thread"
```

- Uses nondeterminism

III. Abstract

Refinement

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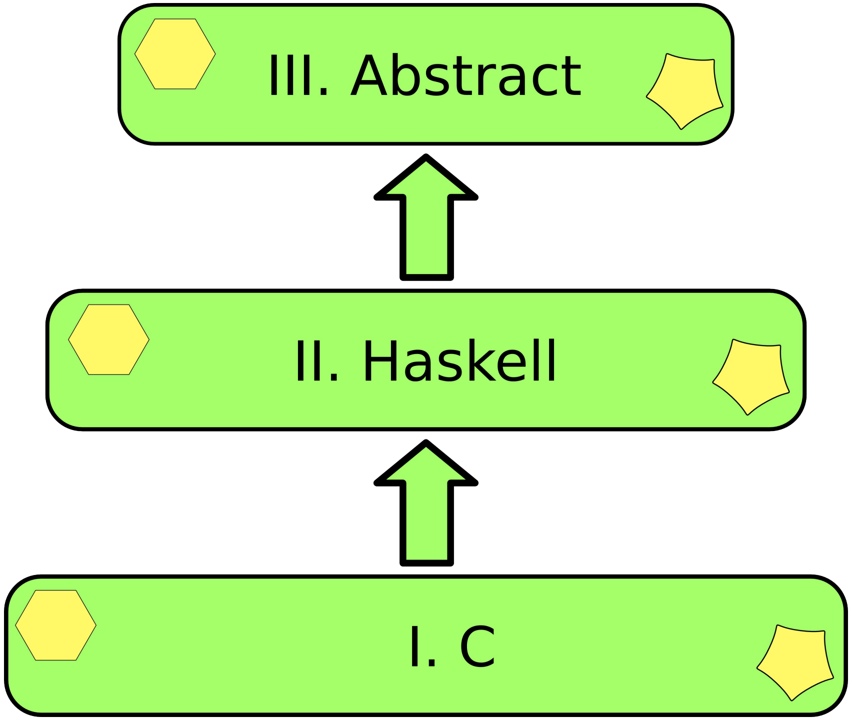
- L4.verified aims to show refinement
- Refinement equates to the subset property on behaviours
- Refinement is transitive

- We establish assertions as side conditions



Refinement: Behaviours

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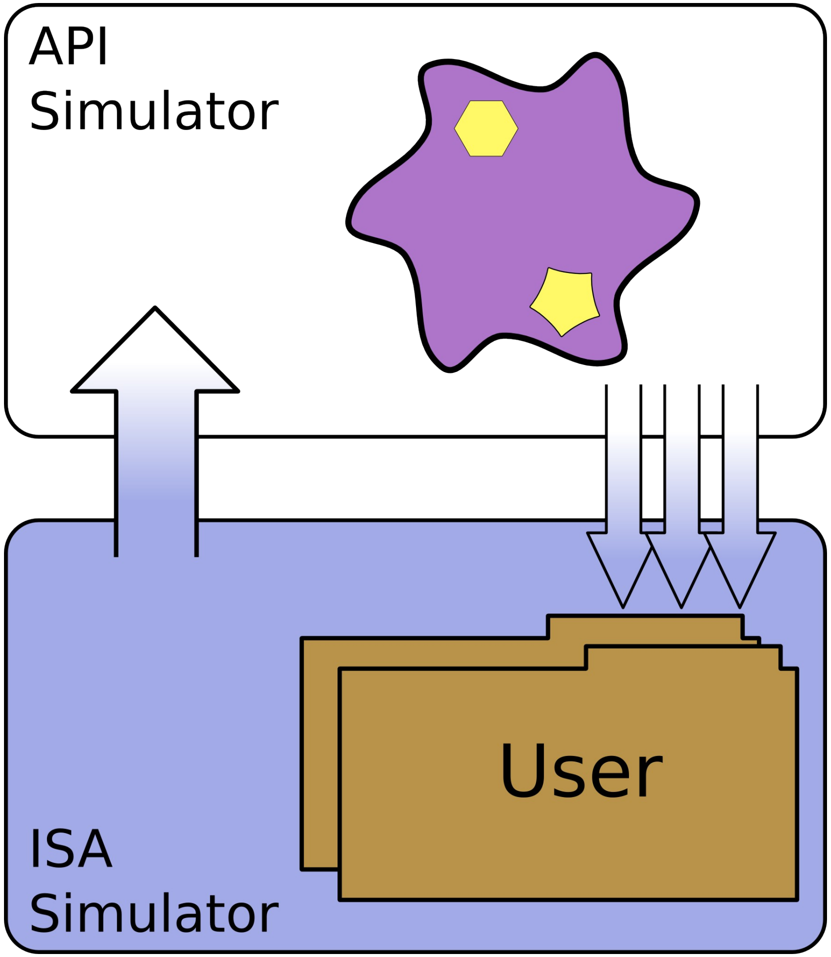
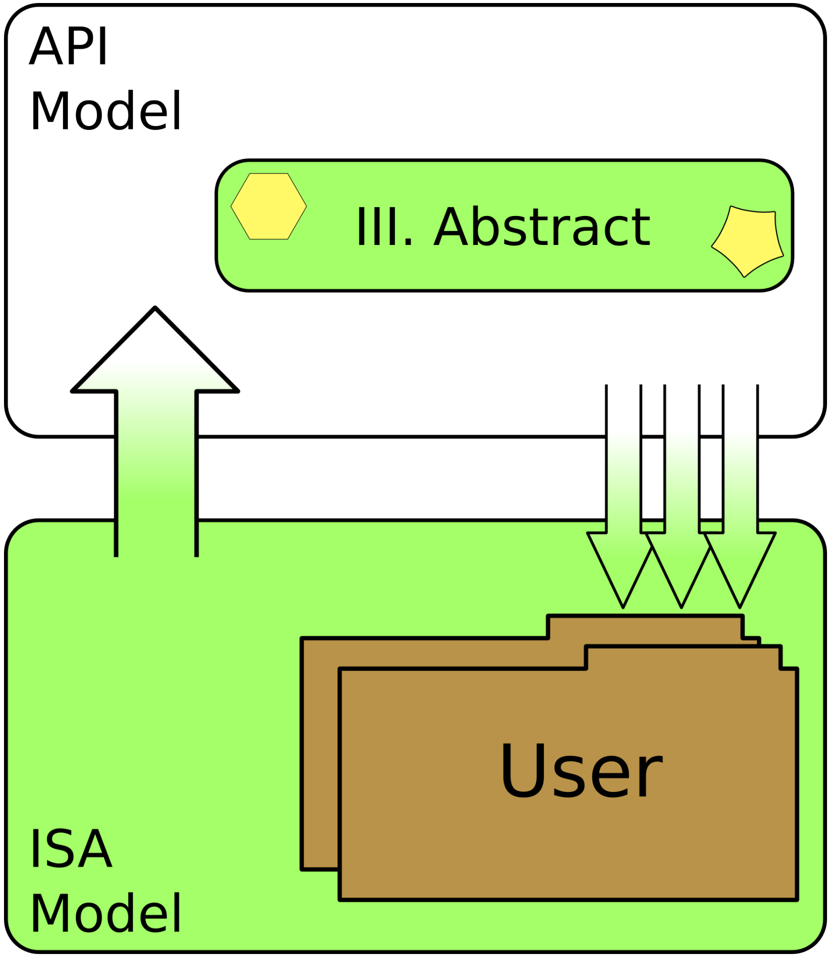
- Recall that the Haskell specification was originally designed to fit in a simulator



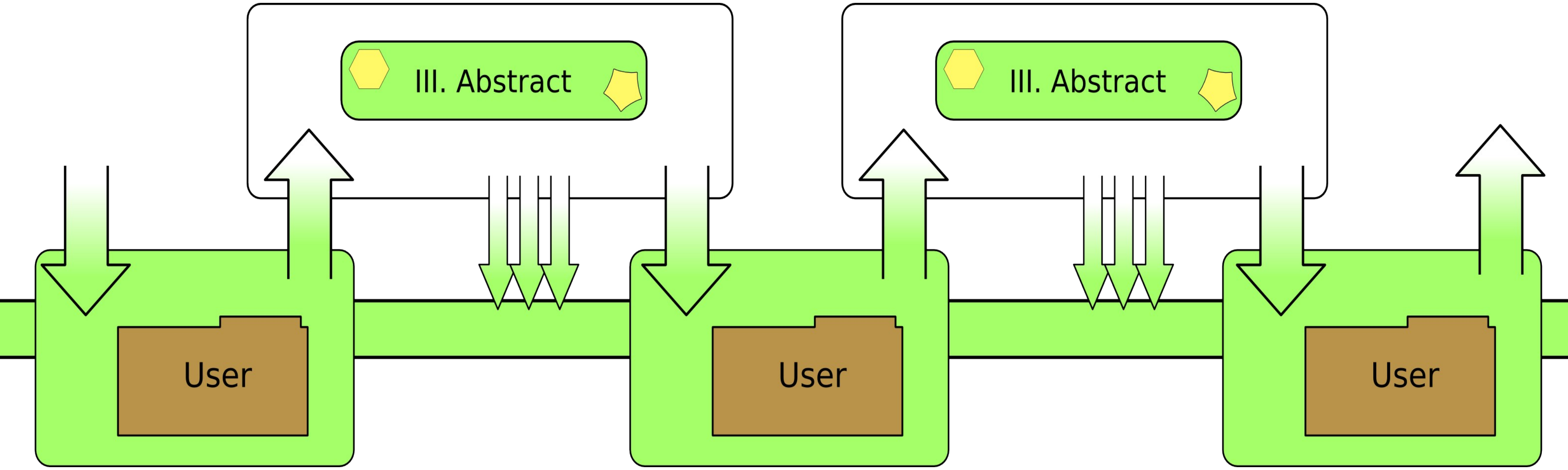
Refinement: Behaviours

- Recall that the Haskell specification was originally designed to fit in a simulator
- The formal models are conceptually used the same way.
- The simulator for user behaviour is replaced with nondeterminism



Refinement: Behaviours

- Recall that the Haskell specification was originally designed to fit in a simulator
- The formal models are conceptually used the same way.
- Behaviours of the models are traces of user and kernel interaction



Decomposition

- The specifications share common structure
  - Partly by design
  - Partly by failure of abstraction
  - Largely because of correct programming

- Verification methods should exploit this

Decomposition

NICTA

- All models have the same overall structure:
  - Figure out what the user wants/needs
  - Check if that is permitted
  - Perform an action or send an error message
  - Decide which user will run next
- Sequential decomposition of steps
- Case decomposition by action types

Decomposition Example

NICTA

```
definition
  empty_slot :: "cslot_ptr ⇒ irq option ⇒ unit s_monad"
where
 "empty_slot slot free_irq ≡ do
     cap ← get_cap slot;
     if cap = NullCap then
       return ()
     else do
       cdt ← gets cdt;
       parent ← return $ cdt slot;
       set_cdt ((λp. if cdt p = Some slot
                     then parent
                     else cdt p) (slot := None));
       set_revokable slot False;
       set_cap NullCap slot;

       case free_irq of Some irq ⇒ deleted_irq_handler irq
          | None ⇒ return ()
     od
  od"
```

```
defs emptySlot_def:
"emptySlot slot irq≡ (do
    newCTE ← getCTE slot;
    mdbNode ← return ( cteMDBNode newCTE);
    prev ← return ( mdbPrev mdbNode);
    next ← return ( mdbNext mdbNode);
    (case (cteCap newCTE) of
          NullCap ⇒   return ()
        | _ ⇒   (do
            updateMDB prev (λ mdb. mdb (| mdbNext := next |) );
            updateMDB next (λ mdb. mdb (|
                    mdbPrev := prev,
                    mdbFirstBadged :=
                        mdbFirstBadged mdb
                         ∨ mdbFirstBadged mdbNode |) );
            updateCap slot NullCap;
            updateMDB slot (const nullMDBNode);
            (case irq of
                  Some irq ⇒   deletedIRQHandler irq
                | None ⇒   return ()
                )
        od)
        )
od)"
```

Decomposition Example II

NICTA

```
"schedule = do
    cur ← gets cur_thread;
    threads ← allActiveTCBs;
    thread ← select threads;
    if thread = cur then
      return () OR switch_to_thread thread
    else switch_to_thread thread
 od OR switch_to_idle_thread"
```

```
defs chooseThread_def:
"chooseThread ≡
   let
      chooseThread'' = (λ  thread. (do
         runnable ← isRunnable thread;
         if Not runnable
            then (do
               tcbSchedDequeue thread;
               return False
            od)
            else (do
               switchToThread thread;
               return True
            od)
      od));
      chooseThread' = (λ  prio. (do
         q ← getQueue prio;
         liftM isJust $ findM chooseThread'' q
      od))
   in
               (do
      r ← findM chooseThread' (reverse [minBound  .e.  maxBound]);
      when (r = Nothing) $ switchToIdleThread
               od)"
```

Decomposition Example II

NICTA

```
corres

(do
    cur ← gets cur_thread;
    threads ← allActiveTCBs;
    thread ← select threads;
    if thread = cur then
      return () OR switch_to_thread thread
    else switch_to_thread thread
 od OR switch_to_idle_thread)
```

```
let
   chooseThread'' = (λ  thread. (do
      runnable ← isRunnable thread;
      if Not runnable
         then (do
            tcbSchedDequeue thread;
            return False
         od)
         else (do
            switchToThread thread;
            return True
         od)
   od));
   chooseThread' = (λ  prio. (do
      q ← getQueue prio;
      liftM isJust $ findM chooseThread'' q
   od))
in
              (do
   r ← findM chooseThread' (reverse [minBound  .e.  maxBound]);
   when (r = Nothing) $ switchToIdleThread
              od)
```

Decomposition Example II

NICTA

$\forall$x. corres (op =)

(return False

OR (do assert (x $\in$ S); return True))

(f x)

$\Longrightarrow$ corres (op =)

(select S) (findM f xs)

Decomposition Example II

NICTA

$\forall$x. corres (op =) (P S) UNIV
  (return False
    OR (do assert (x $\in$ S); return True))
  (f x)
$\Longrightarrow$ corres (op =) (P S) UNIV
   (select S) (findM f xs)

Decomposition Example II

NICTA

corres rvr {s. S = allActiveTCBs s} UNIV

f f'

$\Longrightarrow$ corres rvr UNIV

{s. st_tcb_at active' t s $\longrightarrow$ t $\in$ S}

f f'

Refinement: Observations

- Approach uses predicates and decomposition by introduction rules
- Both powerful and fiddly
- Challenge to automate

Haskell/C Refinement

- Refinement between Haskell and C proceeds similarly
- Very similar sequential structure
- C introduces new decomposition challenges
  - Local variables
  - Early return

Evaluation

- Refinement process works.
- 200,000 lines of proof.
- Estimates of effort:
  - 15% on apparatus (C parser, memory semantics, Haskell translator)
  - 10-15% on Abstract/Haskell refinement
  - 20% on Haskell/C refinement

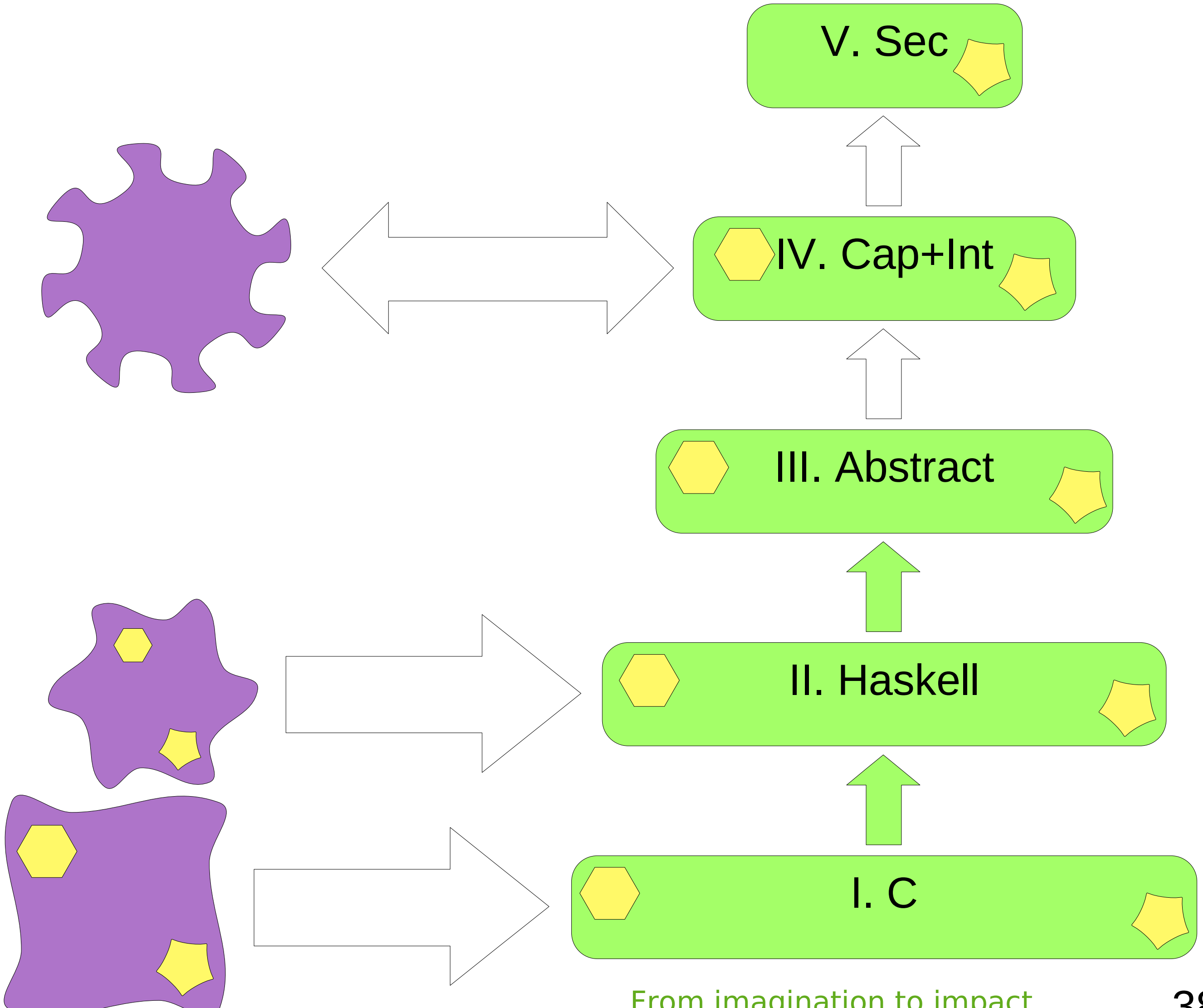
What have we shown?

$$\Longrightarrow ?$$

- The system never behaves exceptionally
- The system always behaves as you would expect
  – If you understood the specification very well

- We've met our simplistic goals.
- How about security & reliability?

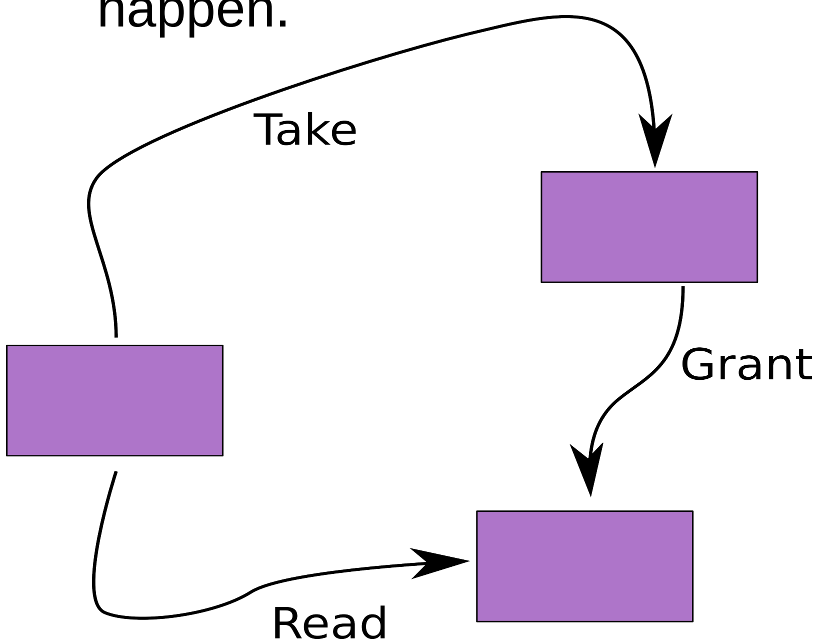
Refinement



SEC Specification

NICTA

- Abstraction of API to a graph of entities connected by capabilities
- Captures what operations are possible, not why operations happen.



V. Sec

```
definition
  removeOperation ::
  "entity_id ⇒ scap ⇒ scap ⇒
modify_sstate"
where
  "removeOperation e c c' s ≡
  if is_entity s (entity c) then
   s ((entity c) ↦ (direct_scaps s (entity c)) -
        {c'} )
  else
   s"
```

(* No notion of current thread *)

SEC Specification

- Abstraction of API to a graph of entities connected by capabilities
- Captures what operations are possible, not why operations happen.

- Connects to Take/Grant model from security literature.
- Weak model of security: no way to trust an entity.

V. Sec

```
definition
  removeOperation ::
  "entity_id ⇒ scap ⇒ scap ⇒
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where
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  else
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(* No notion of current thread *)
```
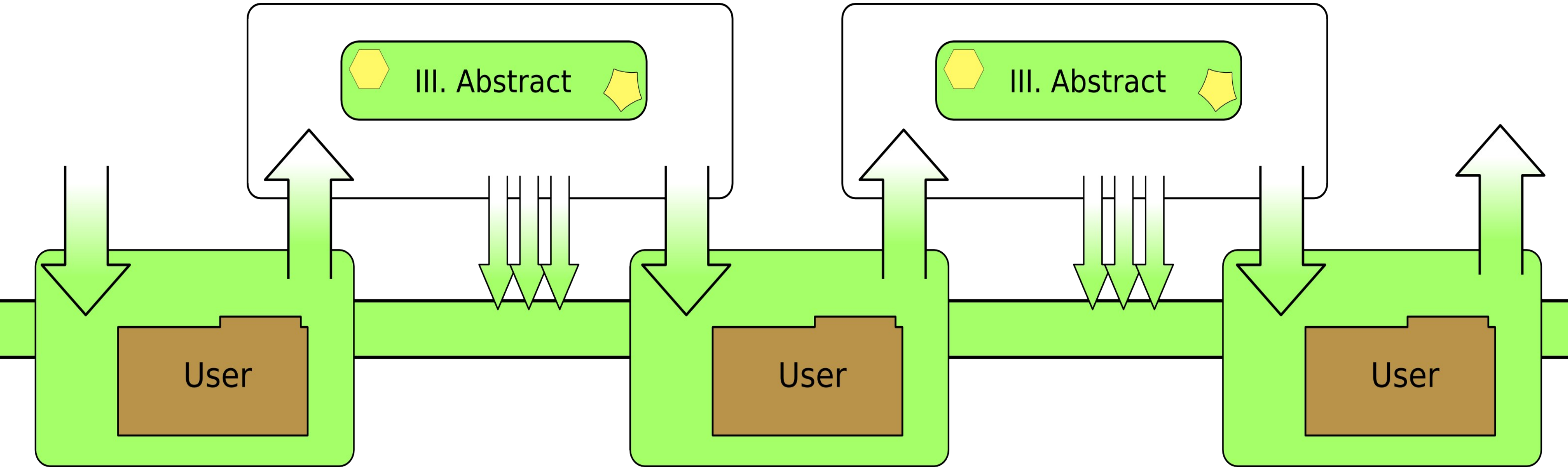

User Behaviours

NICTA

- The system is composed sequentially with user execution and in parallel with hardware operation. The current model confuses these.
- The current model confuses the actions of different user tasks.

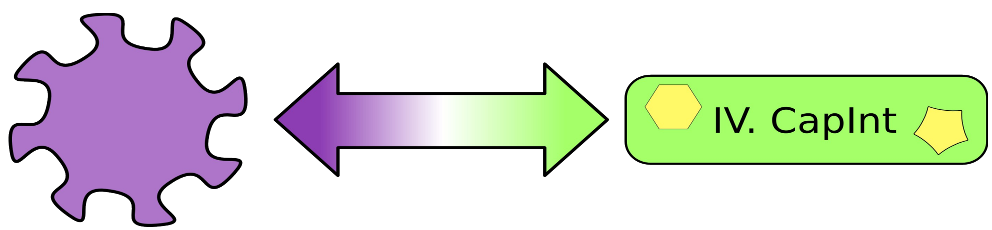


Cap+Intent Specification

- Began as a bootstrappping project
- Abstraction of API to capabilities, threads with known intentions, and other entities
- Work in progress

```
definition
  empty_slot :: "cdl_cap_ref ⇒ cdl_irq option
        ⇒ unit k_monad"
where
 "empty_slot slot free_irq ≡ TODO"

(* from definition of schedule *)
"do
     threads ← gets all_active_tcbs;
     next_thread ← option_select threads;
     return thread
 od"
```

- Together with a model change will provide a stronger execution model



Conclusion

- Verification of a microkernel is possible using straightforward approaches
- Decomposition is crucial, but there are still hard problems
- There is always more work to be done