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Ad hoc C: Reflections on Pragmatic Semantics

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Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

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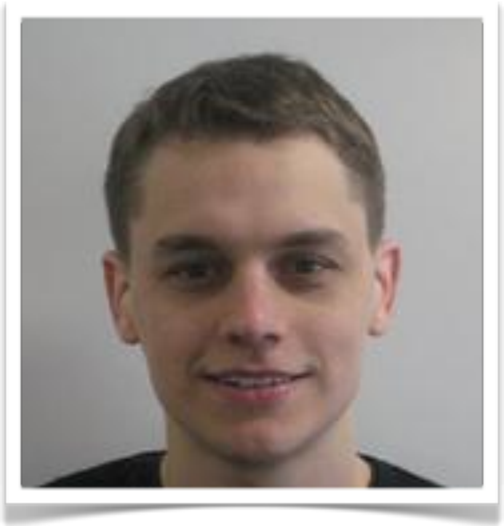
Three seL4 Stories

Basic C Technology (the "C parser")

- worryingly *ad hoc*

Binary Validation (Sewell & Myreen)

- *ad hoc,* but **dispels** worry
- PLDI 2013



Automatic Abstraction (Greenaway)

- *ad hoc* complexity/effort removal
- ITP 2012

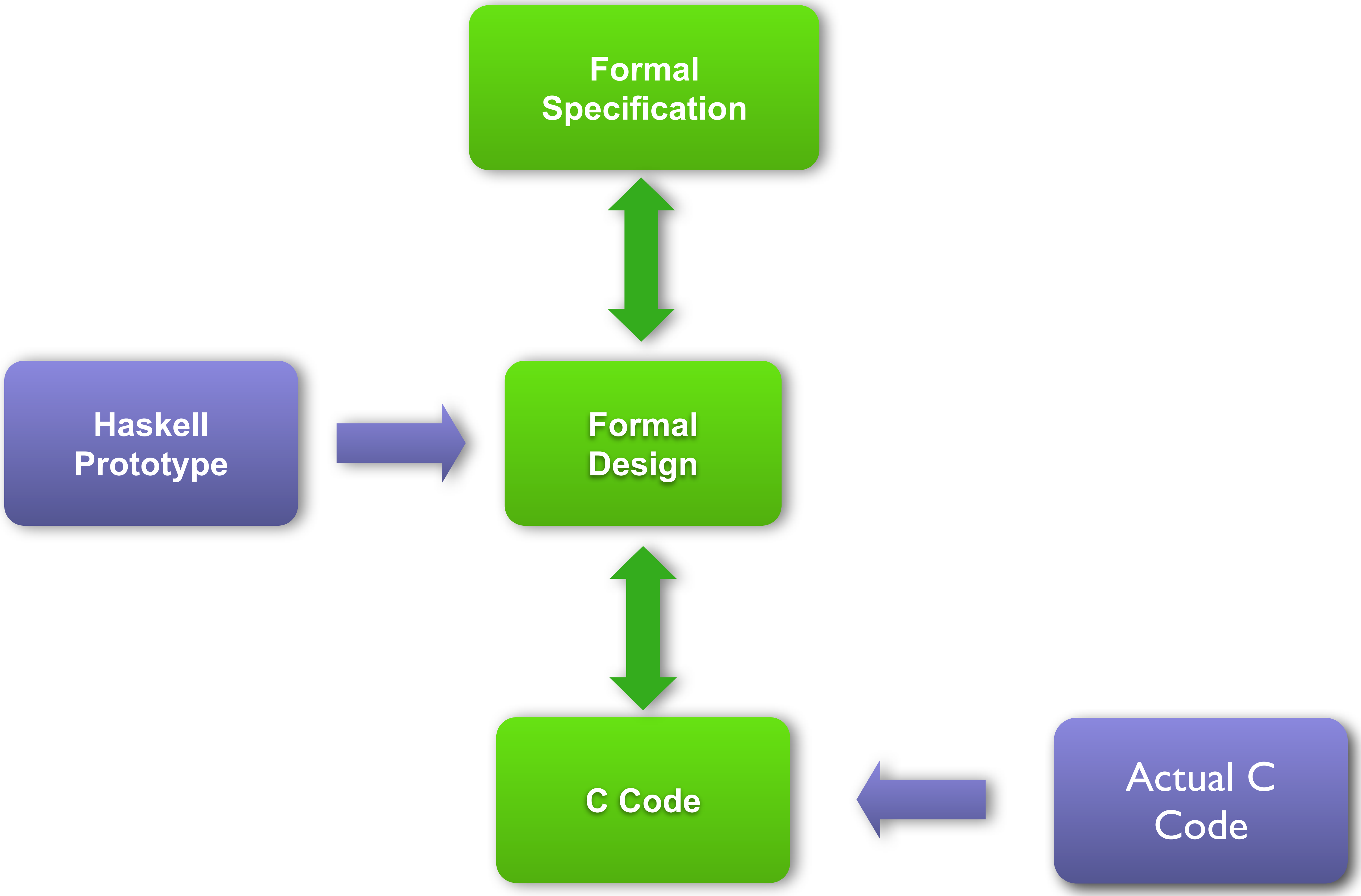
seL4, *c*2009

Fully featured operating system kernel

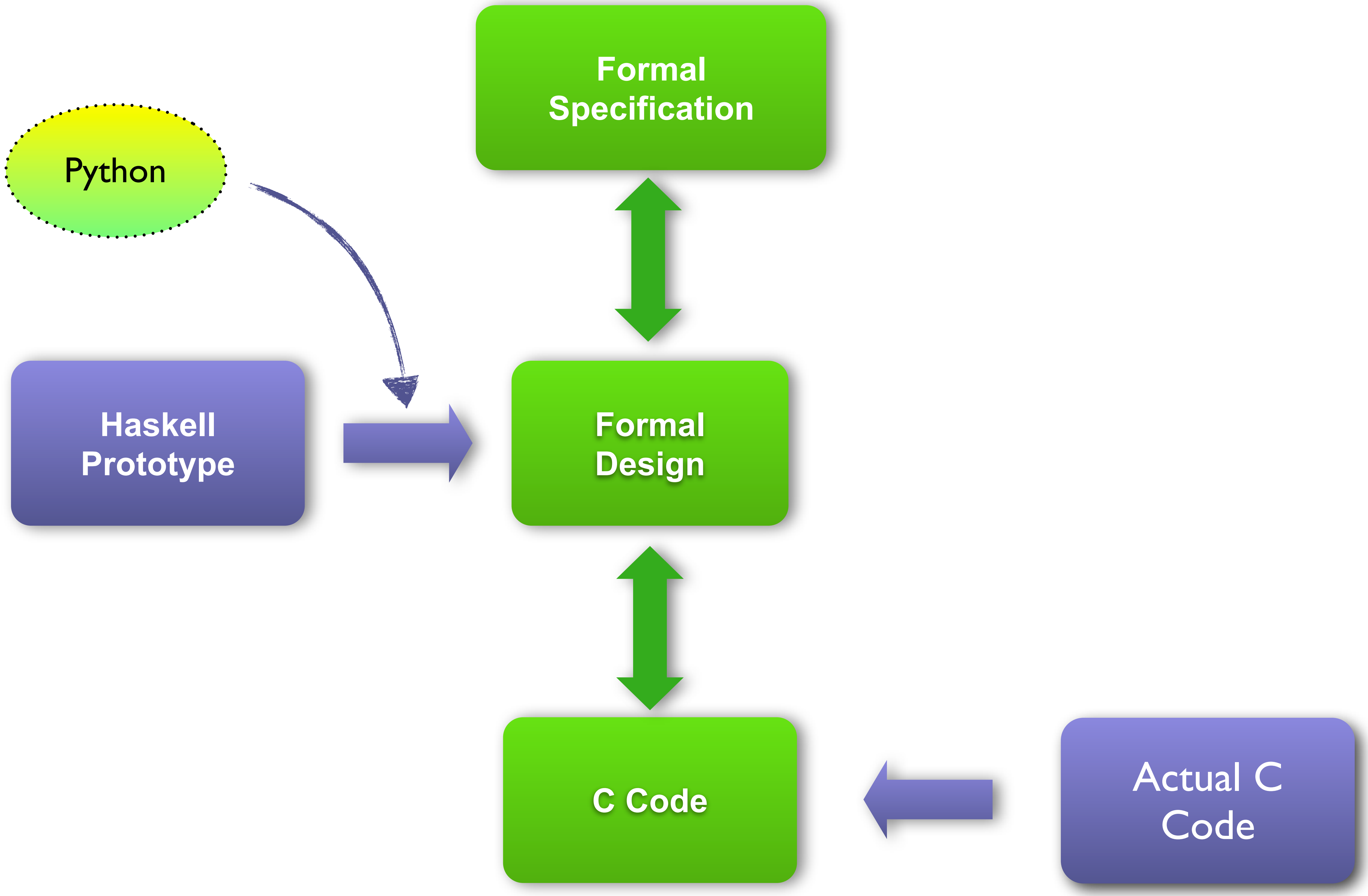
9000 lines of source code

Full functional correctness

25 person-years of effort



Formal Specification
Haskell Prototype
Formal Design
C Code
Actual C Code



Python
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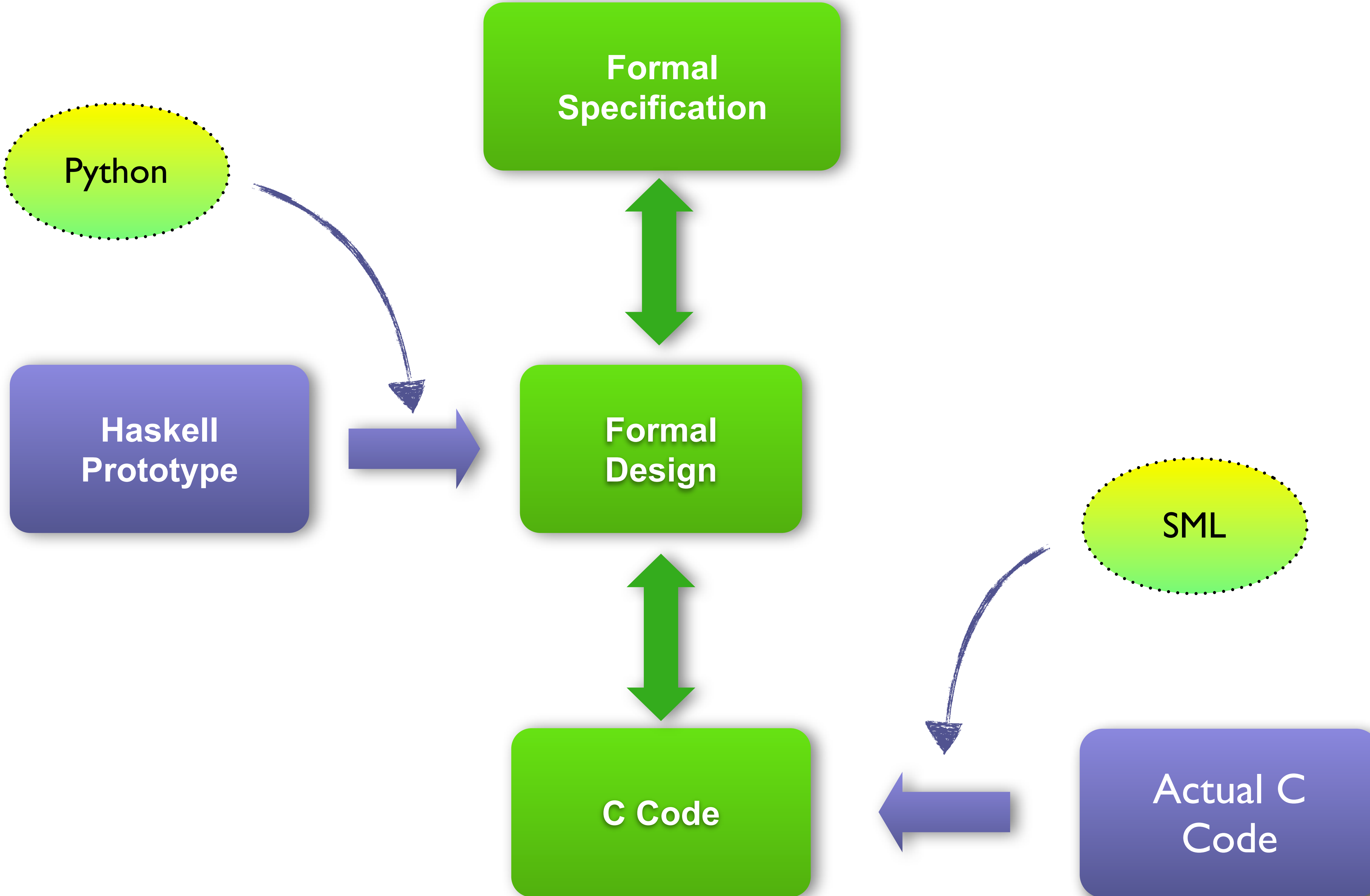
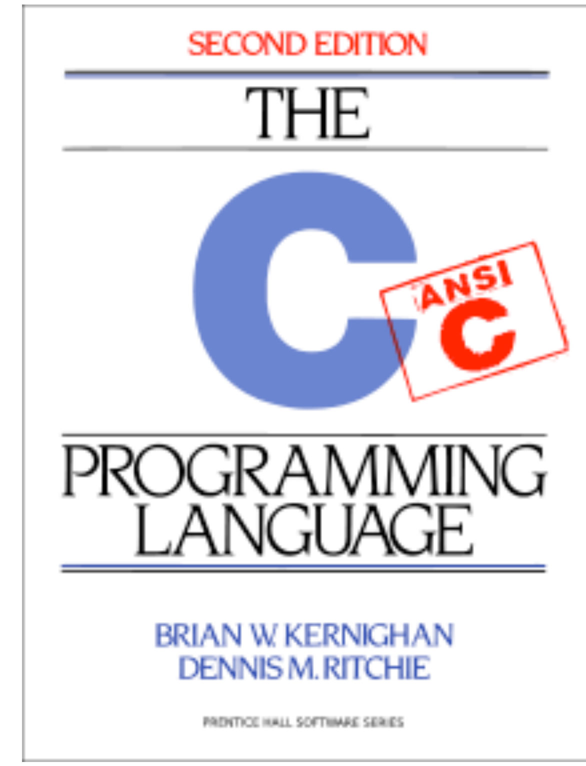

Formal Specification
Python
Haskell Prototype
Formal Design
SML
C Code
Actual C Code

C

Making C a high integrity language?

- some industrial experience, *e.g.*, MISRA C
- Better, CompCert is a **verified compiler**!
- but we can't use it



C in L4.verified

- for the OS hackers: pointer arithmetic, casts, interpreting memory as untyped bytes
- for the verifiers: restrictions on side effects
- tool-chain: very dependent on `gcc -O2` and linker

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

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

    case (word_t)SchedulerAction_ChooseNewThread:
        chooseThread();
        ksSchedulerAction = SchedulerAction_ResumeCurrentThread;
...
        thread; thread = next) {

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

    switchToIdleThread();
}
```

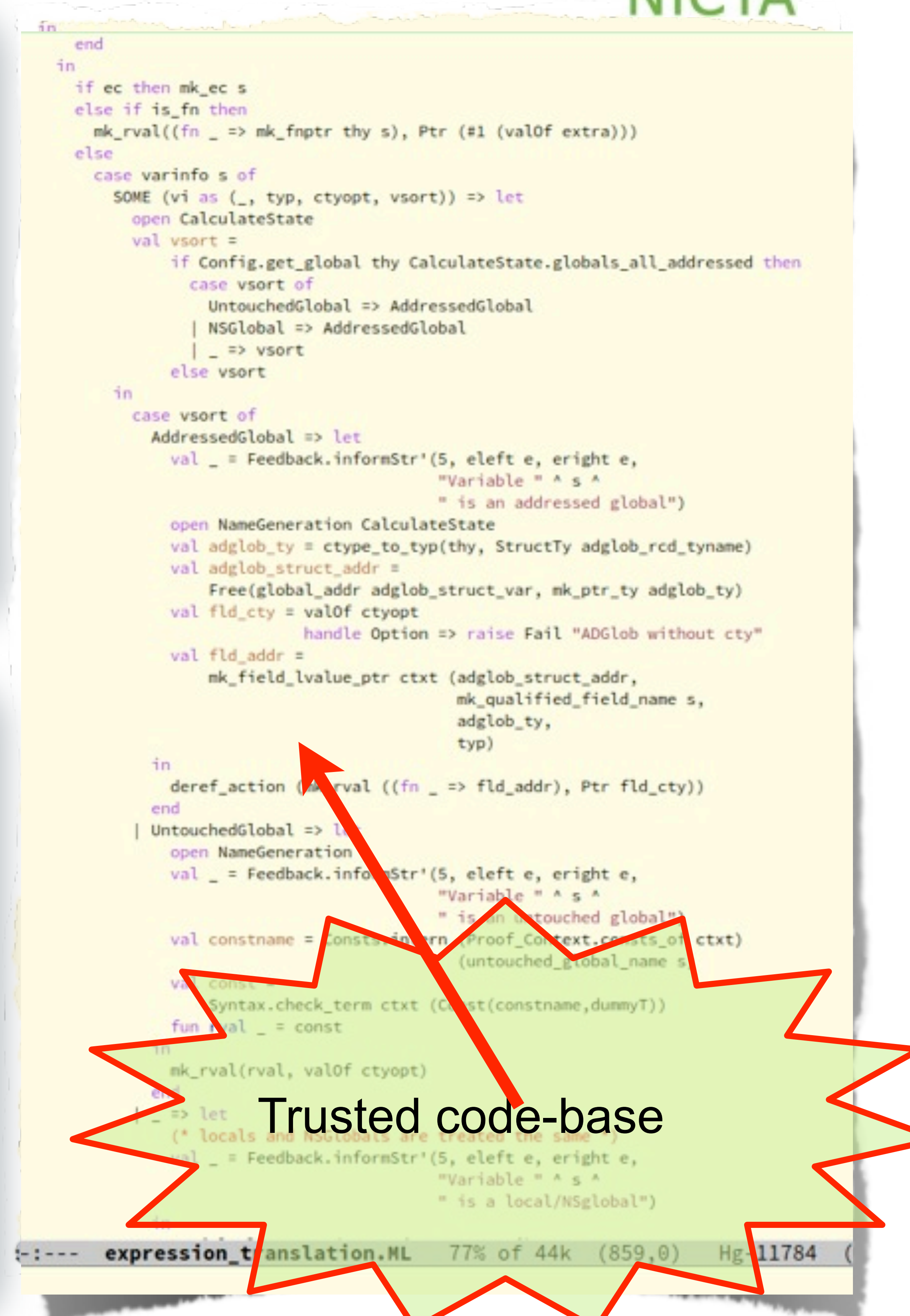
C, as defined by our tools

11000 lines of SML

- (+19kloc in parser/lexer code)
- turns C into Isabelle/HOL definitions
- Verifier uses Isabelle to prove refinement theorem

Errors

- In translator: unexpected goals
  - (Verifier says “This isn’t what I think the C means”)
- In the code: unsolvable goals



Other Bits of C Technology

SIMPL's Verification Condition Generator

- general tool that often "just works"

seL4 Refinement Tactic

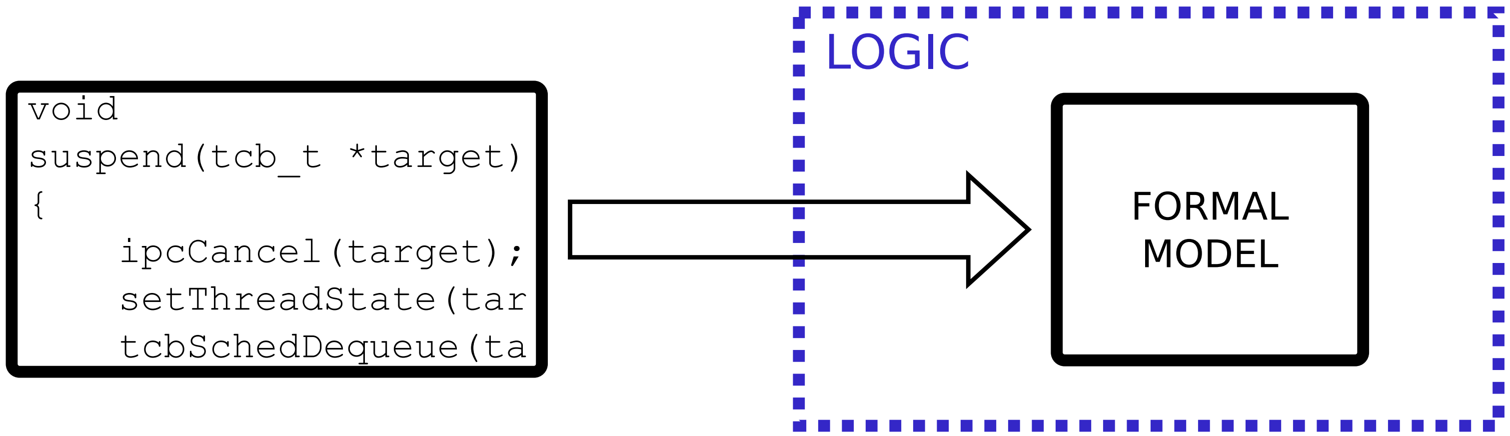
- used to verify link between C code to and (Haskell-derived) design-level spec.

Union preprocessing

- seL4 hackers didn't trust/like gcc's implementation of unions
- custom tool translates out all unions into structs and casts

[TPHOLs 2009]

Binary Validation: the Problem



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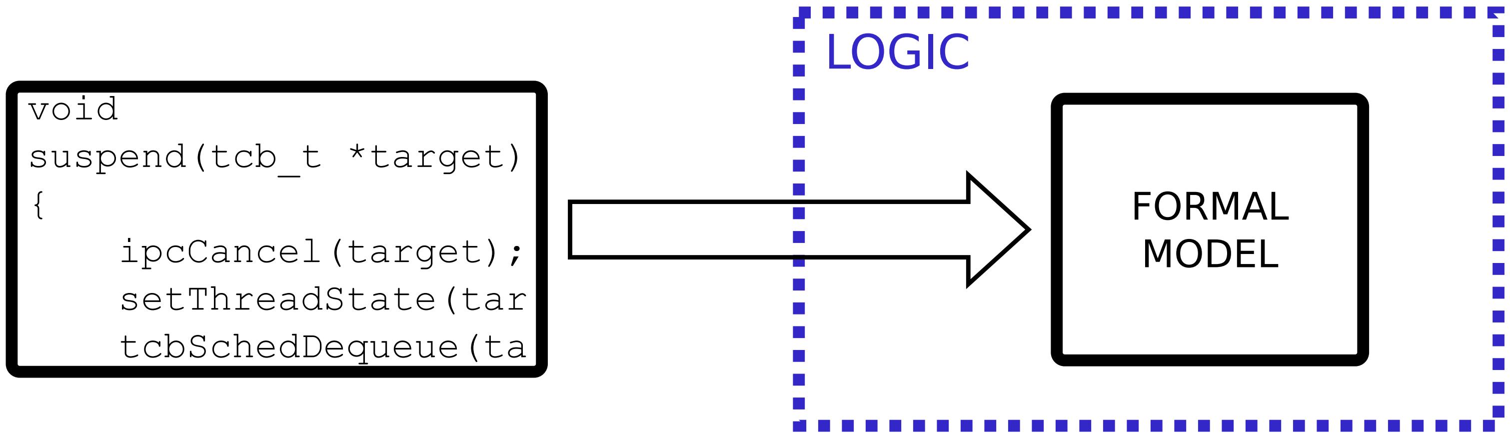

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seL4: Formal Verification and All That

Gerwin Klein, Kevin Elphinstone, Gernot Heiser, June Andronick,
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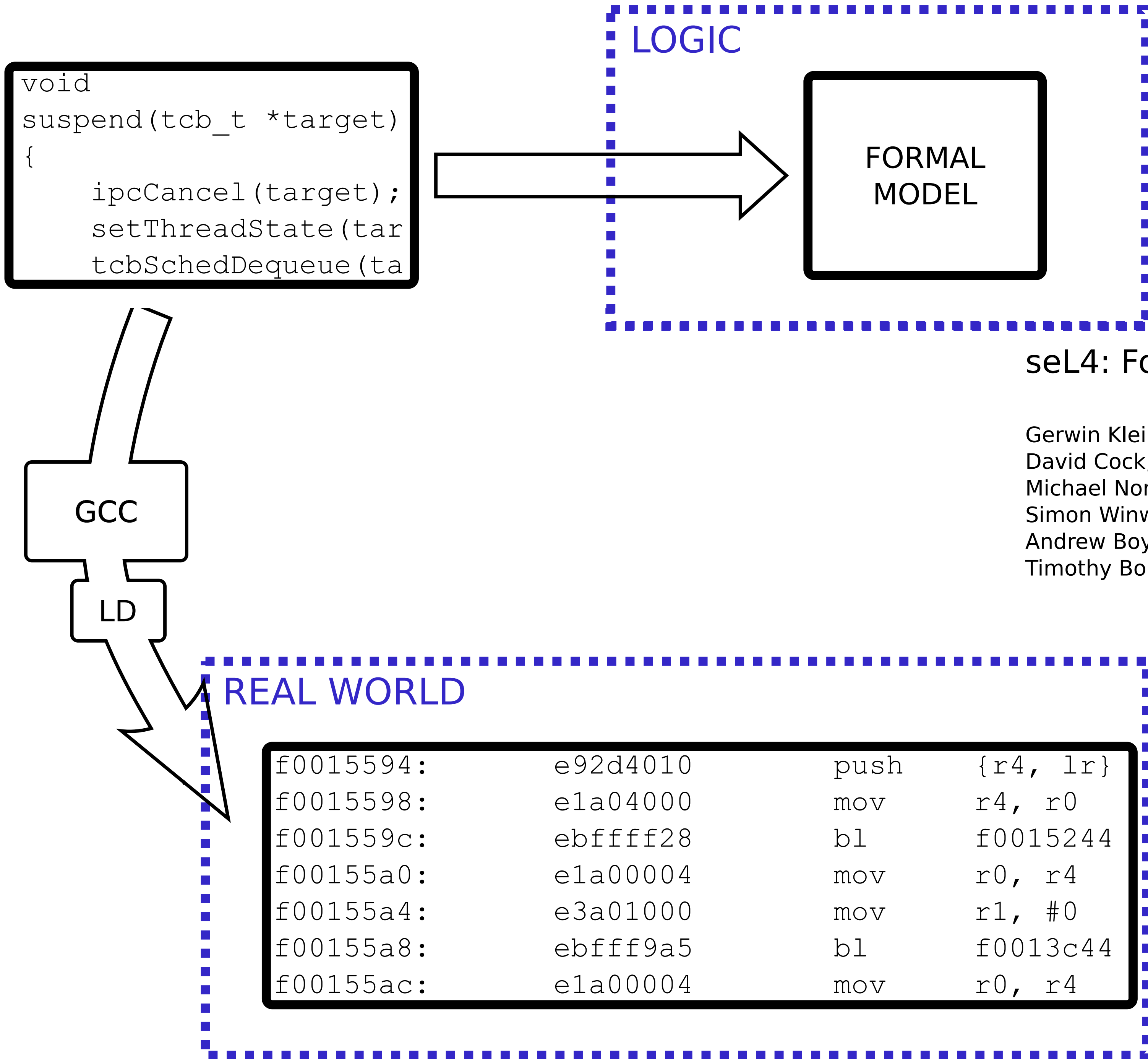

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Binary Validation: the Problem

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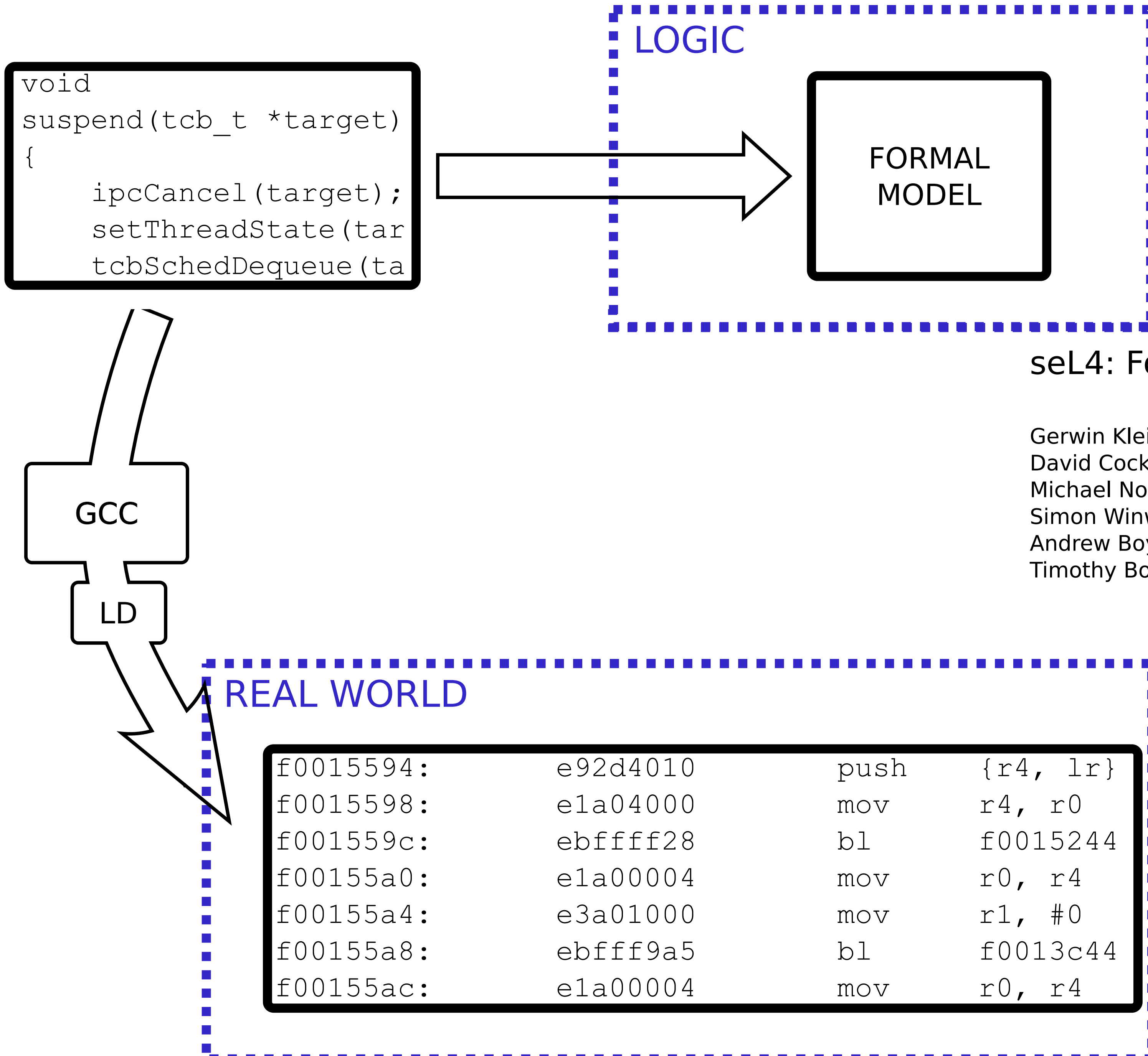

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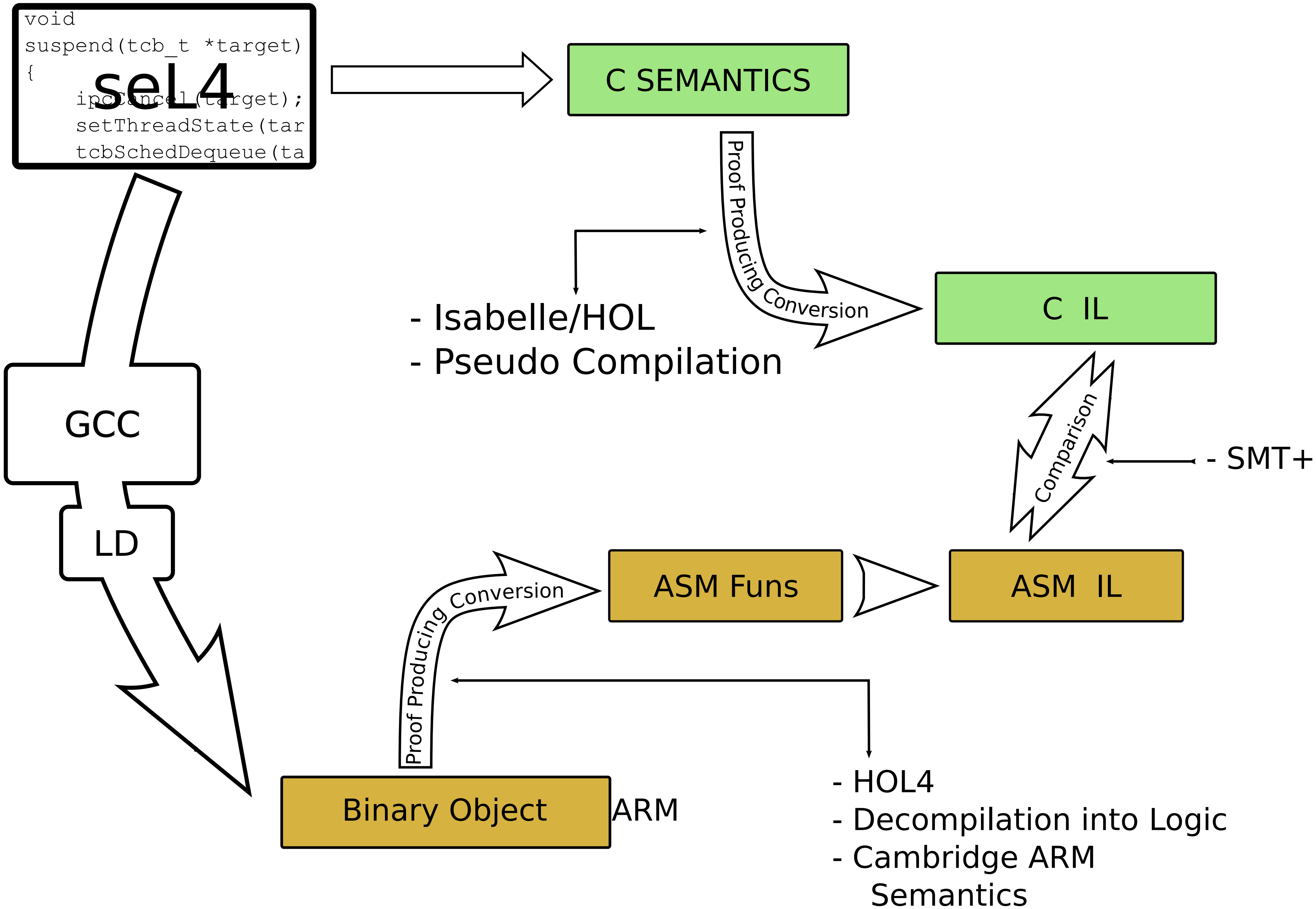
UNIVERSITY OF CAMBRIDGE

ARM ISA and Decompiler

Anthony Fox and Magnus Myreen

Binary Validation: Solution in a Graph



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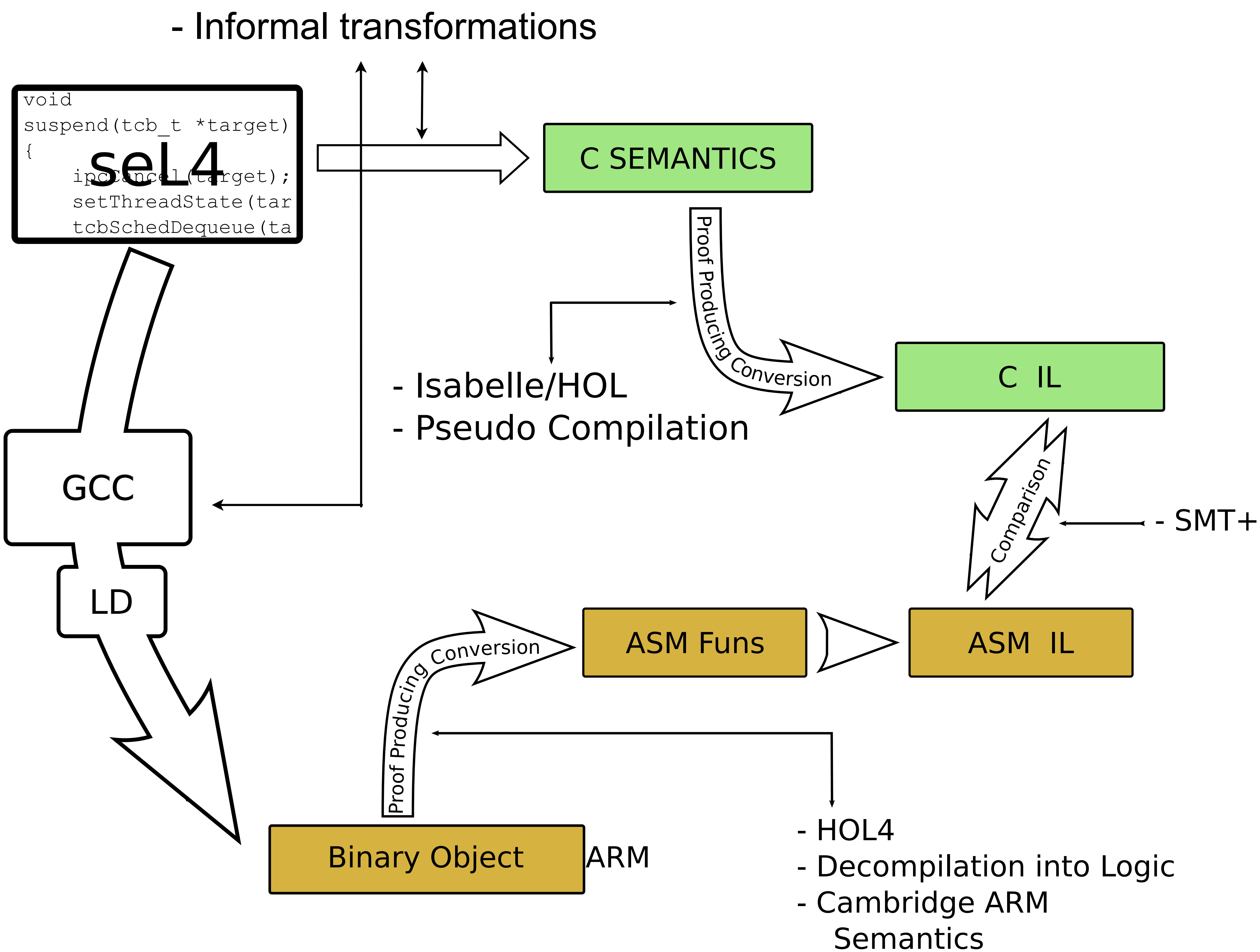
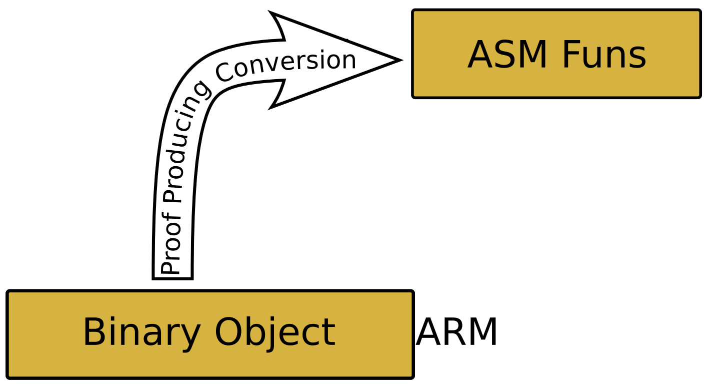


Machine Code Decompilation




```
uint avg (uint i, uint j) {
  return (i + j) / 2;
}
```

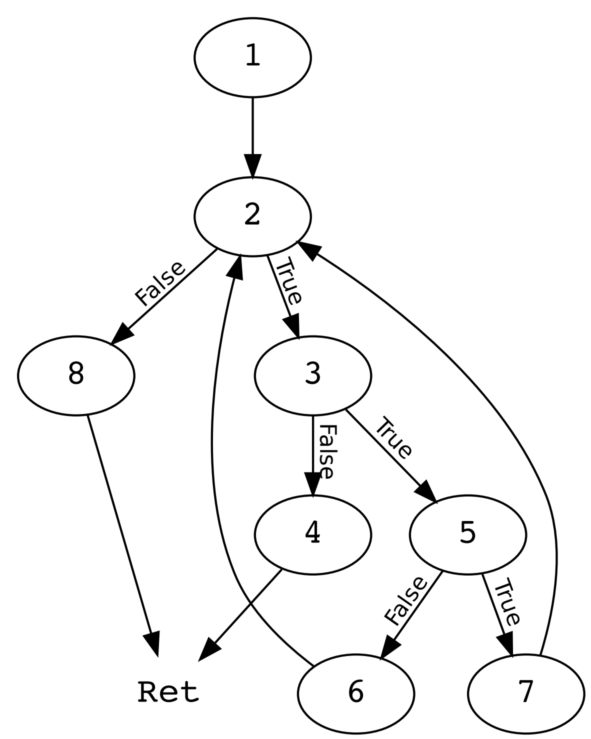
```
<avg>:
avg+0    e0810000    add r0, r1, r0    // add r1 to r0
avg+4    e1a000a0    lsr r0, r0, #1    // shift r0 right
avg+8    e12fff1e    bx  lr            // return
```

$$
\begin{aligned}
\text{avg}\,(r_0, r_1) \quad = \quad & \text{let } r_0 = r_1 + r_0 \text{ in} \\
& \text{let } r_0 = r_0 >>> 1 \text{ in} \\
& \quad r_0
\end{aligned}
$$

Control-Flow Graphs

Machine code and C code eventually turn into annotated control flow graphs

```
struct node *
find (struct tree *t, int k) {
  struct node *p = t->trunk;
  while (p) {
    if (p->key == k)
      return p;
    else if (p->key < k)
      p = p->right;
    else
      p = p->left;
  }
  return NULL;
}
```




```
1: p := Mem[t + 4];

2: p == 0 ?

8: ret := 0
3: Mem[p] == k ?

4: ret := p;
5: Mem[p] < k ?

6: p := Mem[p + 4];
7: p := Mem[p + 8];
```

Critically, can consider one function at a time when verifying (modulo inlining).

Comparing Graphs: Challenges

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inlining

- if gcc inlines a function, the “C graph” has to do so too

loops

- must prove that loop points are reached the same number of times
- must also cope with complete or partial unrollings

treatment of the stack

- machine code accesses to memory that are loads/stores of spilled parameters need to be recognised as such

Loops, Loops, Loops, Loops, Loops, ...

Can sometimes infer that a loop should only ever execute a fixed *n* times.

- *e.g.*, `for(i=0; i < 10; i++) { .... }`
- SMT solver can confirm such an inference ...
  - formula is finite, of size *O(n)*
- *...* and establish appropriate post-condition(s)

Alternatively, use *k*-induction to prove that every visit to a loop point in the binary is matched by one in the C.

- invariant relating C and binary variables is also preserved
- offsets may be required to handle partial unrollings

Graph Equivalence Technology

Problem domain is good fit for QF_ABV SMT category

- *i.e.*, arrays + boolean vectors

Used both Z3 and Sonolar

- Sonolar performs better on arrays (used to represent memory)
- Z3 can restart (retracting facts), making efficiency performance better

seL4, *c*2009

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Full functional correctness

25 person-years of effort

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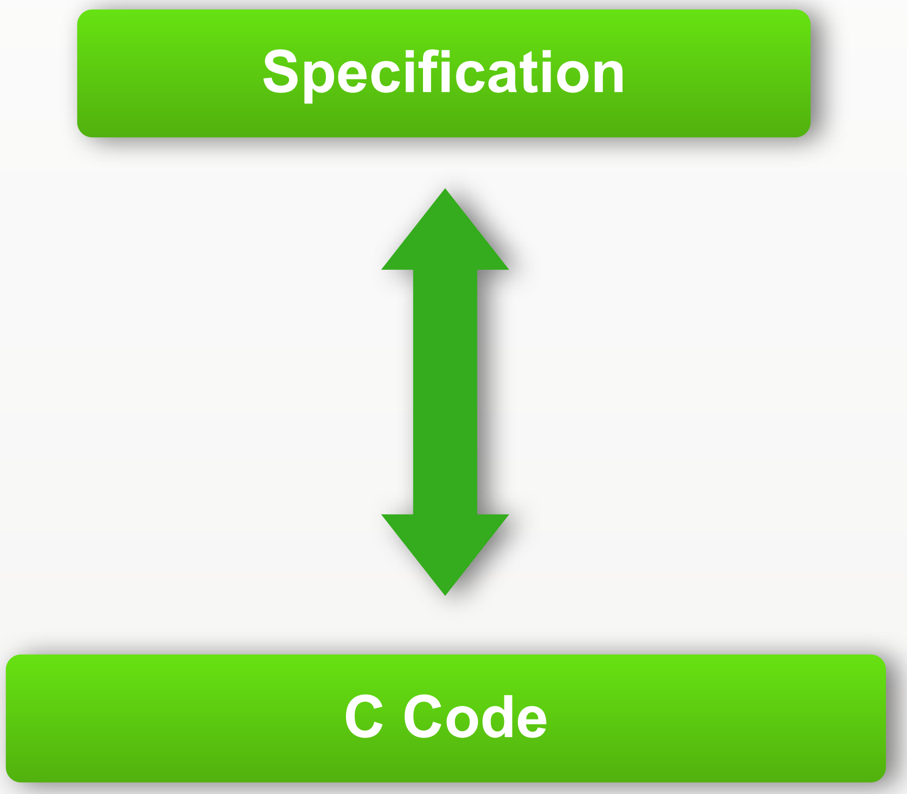
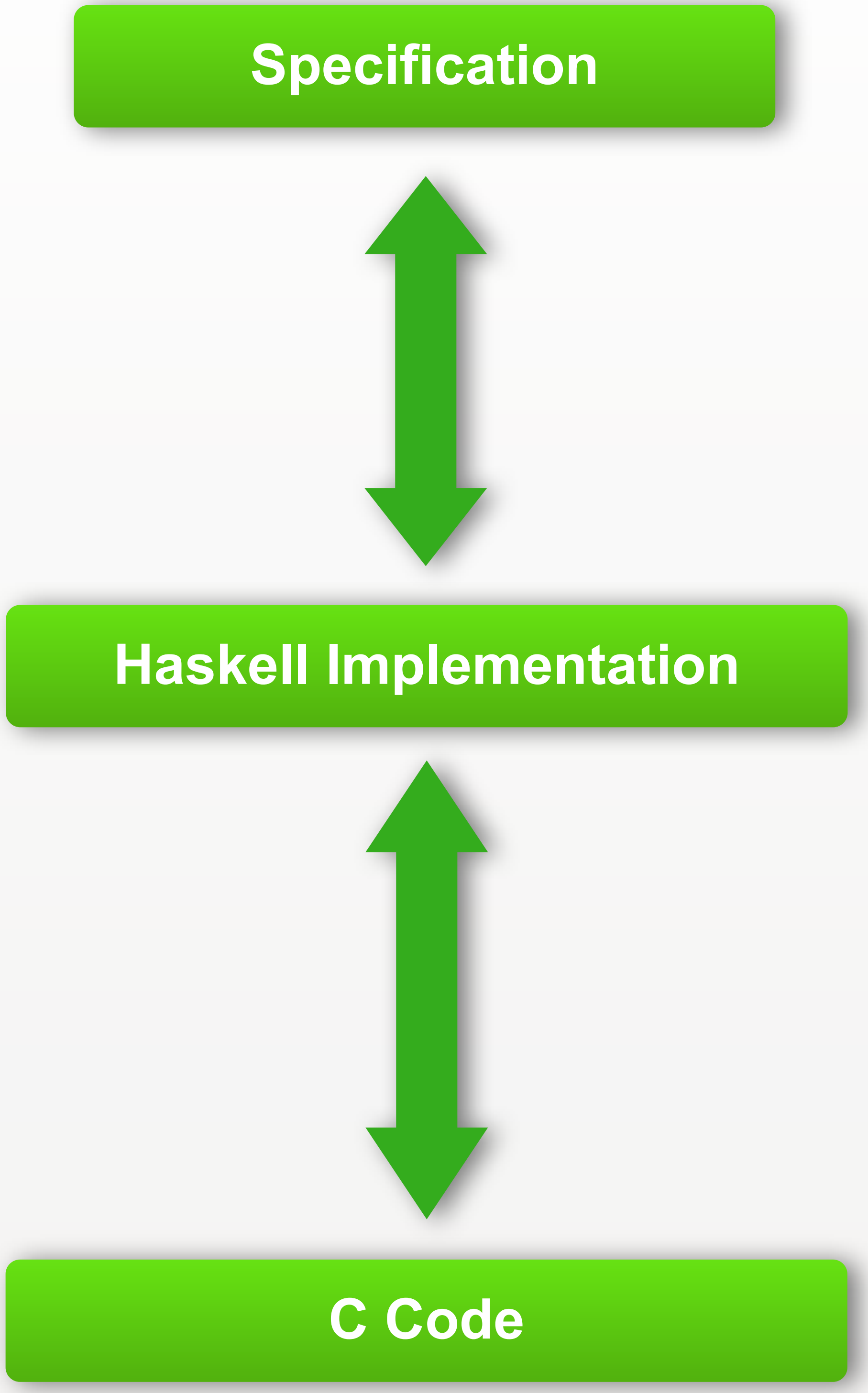
This is a disturbingly large number; where can we improve productivity?


Specification
C Code


Specification
Haskell Implementation
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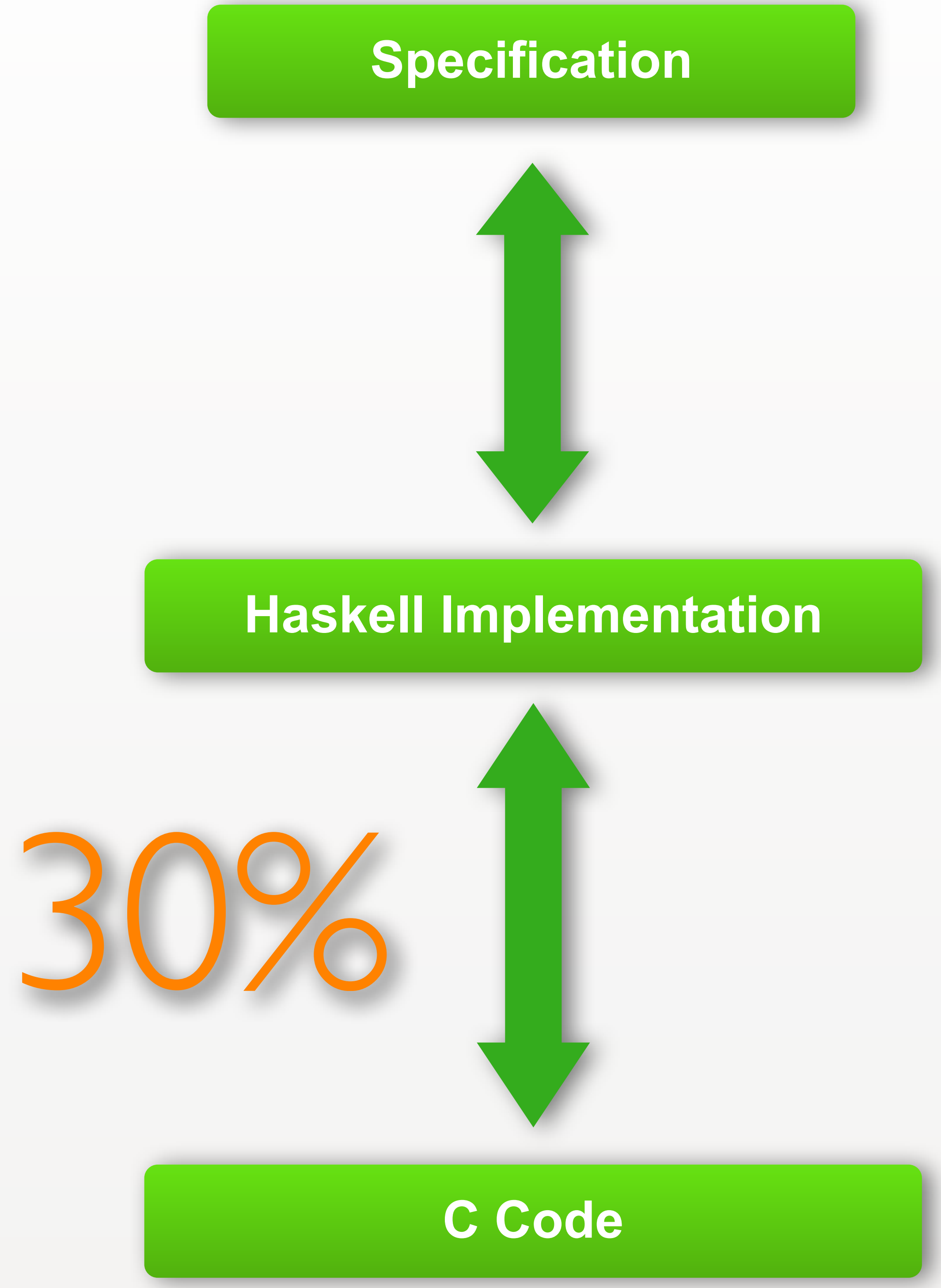
Specification
Haskell Implementation
30%
C Code

Some background to this mess

```
int max(int a, int b) {
    if (a < b) {
        return b;
    }
    return a;
}
```

Some background to this mess

Source Code

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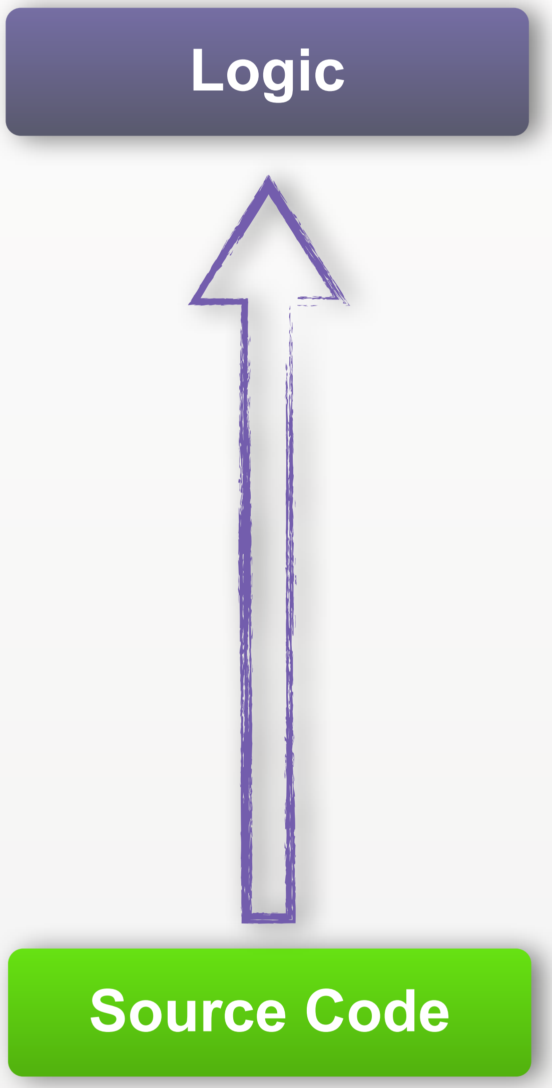


```
max a b ≡
  if a > b then b else a
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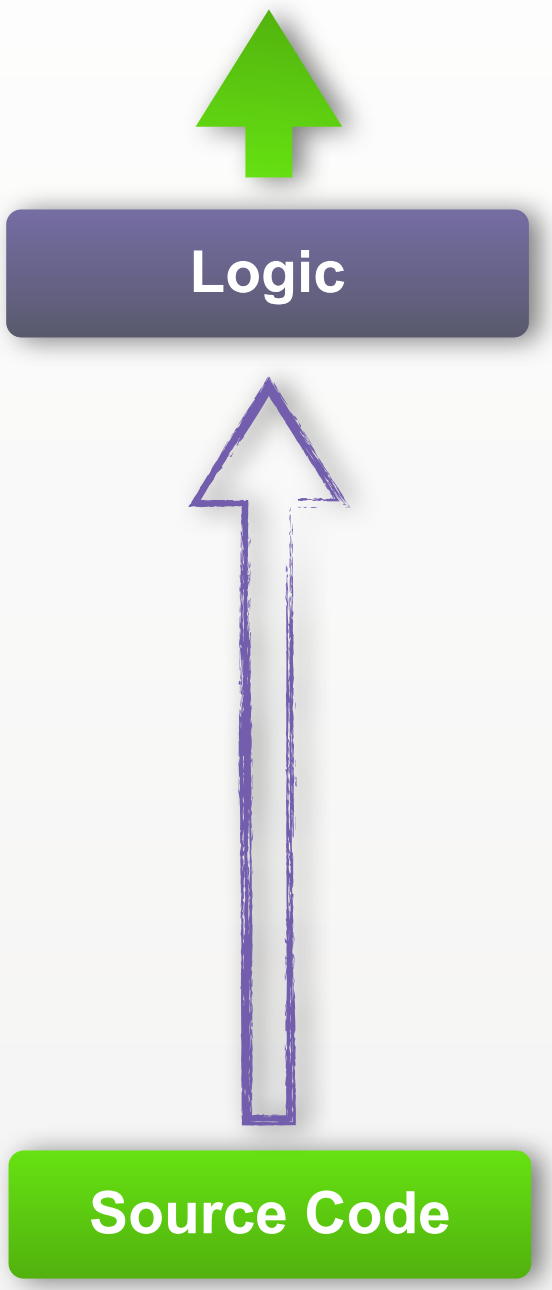


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```
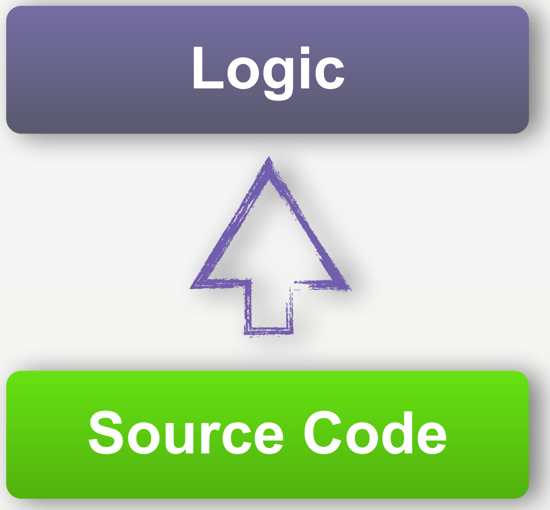

- Uninitialised variables
- Undefined behaviour
- Pointer arithmetic
- Type casting

Our approach

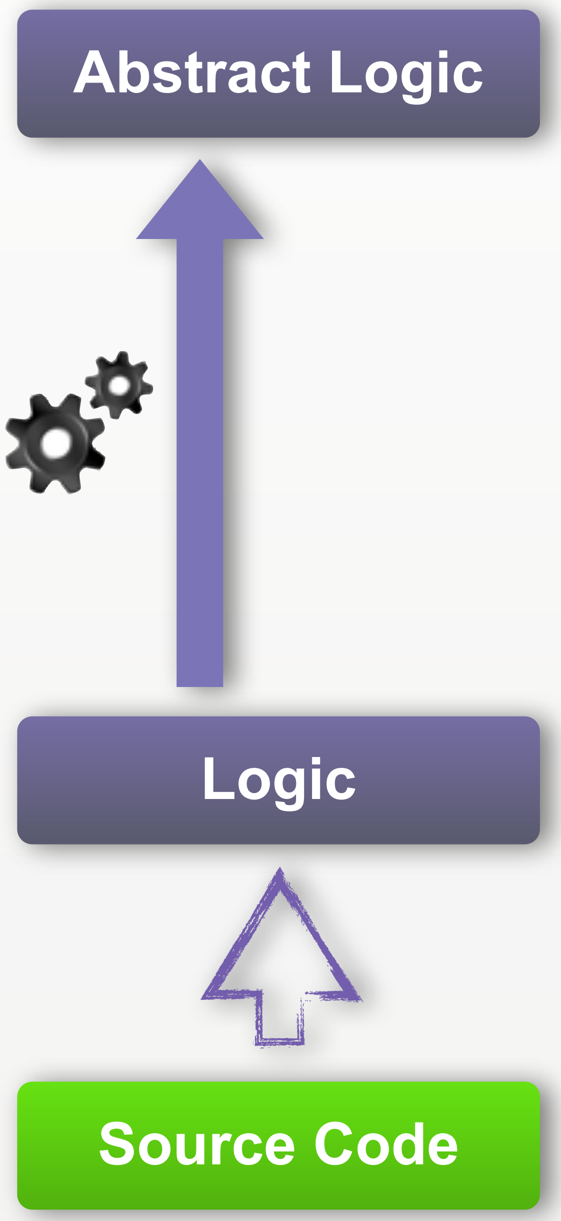
Source Code

Our approach



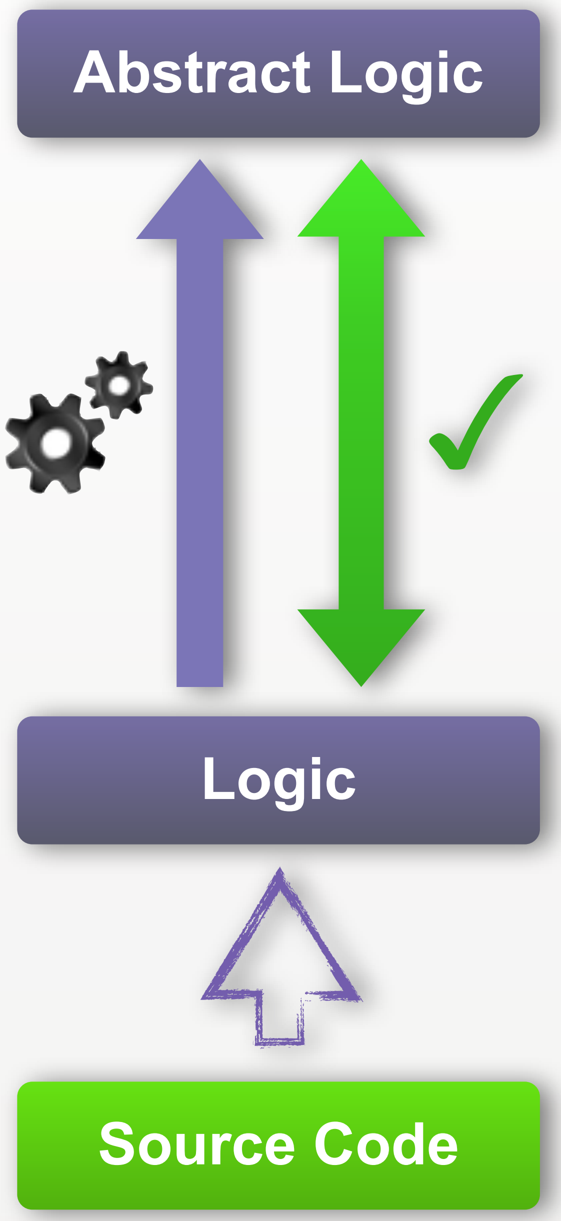
- Start with a conservative logical representation

Our approach



- Start with a conservative logical representation
- Automatically abstract low-level spec into higher-level spec
  - Goal: Suitable for human consumption

Our approach



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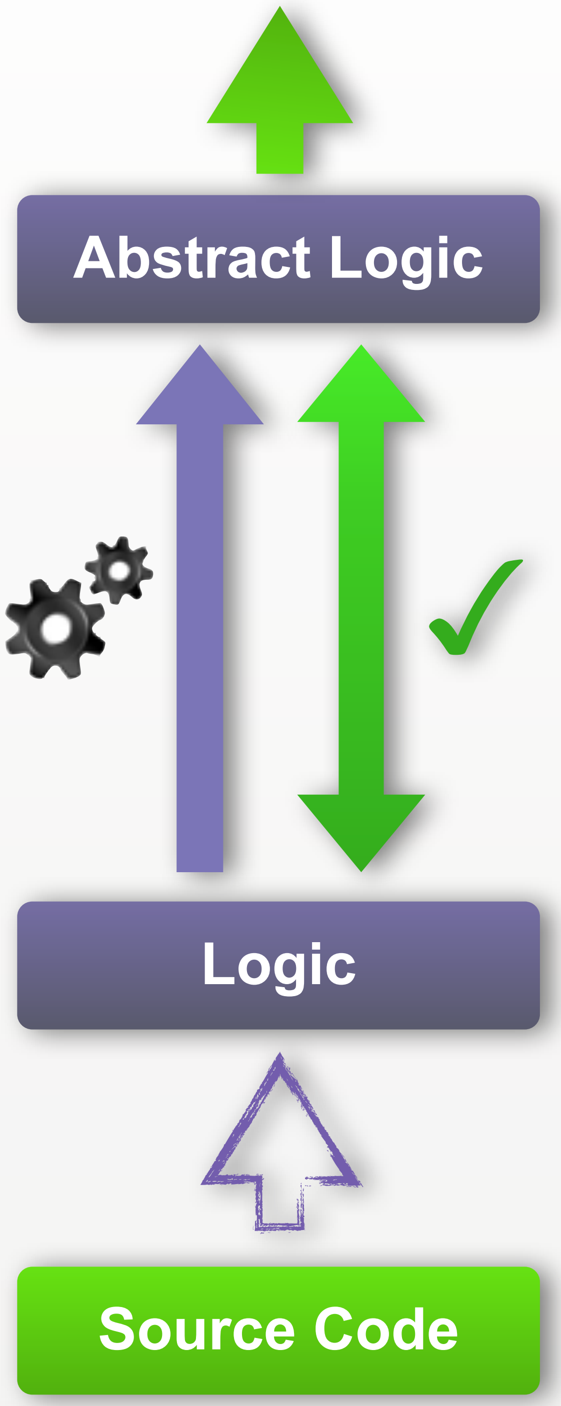
Our approach



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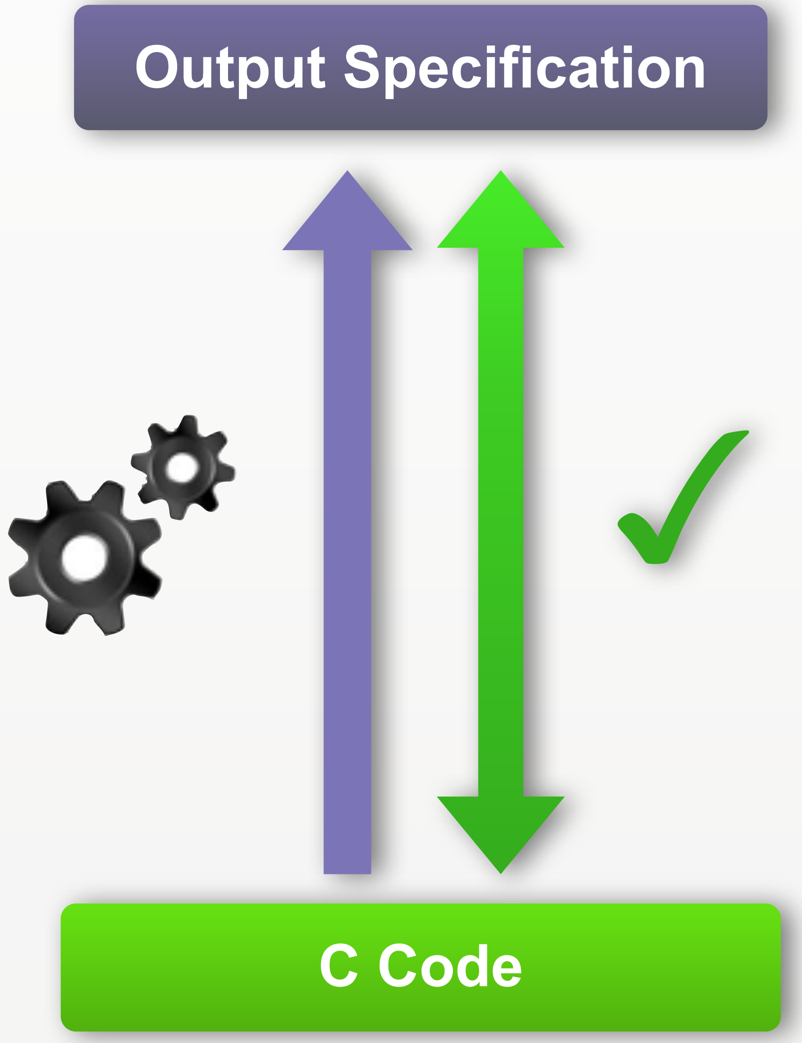

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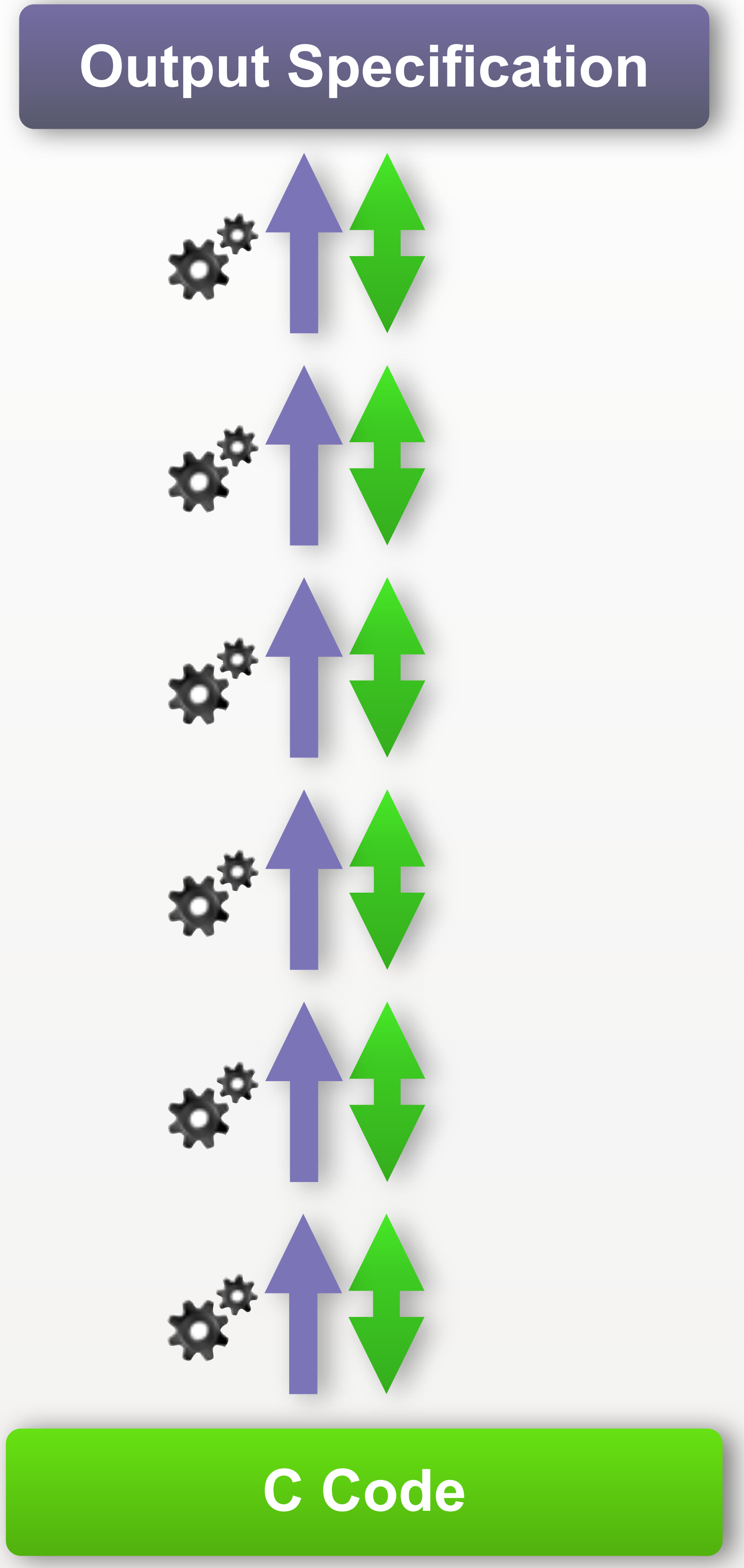

Our approach

⑥ Type Strengthening

⑤ Flow-Sensitive Optimisations

④ Local Variable Extraction

③ Exception Elimination

② Peephole Optimisations

① Shallow Embedding

```
max ≡
  TRY
    IF {| ´a <s ´b |} THEN
      ´ret_int :== ´b;;
      ´exn_var :== Return;;
      THROW
    ELSE
      SKIP
    FI;;
    ´ret_int :== ´a;;
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    THROW;
    GUARD DontReach {}
      SKIP;;
  CATCH
    SKIP
  END
```

```
max a b ≡
  if (a <s b) then b else a
```

⑥ Type Strengthening

```
max a b ≡
  condition (a <s b)
    return b
    return a
```

```c
int max(int a, int b) {
    if (a < b) {
        return b;
    }
    return a;
}
```

```
int max(int a, int b) {
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    ...
      ´ret_int :== ´a;;
      ´exn_var :== Return;
      THROW;
      GUARD DontReach {}
        SKIP;;
  CATCH
    SKIP
  END
```

```
int gcd(int a, int b) {
    int c;
    while (a != 0) {
        c = a;
        a = b % a;
        b = c;
    }
    return b;
}
```

```c
int gcd(int a, int b) {
    int c;
    while (a != 0) {
        c = a;
        a = b % a;
        b = c;
    }
    return b;
}
```

```
gcd ≡
  TRY
    NonDetInit ´c ´c_update
    WHILE {| ´a ≠ 0 |} THEN
      ´c :== ´a;;
      GUARD Div0 {| ´a ≠ 0 |}
        ´a :== ´b mod ´a;;
      ´b :== ´c
    OD;;
    ´ret_int :== ´b;
    ´exn_var :== Return;
    THROW;
    GUARD DontReach {}
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gcd ≡
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    int c;
    while (a != 0) {
        c = a;
        a = b % a;
        b = c;
    }
    return b;
}
```

```
gcd a b ≡ do
  (a, b) ←
    while (λ(a, b) _. a ≠ 0)
      (λ(a, b). return (b mod a, a))
                                  (a, b);
  return b
od
```

```
    THROW;
    GUARD DontReach {}
      SKIP
  CATCH
    SKIP
  END
```

```
void swap(int *a, int *b)
{
    int t = *a;
    *a = *b;
    *b = t;
}
```

```
void swap(int *a, int *b)
{
    int t = *a;
    *a = *b;
    *b = t;
}
```

```
swap ≡
TRY
  GUARD C_Guard {|c_guard ´a|}
   (´t :== h_val (hrs_mem ´t_hrs) ´a);;
  GUARD C_Guard {|c_guard ´a|}
   (GUARD C_Guard {|c_guard ´b|}
     (´globals :==
        t_hrs_'_update
         (hrs_mem_update
           (heap_update ´a
             (h_val (hrs_mem ´t_hrs)
               ´b))))));;
  GUARD C_Guard {|c_guard ´b|}
   (´globals :==
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  GUARD C_Guard {|c_guard ´a|}
   (GUARD C_Guard {|c_guard ´b|}
```

```
swap a b ≡
  do guard (λs. c_guard a);
     t ← gets (λs. h_val (hrs_mem (t_hrs_' s)) a);
     guard (λs. c_guard b);
     modify
      (λs. t_hrs_'_update
             (hrs_mem_update
               (heap_update a
                 (h_val (hrs_mem (t_hrs_' s)) b))) s);
     modify
      (t_hrs_'_update
        (hrs_mem_update (heap_update b t)))
  od
```

C Heap Semantics

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swap a b ≡
  do guard (λs. c_guard a);
     t ← gets (λs. h_val (hrs_mem (t_hrs_' s)) a);
     guard (λs. c_guard b);
     modify
      (λs. t_hrs_'_update
             (hrs_mem_update
               (heap_update a
                 (h_val (hrs_mem (t_hrs_' s)) b))) s);
     modify
      (t_hrs_'_update
        (hrs_mem_update (heap_update b t)))
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Ensure “a” is aligned, non-NULL.

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Ensure “a” is aligned, non-NULL.

Decode the bytes at “a”.

Decode the bytes at “b”,
encode back into bytes,
store at “a”.

In Short

Treatment of Heap is Promising Work in Progress

Word Arithmetic Made More Beautiful

- having to worry about overflow is drudgery...
- make the tools do it as automatically as possible

Conclusion

Ad hoc **Proof** makes ad hoc hackery

- sound, and
- beautiful

Tools:

– ssrg.nicta.com.au/software/TS/{c-parser,graph-refine}
– ssrg.nicta.com.au/projects/TS/autocorres/