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Translation Validation for a Verified OS Kernel

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L4.verified

seL4 = a formally verified general-purpose microkernel

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about 10,000 lines of C code and assembly

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200,000 lines of Isabelle/HOL proofs

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- inline assembly
- hardware
- hardware management
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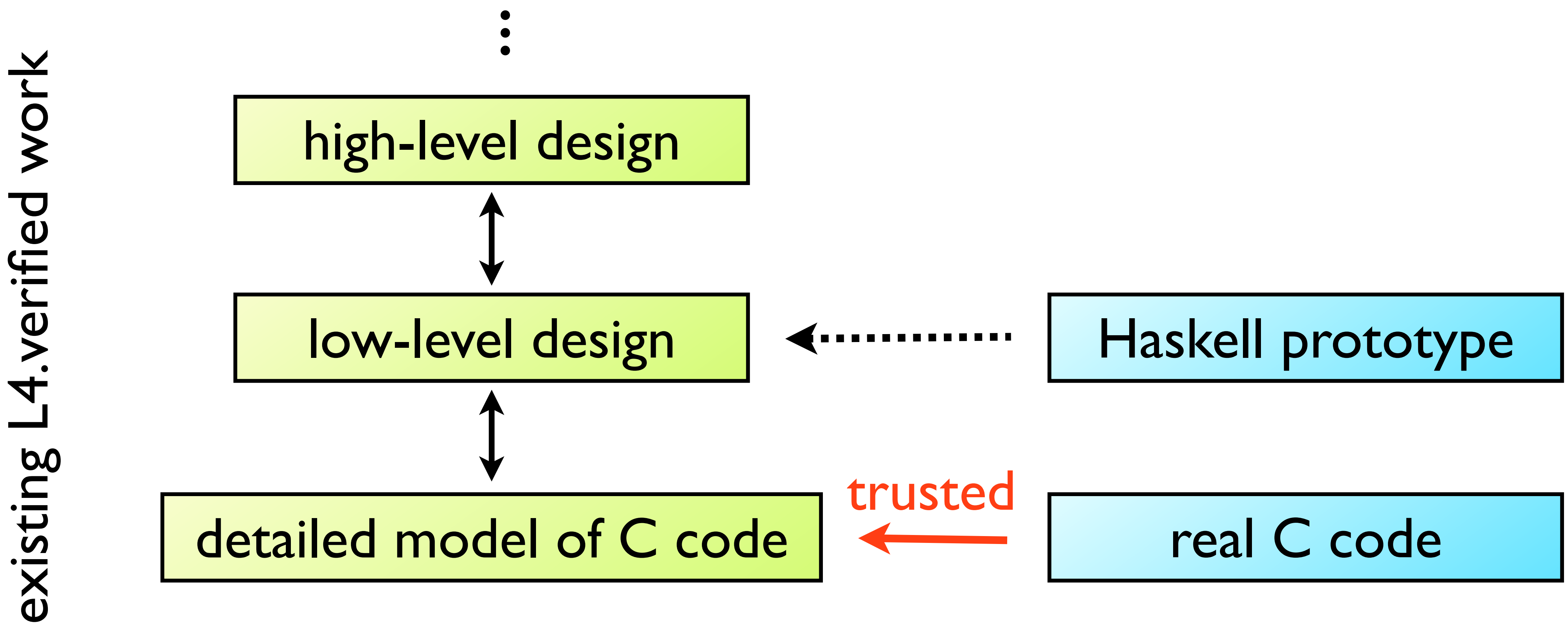
And also to validate L4.verified's C semantics.

Aim: extend downwards



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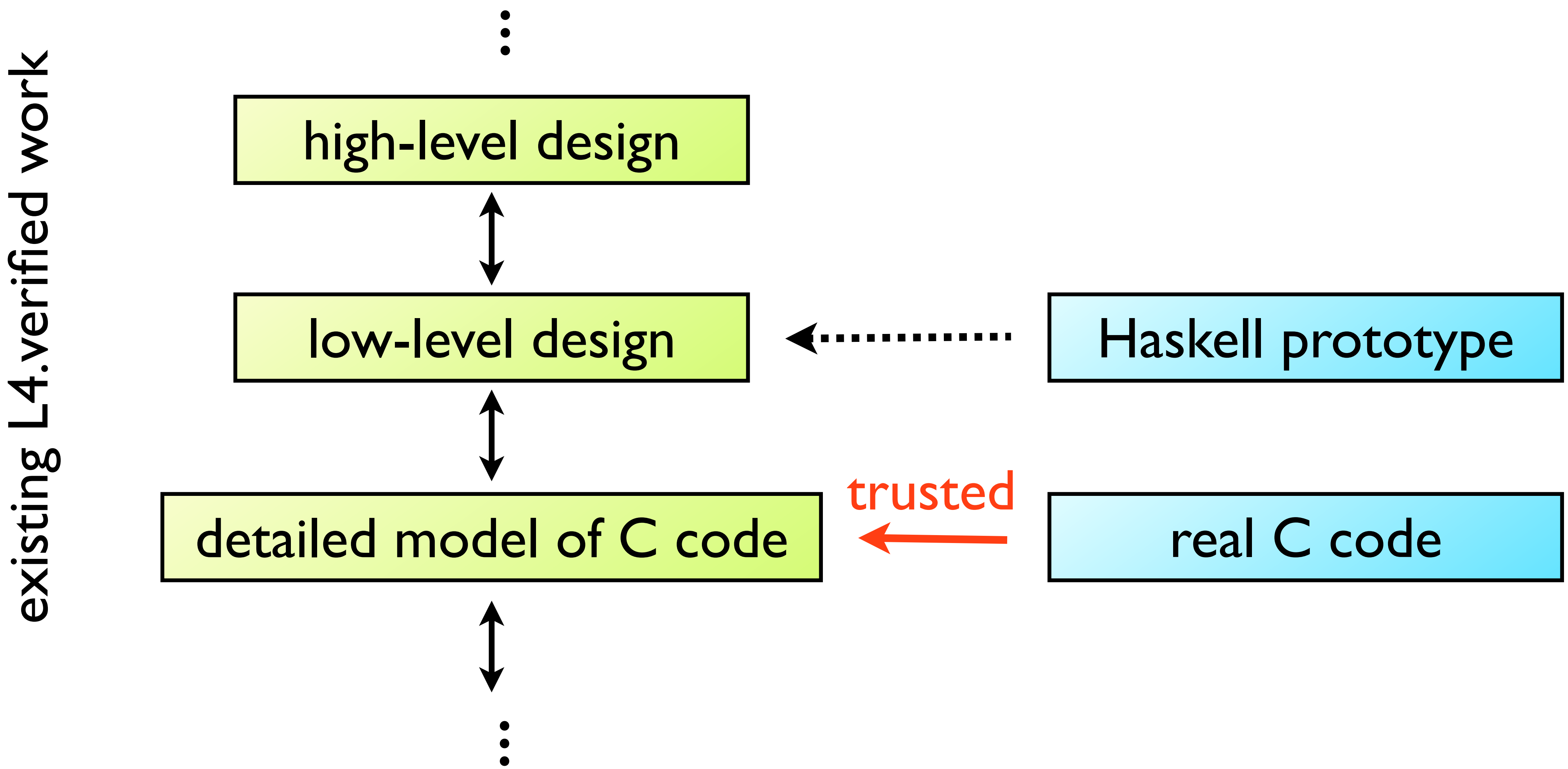

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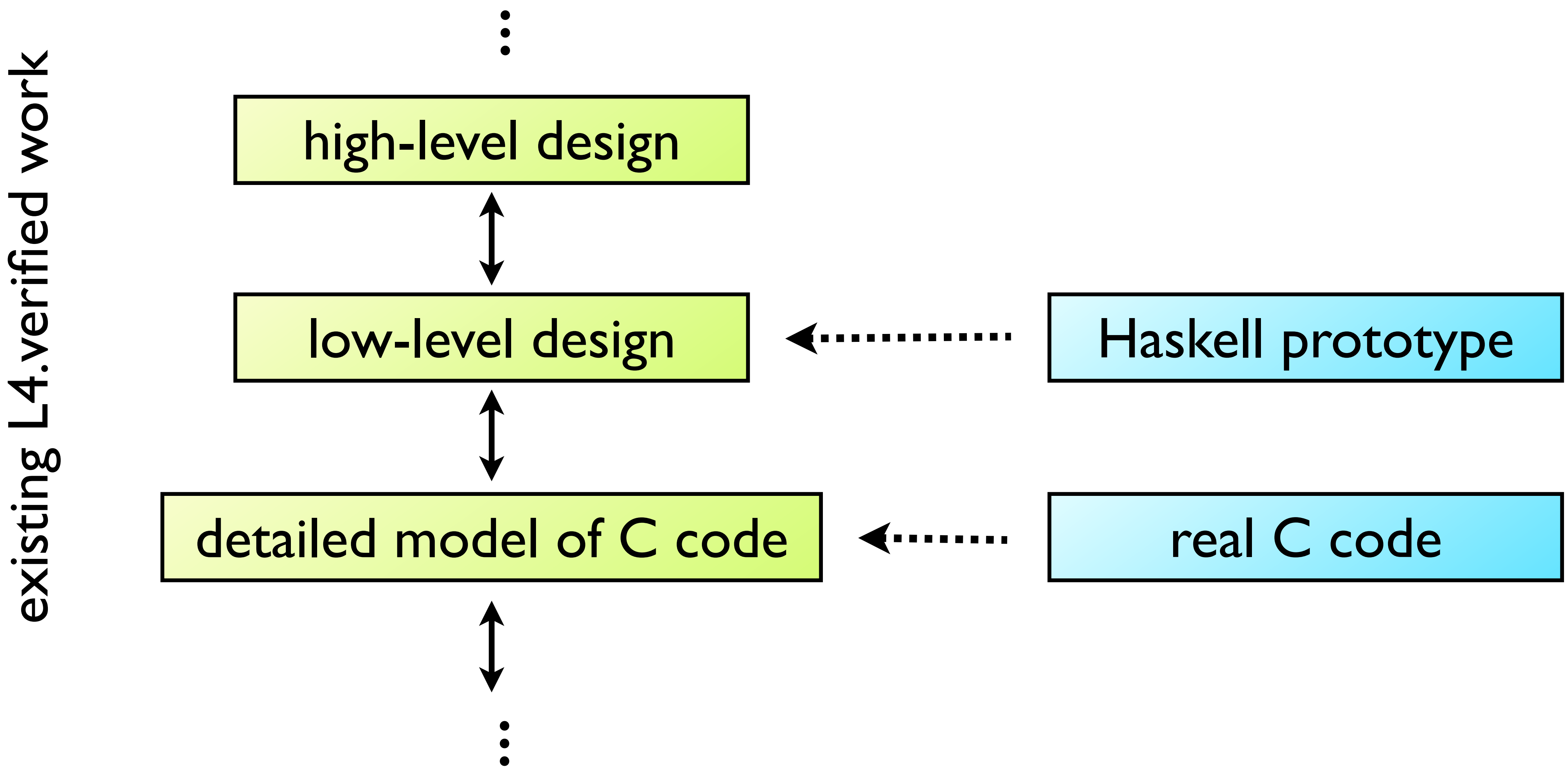

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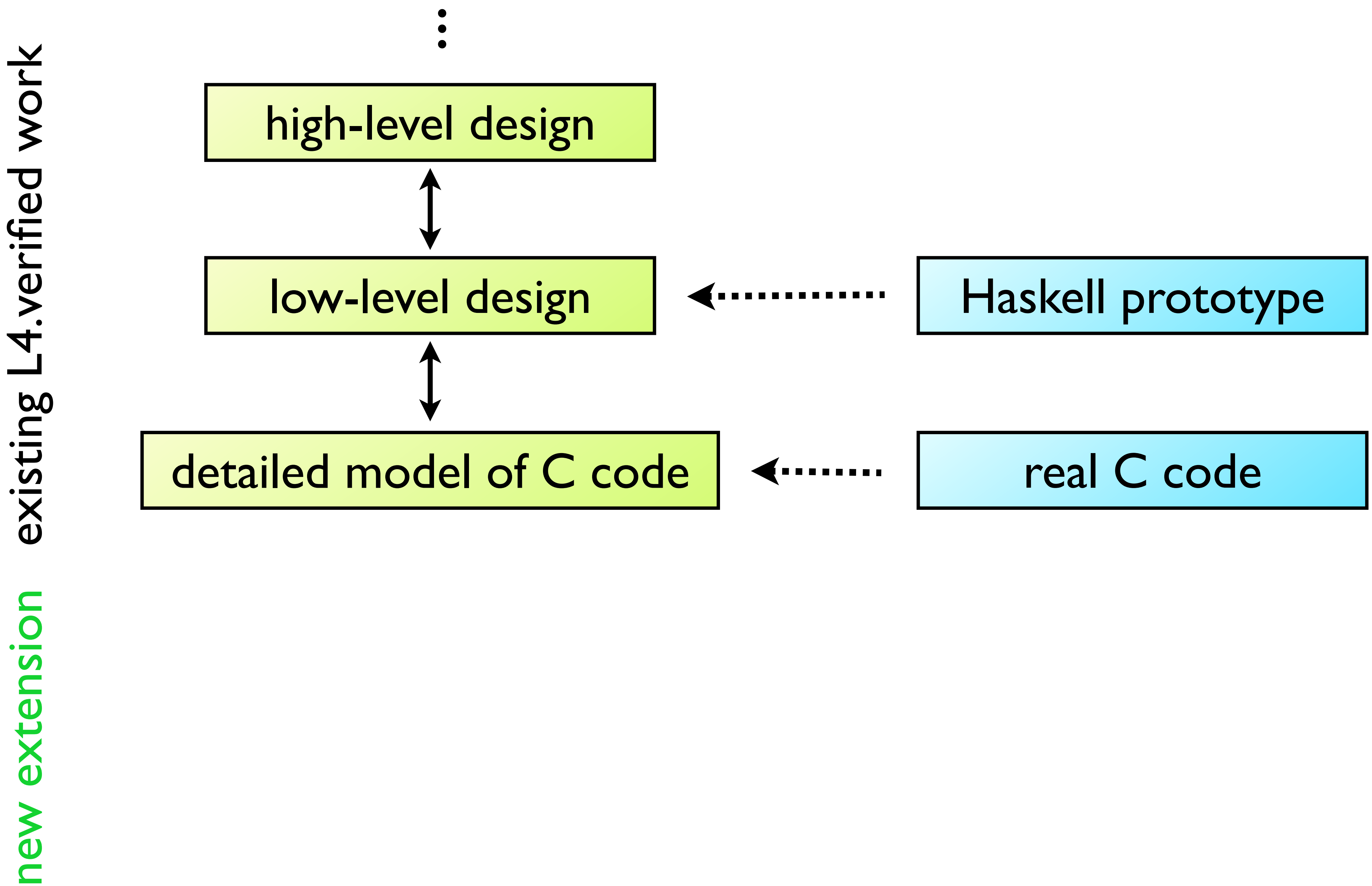
Connection to CompCert



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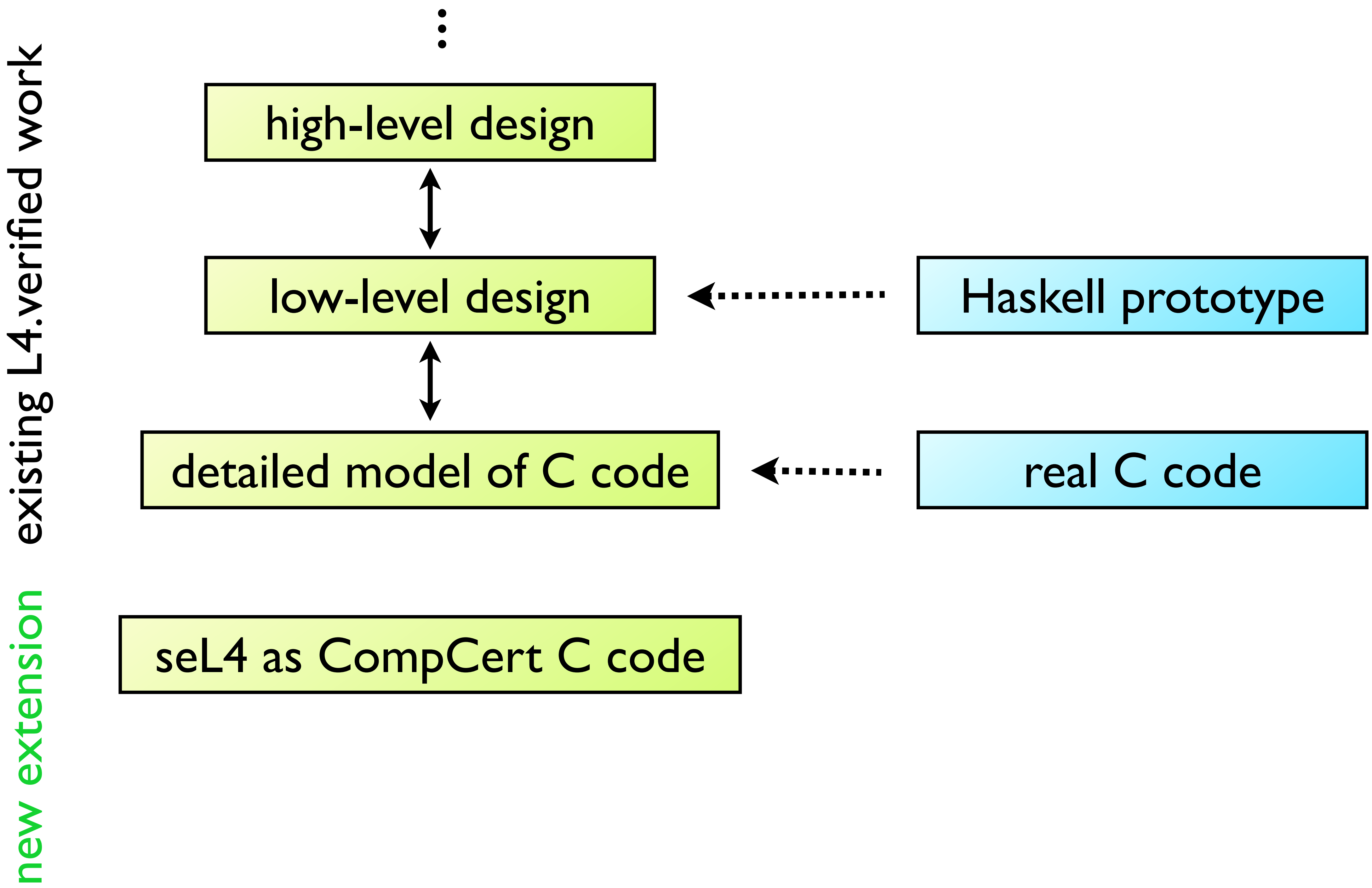

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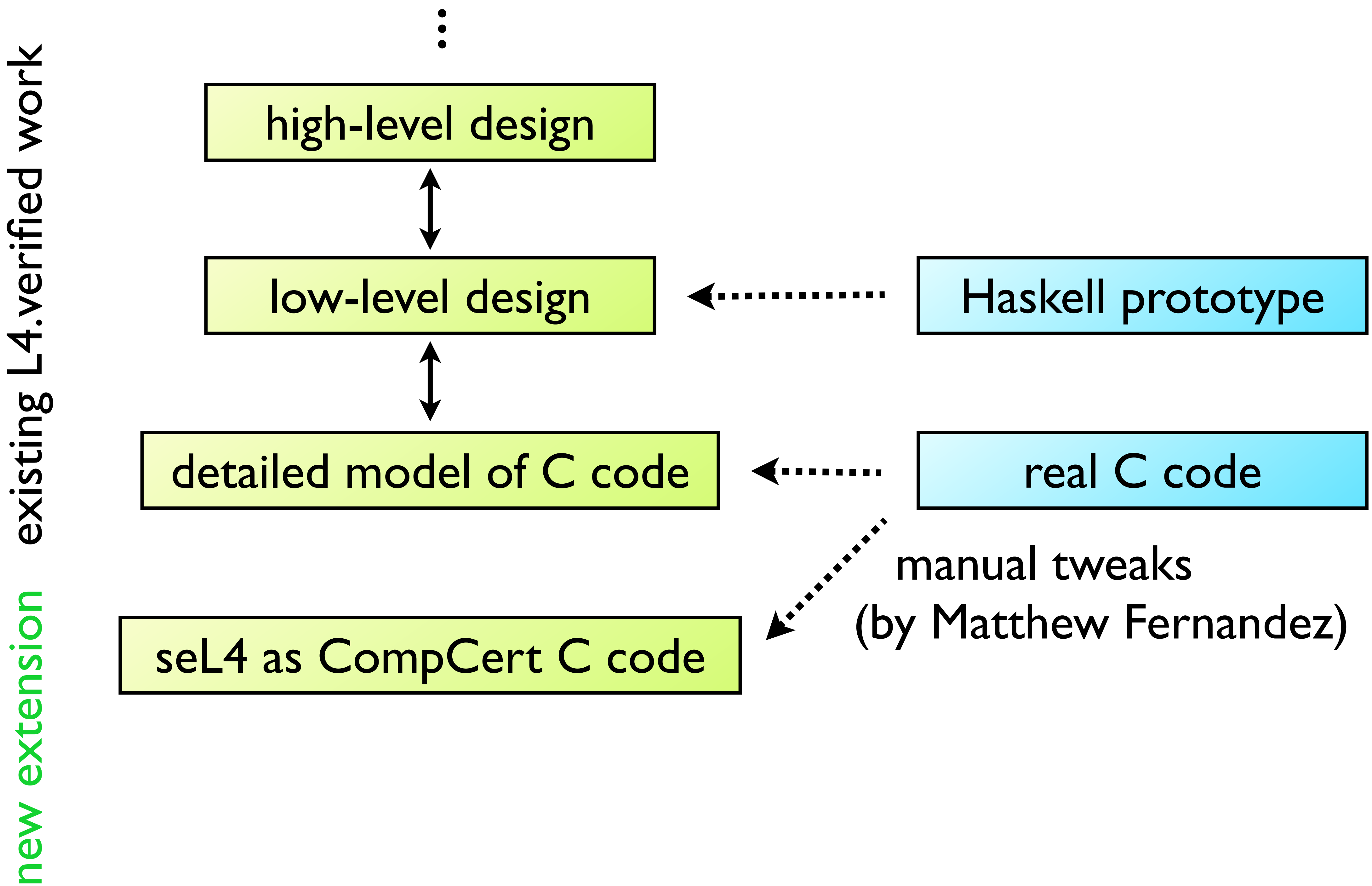

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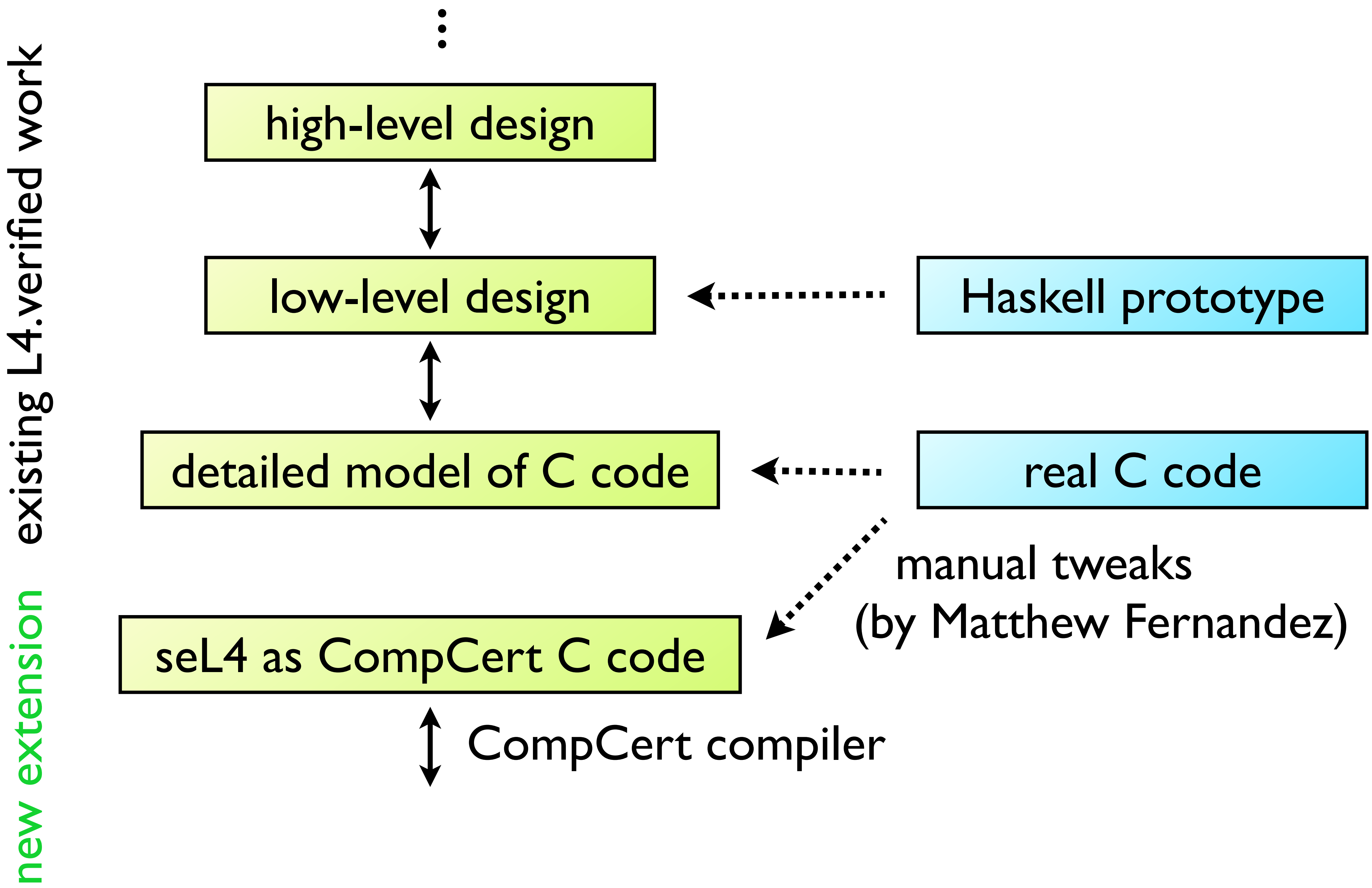

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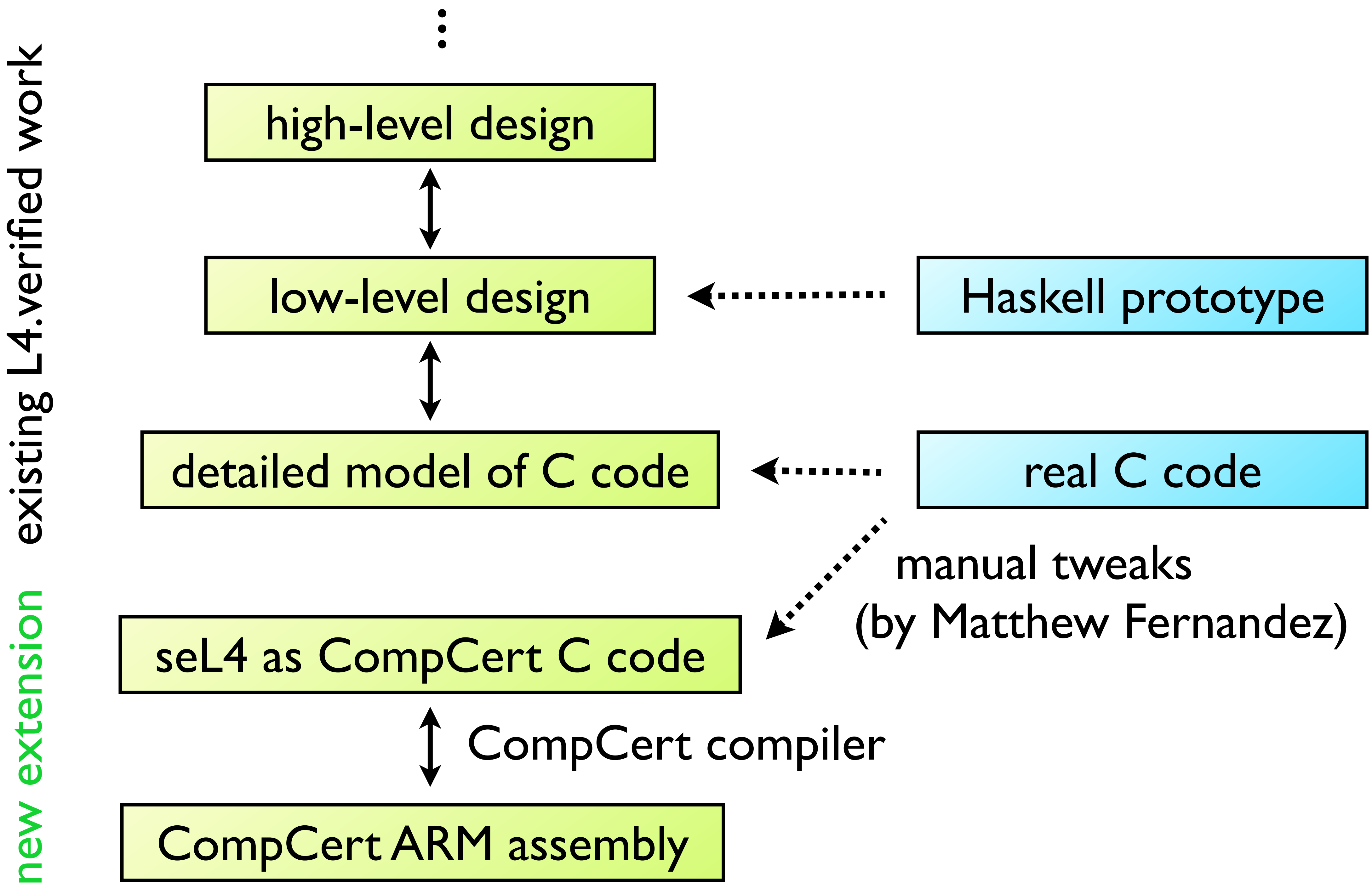

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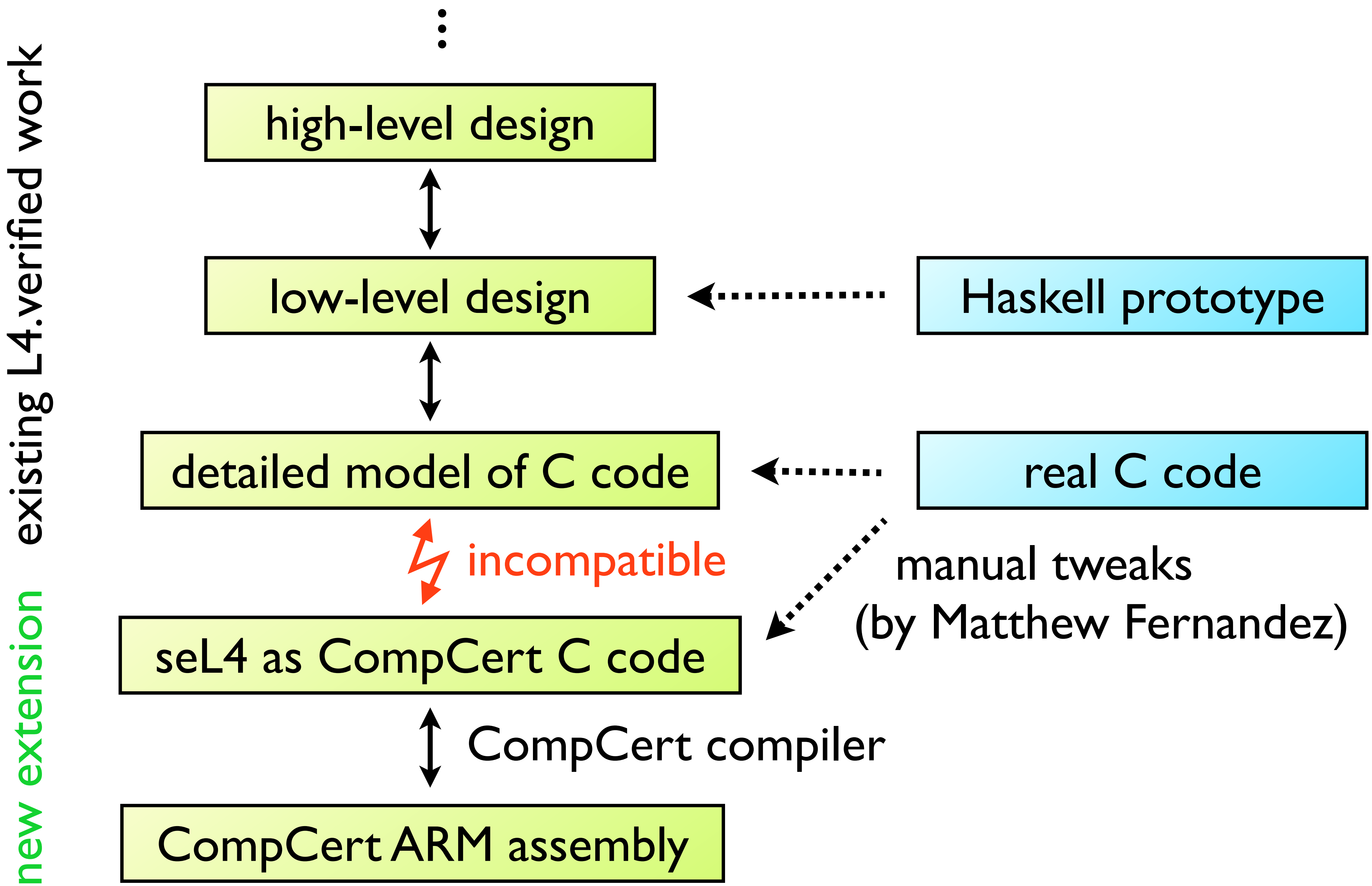

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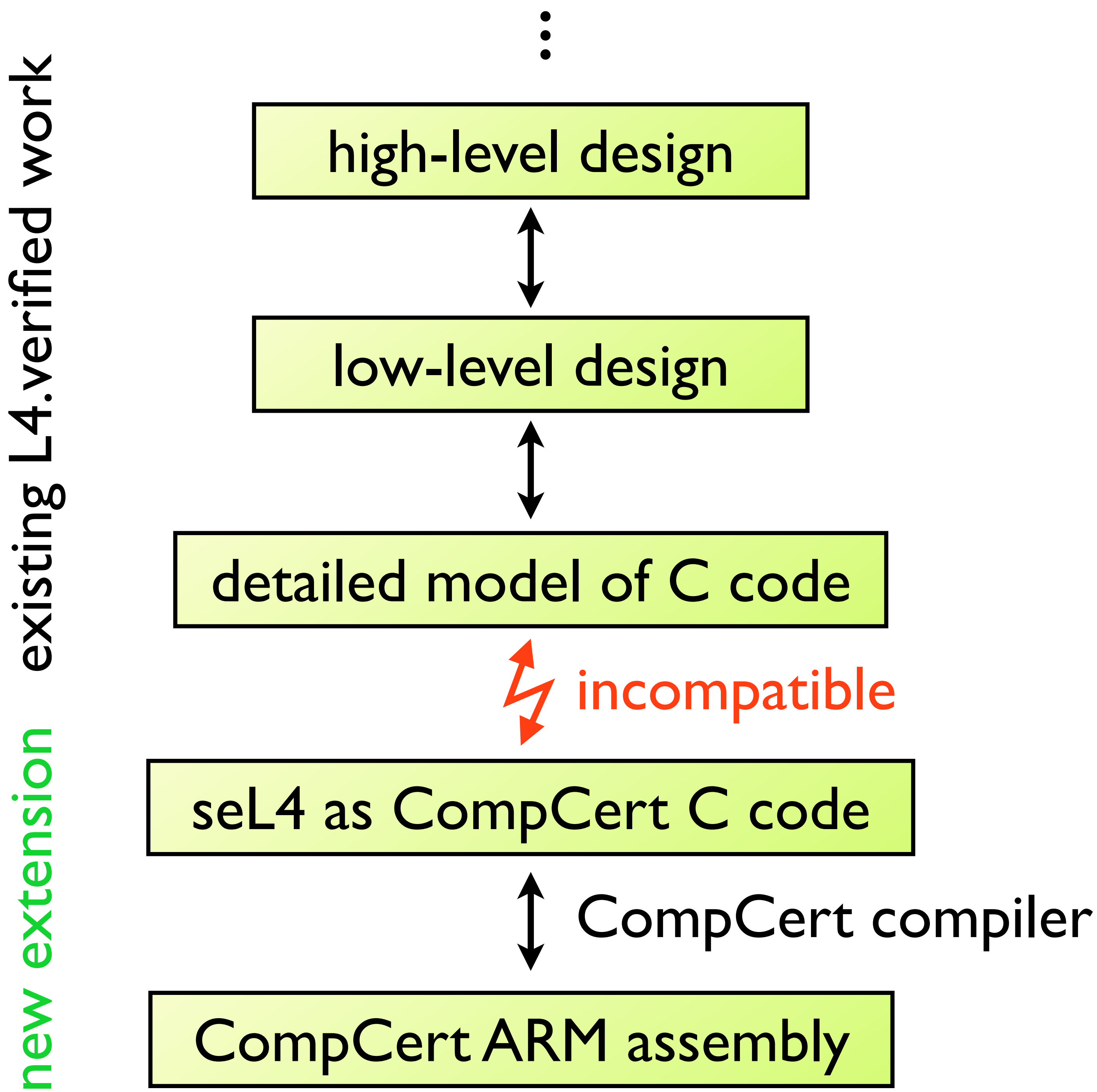
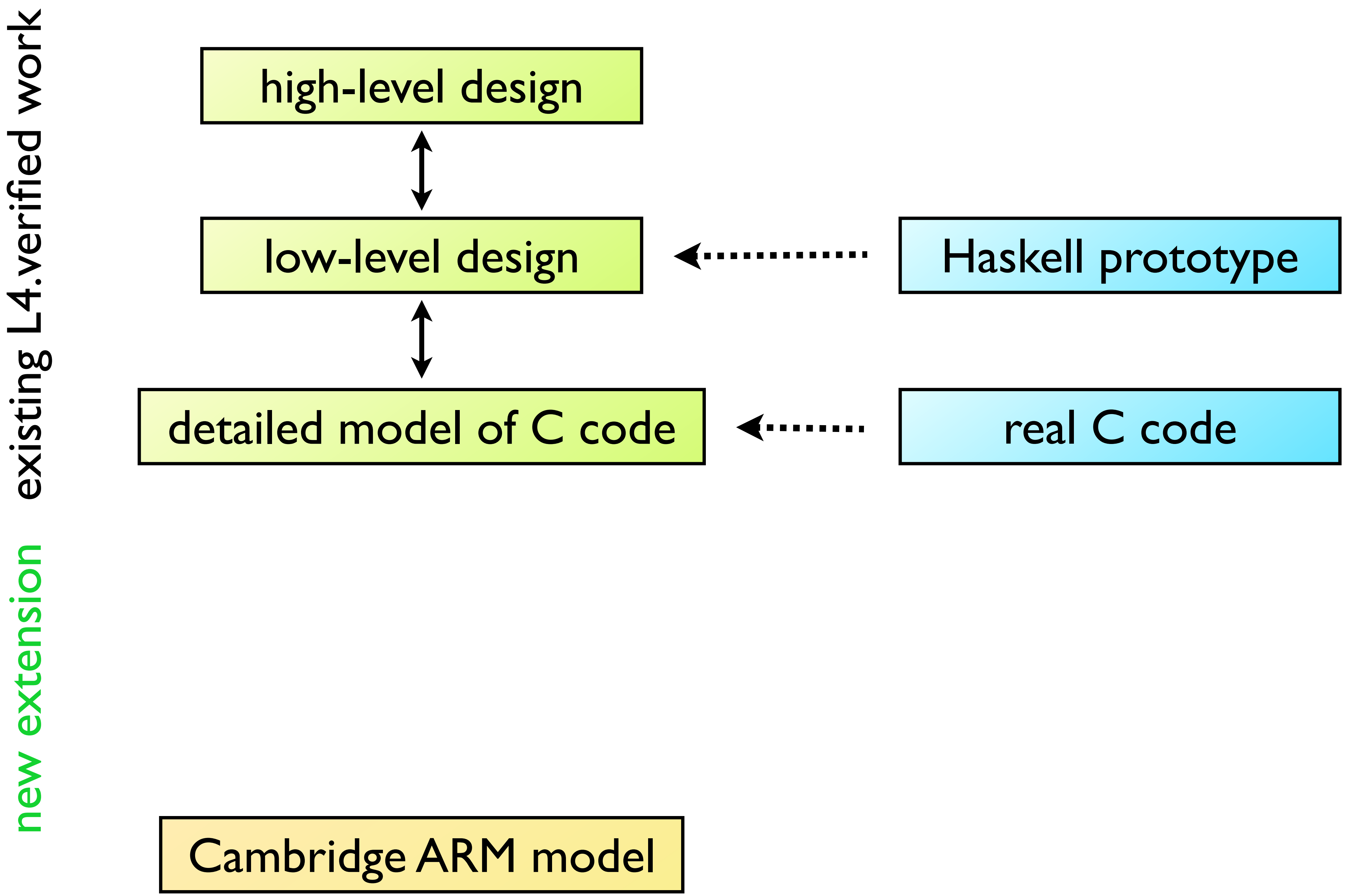


Incompatible:

- different view on what valid C is
- pointers treated differently
- memory more abstract in CompCert C sem.
- different provers (Coq and Isabelle)

Using Cambridge ARM model



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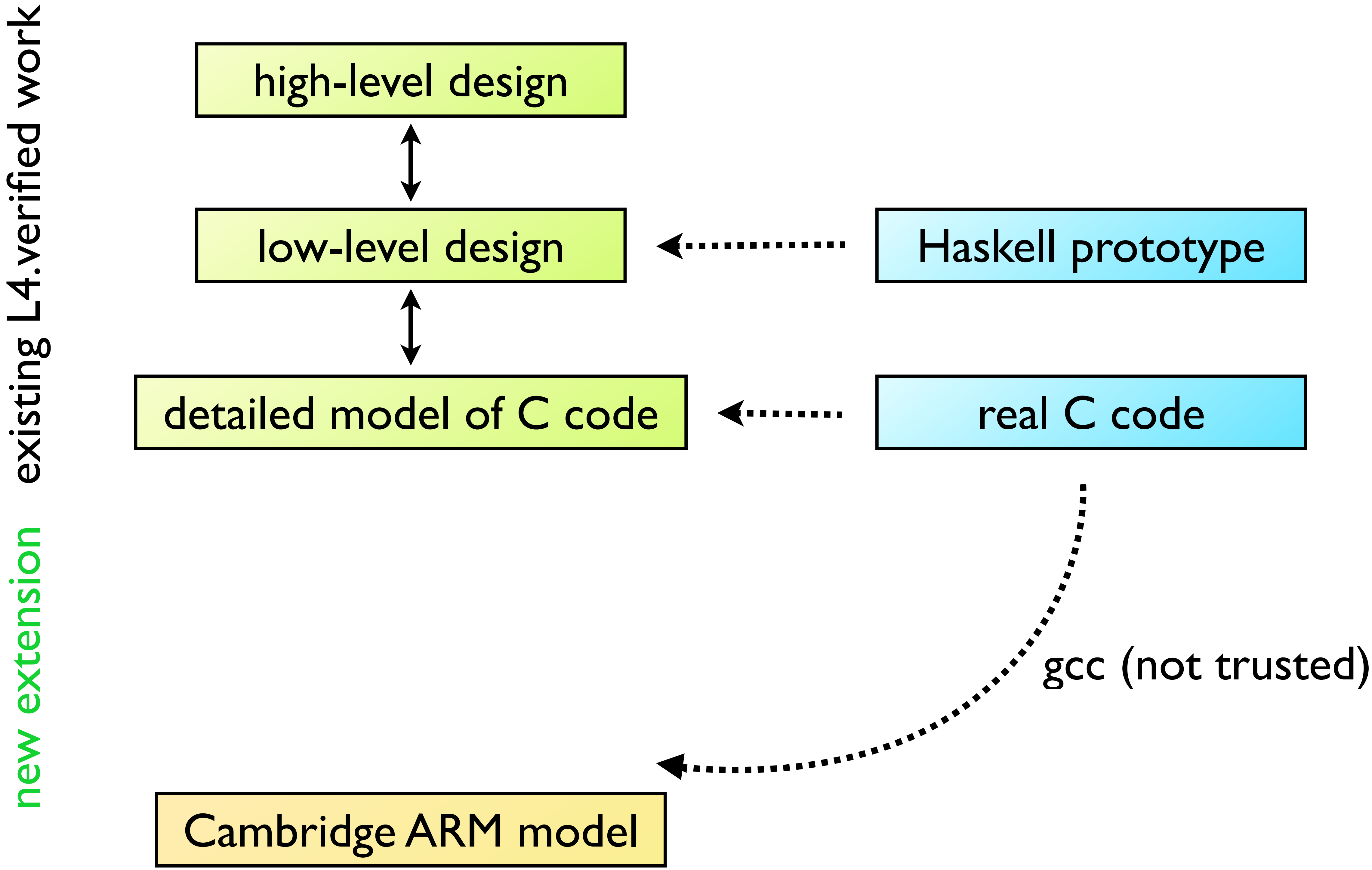

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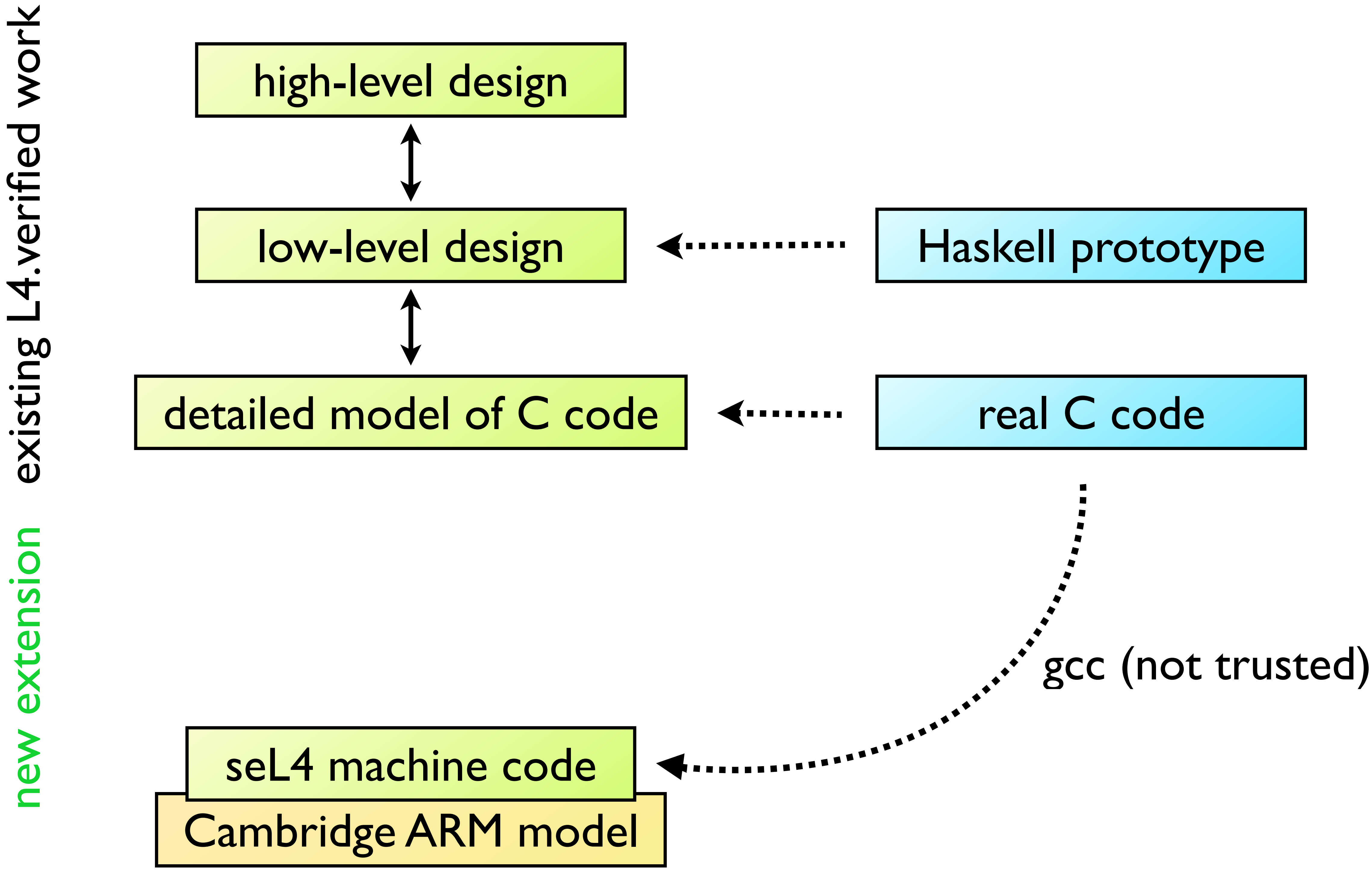

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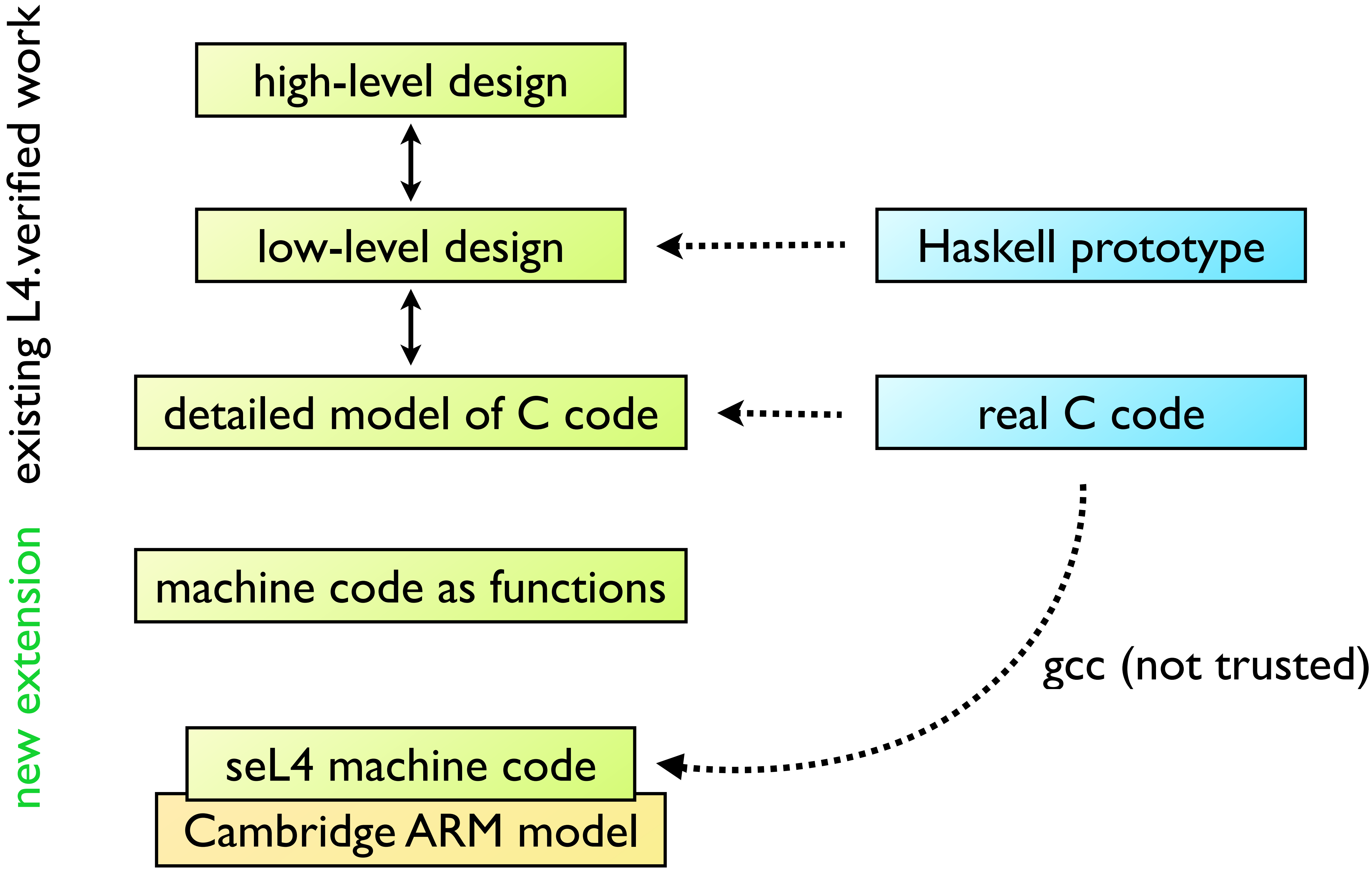

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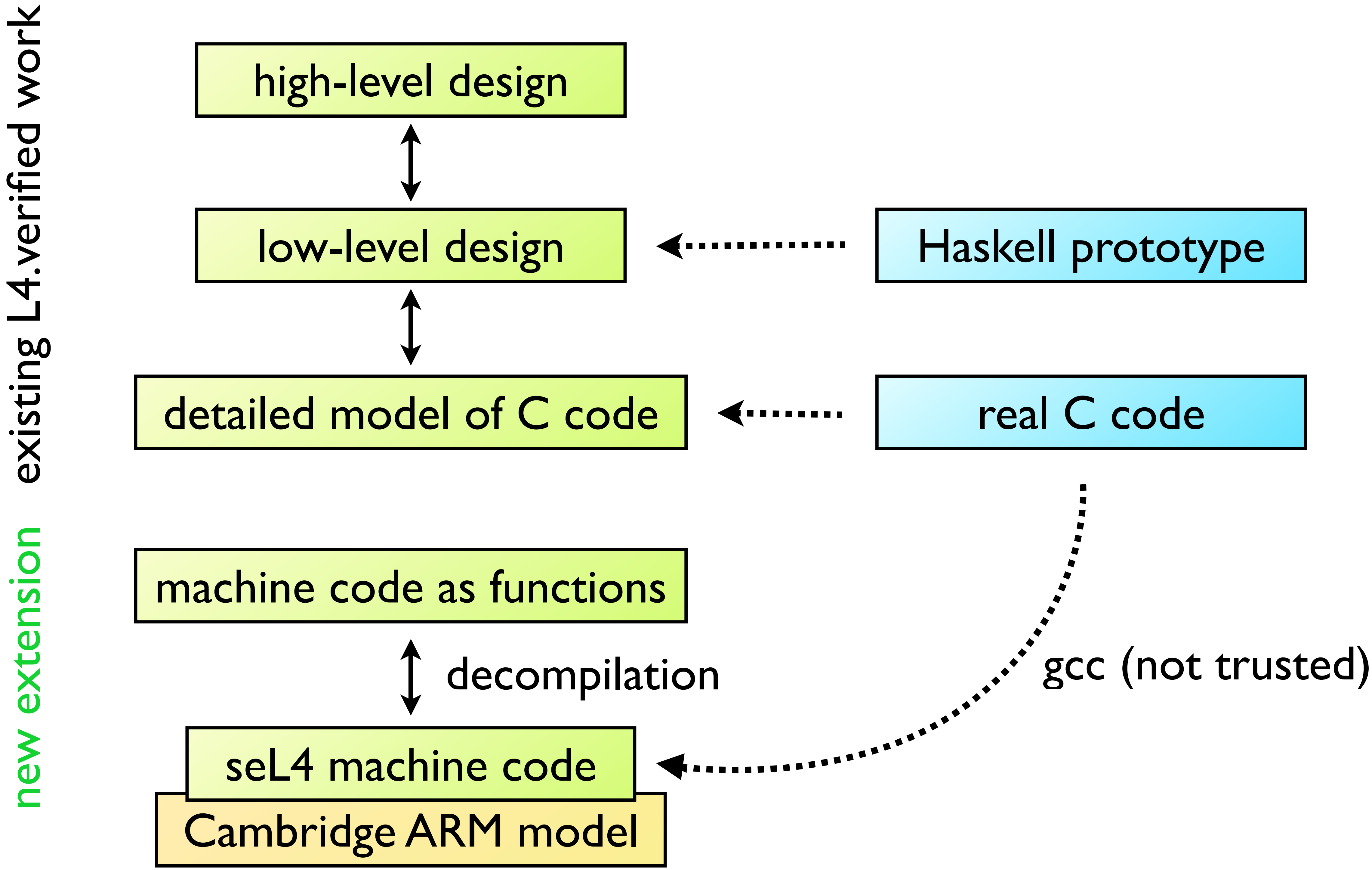

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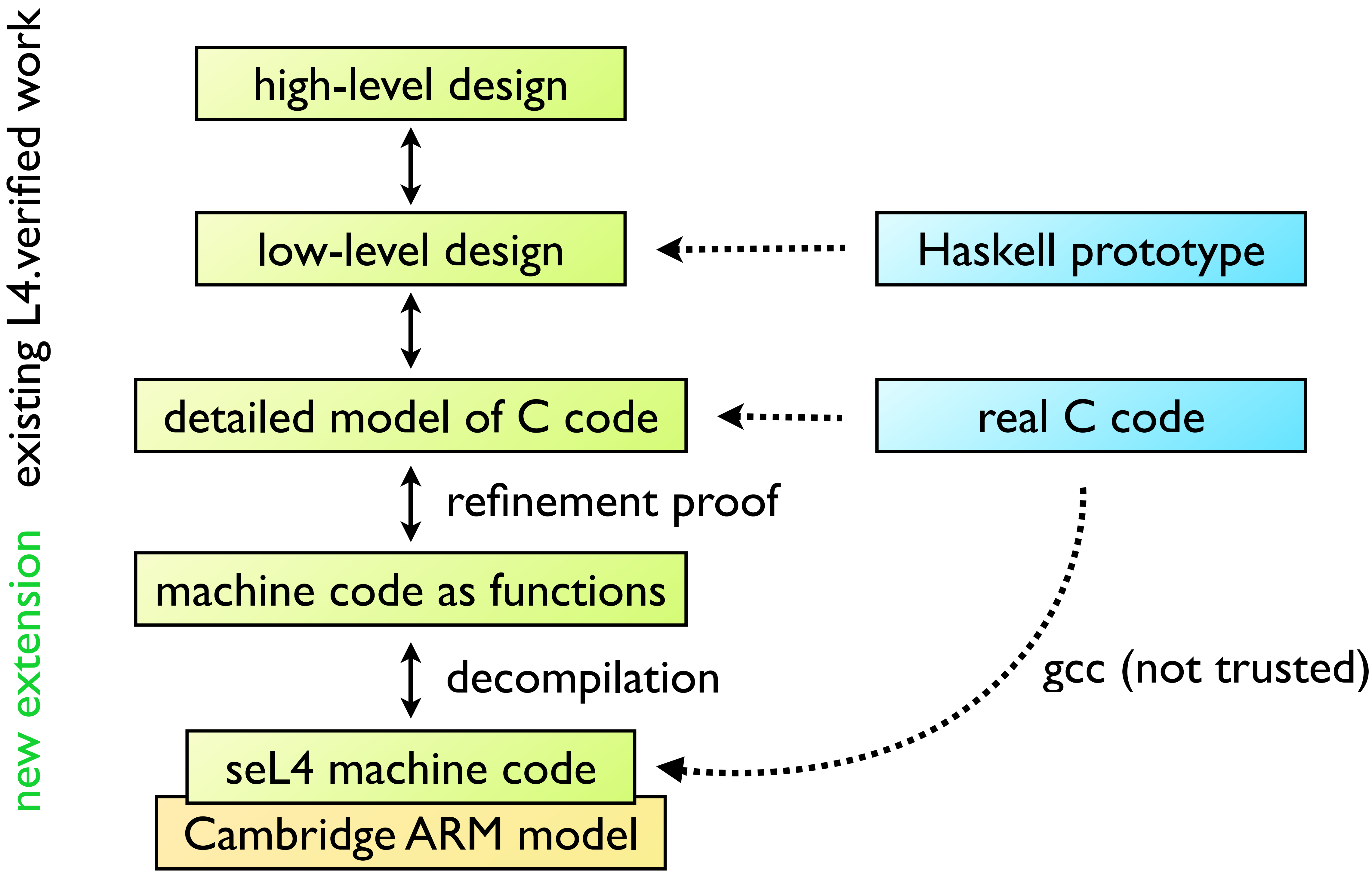
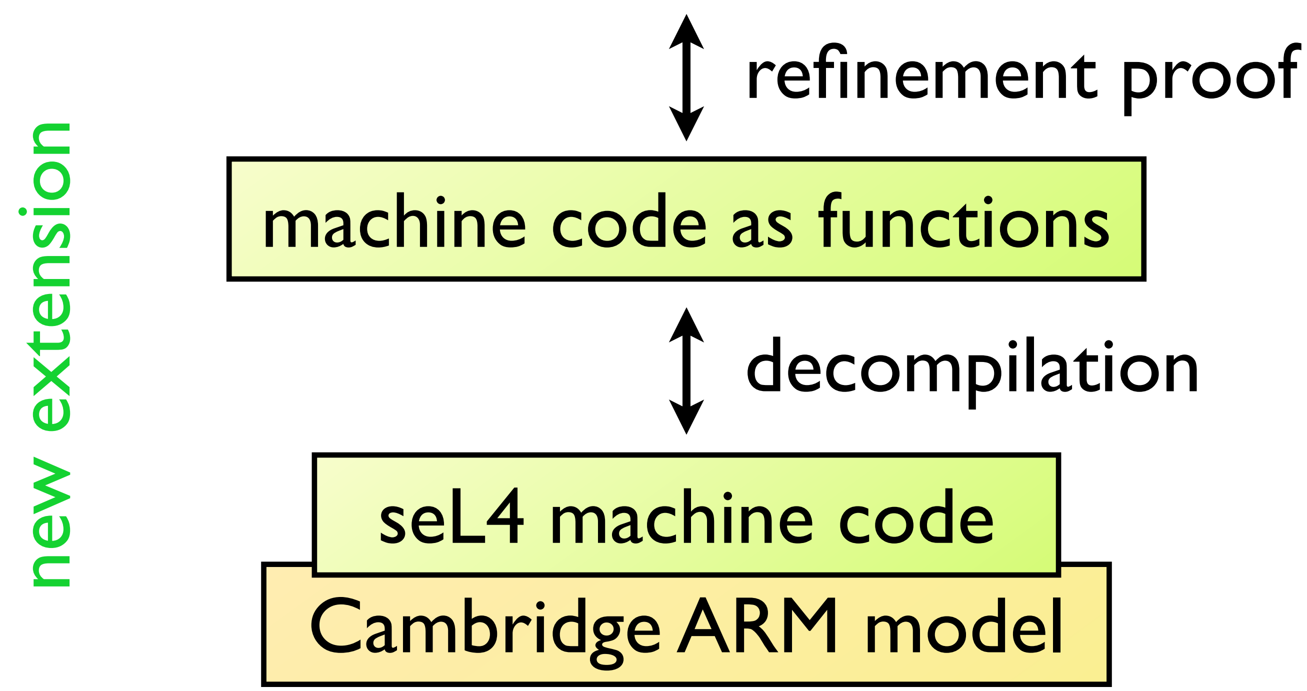


Translation validation

Translation Validation efforts:

- Pnueli et al, 1998. Introduce translation validation. Want to maintain a compiler correctness proof more easily.
- Necula, 2000. Translation validation for a C compiler. Also wants to pragmatically support compiler quality.
- Many others for many languages and levels of connection to compilers.
- …
- Sewell & Myreen, 2013. Not especially interested in compilers. Want to validate a source semantics.

Talk outline



Part 1: automatic translation / decompilation

Part 2: pseudo compilation and refinement proof (SMT)

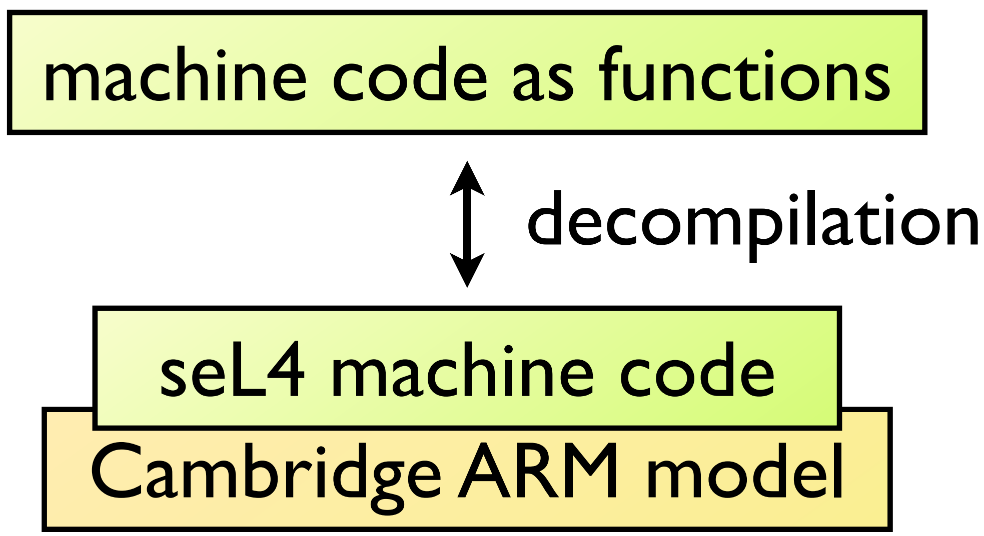
Cambridge ARM model

Cambridge ARM model developed by Anthony Fox

- high-fidelity model of the ARM instruction set architecture formalised in HOL4 theorem prover
- originates in a project on hardware verification (ARM6 verification)
- extensively tested against different hardware implementations

Web: http://www.cl.cam.ac.uk/~acjf3/arm/

Stage 1: decompilation



Decompilation

Sample C code:

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

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machine code:

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e0810000   add   r0, r1, r0
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decompilation via ARM model

Resulting function:

```
avg (r0, r1) = let r0 = r1 + r0 in
               let r0 = r0 >> 1 in
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HOL4 certificate theorem:

{ R0 i * R1 j * LR lr * PC p }
p : e0810000 e1a000a0 e12fff1e
{ R0 (avg(i,j)) * R1 _ * LR _ * PC lr }

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separation logic: *

Decompilation

How to decompile:

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Decompilation

{ R0 i * R1 j * PC p }
p+0 : e0810000
{ R0 (i+j) * R1 j * PC (p+4) }

{ R0 i * PC (p+4) }
p+4 : e1a000a0
{ R0 (i >> 1) * PC (p+8) }

{ LR lr * PC (p+8) }
p+8 : e12fff1e
{ LR lr * PC lr }

How to decompile:

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e0810000  add   r0, r1, r0
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1. derive Hoare triple theorems using Cambridge ARM model

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2

{ R0 i * R1 j * LR lr * PC p }
p : e0810000 e1a000a0 e12fff1e
{ R0 ((i+j)>>1) * R1 j * LR lr * PC lr }

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1. derive Hoare triple theorems using Cambridge ARM model
2. compose Hoare triples

Decompilation

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3

avg (i,j) = (i+j)>>1

How to decompile:

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e1a000a0   lsr   r0, r0, #1
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1. derive Hoare triple theorems using Cambridge ARM model
2. compose Hoare triples
3. extract function

(Loops result in recursive functions.)

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- seL4 is ~12,000 lines of machine code
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- compiled using gcc -O1 and gcc -O2
  - ✓ gcc implements ARM/C calling convention
- must be compatible with L4.verified proof
  - ➡ stack requires special treatment

Stack visible in machine code

C code:

```
uint avg8 (uint x0, x1, x2, x3, x4, x5, x6, x7) {
  return (x0+x1+x2+x3+x4+x5+x6+x7) / 8;
}
```

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gcc

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add   r1, r1, r0
add   r1, r1, r2
ldr   r2, [sp]
add   r1, r1, r3
add   r0, r1, r2
ldmib sp, {r2, r3}
add   r0, r0, r2
add   r0, r0, r3
ldr   r3, [sp, #12]
add   r0, r0, r3
lsr   r0, r0, #3
bx    lr
```

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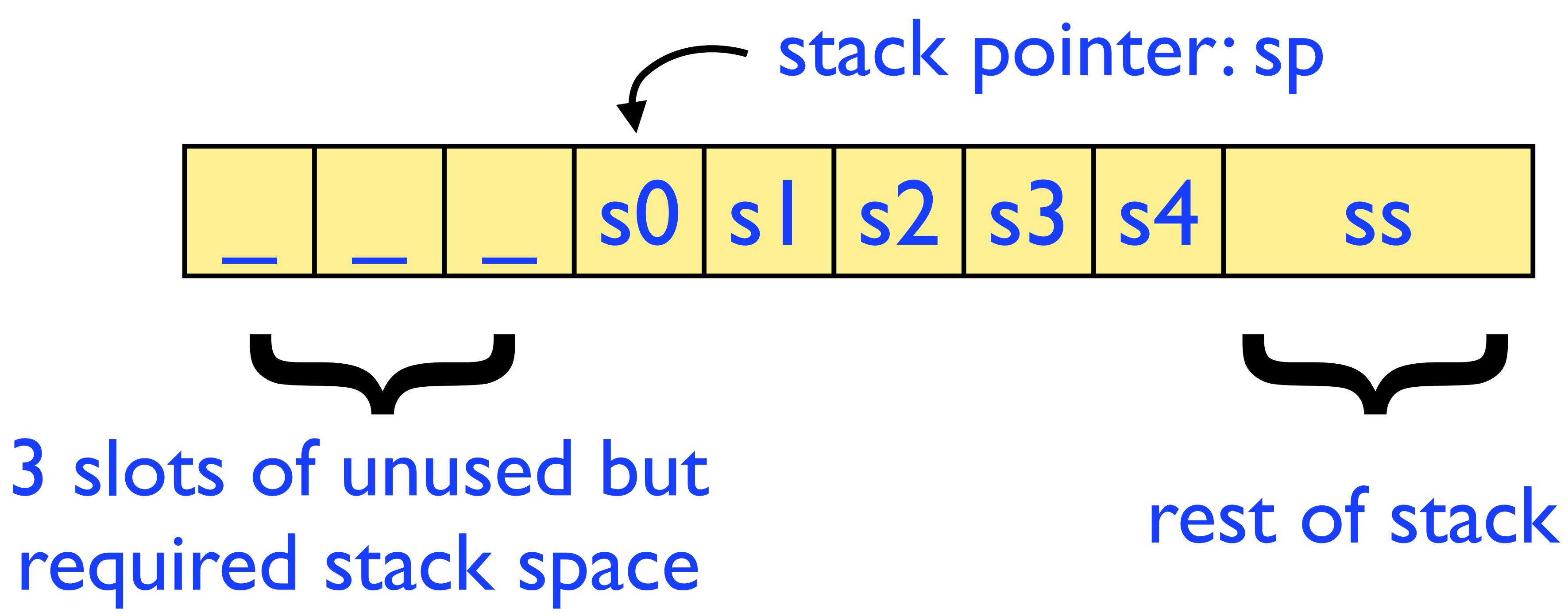
```

Some arguments are passed on the stack, and cause memory ops in machine code

... that are not present in C semantics.

Solution

Use separation-logic inspired approach



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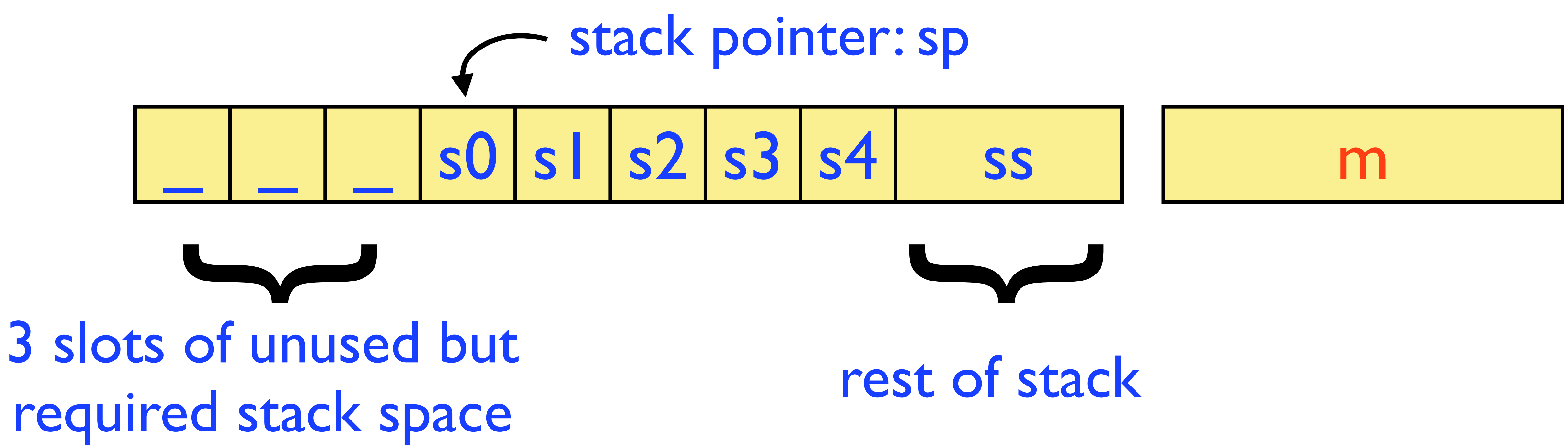

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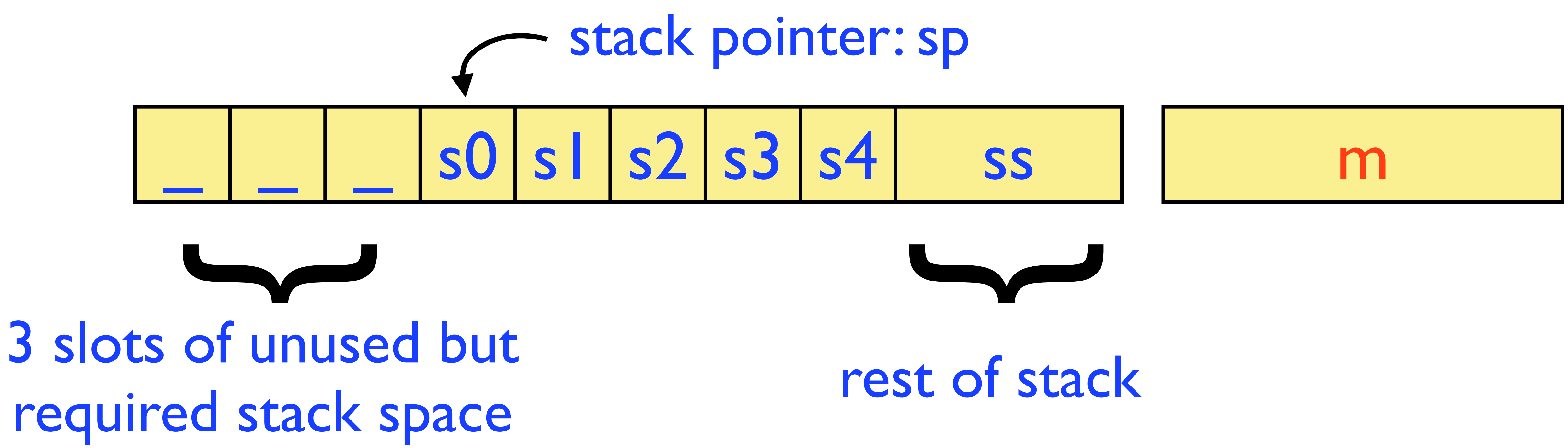

stack sp 3 (s0::s1::s2::s3::s4::ss)

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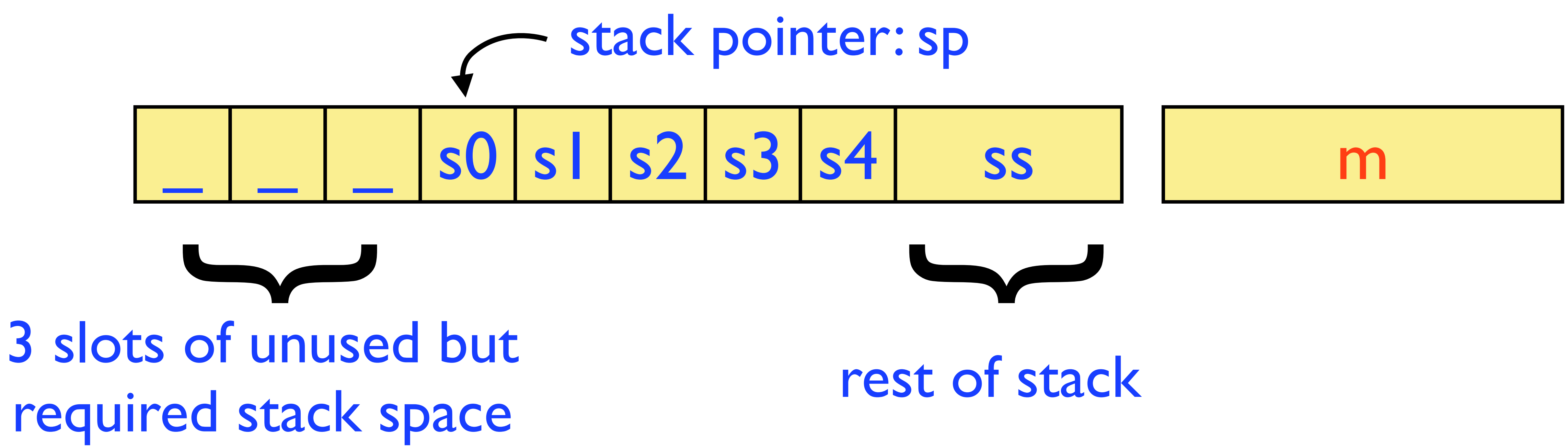

stack sp 3 (s0::s1::s2::s3::s4::ss) * memory m

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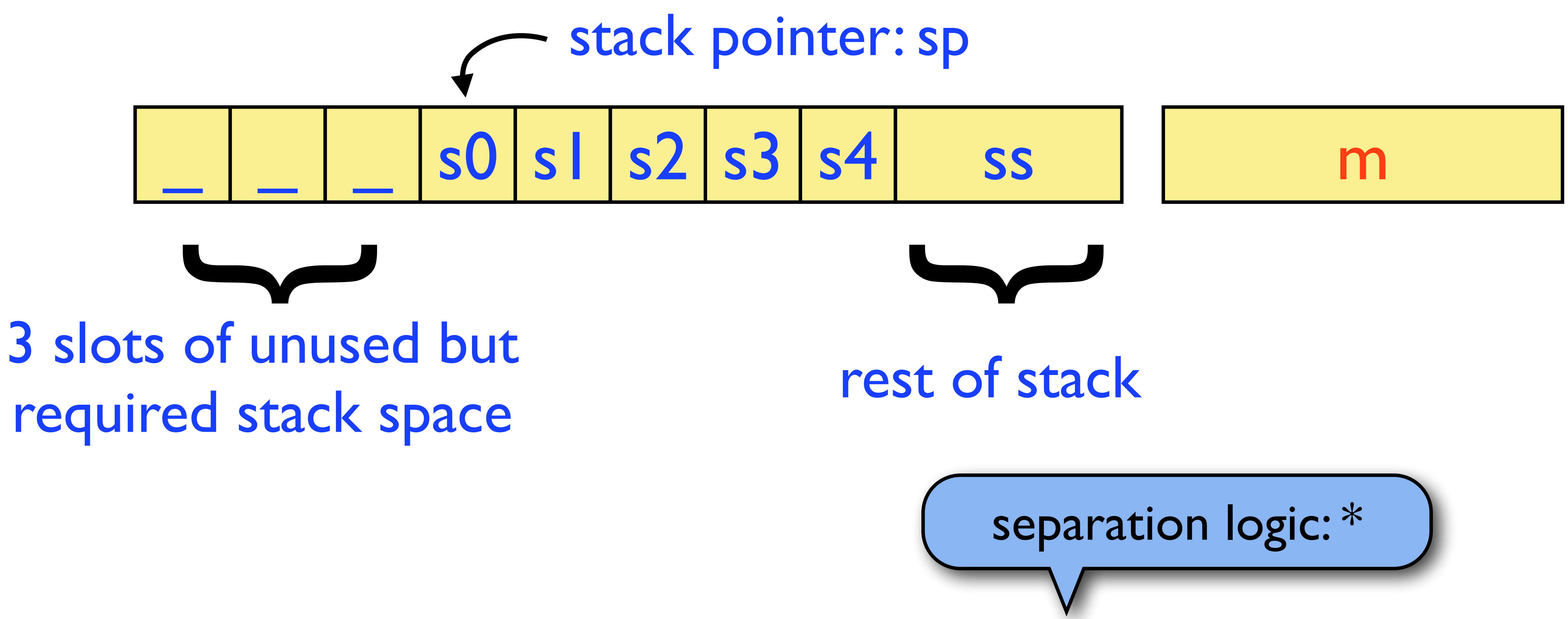

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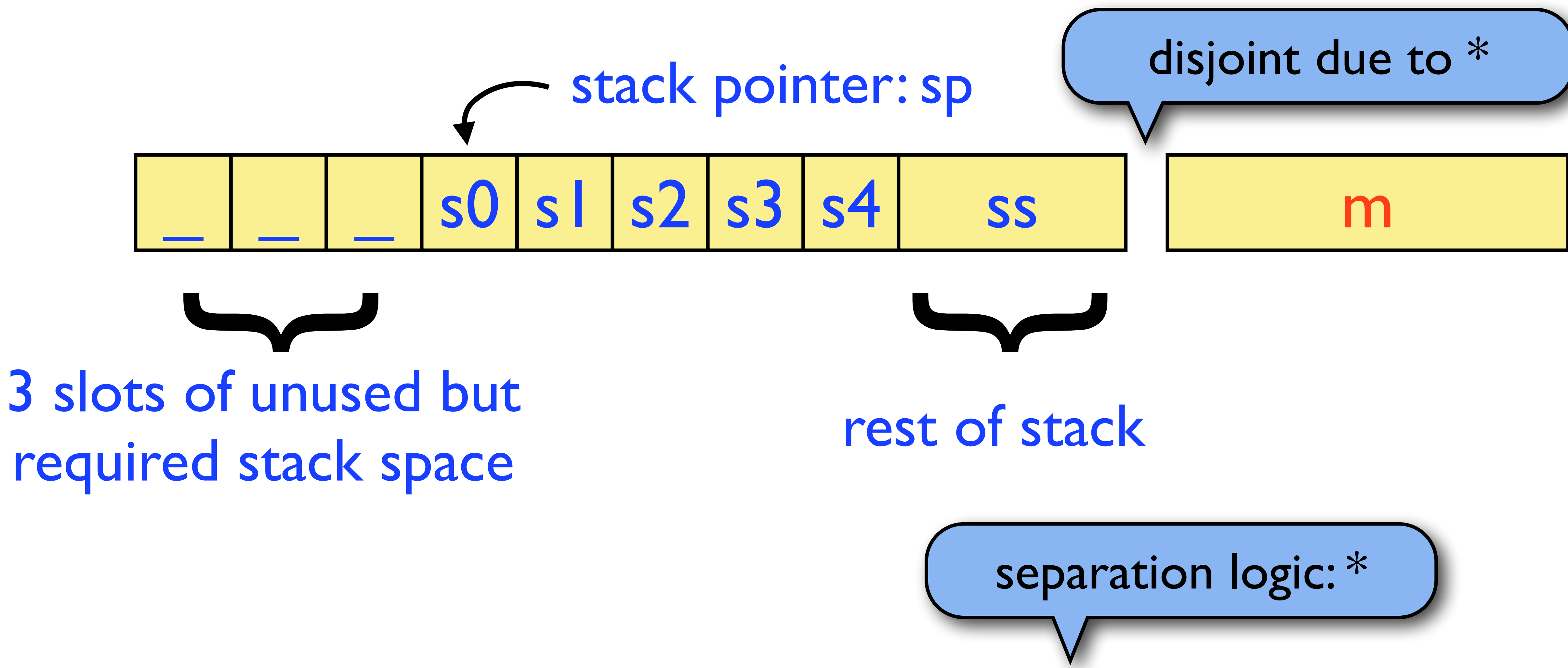

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Solution (cont.)

```
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ldr  r2, [sp]
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add r0, r1, r2
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ldr  r3, [sp, #12]
add r0, r0, r3
lsr  r0, r0, #3
bx   lr
```

Method:

1. static analysis to find stack operations,
2. derive stack-specific Hoare triples,
3. then run decompiler as before.

Solution (cont.)

```
    add r1, r1, r0
    add r1, r1, r2
➡   ldr   r2, [sp]
    add r1, r1, r3
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Method:

1. static analysis to find stack operations,
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Result

Stack load/stores become straightforward assignments.

```
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add r1, r1, r2
ldr  r2, [sp]
add r1, r1, r3
add r0, r1, r2
ldmib sp, {r2, r3}
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```

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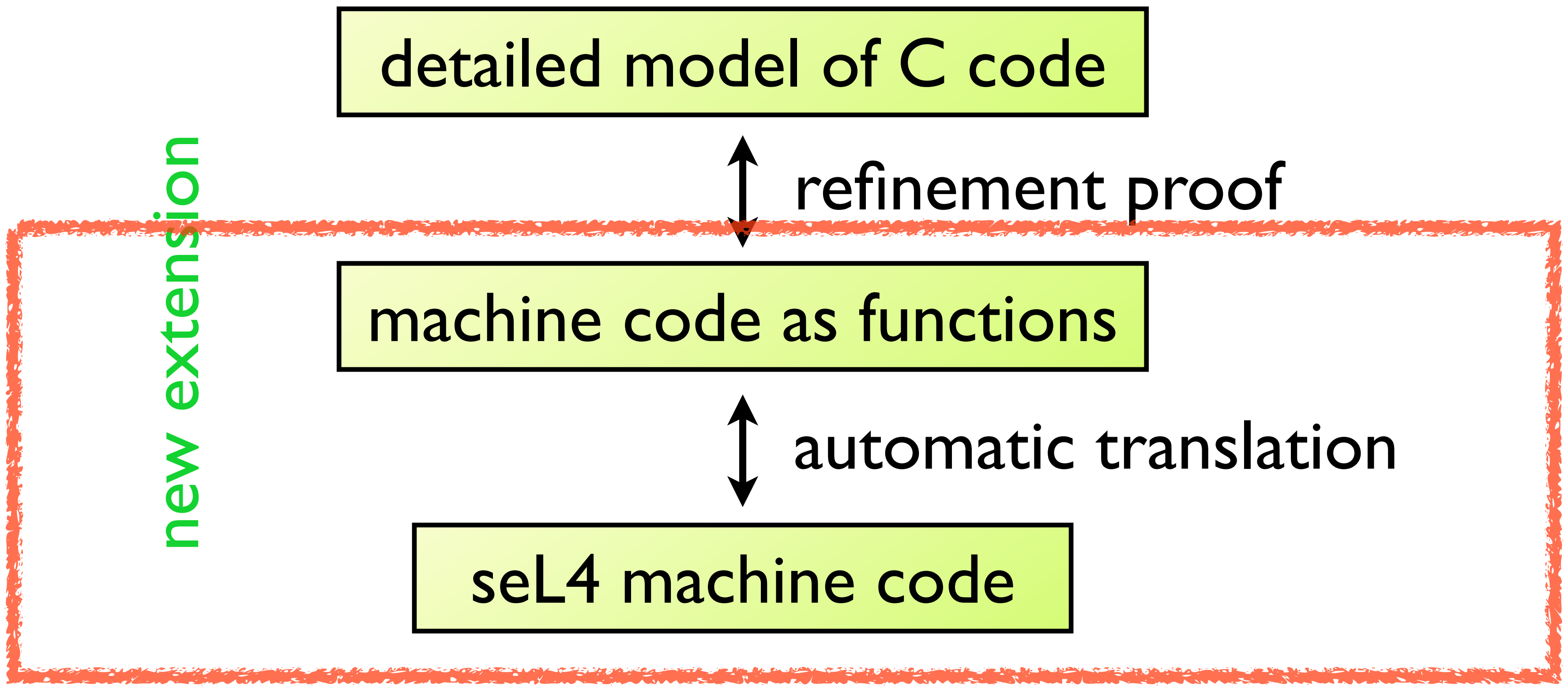
avg8(r0,r1,r2,r3,s0,s1,s2,s3) =
  let r1 = r1 + r0 in
  let r1 = r1 + r2 in
  let r2 = s0 in
  let r1 = r1 + r3 in
  let r0 = r1 + r3 in
  let (r2,r3) = (s1,s2) in
  let r0 = r0 + r2 in
  let r0 = r0 + r3 in
  let r3 = s3 in
  let r0 = r0 + r3 in
  let r0 = r0 >> 3 in
    r0
```

Other C-specifics

- struct as return value
  - case of passing pointer of stack location
  - stack assertion strong enough
- switch statements
  - position dependent
  - must decompile elf-files, not object files
- infinite loops in C
  - make gcc go weird
  - must be pruned from control-flow graph

Moving on to stage 2



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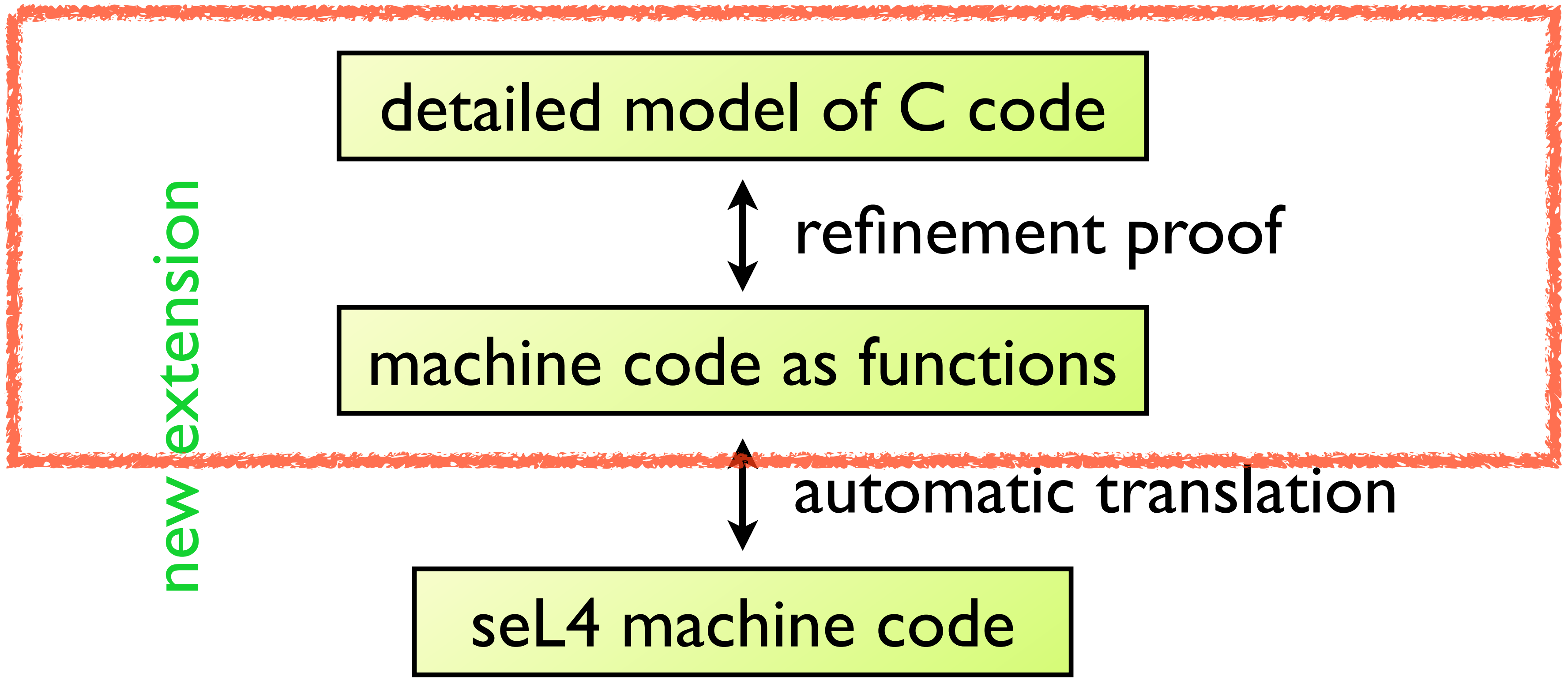
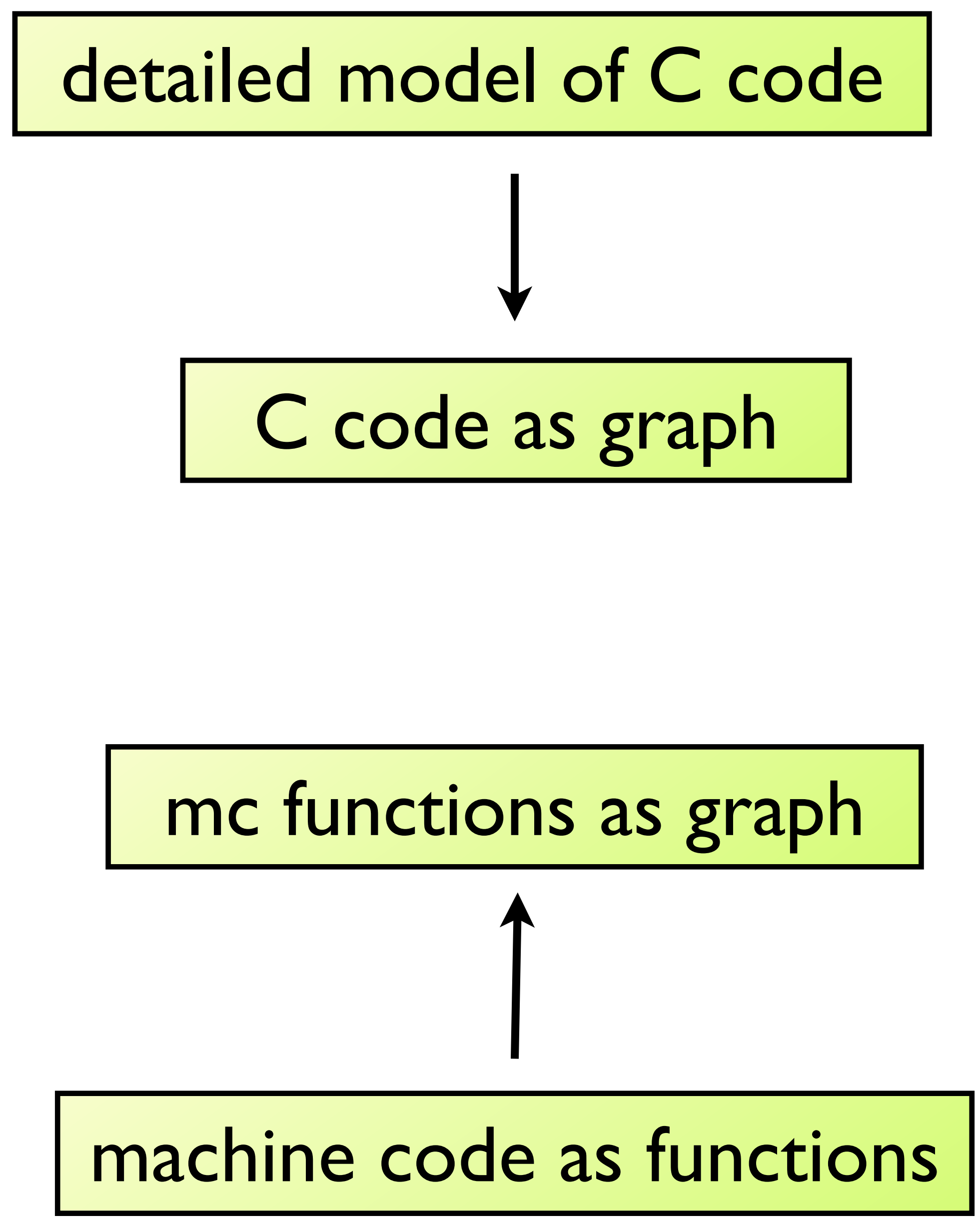


Approach for refinement proof

detailed model of C code

machine code as functions

Approach for refinement proof



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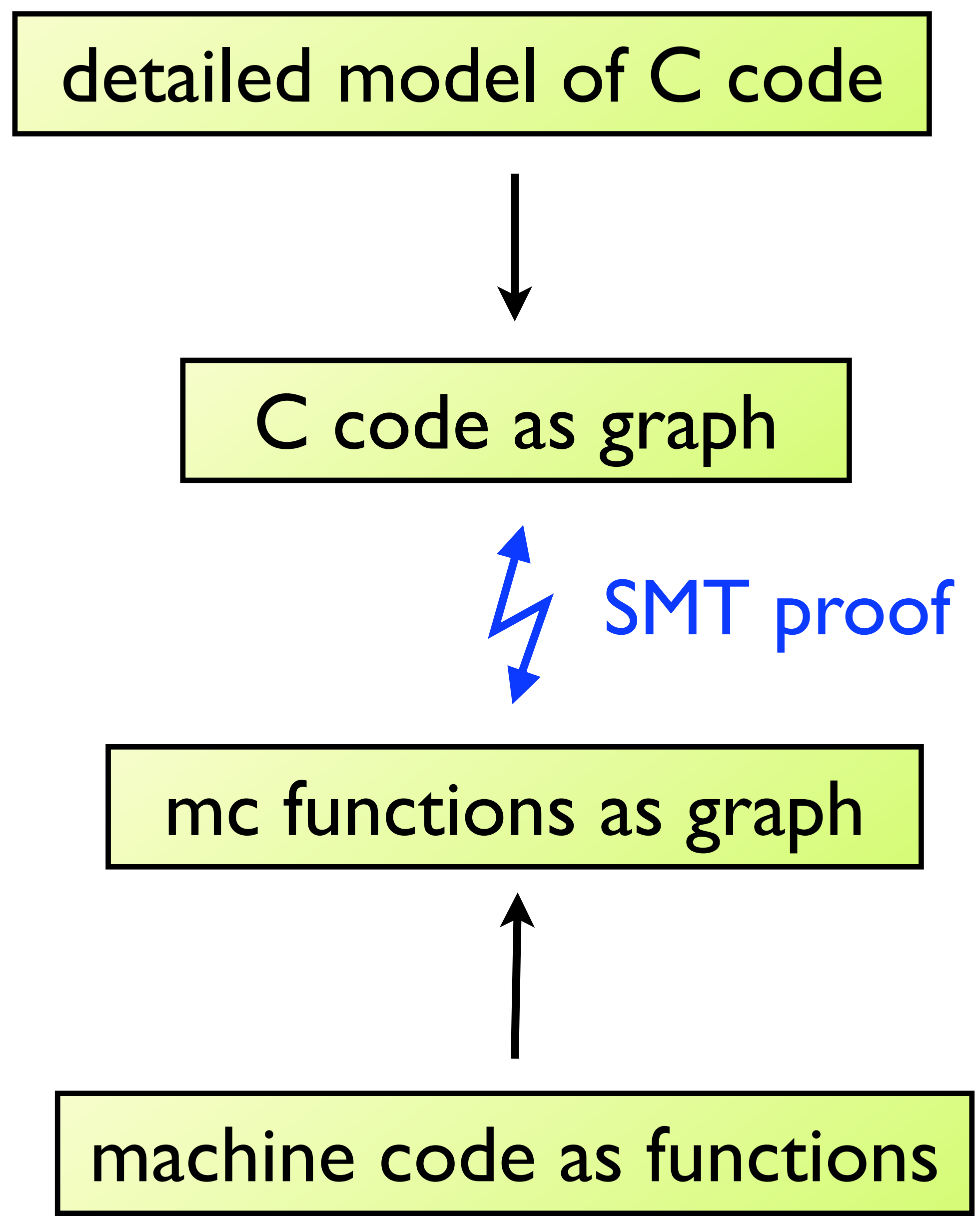

Translating C into graphs

```
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;
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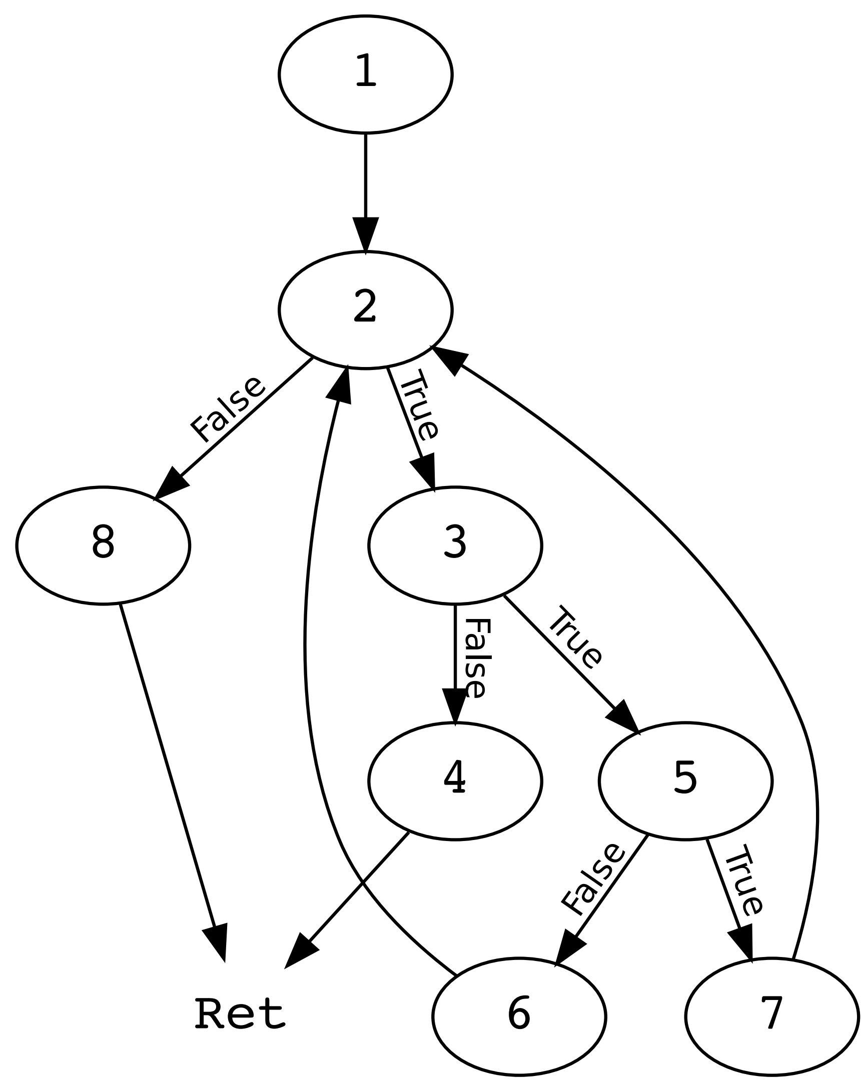

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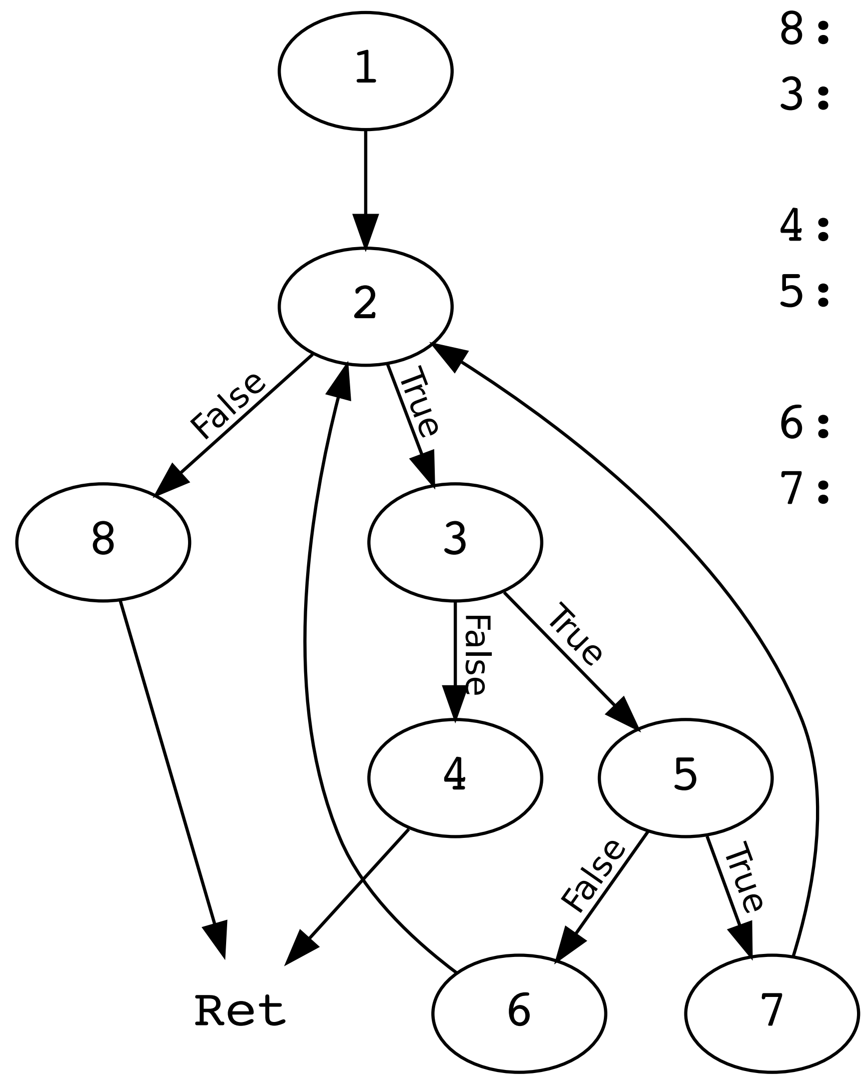



```
1: p := Mem[t + 4];

2: p == 0 ?

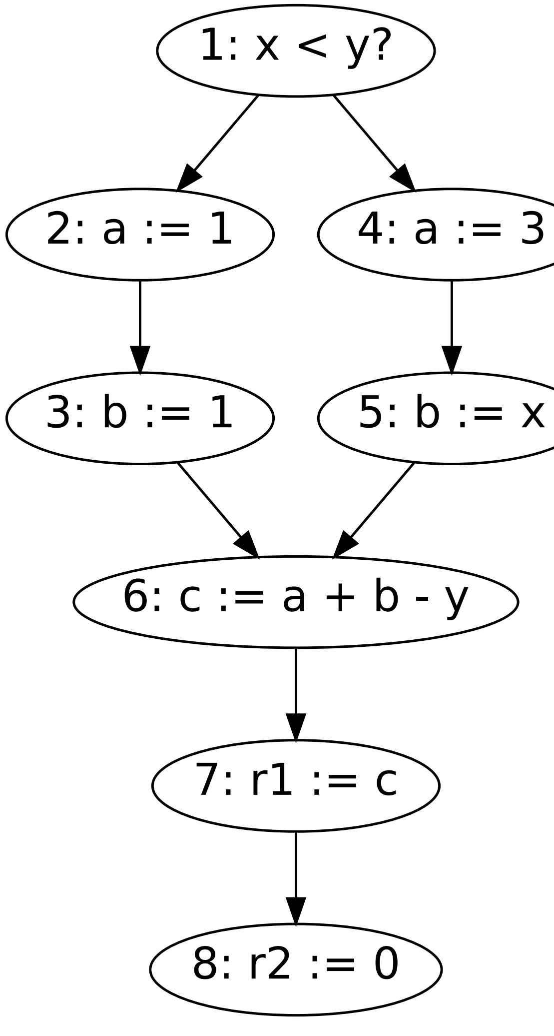
8: ret := 0
3: Mem[p] == k ?

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

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

Translating mc functions into graphs

```
f x y =
  let (a, b) = if x < y
    then (1, 2)
    else (3, x)
  in let c = a + b - y
  in (c, 0)
```



The SMT proof step

Following Pnuelli's original translation validation, we split the proof step:

Part 1: proof search (proof script construction)

Part 2: proof checking (checking the proof script)

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The heavy lifting is done by calls to SMT solvers for both the proof search and checking.

Translating graphs into SMT exps

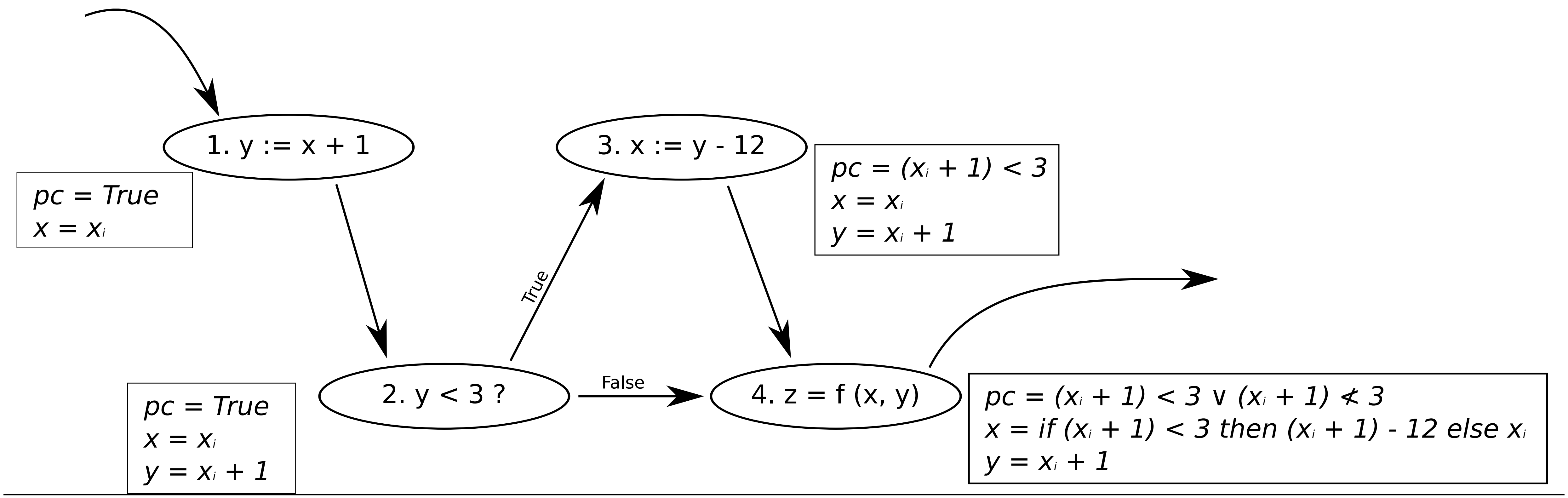
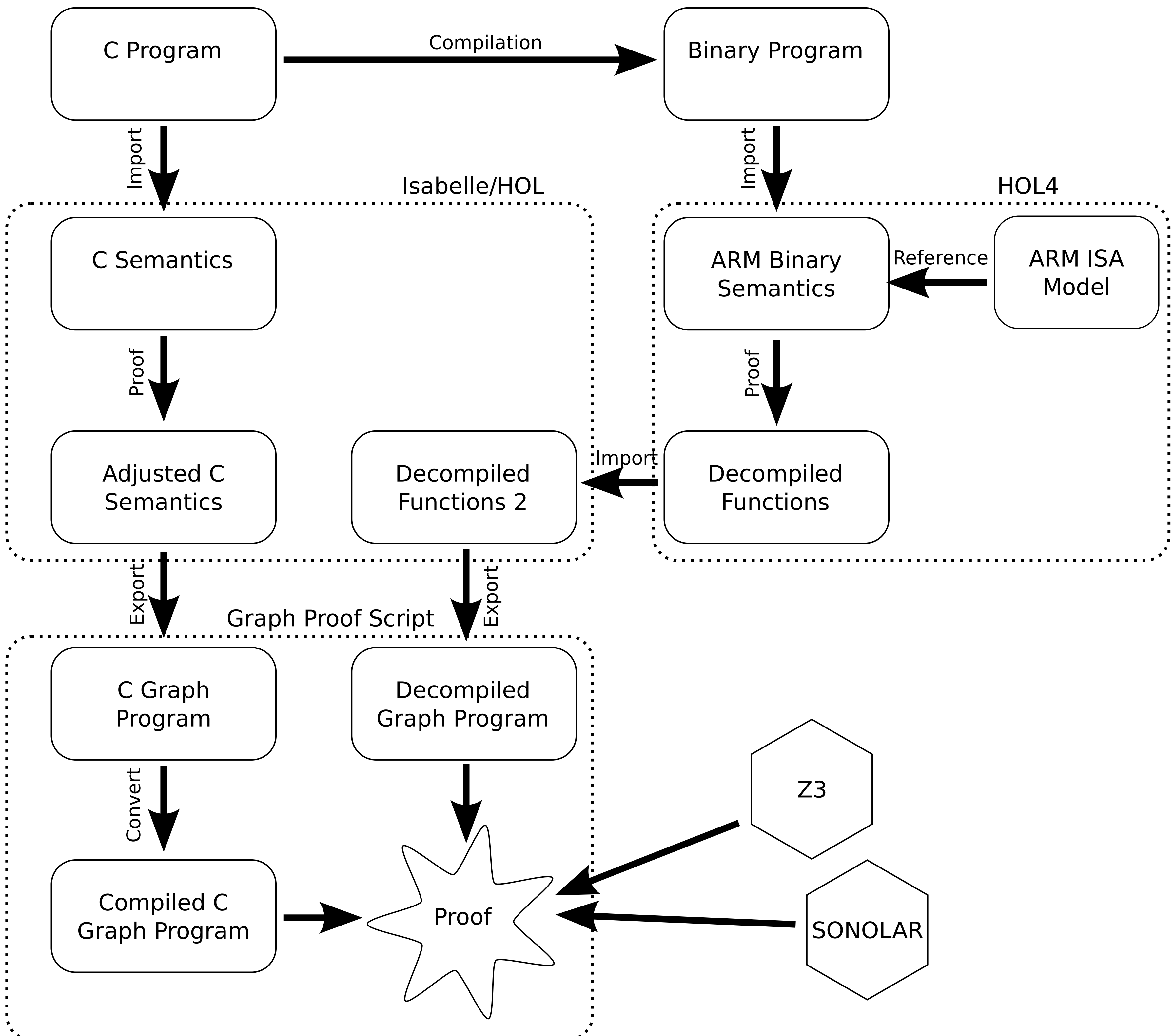


Figure 5. Example Conversion to SMT

Here: 'pc' is the accumulated path condition and variables (x, y etc.) are values w.r.t. inputs (x_i, y_i, etc.)

(The actual translation avoids a blow up in size...)

Full workflow



Results and Summary

We have (almost) proved a full connection between the verified C and seL4 binary.

	gcc -O1	gcc -O2
Instructions in Binary	11 736	12 299
Decompiled Functions	260	259
- Placeholders		3
Function Pairings	260	225
Successes	234	145
Failures	0	18
Aborted	26	62
- Machine Operations	21	13
- Nested Loops	3	2
- Machine Operations Inlined	2	47
Time Taken in Proof	59m	4h 23m

Table 1. Decompilation and Proof Results