Using the Cambridge ARM model to verify the concrete machine code of seL4

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L4.verified

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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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L4.verified project assumes correctness of:

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- boot code
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- hardware management
- boot code (?)
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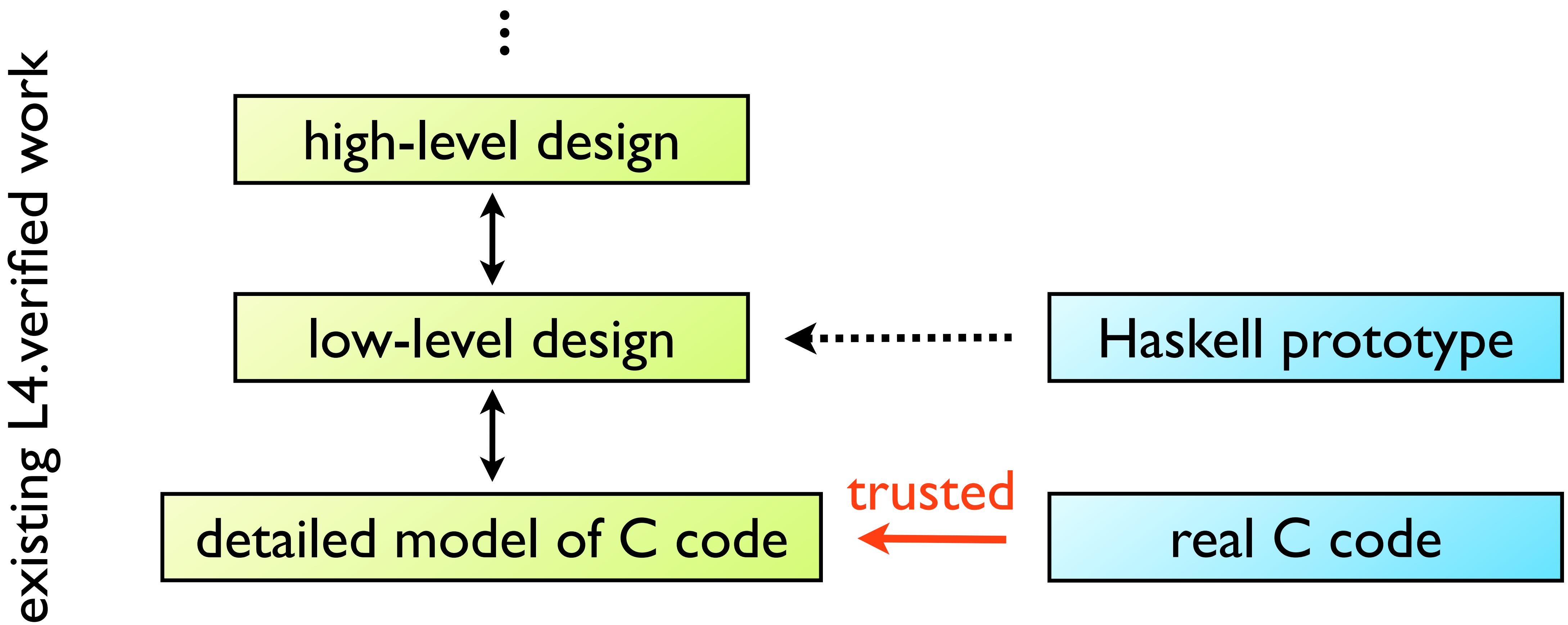

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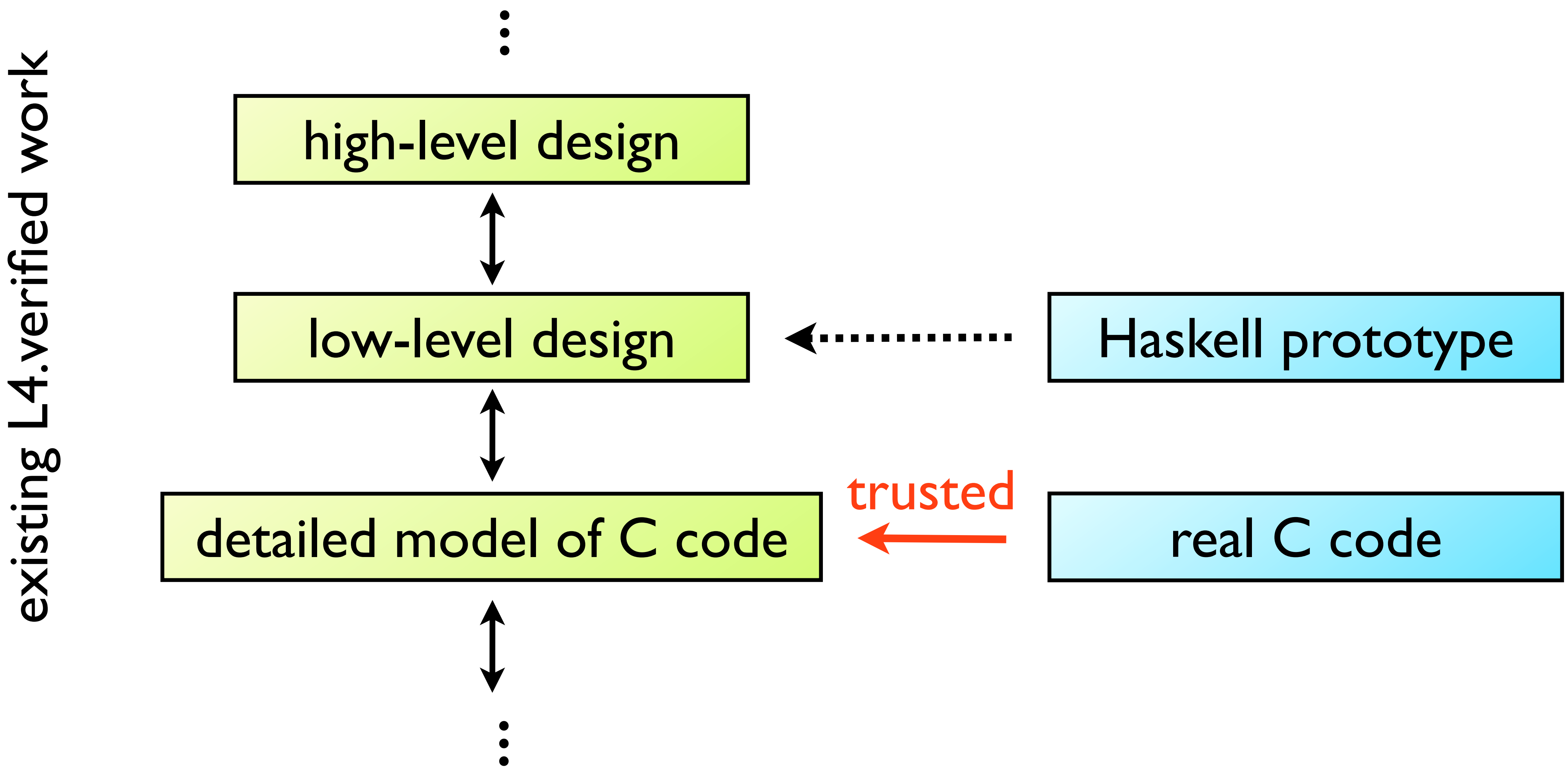

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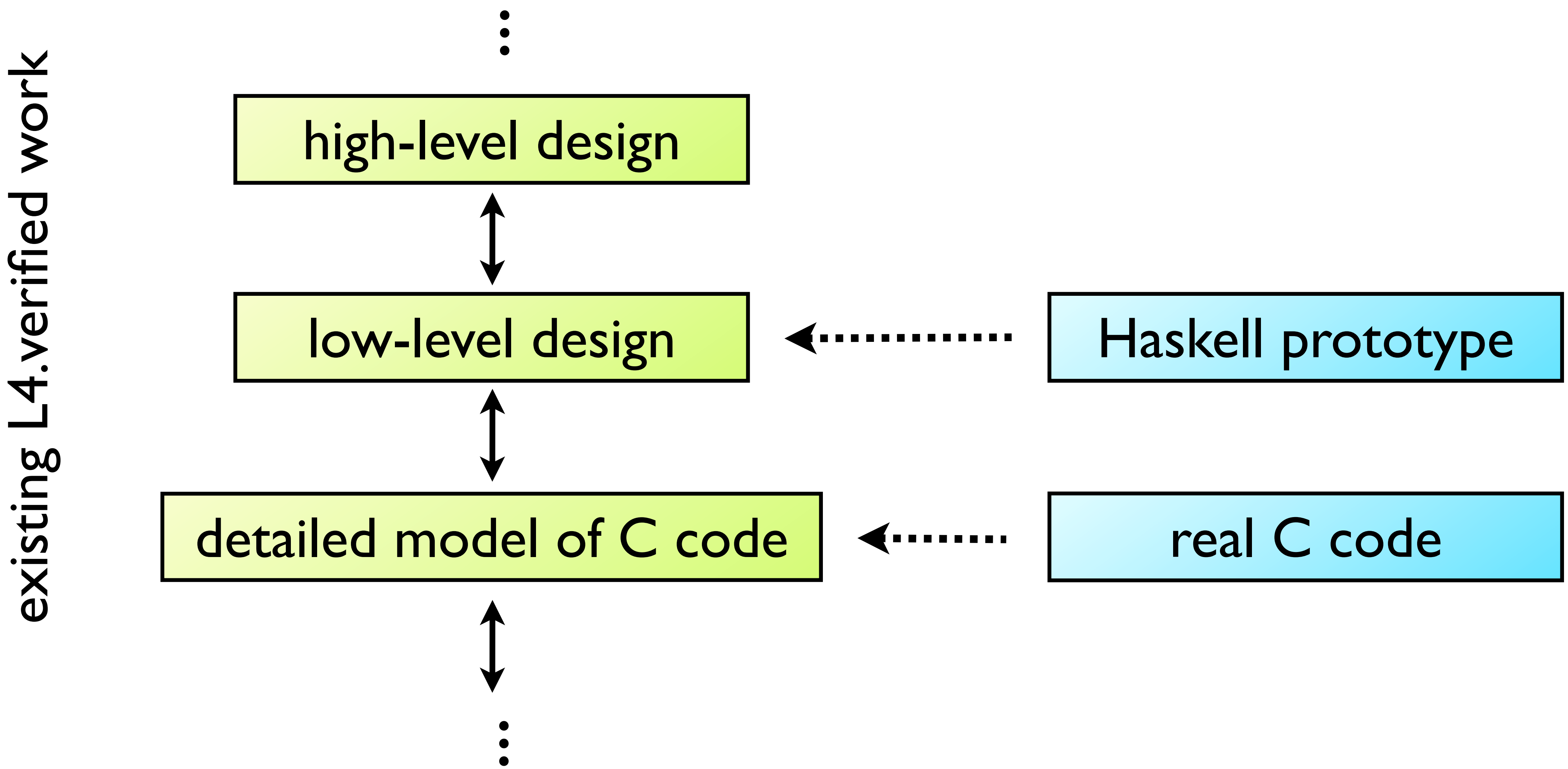

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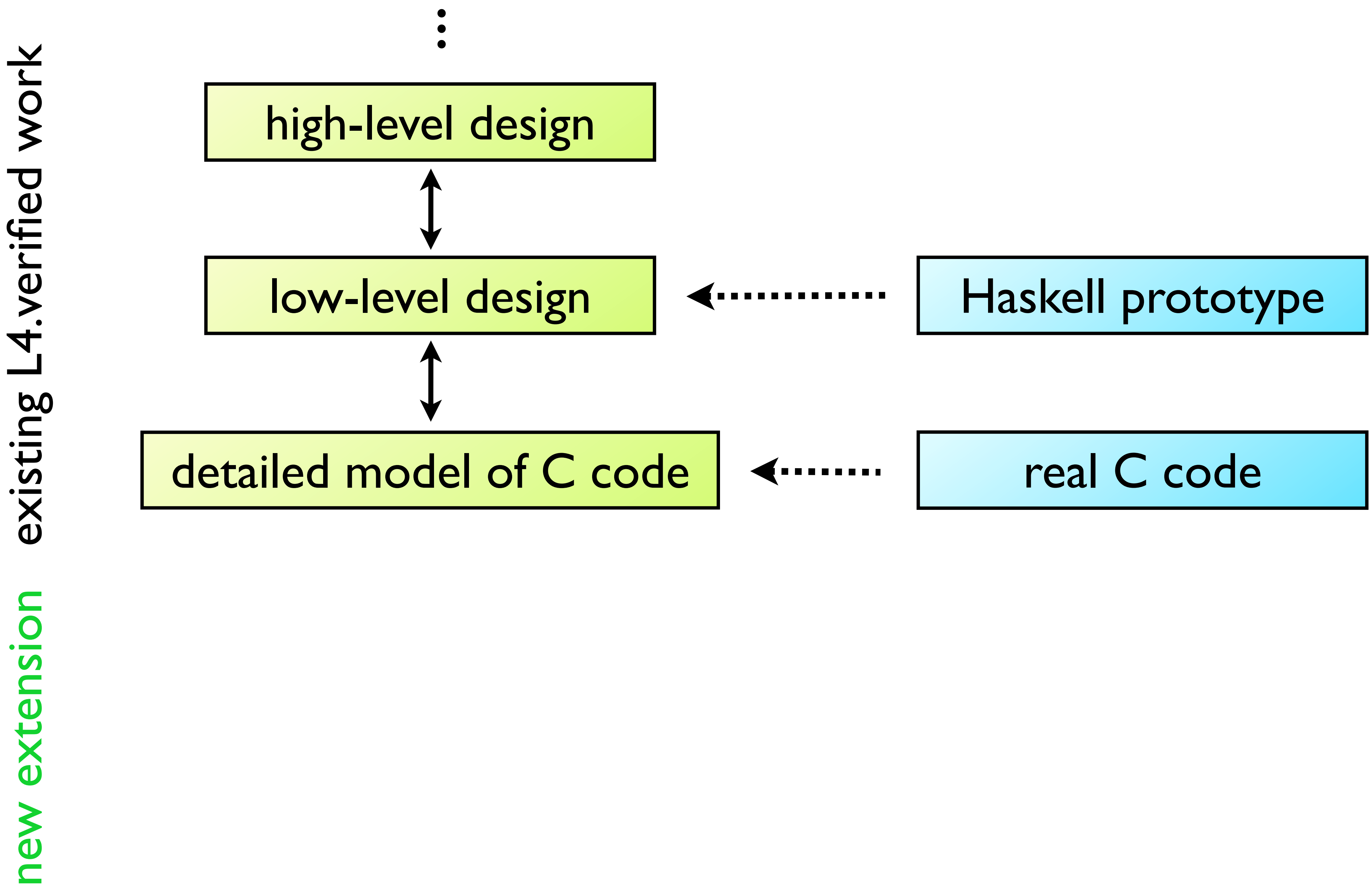
Connection to CompCert



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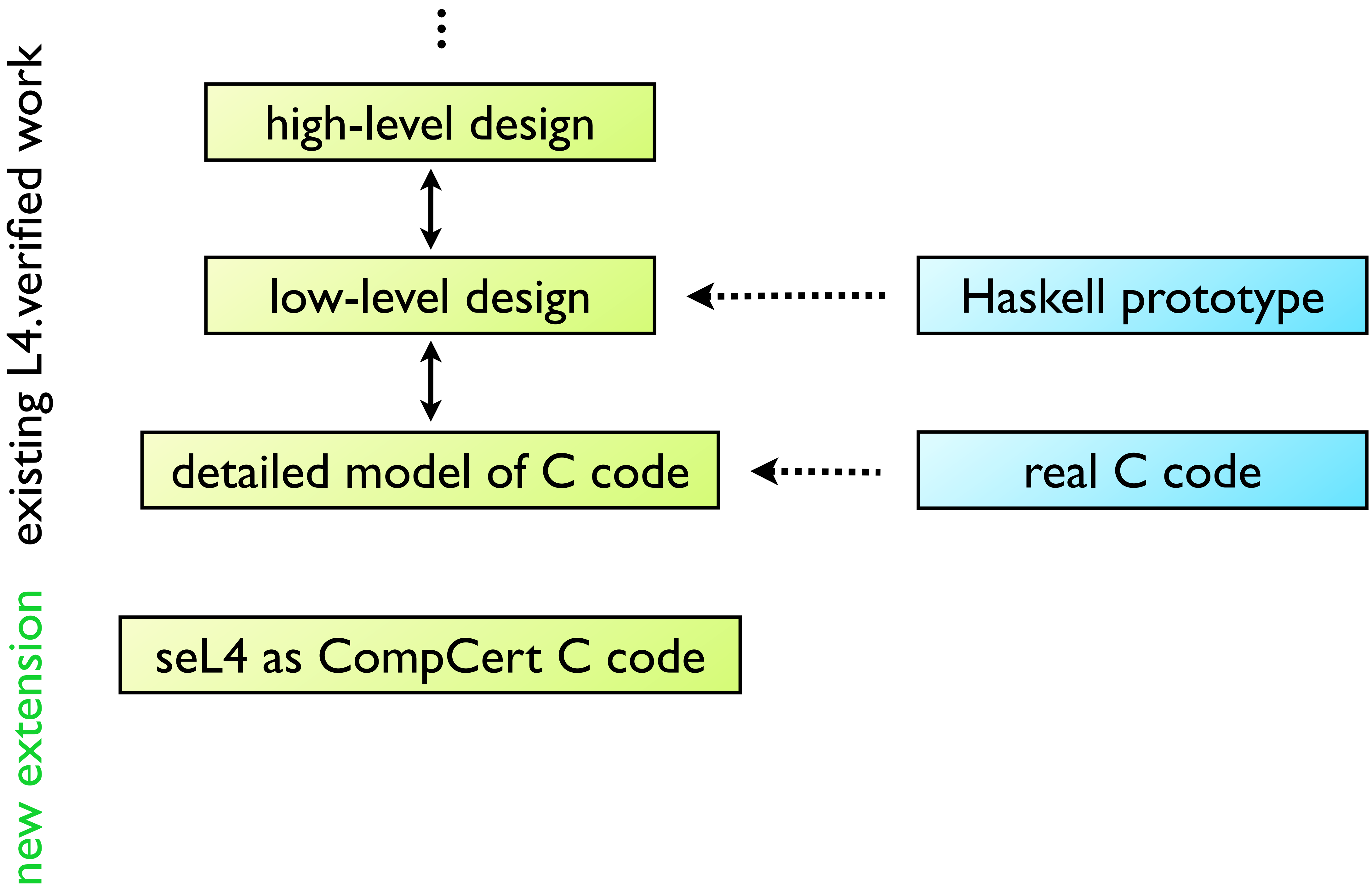

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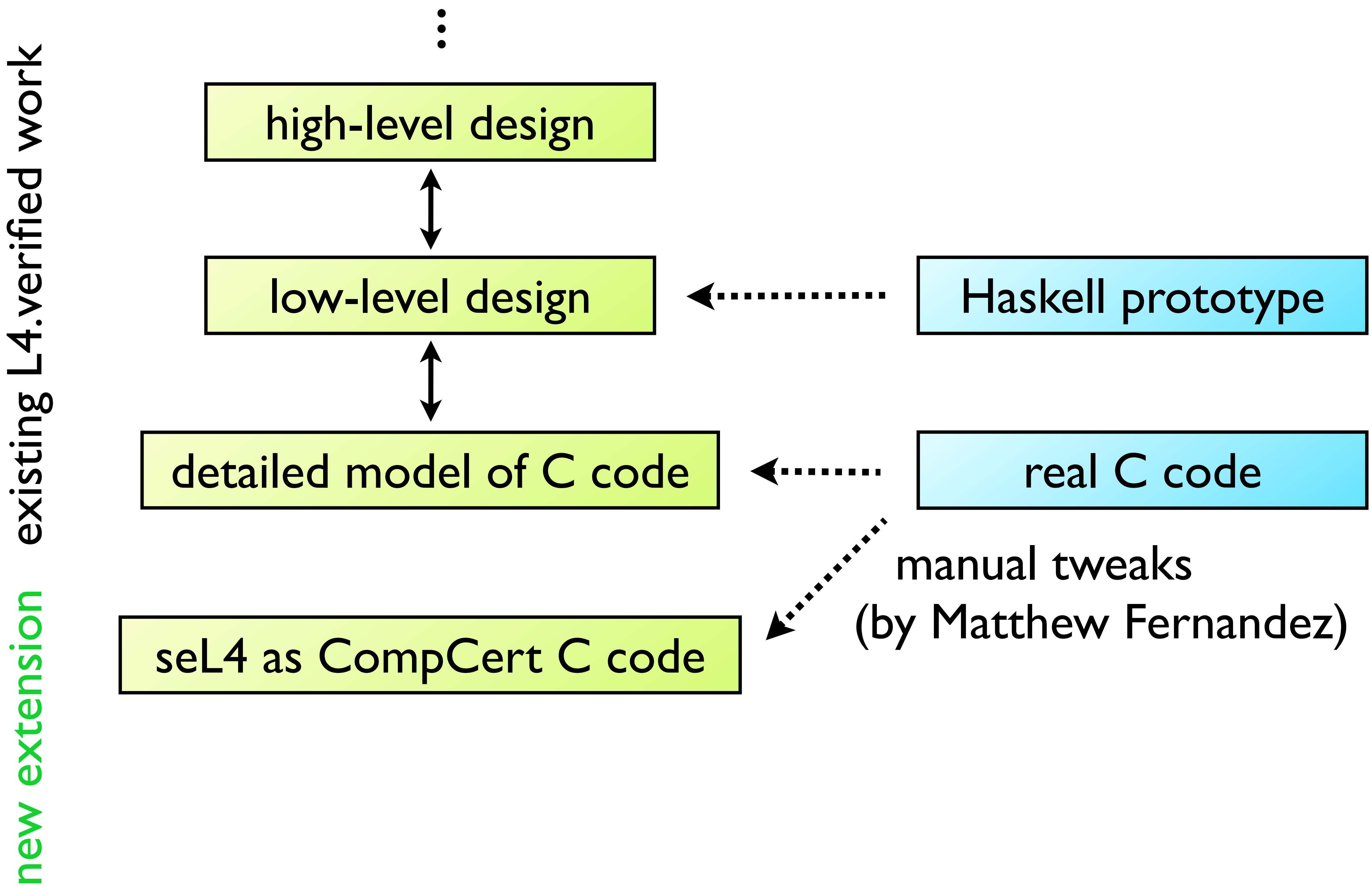

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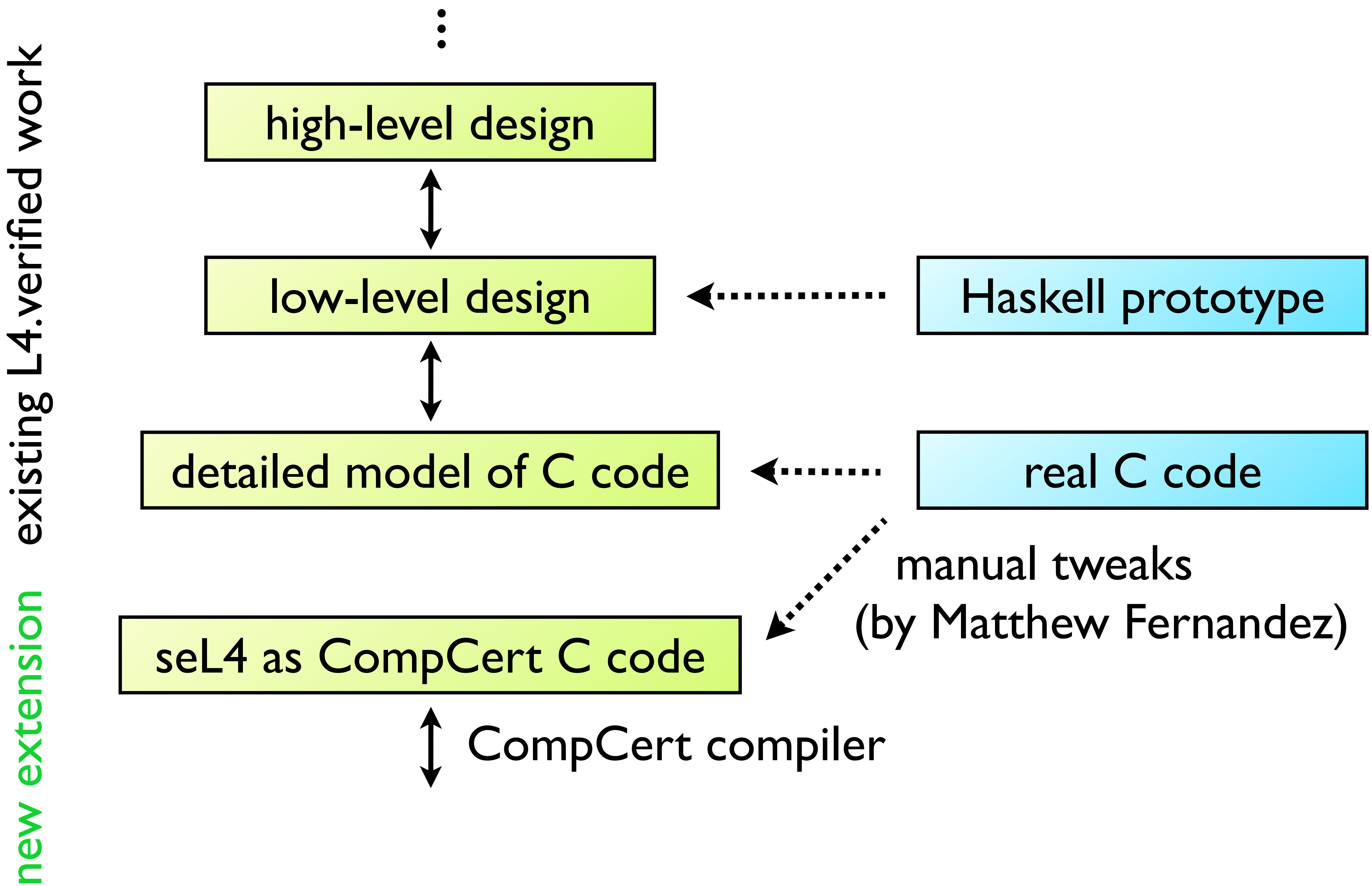

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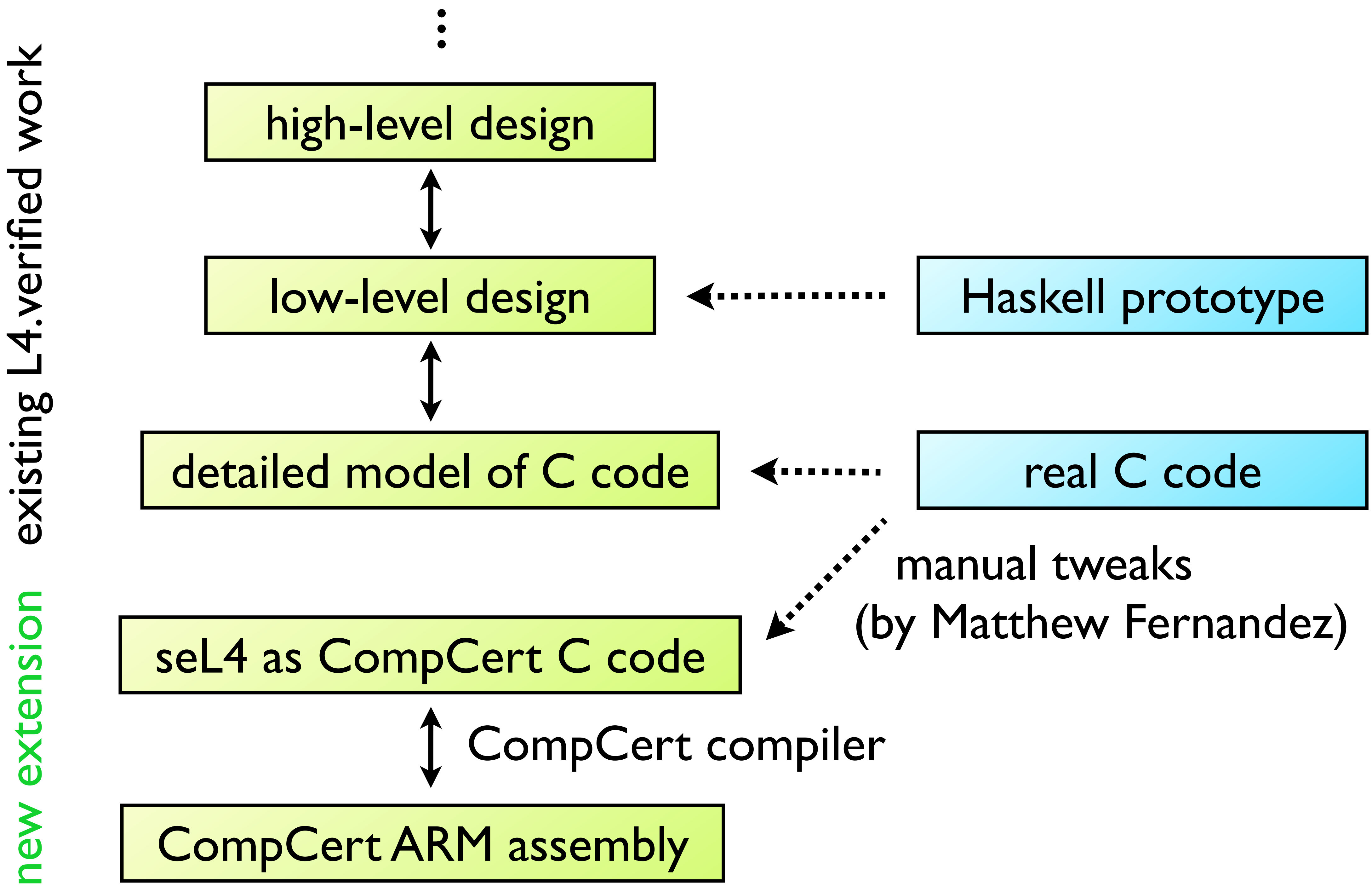

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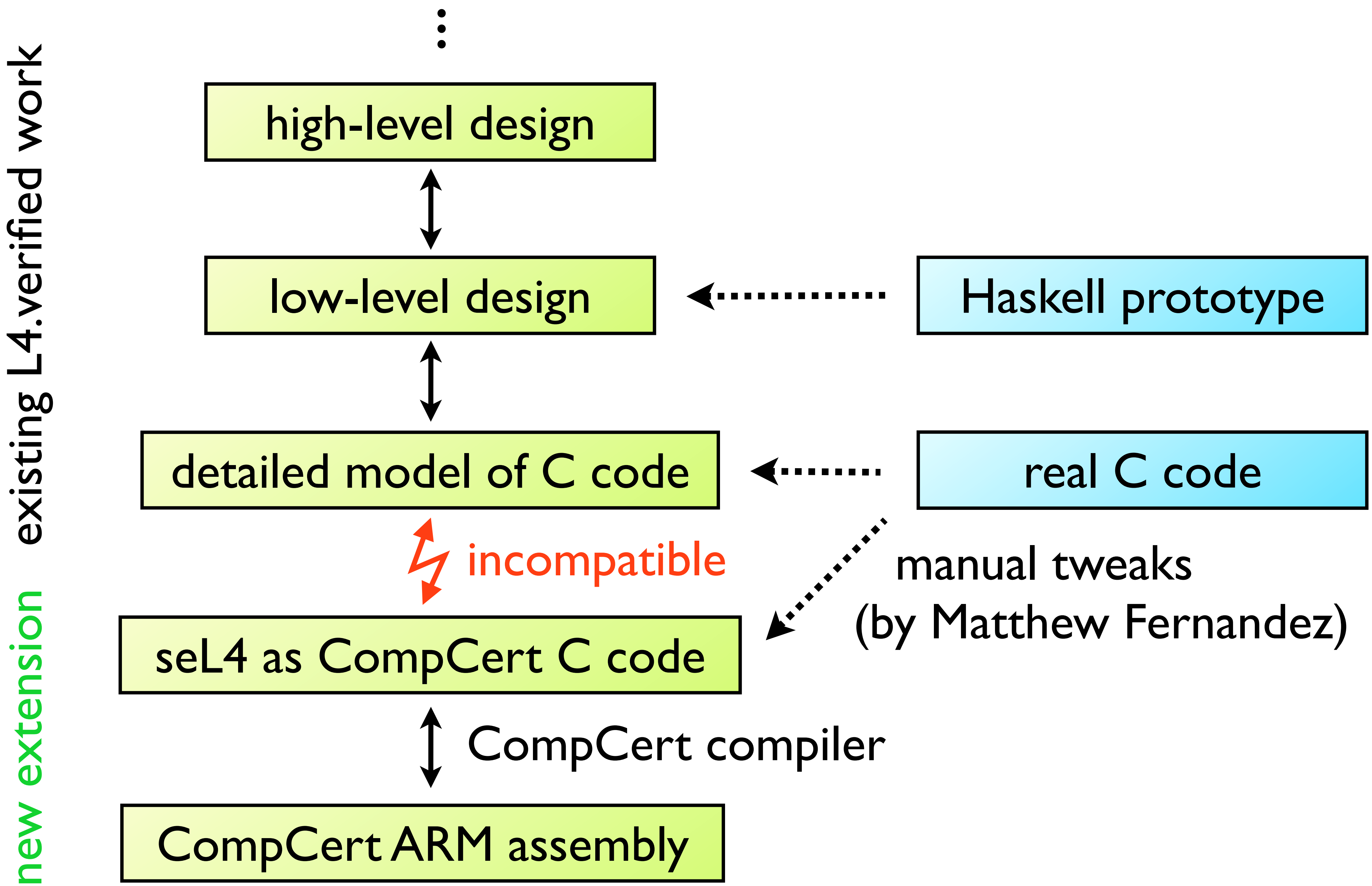

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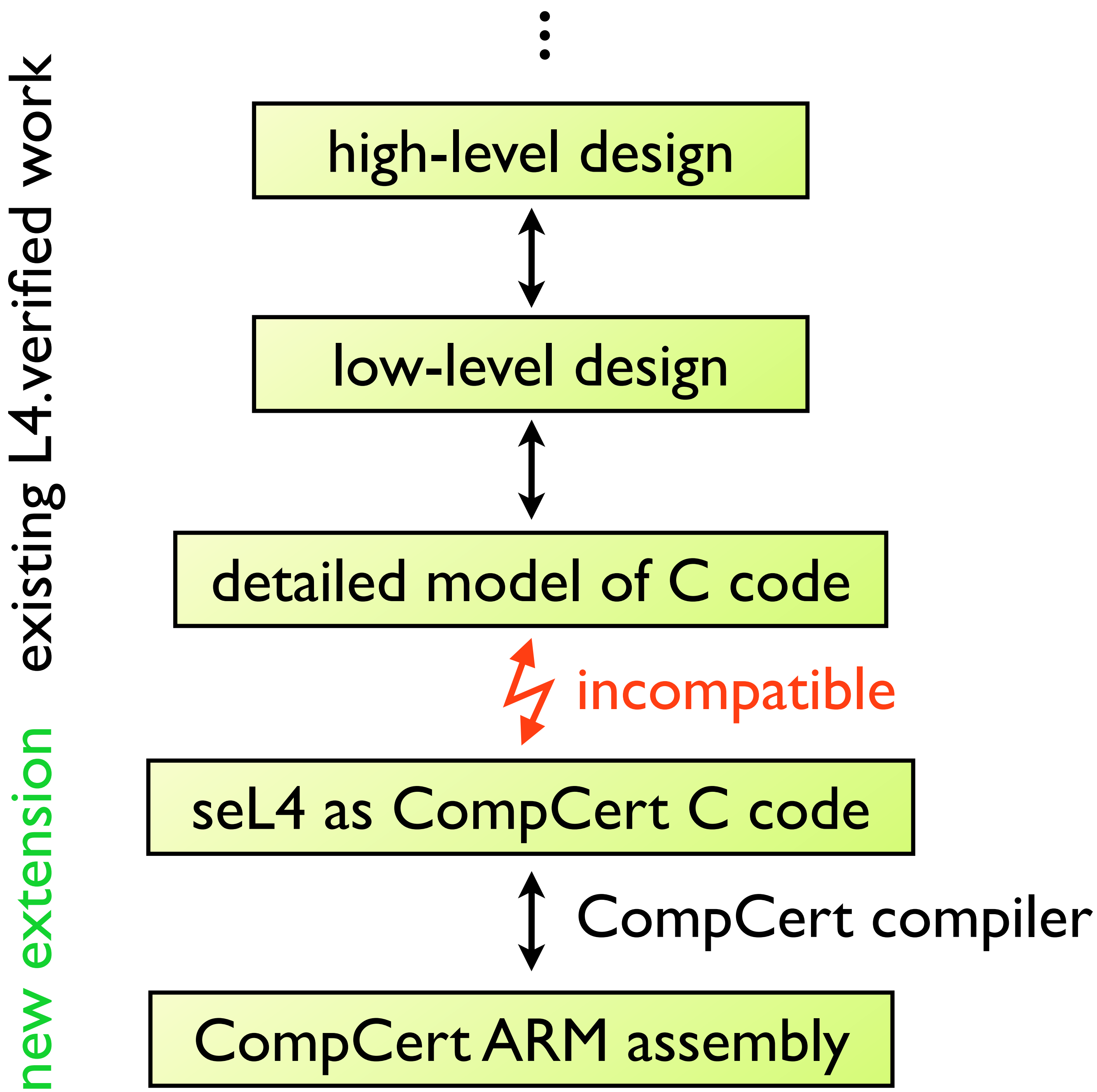

Incompatible:

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

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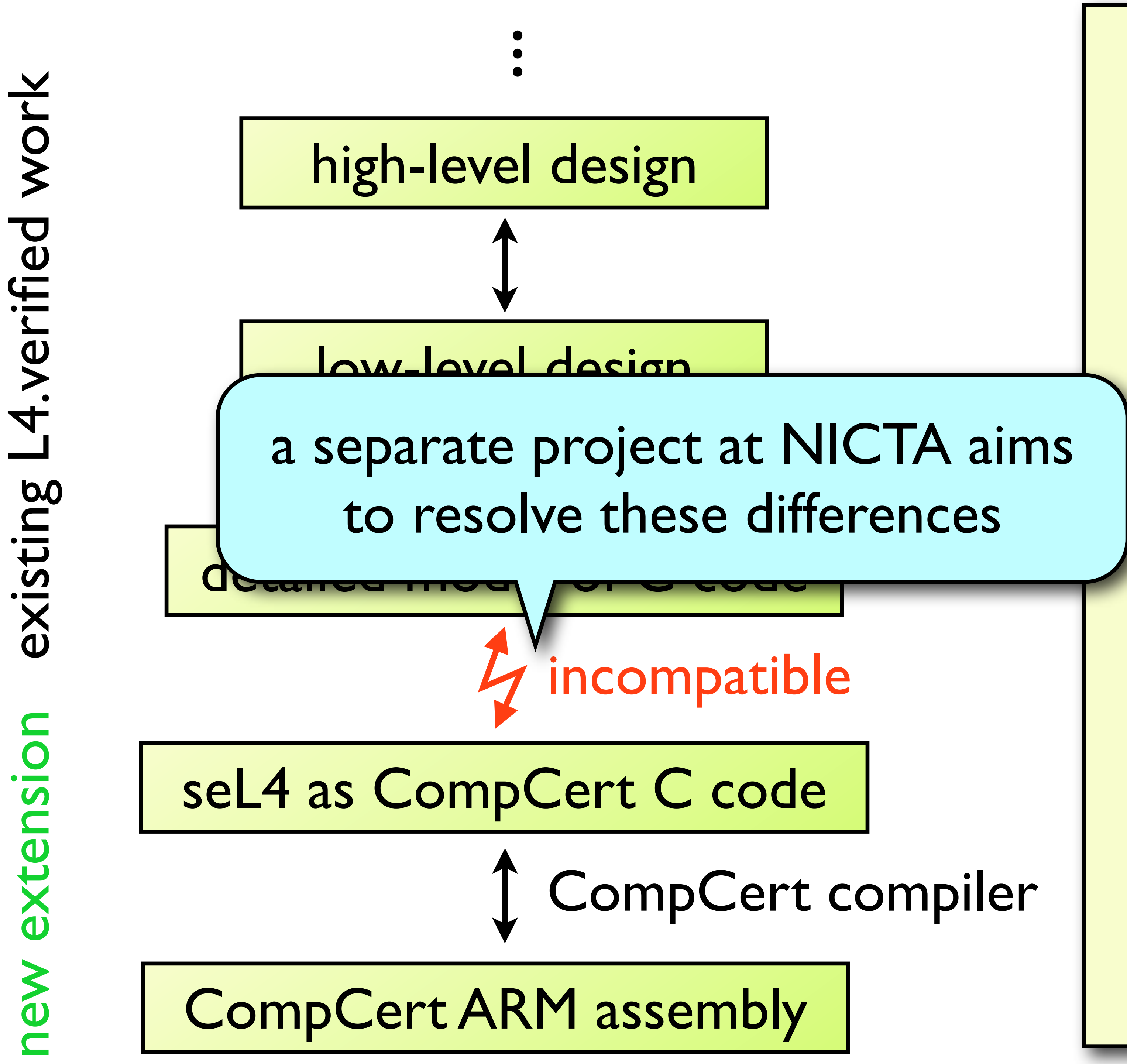

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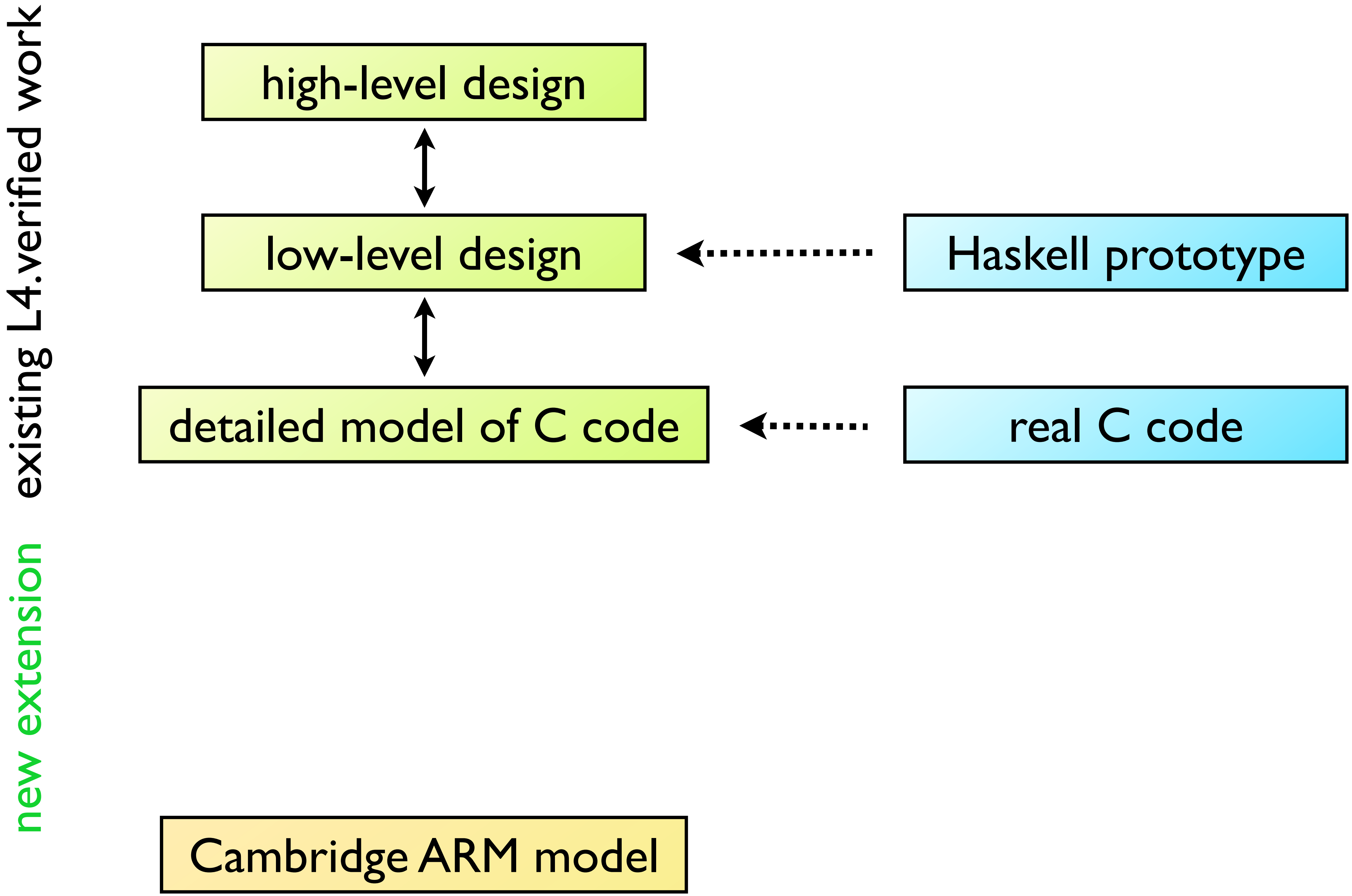

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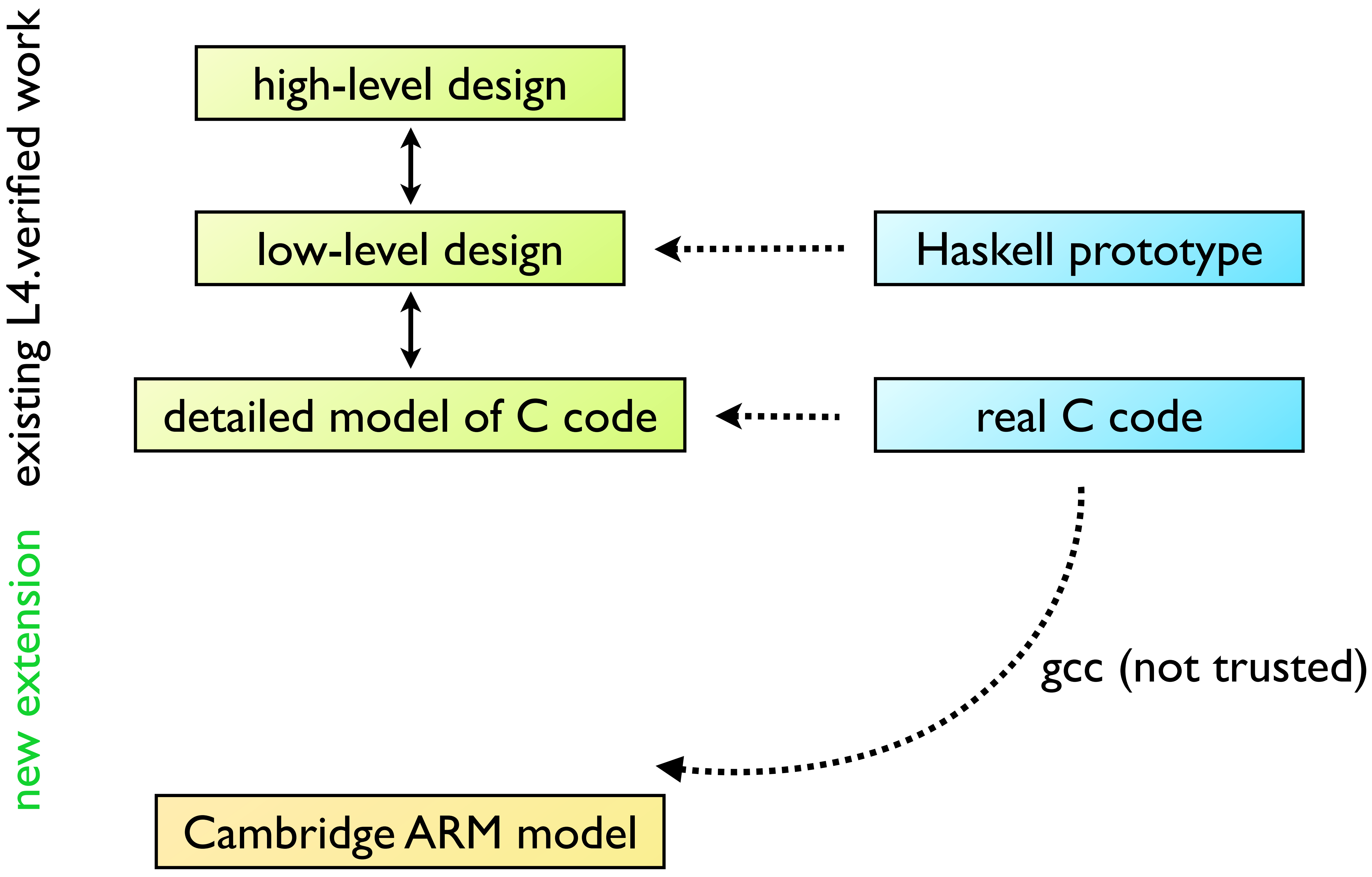

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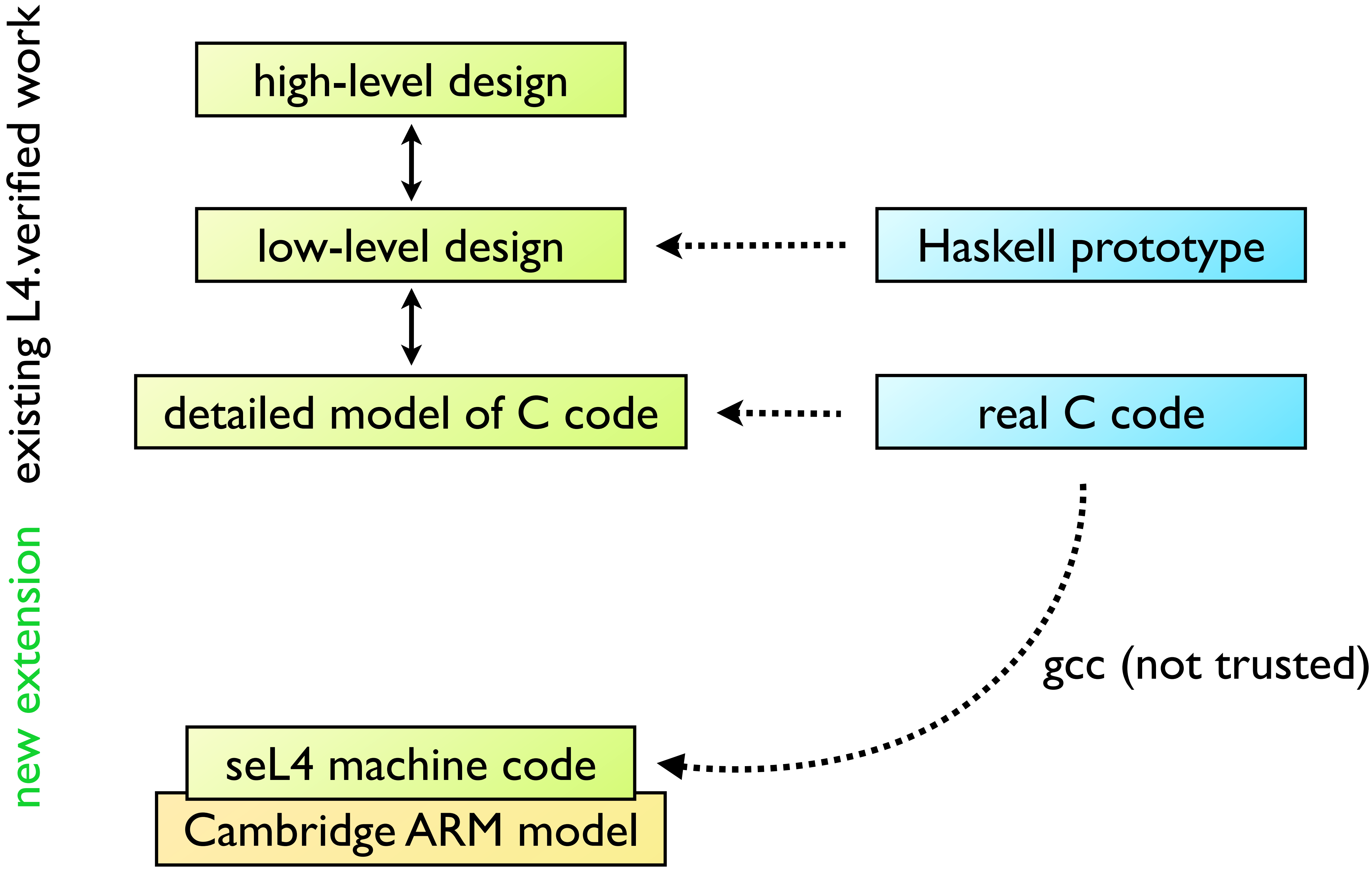

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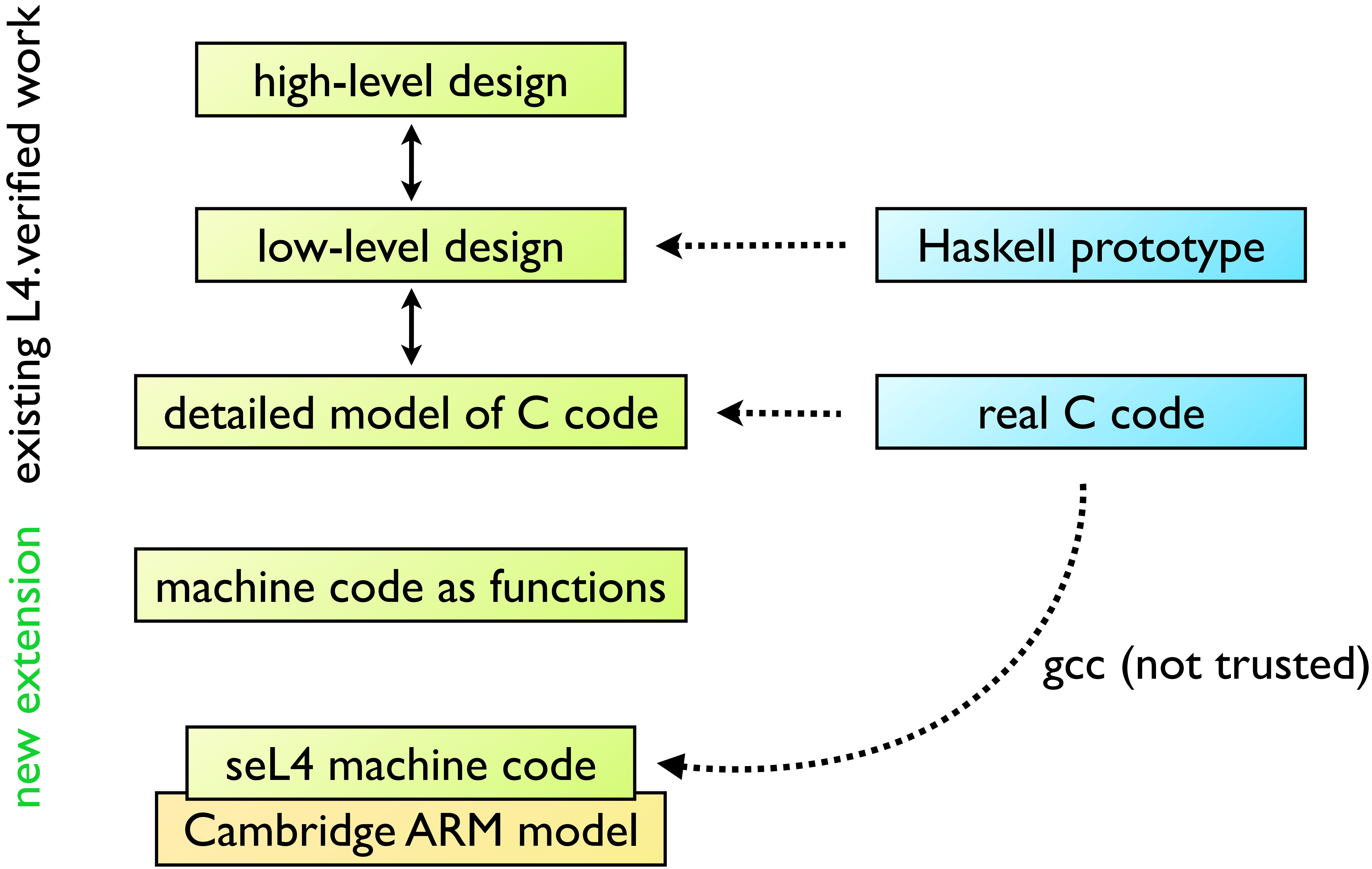

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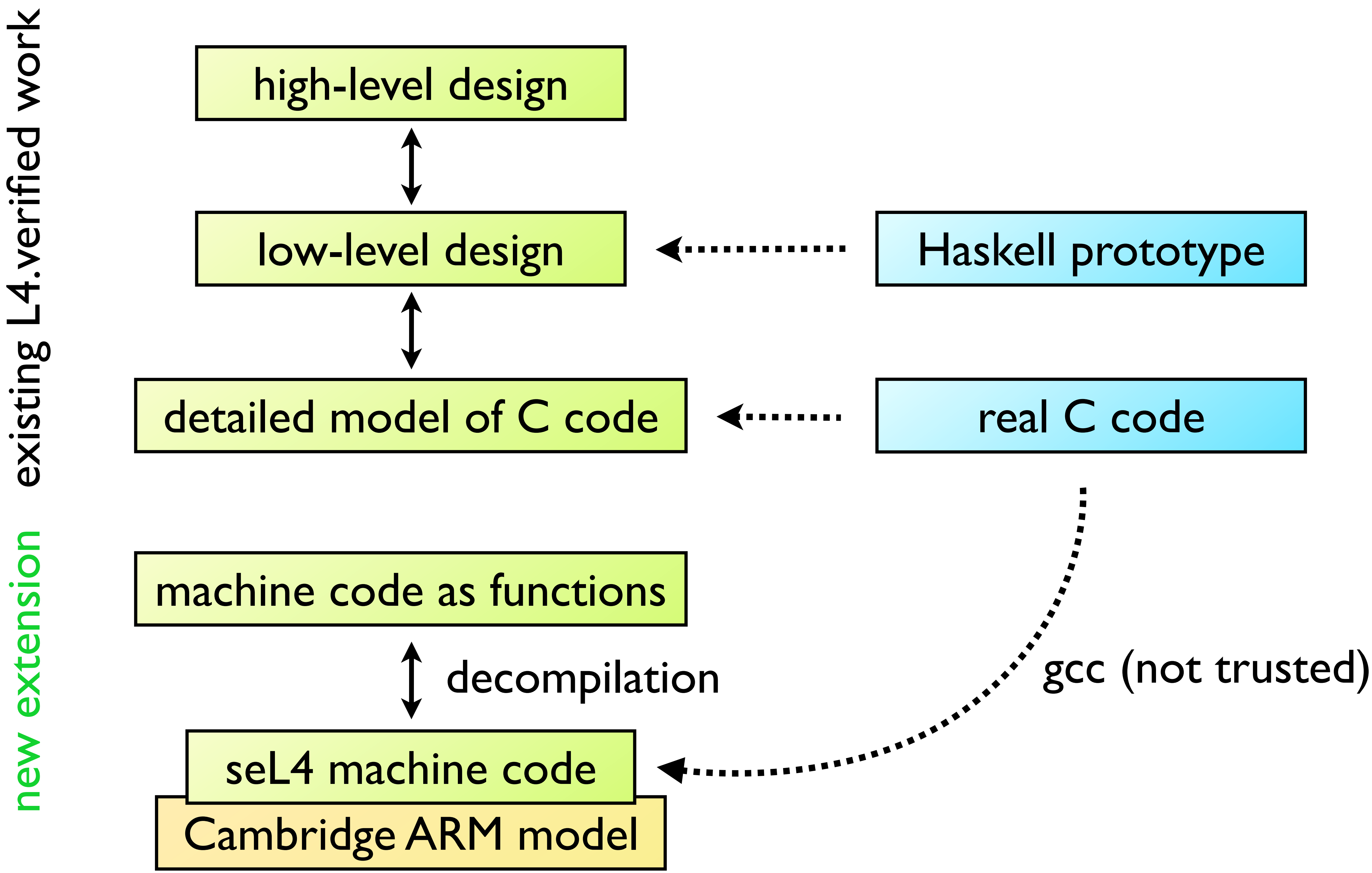

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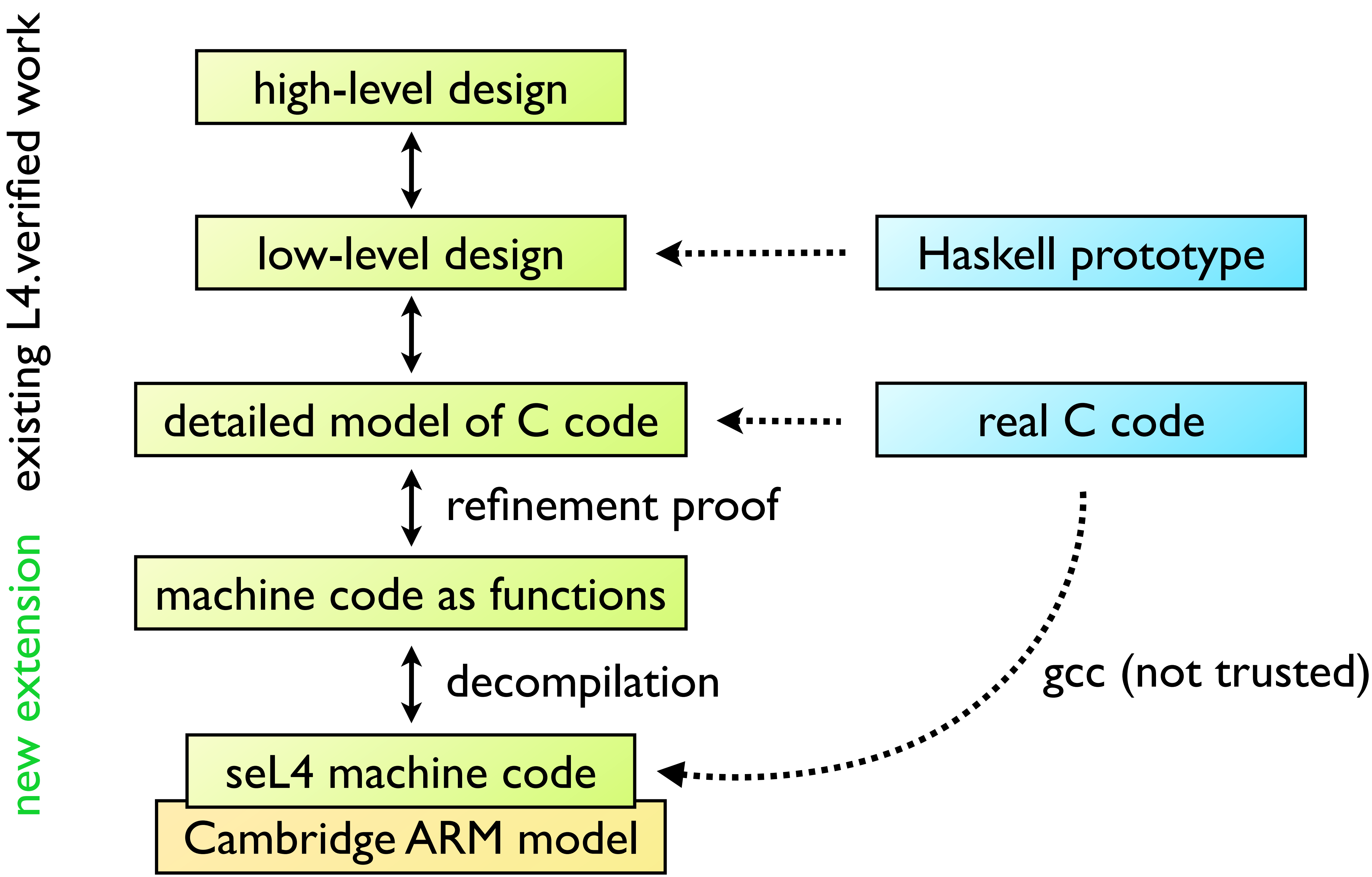
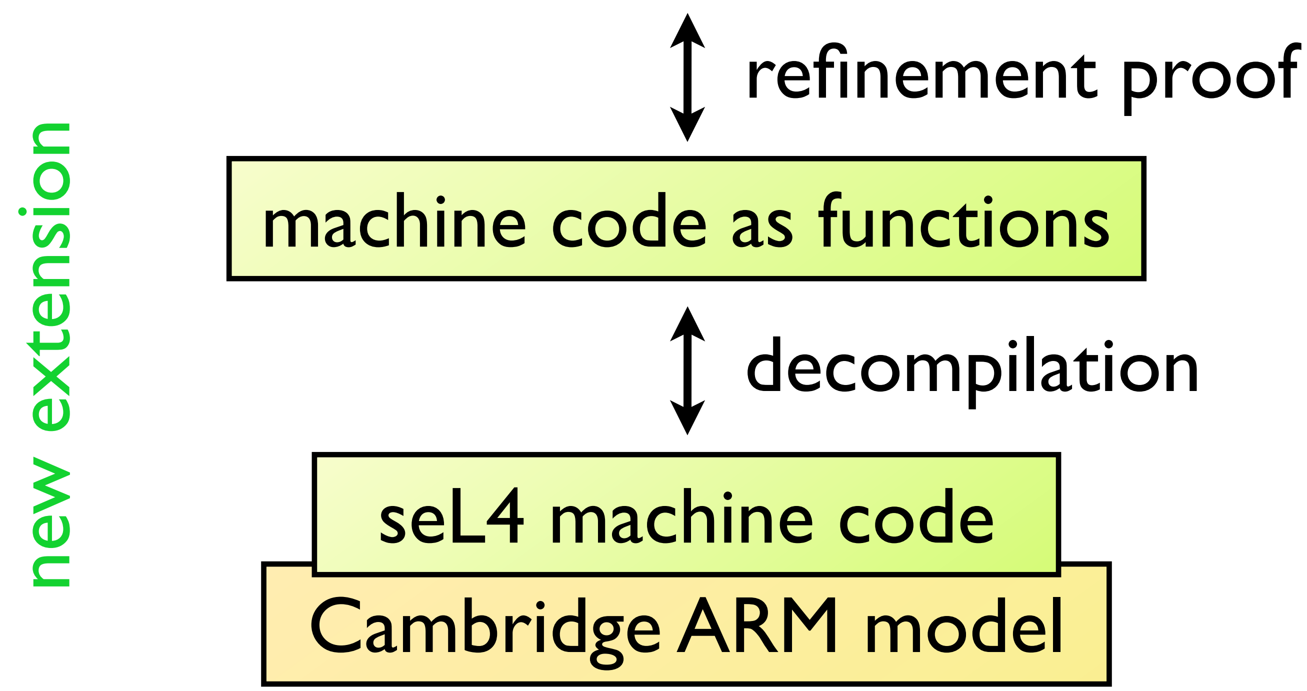


Talk outline



- automatic translation / decompilation
- progress and lessons learnt

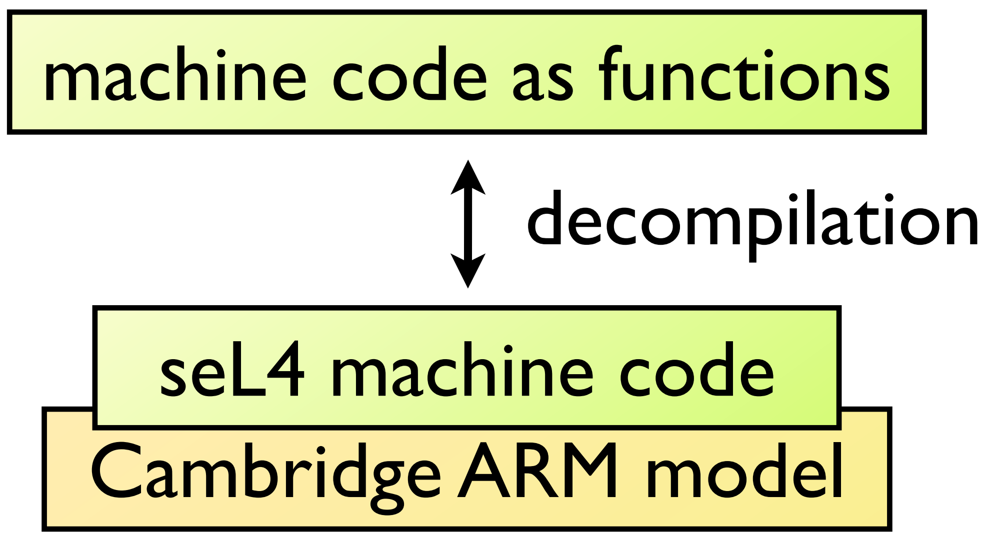
Cambridge ARM model

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:

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uint avg (uint i, uint j) {
  return (i + j) / 2;
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machine code:

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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

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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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1. derive Hoare triple theorems using Cambridge ARM model

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{ R0 i * R1 j * LR lr * PC p }
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1. derive Hoare triple theorems using Cambridge ARM model
2. compose Hoare triples

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

How to decompile:

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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.)

Decompiling seL4: Challenges

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- must be compatible with L4.verified proof
  - ➡ stack requires special treatment

Stack visible in m. 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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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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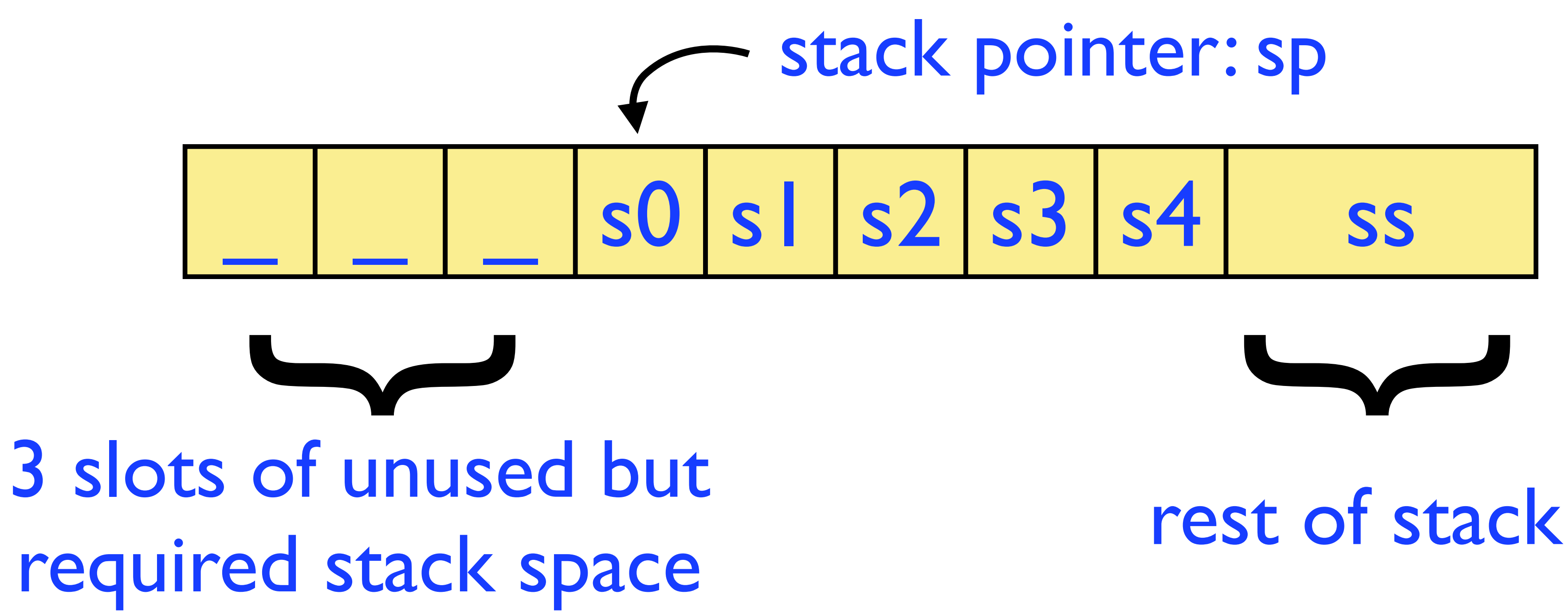
Some arguments are passed on the stack, and cause memory ops in machine code

... that are not present in C semantics.

Solution

Use separation-logic inspired approach



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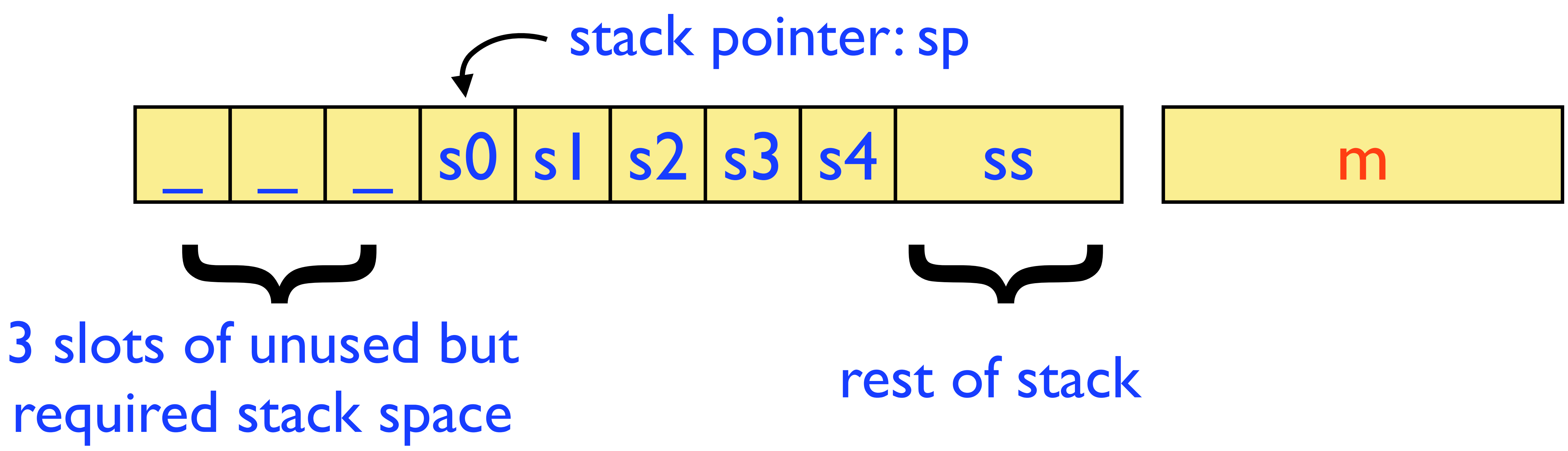

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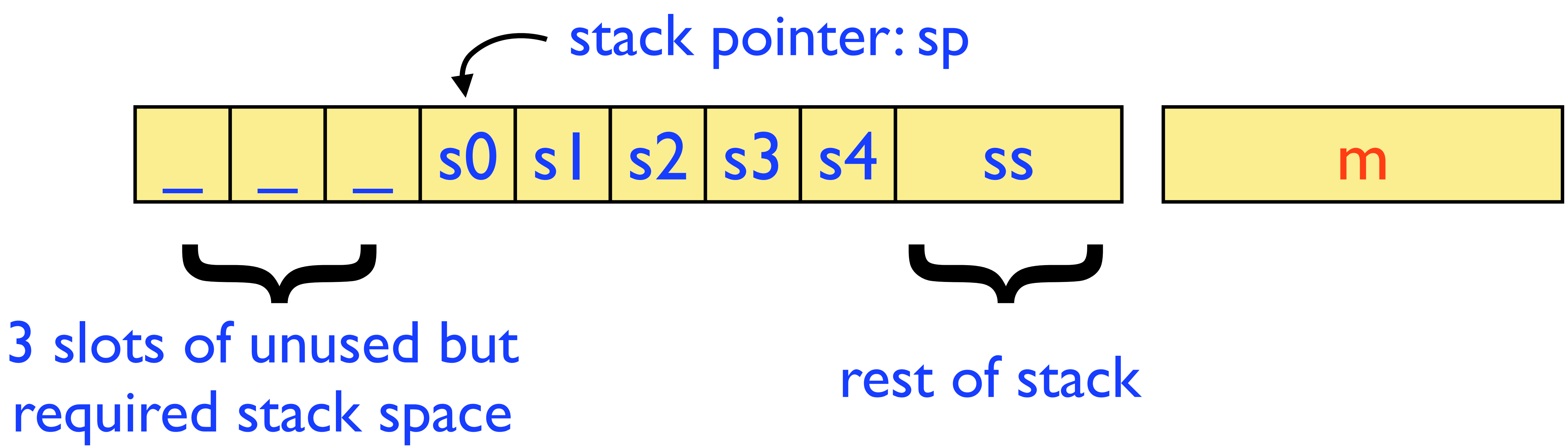

stack sp 3 (s0::s1::s2::s3::s4::ss)

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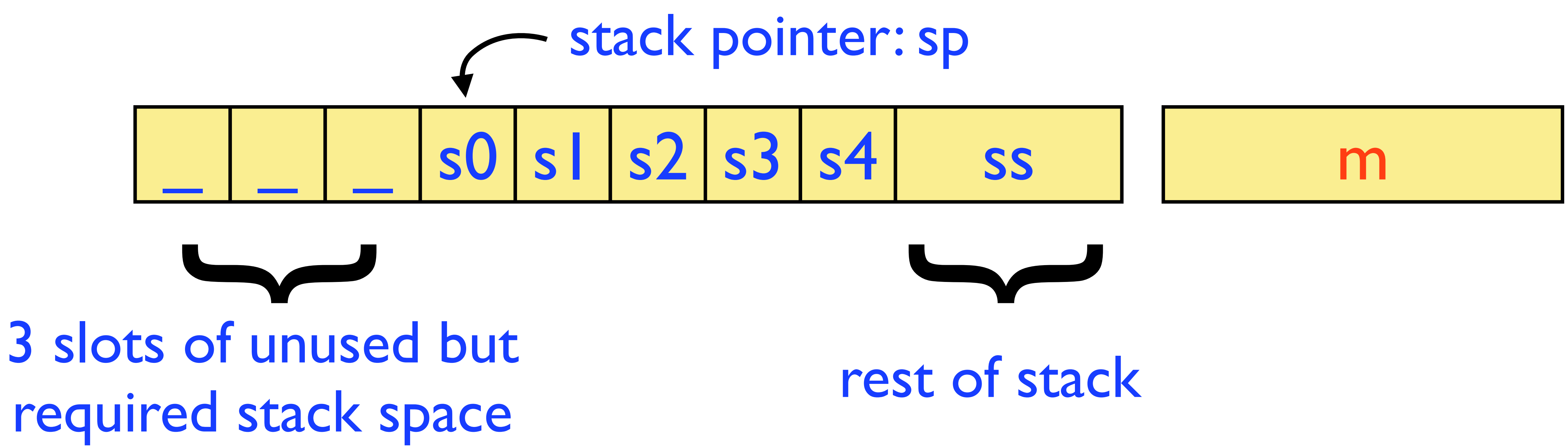

stack sp 3 (s0::s1::s2::s3::s4::ss) * memory m

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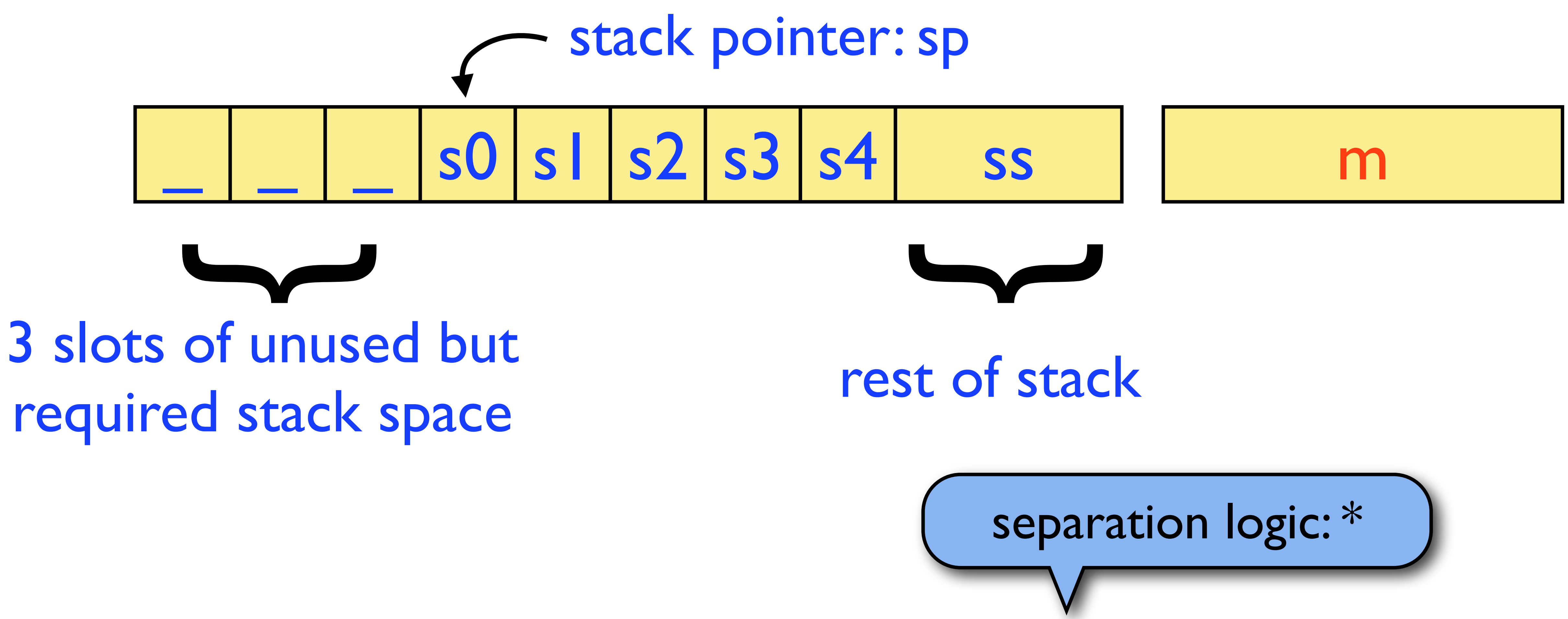

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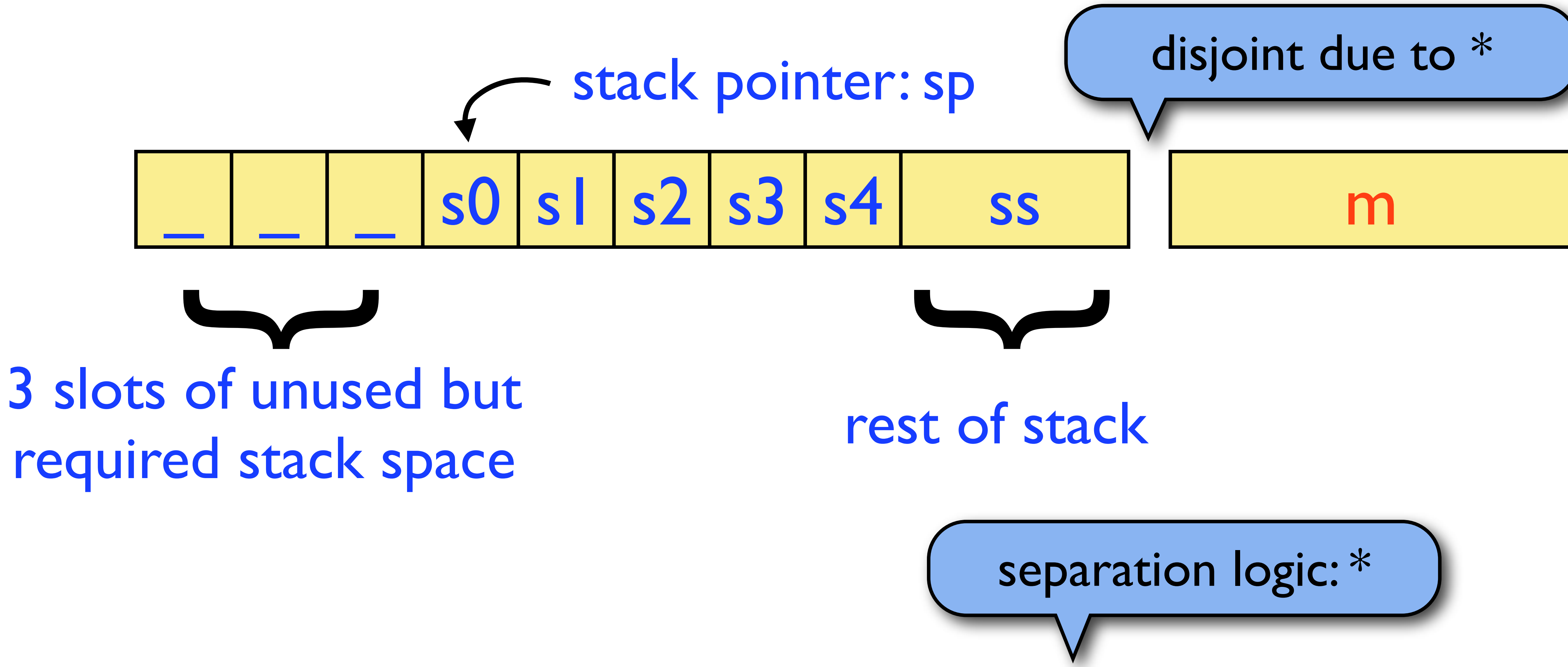

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Solution (cont.)

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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.

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Result

Stack load/stores become straightforward assignments.

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```

→

```
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  let r2 = s0 in
  let r1 = r1 + r3 in
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  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
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Result

Stack load/stores become straightforward assignments.

<u>Additional benefit:</u>

automatically proved certificate theorem
states explicitly stack shape/usage:

{ stack sp n (s0::s1::s2::s3::s) * ... * PC p }
p : code
{ stack sp n (s0::s1::s2::s3::s) * ... * PC lr }

```
bx   lr
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```
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promises to leave stack unchanged

bx   lr

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

Progress

A 6-week visit to NICTA resulted in:

75 % of seL4 decompiled

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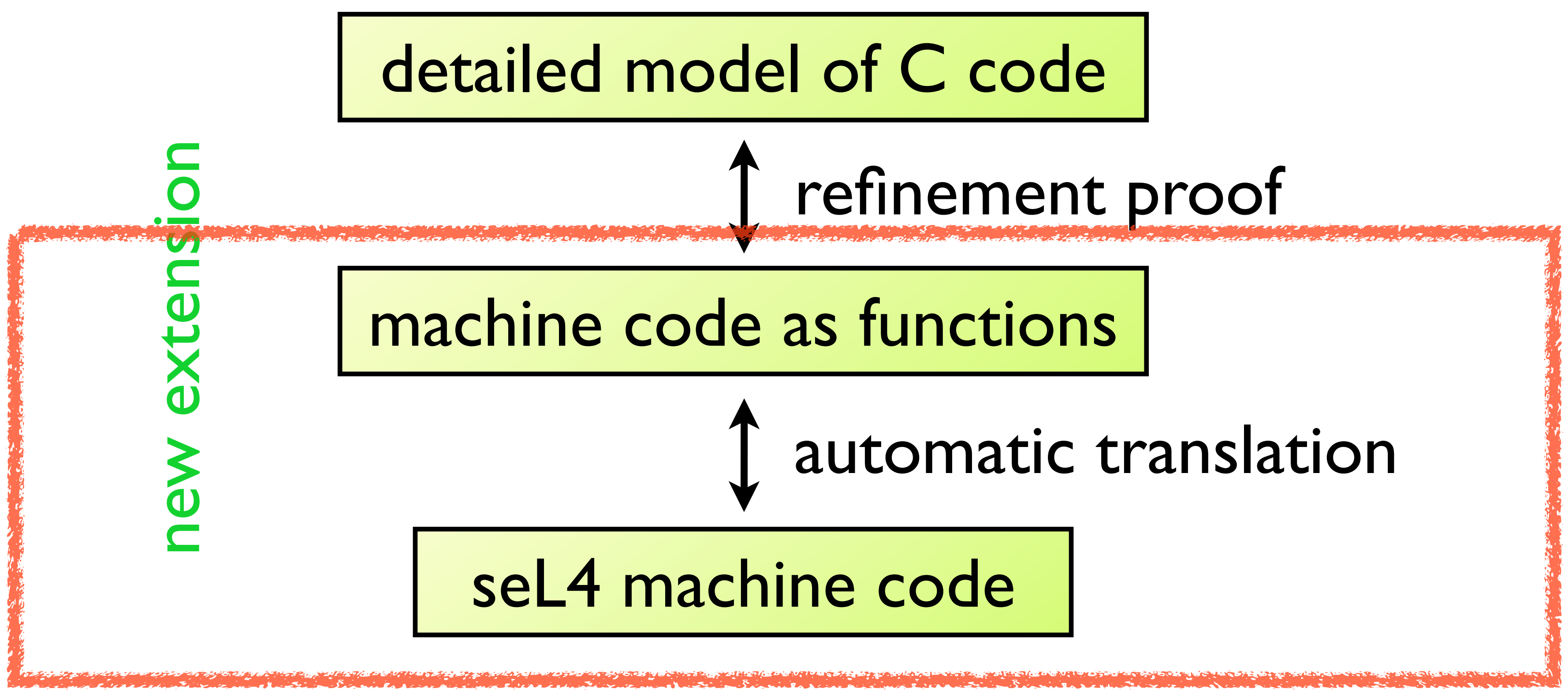
Next visit scheduled for end of this year:

- complete decompilation
  (make stack heuristic stronger)
- concentrate on stage 2... (next slide)

Moving on to stage 2



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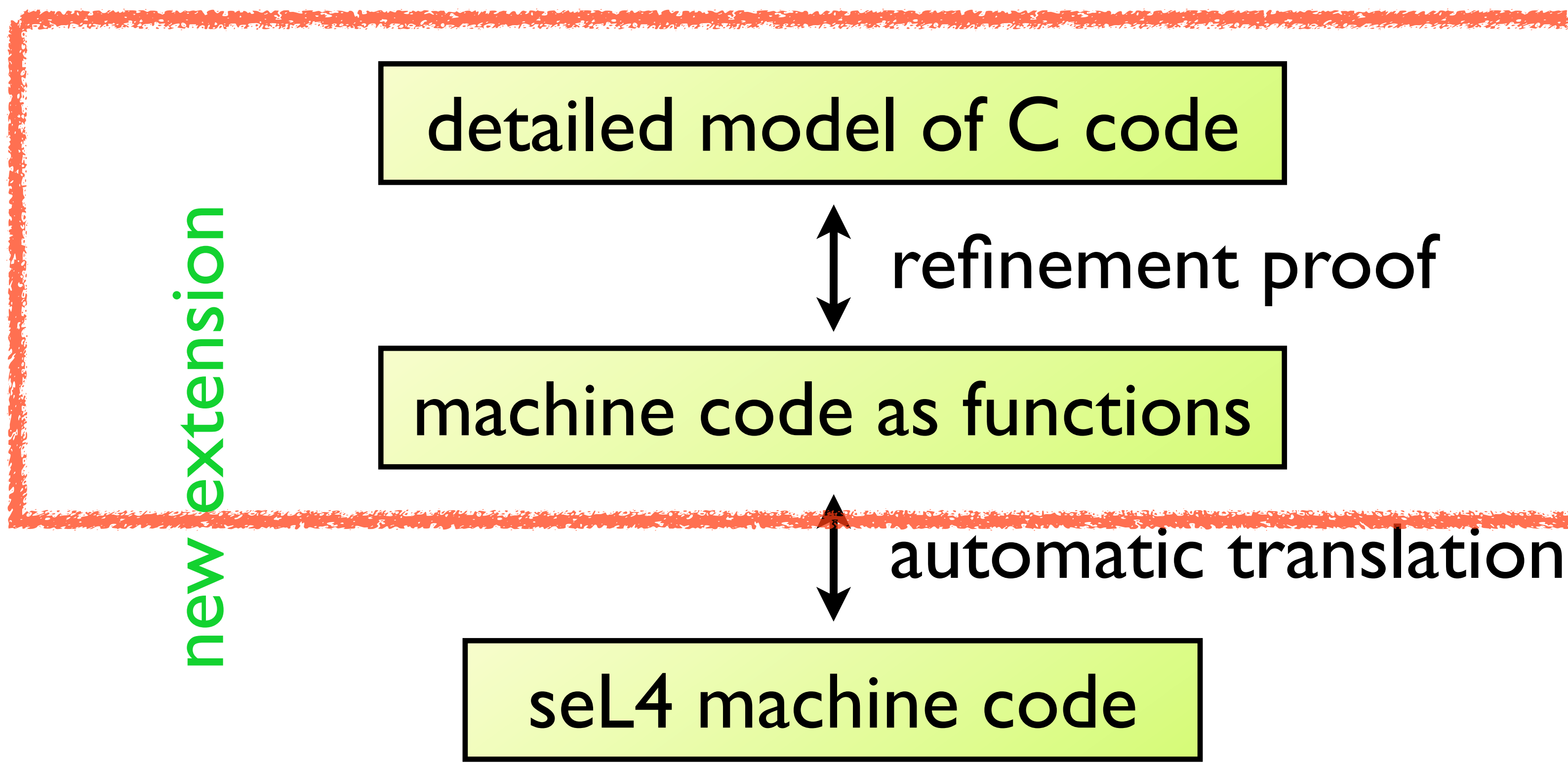

Proving C refinement

Approach 1:

- use a verification condition generator (VCG) to prove C Hoare-triple theorems, approximately:

  { true } code { state_after = code_fun(state_before) }

Aim:

- make solution as automatic as possible
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simplified for easier presentation

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Proving C refinement

Approach 2:

- compose C code inside existing correctness C Hoare triple, e.g.

$$\{\ \text{pre}\ \}\ (\text{Assign } f;\ \text{Assign } g)\ \{\ \text{post}\ \} \;=\; \{\ \text{pre}\ \}\ (\text{Assign } (g \circ f))\ \{\ \text{post}\ \}$$

- then prove, for almost any pre, post:

$$\{\ \text{pre}\ \}\ \text{code}\ \{\ \text{post}\ \} \;\Longrightarrow\; \{\ \text{pre}\ \}\ (\text{Assign code\_fun})\ \{\ \text{post}\ \}$$

Proving C refinement

Approach 2:

Solution to inlined assembly:

naturally compatible with decompilations of inlined assembly, e.g.

{ pre } (Assign inline_asm_fun) { post }

Gets around the problem of C's __asm__.

{ pre } (Assign code_fun) { post }

Final part:

Lessons learnt

gcc: weird and wonderful

Wonderful:

- gcc -O2 produces good/clever code
- decompilation can be made to work on its output
- gcc -O0 produces simple “reference” machine code

Weird:

- fails to spot a few ‘obvious’ optimisations
- gcc -O2 sometimes invents new subroutines

Hardest part?

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So far: connection with C semantics.

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C semantics best avoided?

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HASP?

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C semantics best avoided?

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HASP?

... but C is the reality of OS code

- a simple “hacker’s semantics of C” ?

“a hacker’s C semantics”

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Possibility: use decompilation from gcc -O0
as semantics of C code.

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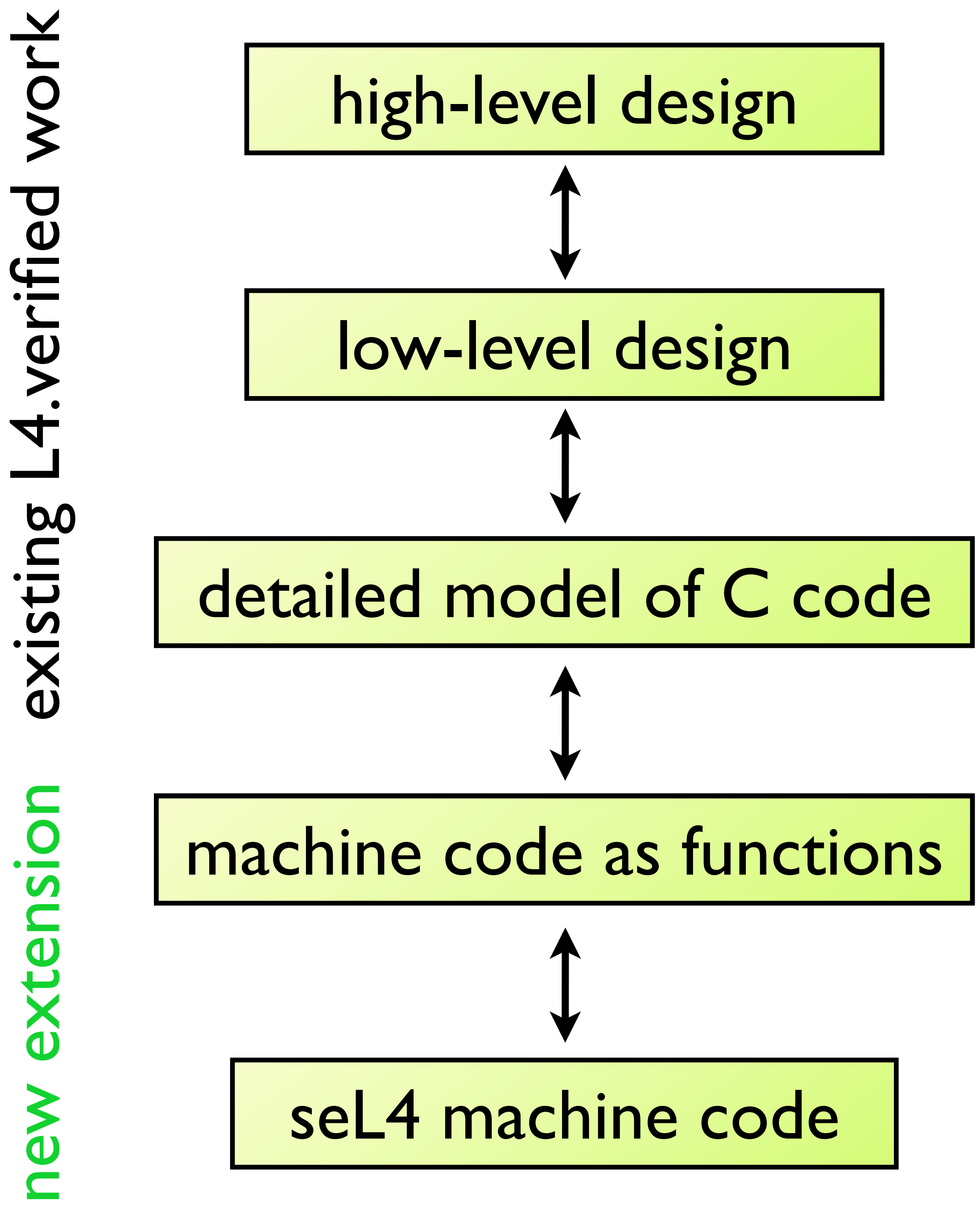
➡ impossible: current L4.verified proofs tied to C sem.

Connecting provers



In general, hard.
Easy in this case.

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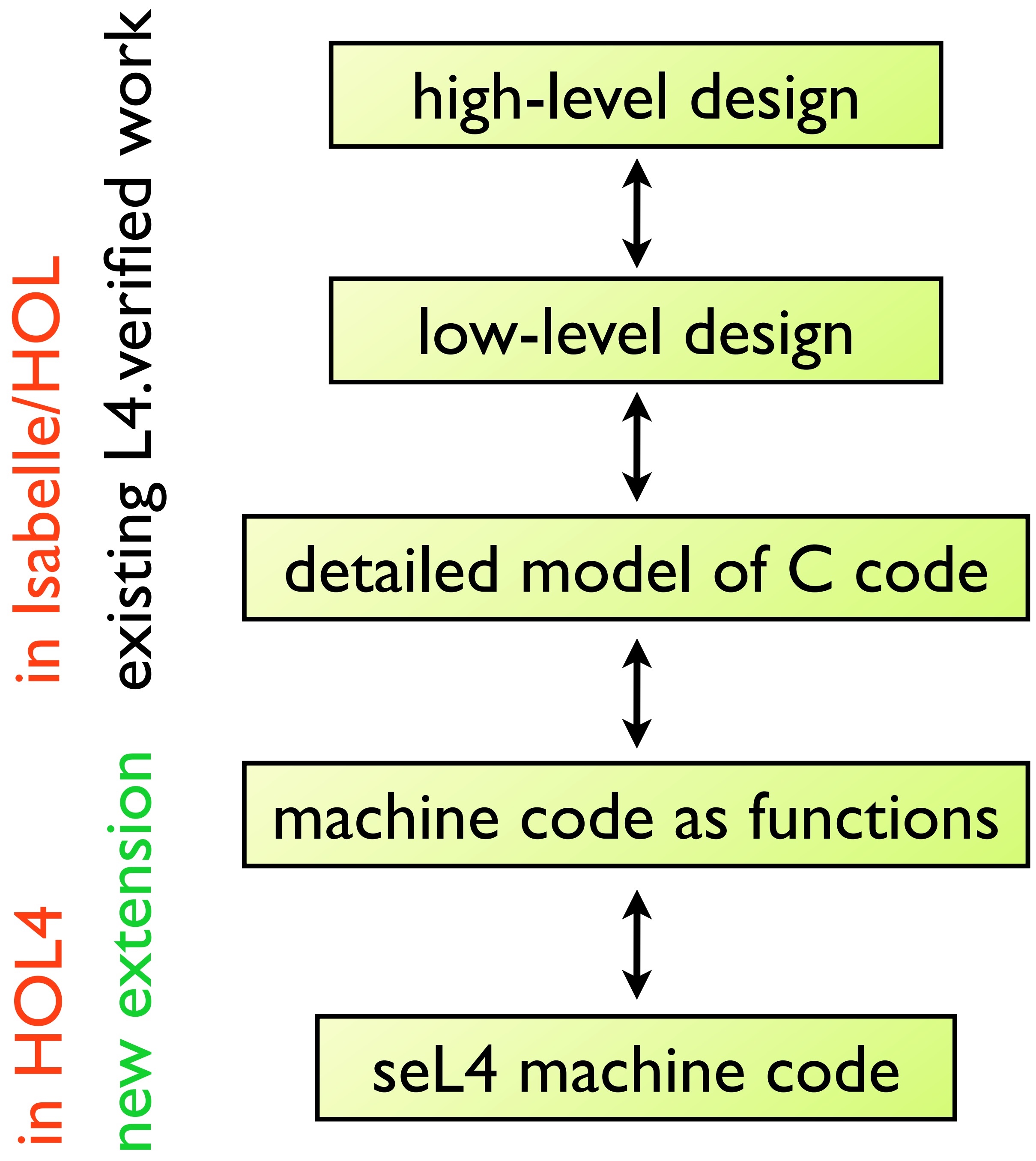

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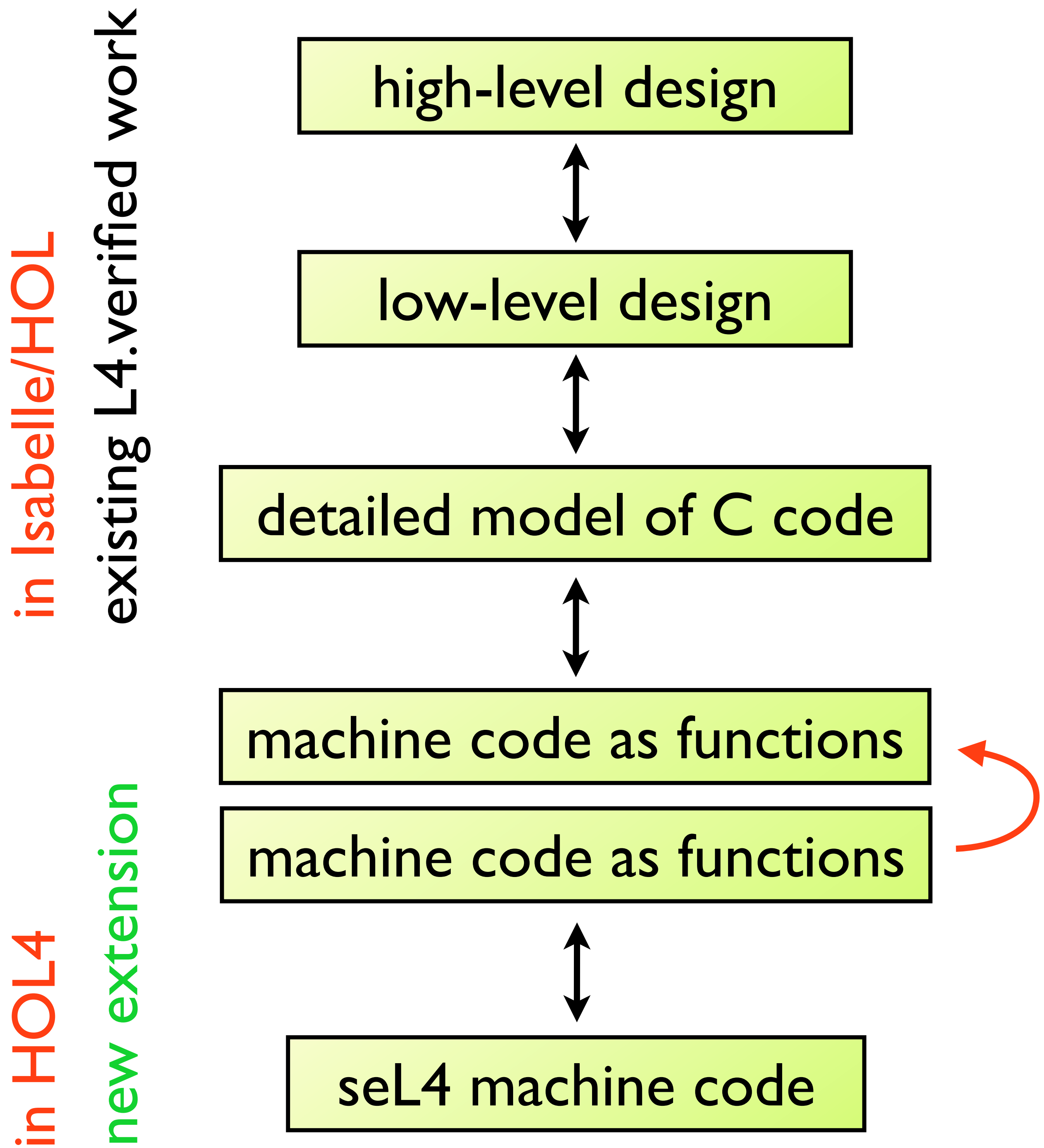

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automatic translation of definitions from HOL4 to Isabelle/HOL

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L4.verified is being extended downwards using the Cambridge ARM model

* work in progress

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