# A Verified Garbage Collector for Gallina

Shengyi Wang[†], Anshuman Mohan[†], Qinxiang Cao[‡], Aquinas Hobor[†]

NUS National University of Singapore (†)

上海交通大學 Shanghai Jiao Tong University (‡)

APLAS NIER
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# Broad Problem

Verify graph-manipulating programs
written in executable C
with machine-checked correctness proofs

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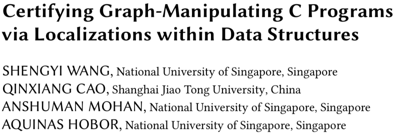
Ubiquitous in critical areas

# Broad Solution

Verified
Software
Toolchain



**Certifying Graph-Manipulating C Programs via Localizations within Data Structures**

SHENGYI WANG, National University of Singapore, Singapore
QINXIANG CAO, Shanghai Jiao Tong University, China
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VST + CompCert + 25000 LOC library

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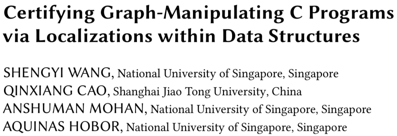

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[Wang *et. al.*, PACMPL OOPSLA 2019]

# This Talk

Gallina ⇝ CompCert C ⇝ Assembly

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Gallina assumes infinite memory
but CompCert C has a finite heap

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Certi Coq

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Solution: garbage collect the CompCert C code

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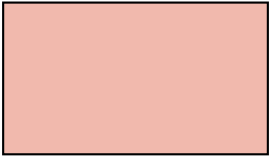
Solution: garbage collect the CompCert C code

New problem: verify the garbage collector

# Our Garbage Collector

GC has jurisdiction over the heap



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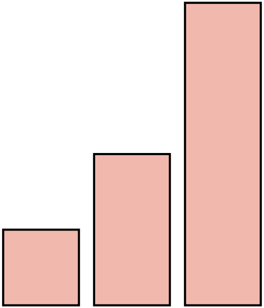

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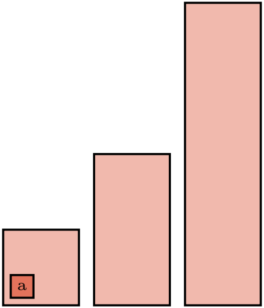
Mutator `allocs` in special subheap



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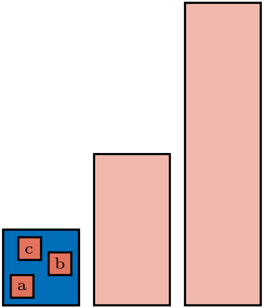
  - If subheap is full



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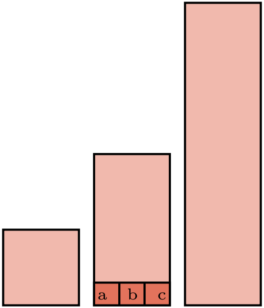
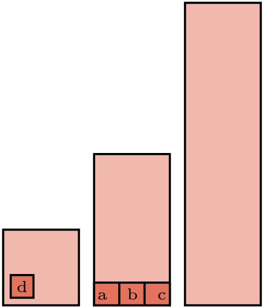
- Mutator `allocs` in special subheap
  - If subheap is full call GC



# Our Garbage Collector

GC has jurisdiction over the heap

- Mutator `allocs` in special subheap
  - If subheap is full call GC and try again



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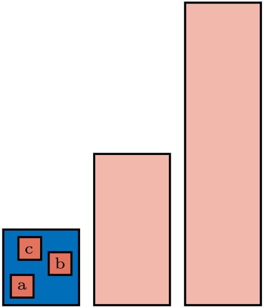
- Functional mutator: no back pointers
- Cheney's mark-and-copy collects gen to next
- Potentially triggers cascade of pairwise collections
- Three key functions:
  `forward` copies individual objects
  `do_scan` repairs copied objects
  `forward_roots` kick-starts the collection

# Intuitive Specification

*Primum non nocere*: first, do no harm



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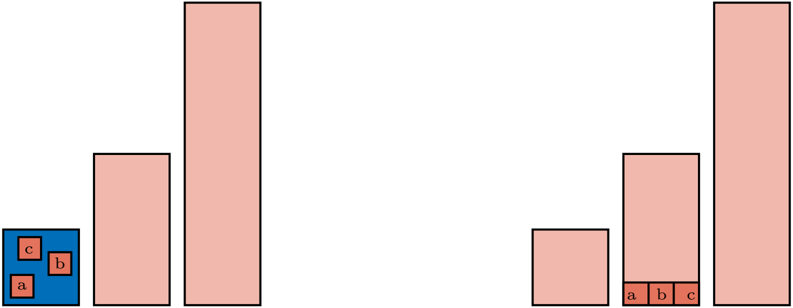

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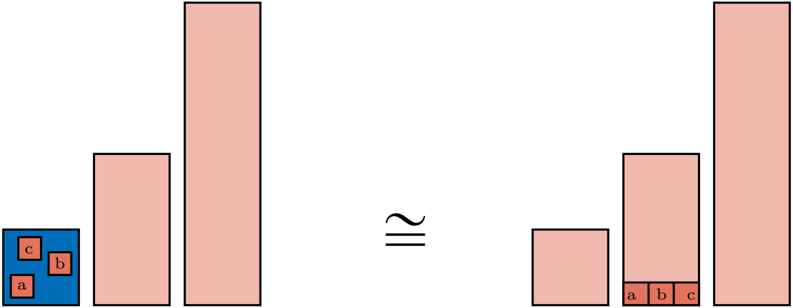
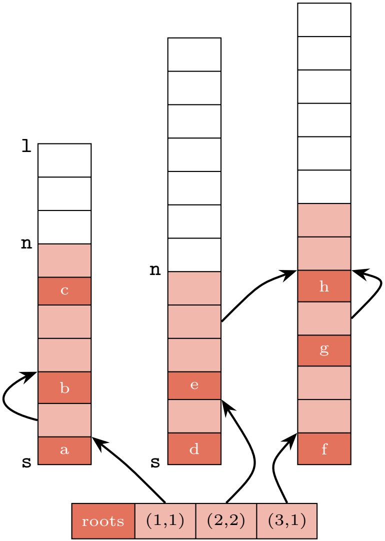


# Overview of Operations

Nursery cannot fit `alloc`



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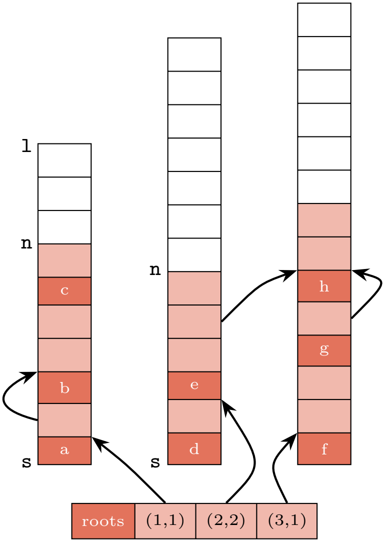
  `do_gen`



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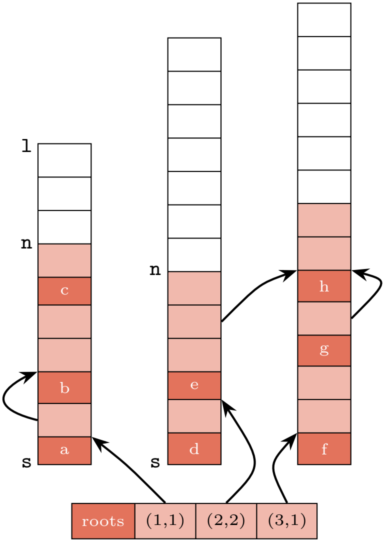

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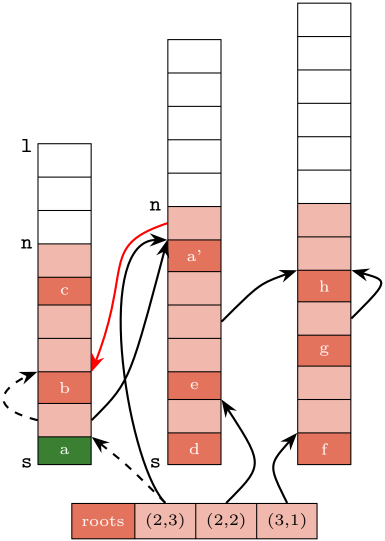

Nursery cannot fit `alloc`

```
do_gen
  forward_roots
    forward
  do_scan
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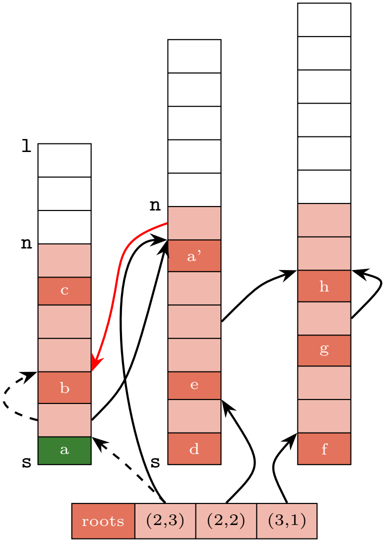

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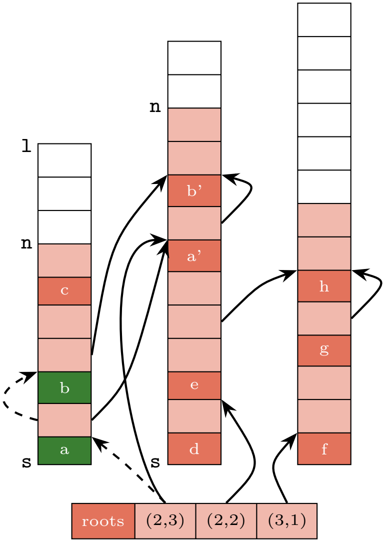

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Nursery cannot fit `alloc`

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do_gen
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  reset_gen
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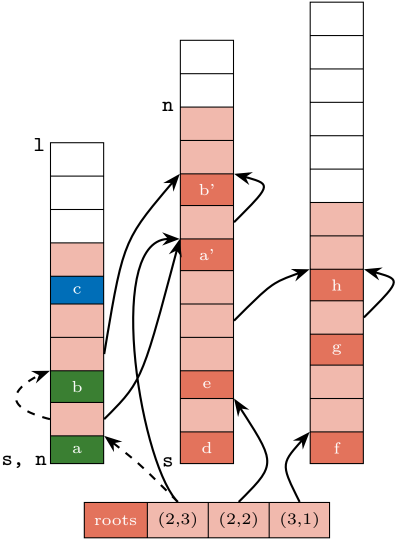

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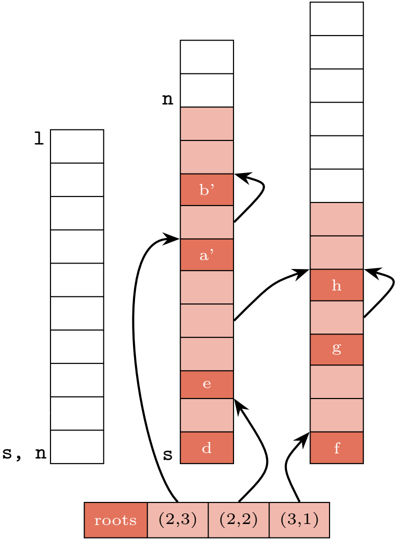

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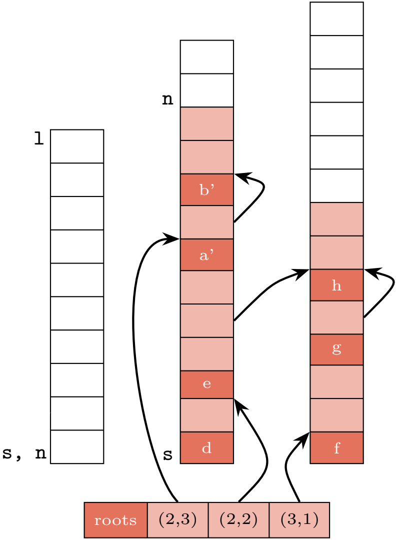
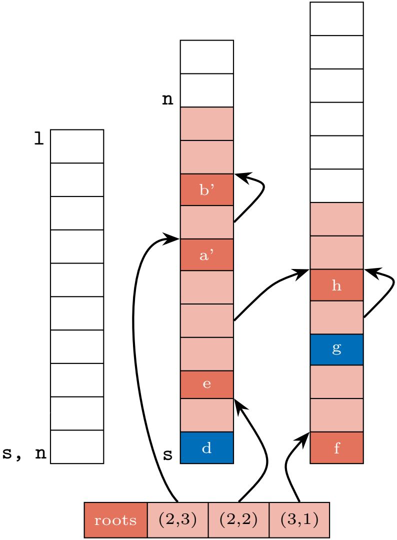
Non-Concerns



# Overview of Operations

Non-Concerns

more garbage



# Overview of Operations

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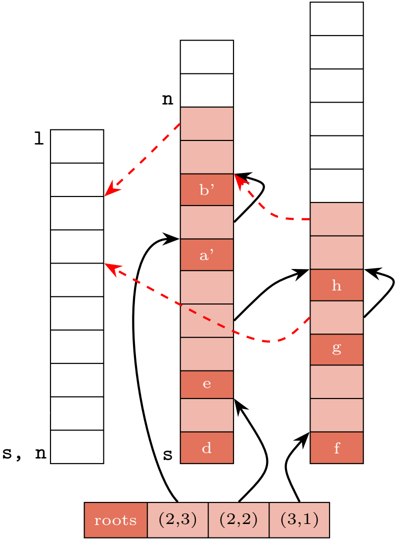
- more garbage
- backward pointers



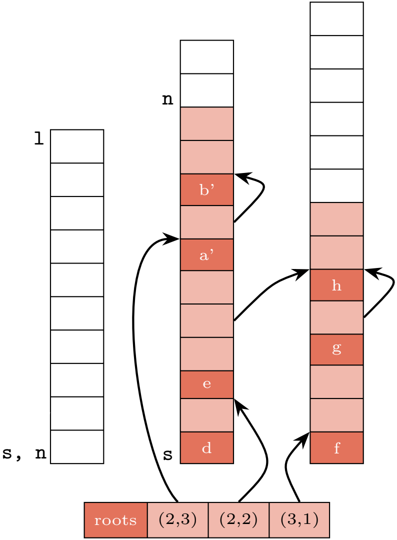
# Overview of Operations

Non-Concerns

more garbage

backward pointers

Sources of Complexity



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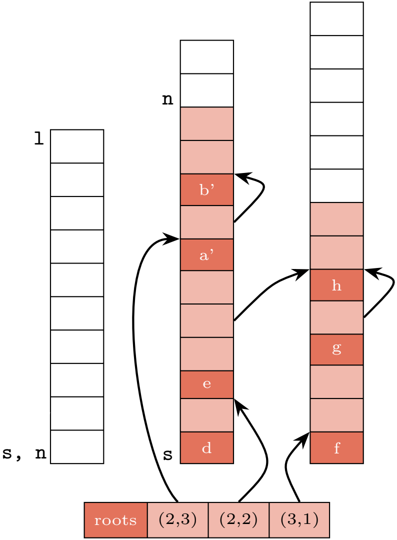
Sources of Complexity

- variable-length objects



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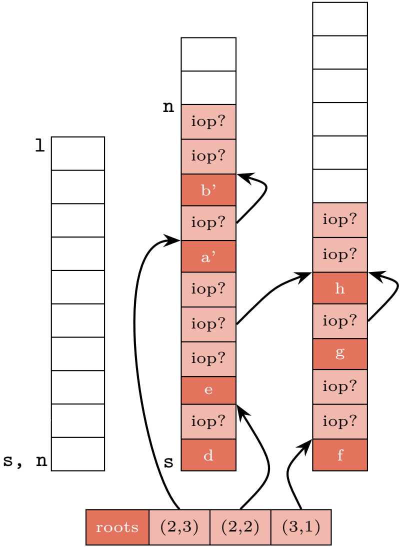
Sources of Complexity

- variable-length objects
- disambiguate int/ptr



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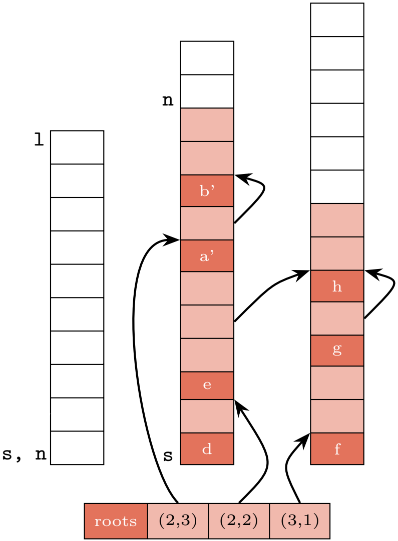

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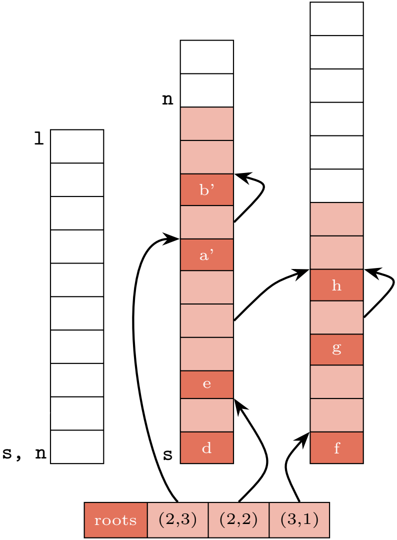

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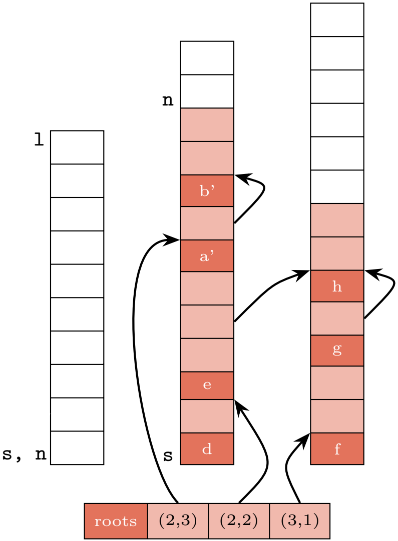

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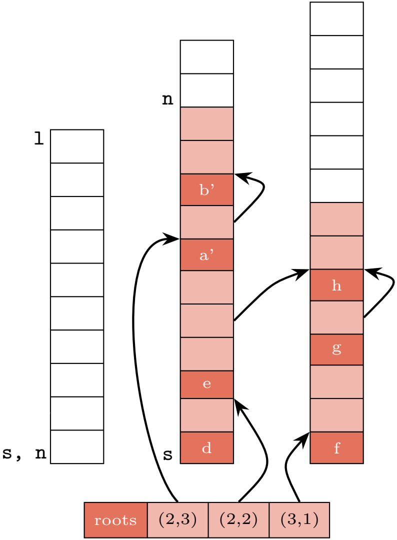
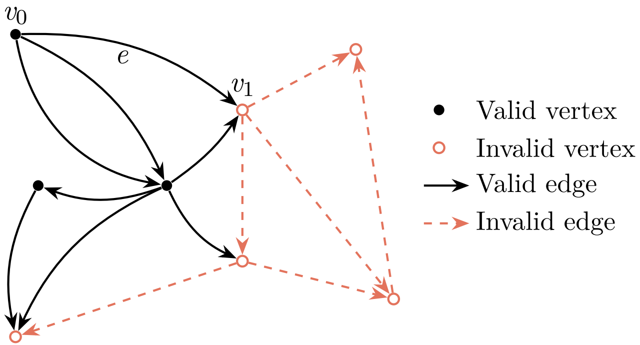
- determine gen size
- what if `malloc` fails?
- mutator's max `alloc`?



# Instantiating GC_Graph

A PreGraph is a hextuple (`VType`, `EType`, `vvalid`, `evalid`, `src`, `dst`)



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A PreGraph is a hextuple (`VType`, `EType`, `vvalid`, `evalid`, `src`, `dst`)

**GC_PreGraph:** `VType := nat * nat`

`EType := VType * nat`

`src := fst`

`dst :=` *unrestricted*

$\forall v.\ \texttt{vvalid}(\gamma, v) \Leftrightarrow \texttt{graph\_has\_v}(\gamma, v)$

$\forall v, out.\ \texttt{evalid}(\gamma, (v, out)) \Leftrightarrow$

$\quad \texttt{vvalid}(\gamma, v) \wedge \texttt{In}\ \ out\ \ (\texttt{get\_edges}(\gamma, v))$

# Instantiating GC_Graph

A LabeledGraph is a quadruple (PreGraph, `VL`, `EL`, `GL`)

**GC_Graph:** GC_PreGraph as shown

```
VL := raw_vert_block
EL := unit
GL := list gen_info
```

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**GC_Graph:** GC_PreGraph as shown

`VL := raw_vert_block`

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```
Definition
 raw_fld := Z + GC_Ptr.

Record raw_vert_block :=
{ raw_mark: bool;
  copied_vertex: VType;
  raw_flds: list raw_fld;
  (* elided *) }.
```

```
Record gen_info :=
{ s_addr: val;
  s_ok: isptr s_addr;
  num_vert: nat;
  (* elided *) }.
```

# Forward: a Deep Dive

forward is robust

```
void forward (value *s, *l, **n, *p) {
 value * v; value va = *p;
 if(Is_block(va)) {
  v = (value*)iop2ptr(va);
  if(Is_from(s, l, v)) {
   header_t hd = Hd_val(v);
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$$\left\{\begin{array}{l}\forall\gamma, \mathit{from}, \mathit{to}, v, n.\ \mathsf{gc\_graph}(\gamma) \wedge \mathit{compat}(\gamma, \mathit{from}, \mathit{to}) \wedge \\ \mathrm{s} = \mathit{start}(\gamma, \mathit{from}) \wedge \mathrm{l} = \mathrm{s} + \mathit{gensz}(\gamma, \mathit{from}) \wedge \\ \mathrm{n} = \mathit{nxtaddr}(\mathit{to}) \wedge \mathrm{p} = \mathit{vaddr}(\gamma, v) + n\end{array}\right\} \overset{\mathrm{def}}{=} \phi_1$$

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$$\left\{\begin{array}{l} \phi_1 \wedge \exists \gamma'.\ \mathsf{gc\_graph}(\gamma') \wedge \gamma' = \mathit{upd\_edge}(\gamma, e, \mathit{copy}(\gamma, v)) \wedge \\ \mathit{compat}(\gamma', \mathit{from}, \mathit{to}) \wedge \mathit{fwd\_relation}(\gamma, \gamma', \mathit{from}, \mathit{to}, v, n) \end{array}\right\}$$

```
 }
```

# Forward: a Deep Dive

```
else {
 int i; int sz; value *new; sz = size(hd);
 new = *next+1; *next = new+sz; Hd_val(new) = hd;
 for(i = 0; i < sz; i++)
   Field(new, i) = Field(v, i);
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 Hd_val(v) = 0; Field(v, 0) = p2iop((void *)new);
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$$\left\{\begin{array}{l} \phi_2 \wedge \exists \gamma''.\ \mathsf{gc\_graph}(\gamma'') \wedge \gamma'' = \mathit{upd\_edge}(\gamma', e, v') \wedge \\ \mathit{compat}(\gamma'', from, to) \wedge \mathit{fwd\_relation}(\gamma, \gamma'', from, to, v, n) \end{array}\right\}$$

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| fr_e_to_fwded : forall e g,
  vgen (dst g e) = from ->
  raw_mark (vlabel g (dst g e)) = true ->
  let new_g := labeledgraph_gen_dst g e
    (copied_vertex (vlabel g (dst g e))) in
  fwd_relation from to (inr e) g new_g
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# forward_relation

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| fr_e_to_not_fwded_Sn : forall e g g',
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  let new_g :=
    labeledgraph_gen_dst (lgraph_copy1v g (dst g e) to)
      e (copy1v_new_v g to) in
  fwd_loop from to
    (make_fields new_g (copy1v_new_v g to)) new_g g' ->
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# Specification

Similar to `forward_relation`, we have

```
  forward_roots_relation
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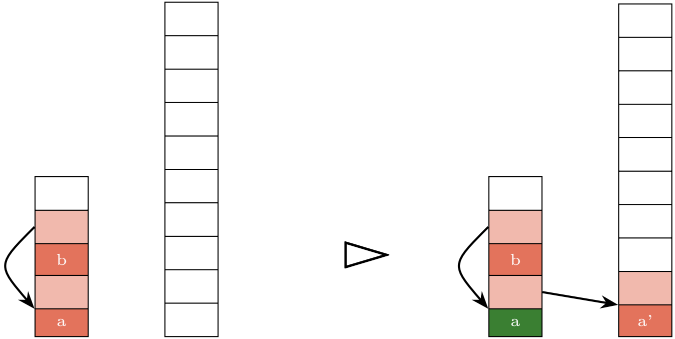
A composition of these gives us our isomorphism

# Isomorphism

But the journey is far from easy!

A brief look at `semi_iso`:



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Lemma fwd_rel_semi_iso:
  forall from to p g1 g2 g3 roots,
    semi_iso g1 g2 from to l1 ->
    forward_relation from to p g2 g3 ->
    semi_iso g1 g3 from to
```

# Isomorphism

And eventually,

```
Theorem garbage_collect_iso: forall roots1 roots2 g1 g2,
  ...
  garbage_collect_relation roots1 roots2 g1 g2 ->
  gc_graph_iso g1 roots1 g2 roots2.
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up to the vertices reachable from roots
The space between `n` and `l` is available for `alloc`

Note that we may still not achieve full isomorphism:
the graph label changes to accommodate new vertices
and may even grow to accommodate new generations

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  Fixed by adjusting nursery size

# Undefined behavior in C

Double-bounded pointer comparisons:

```
int Is_from(value * lo, value * hi, value * v) {
    return (lo <= v && v < hi); }
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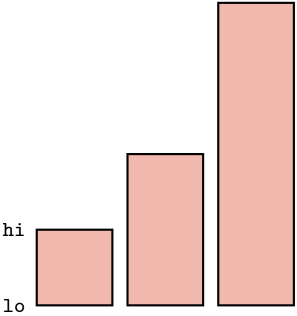

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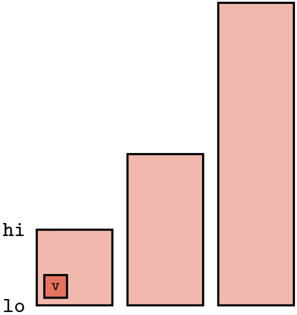

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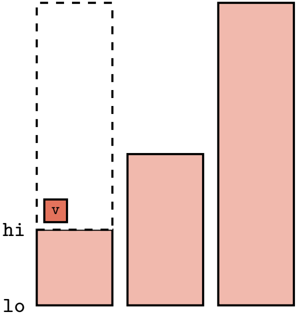

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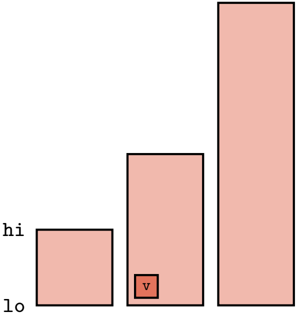

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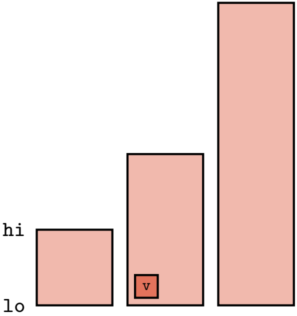

Resolved using CompCert's `extcall_properties`

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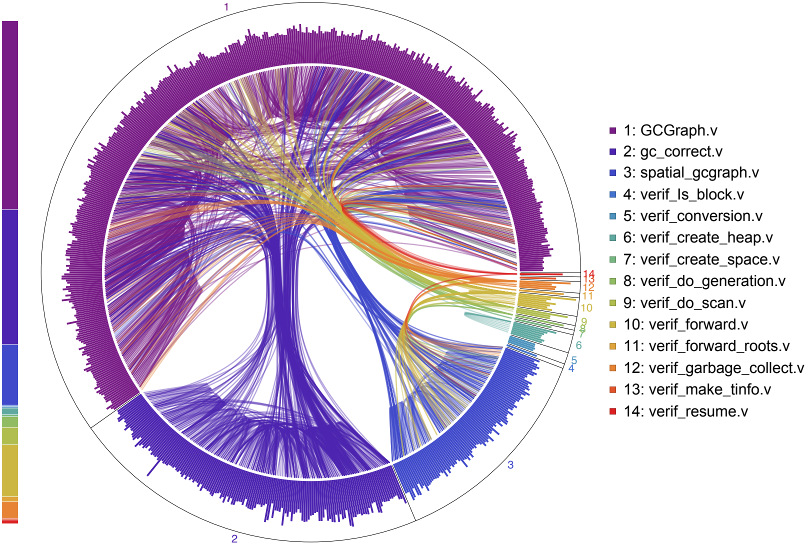
Discussing `char` alignment issues with CompCert

# Reusability: separation between pure and spatial reasoning



# Future Work

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Further refinements required in C semantics
  before we can specify and verify OCaml's GC?