A Verified Garbage Collector for Gallina

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

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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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Hard, but ubiquitous in critical areas

Broad Solution

Certifying Graph-Manipulating C Programs via Localizations within Data Structures

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VST + CompCert + 25000 LOC library

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

This Talk

Gallina $\rightsquigarrow$ CompCert C $\rightsquigarrow$ Assembly

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Gallina assumes infinite memory
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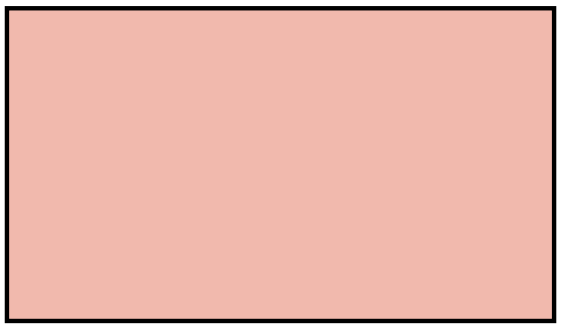
Solution: garbage collect the CompCert C code

New problem: verify the garbage collector

Our Garbage Collector

GC has jurisdiction over the heap



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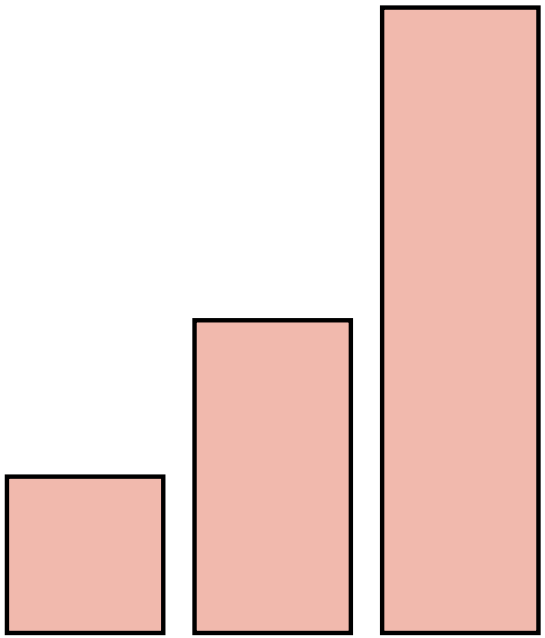

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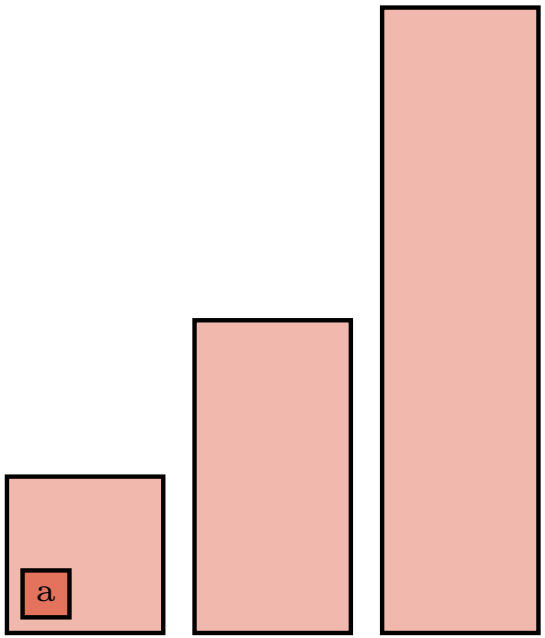
GC has jurisdiction over the heap

- Mutator `allocs` in special subheap



Our Garbage Collector

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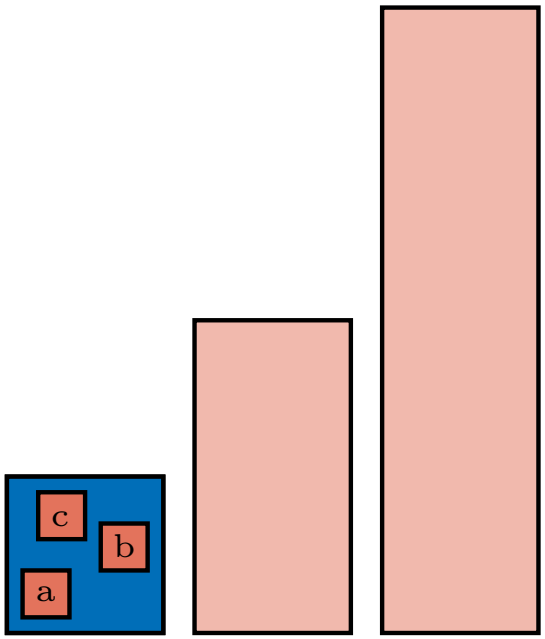
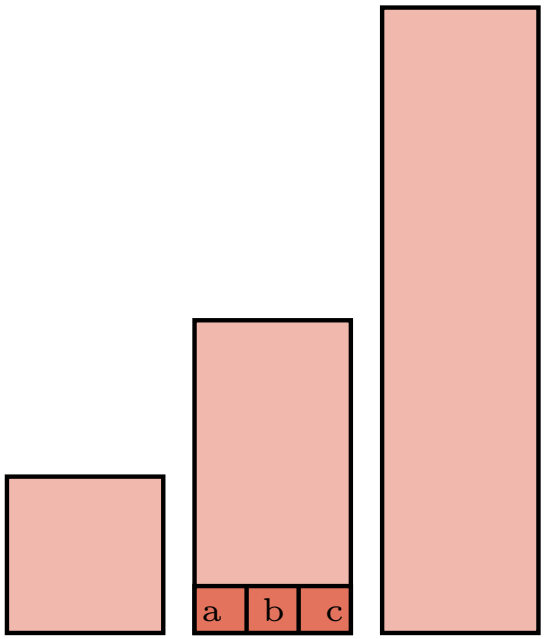
- Mutator `allocs` in special subheap
  - If subheap is full



Our Garbage Collector

GC has jurisdiction over the heap

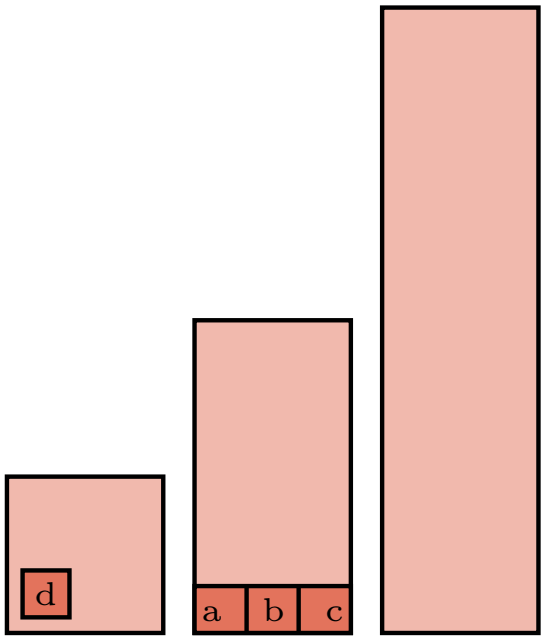
- Mutator `allocs` in special subheap
  - If subheap is full call GC



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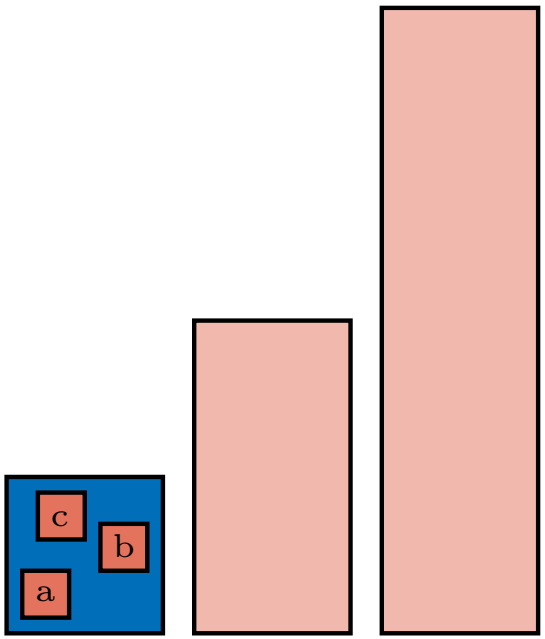
- 12 generations, doubling in size
- Functional mutator: no back pointers
- Cheney's mark-and-copy collects gen to next
- Potentially triggers cascade of pairwise collections
- Three key functions:
  `forward` copies individual objects
  `do_scan` repairs copied objects
  `forward_roots` kick-starts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

Intuitive Specification

Primum non nocere: first, do no harm



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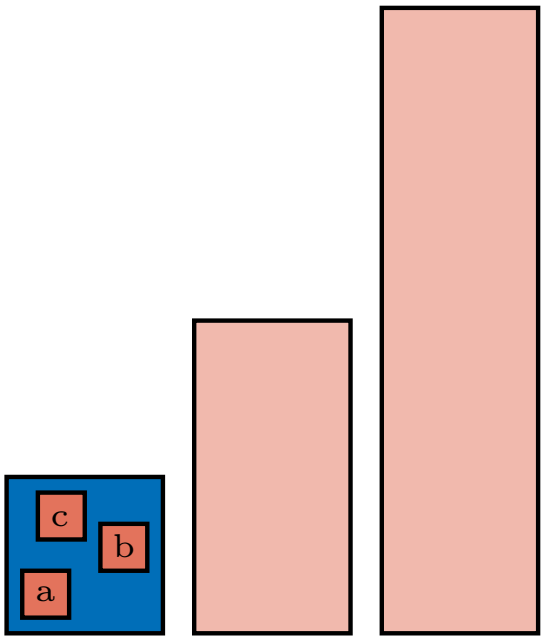

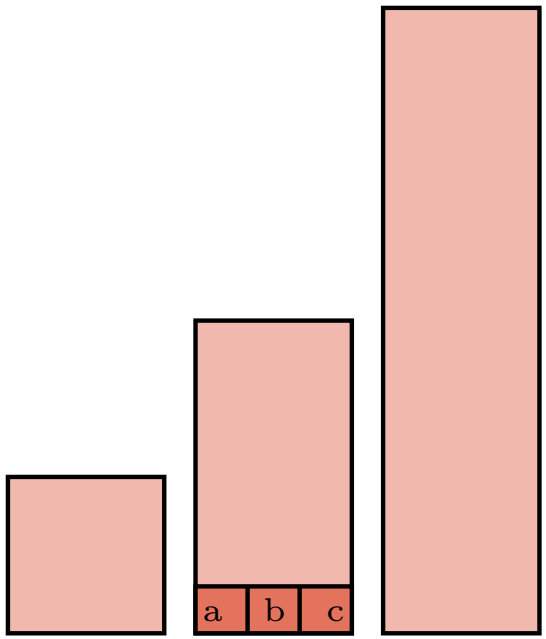

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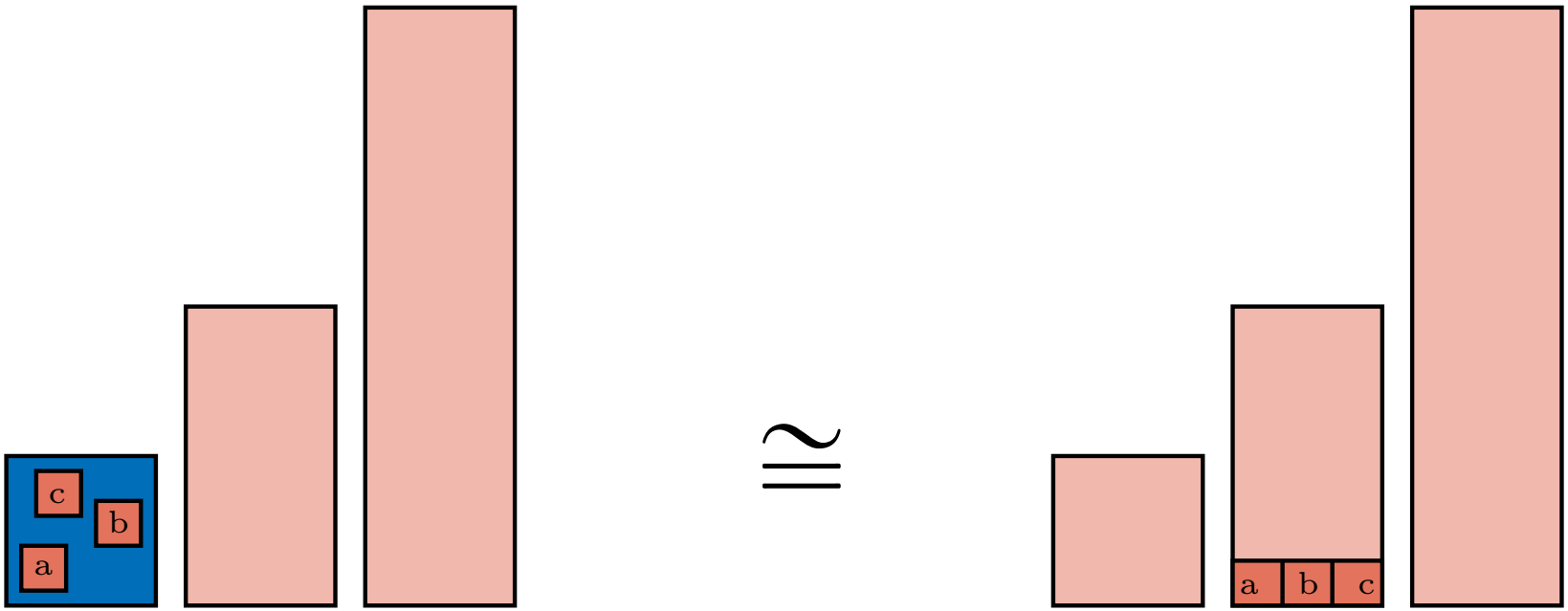
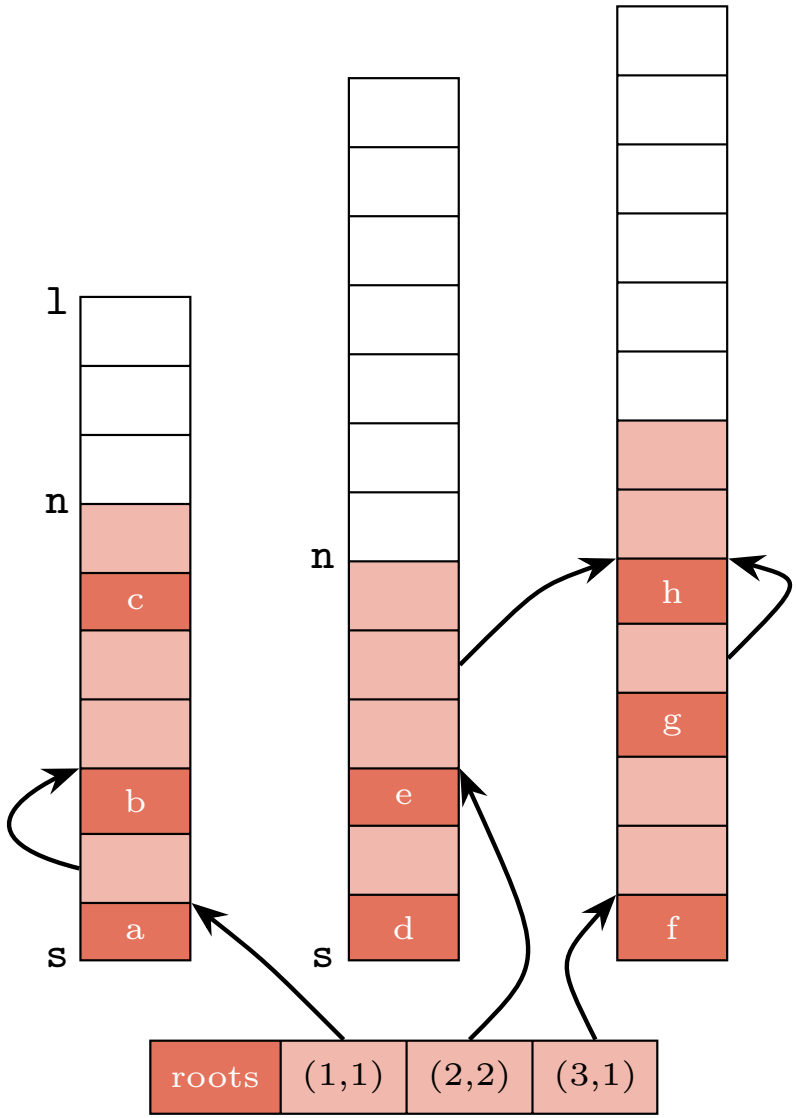


Overview of Operations

Nursery cannot fit `alloc`



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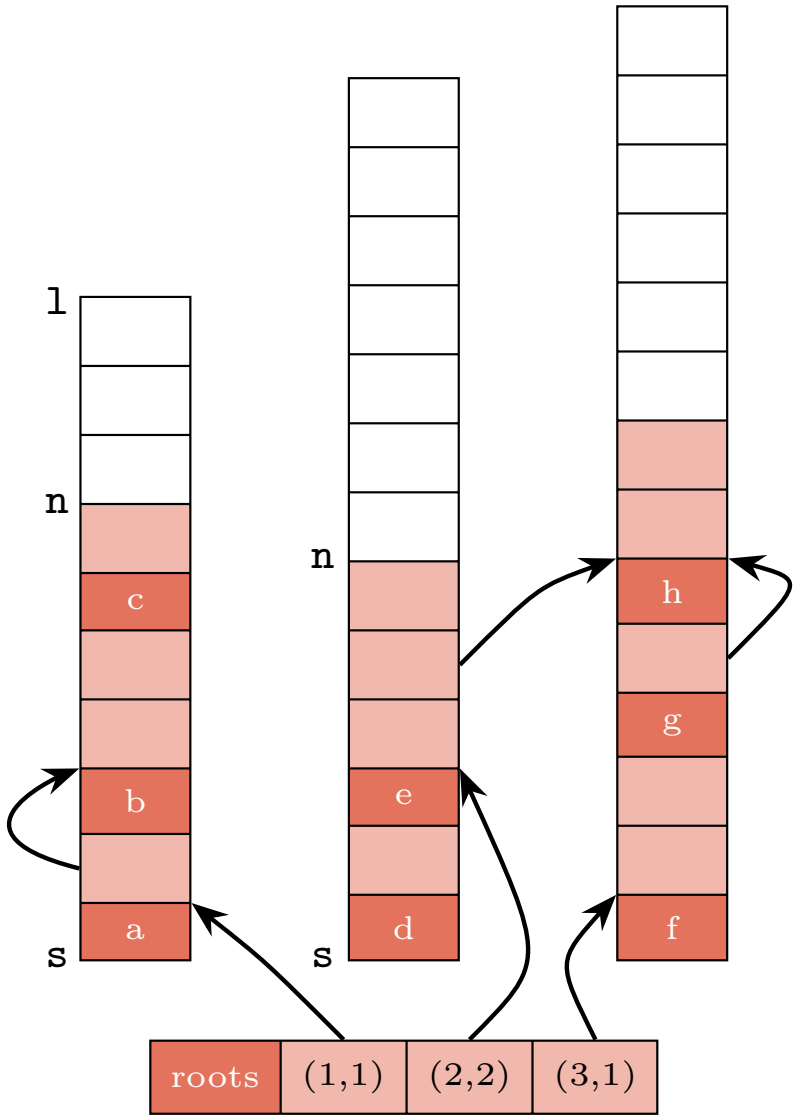
`do_gen`



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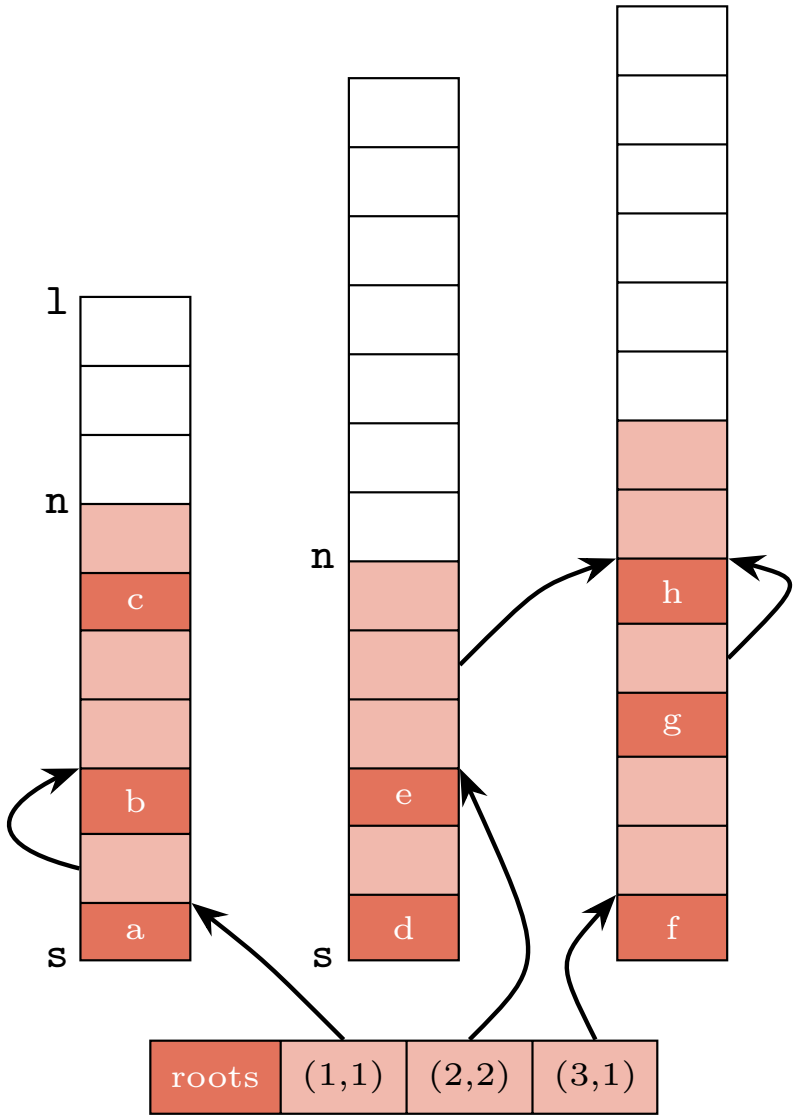

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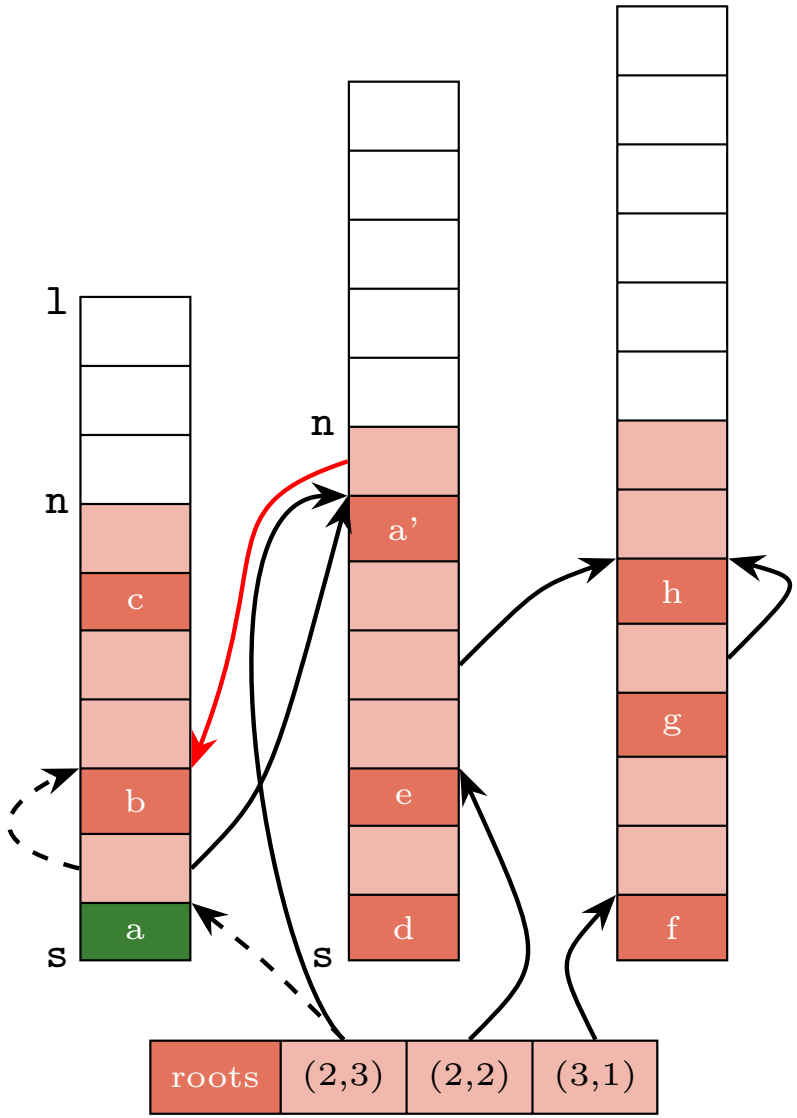

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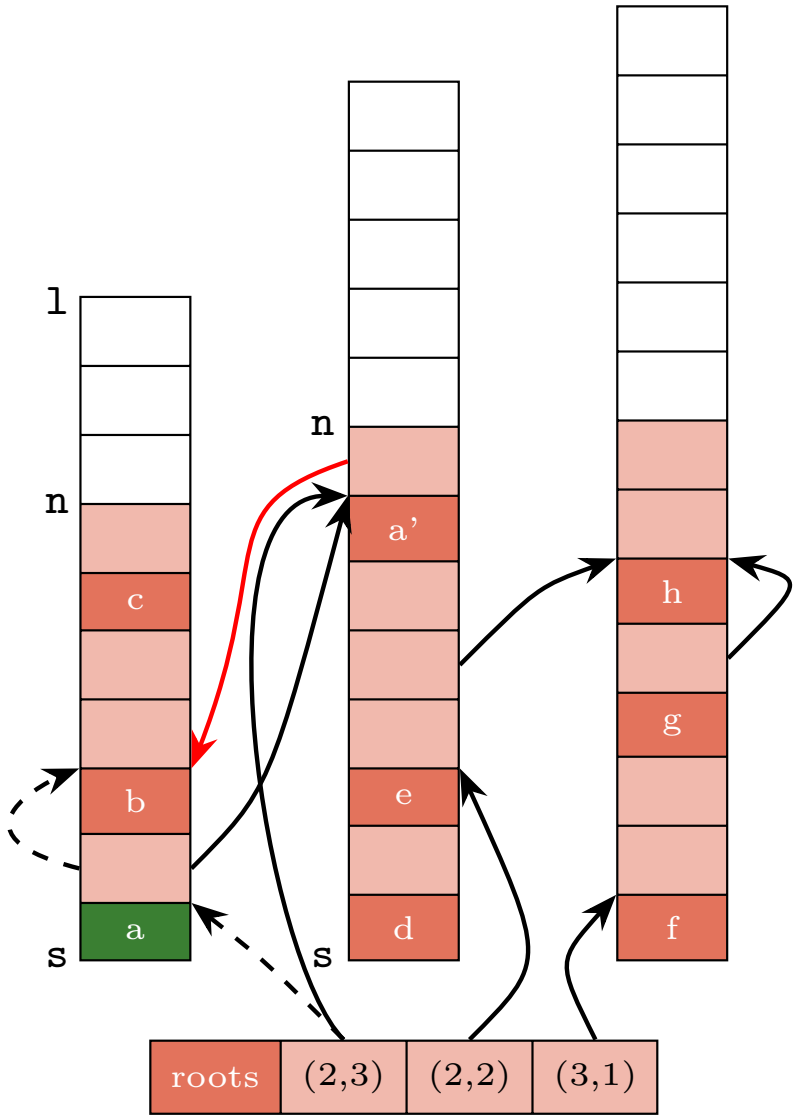

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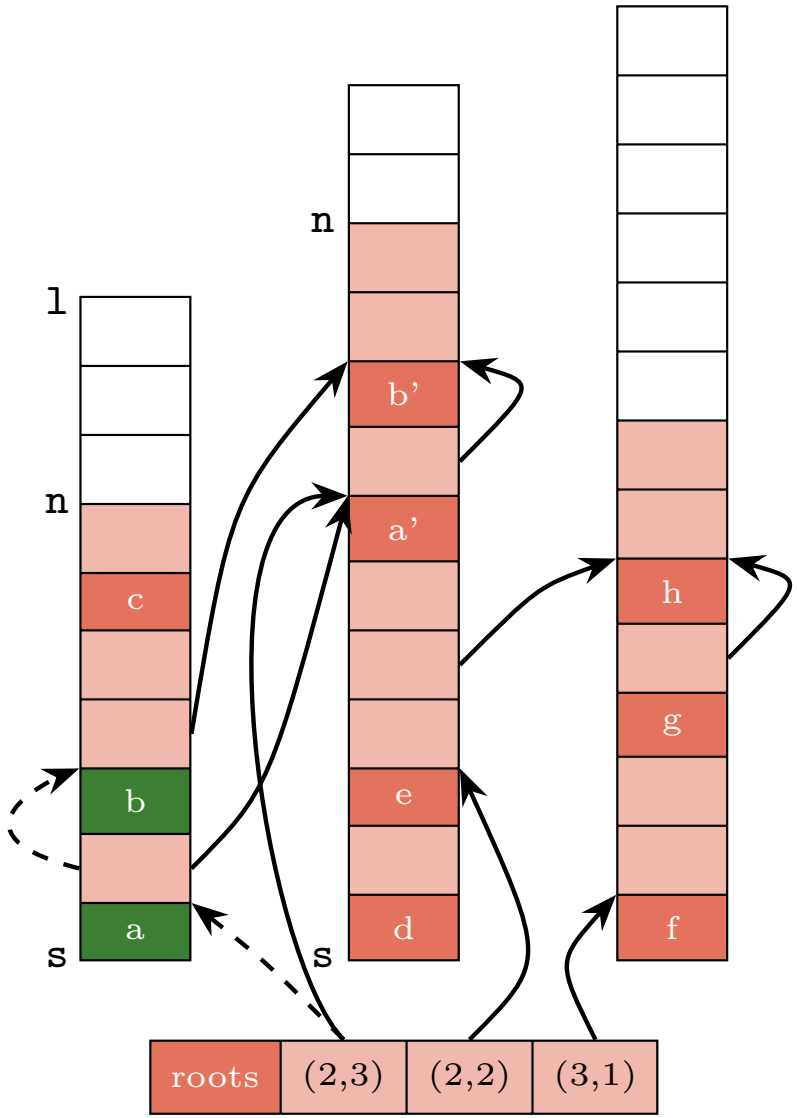

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Nursery cannot fit `alloc`

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do_gen
  forward_roots
    forward
  do_scan
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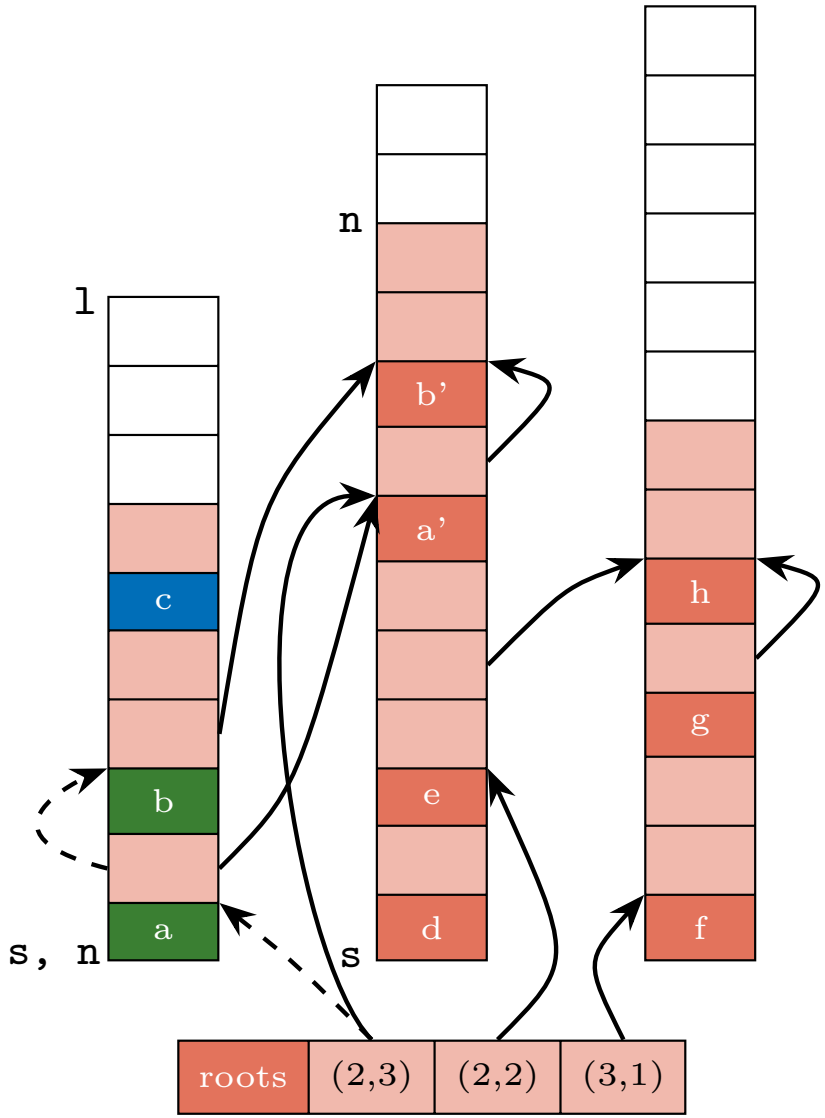
  reset_gen
```



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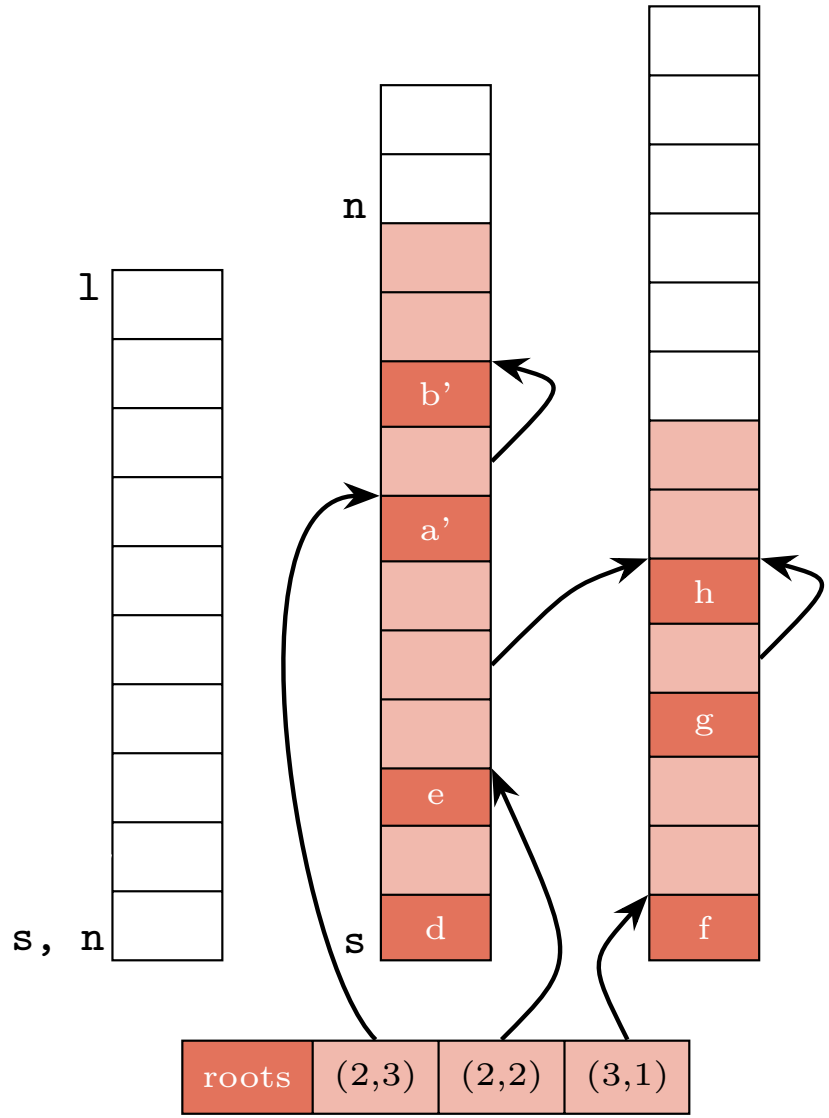

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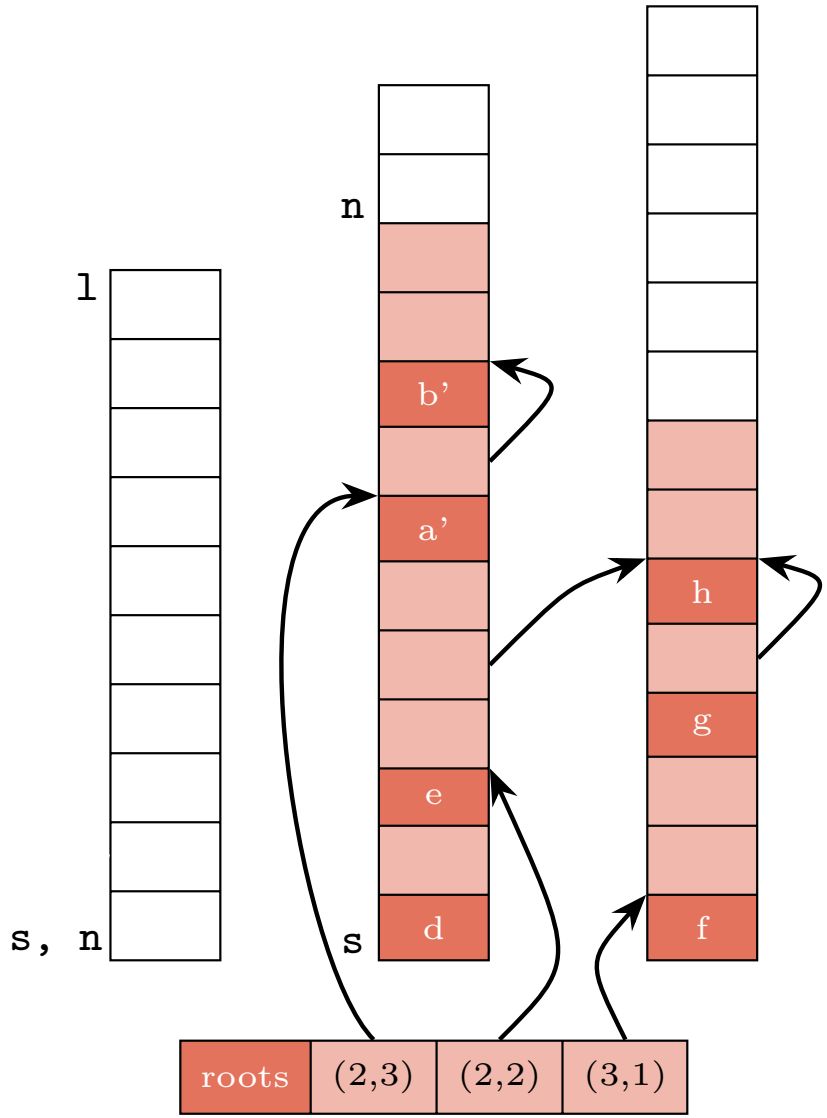
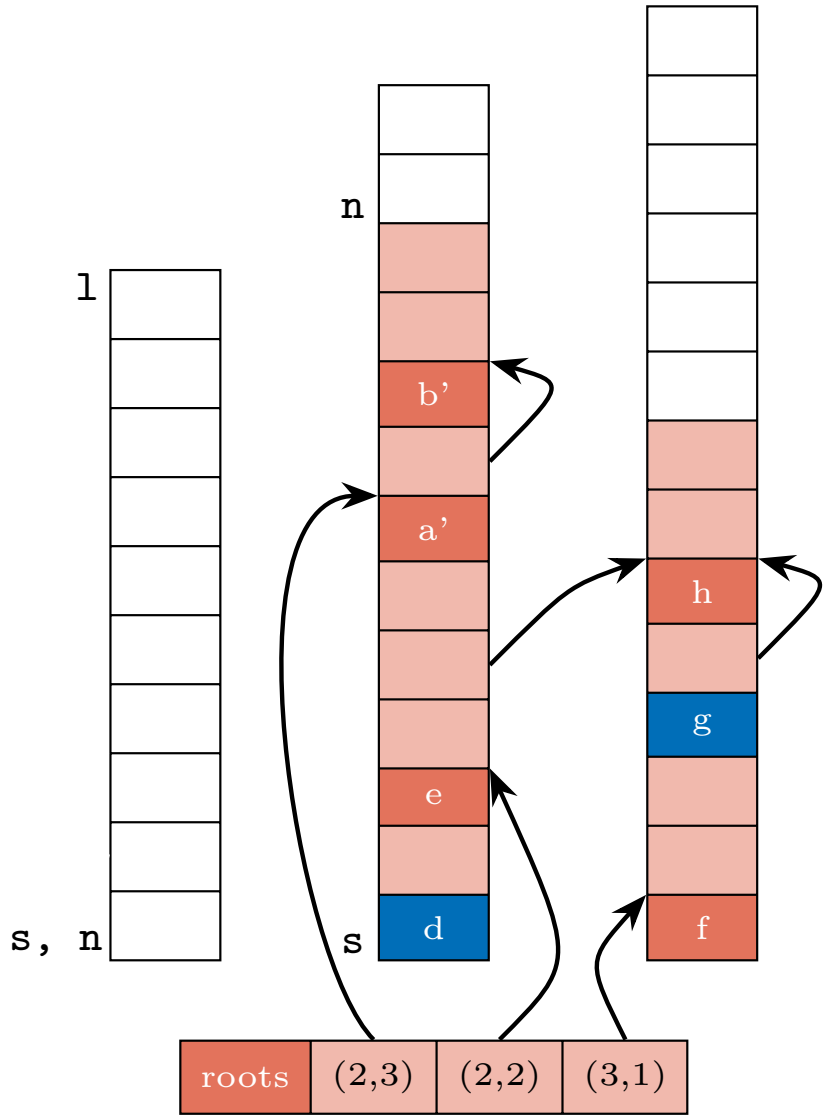


Overview of Operations

Non-Concerns

more garbage



Overview of Operations

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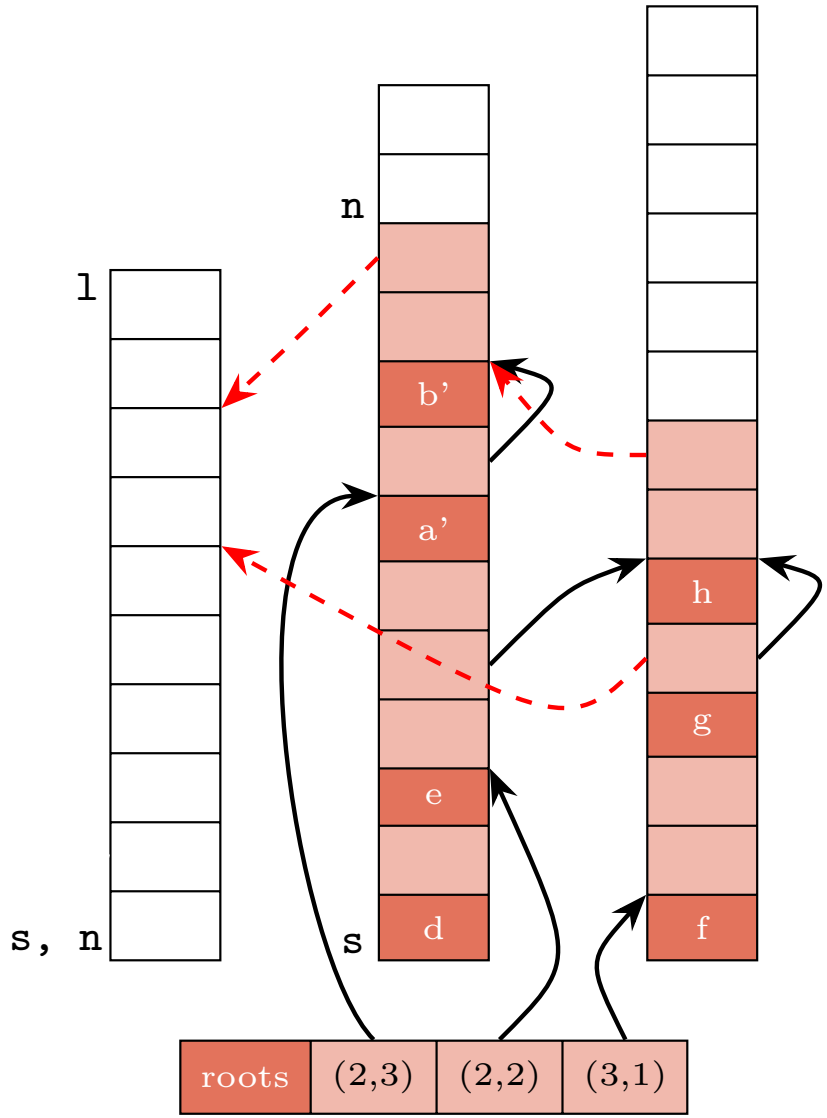

Overview of Operations

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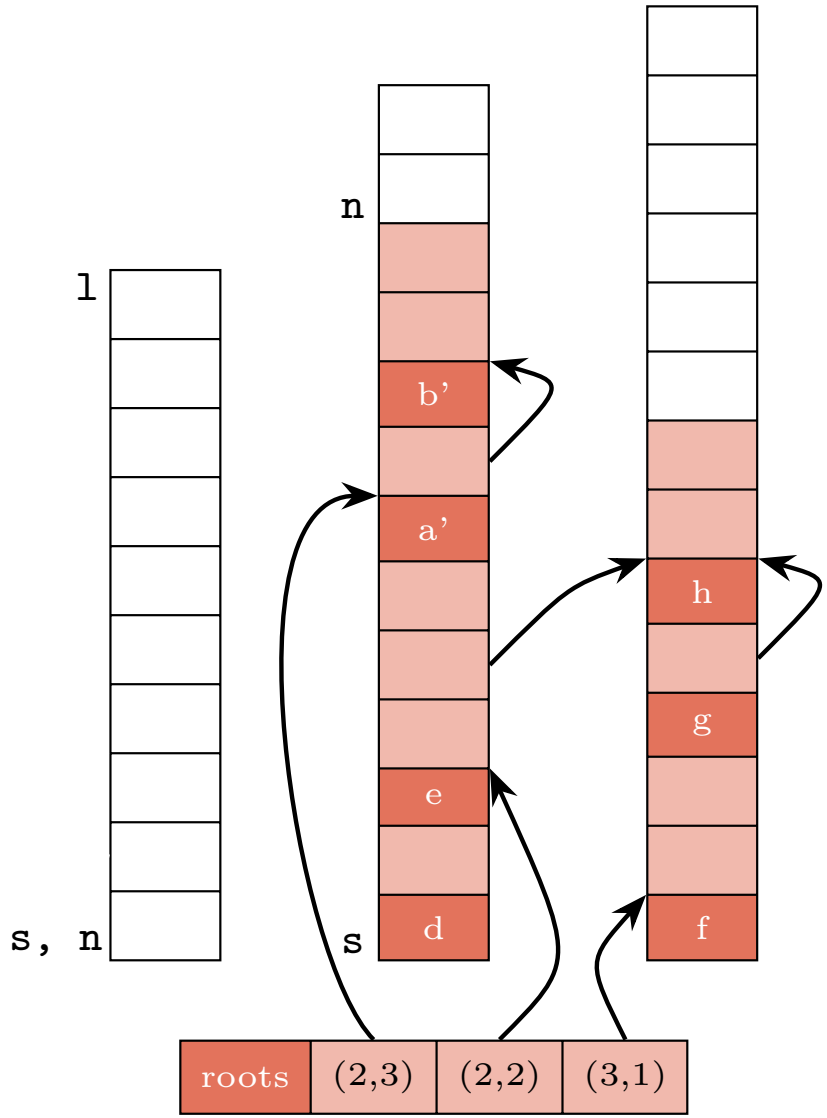
Sources of Complexity



Overview of Operations

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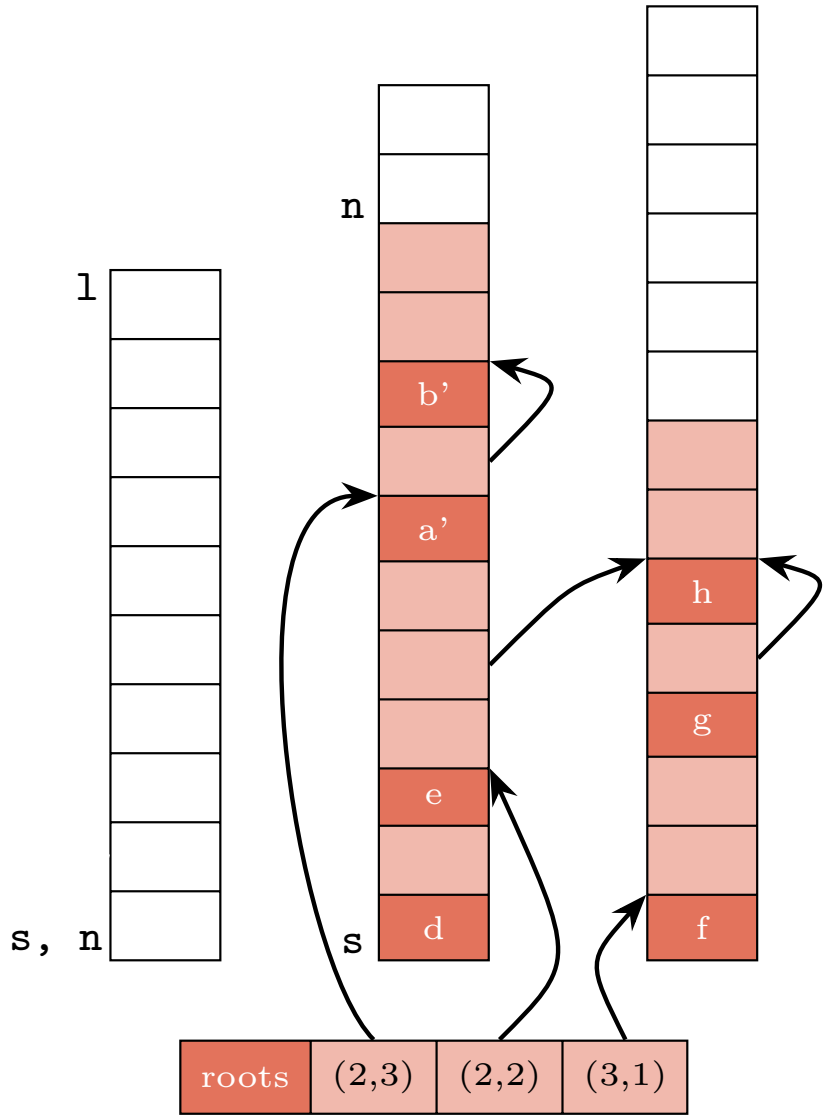
Sources of Complexity
- variable-length objects



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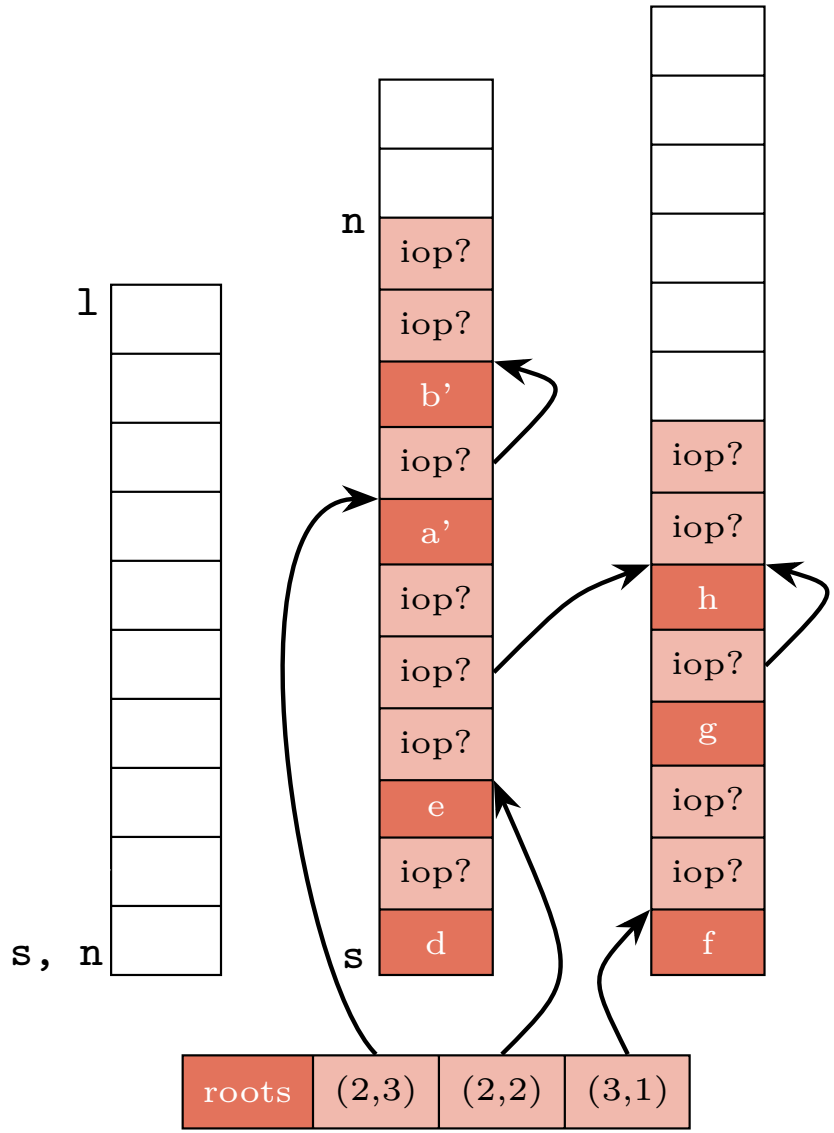
Sources of Complexity
- variable-length objects
- disambiguate int/ptr



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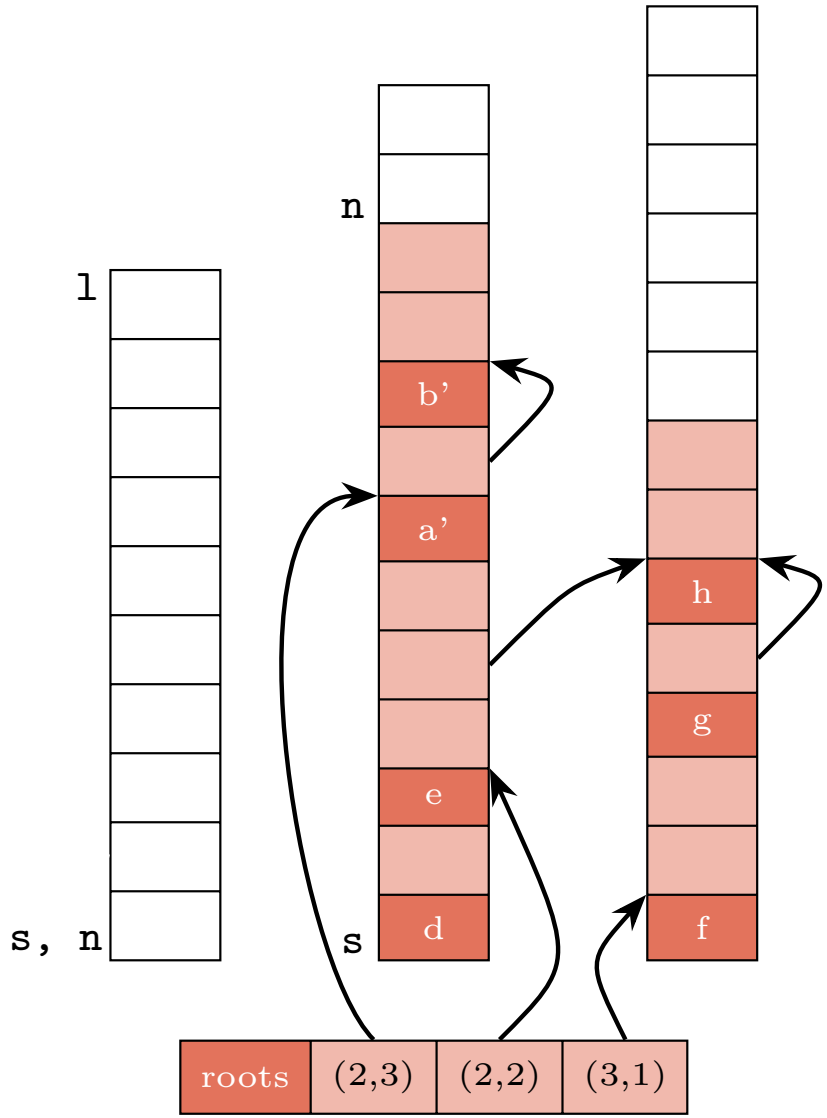

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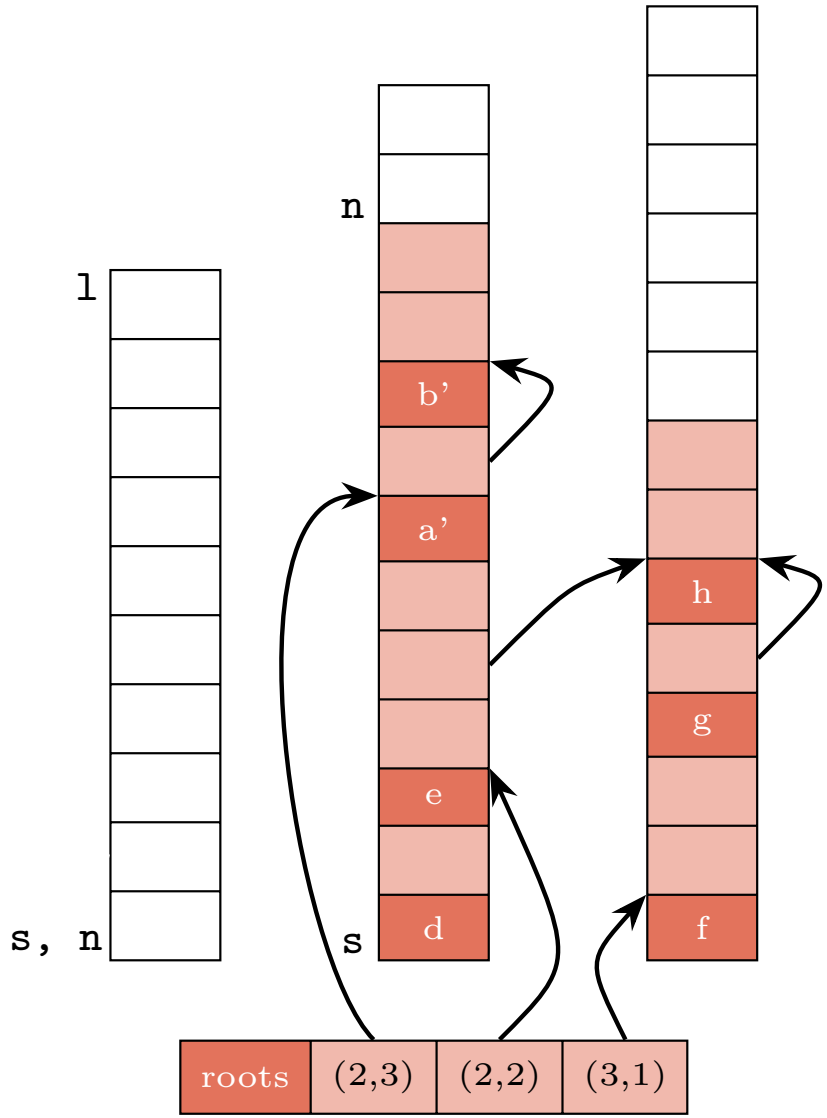

Overview of Operations

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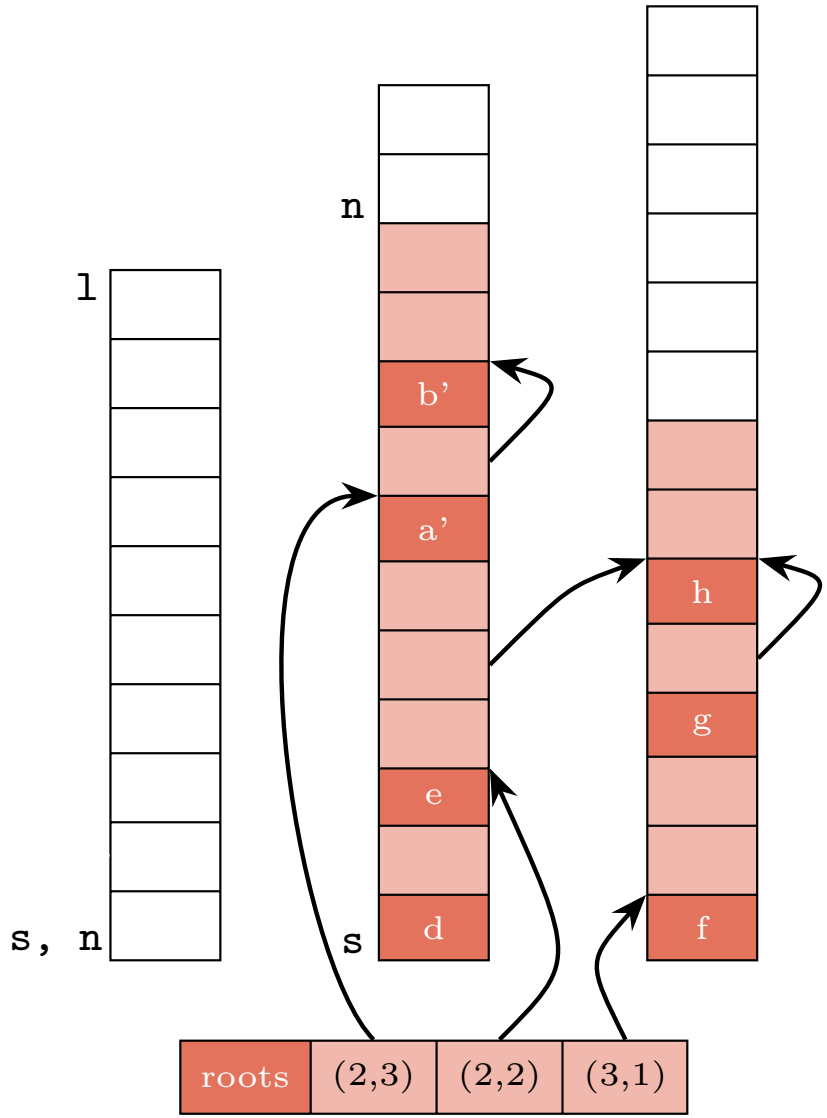
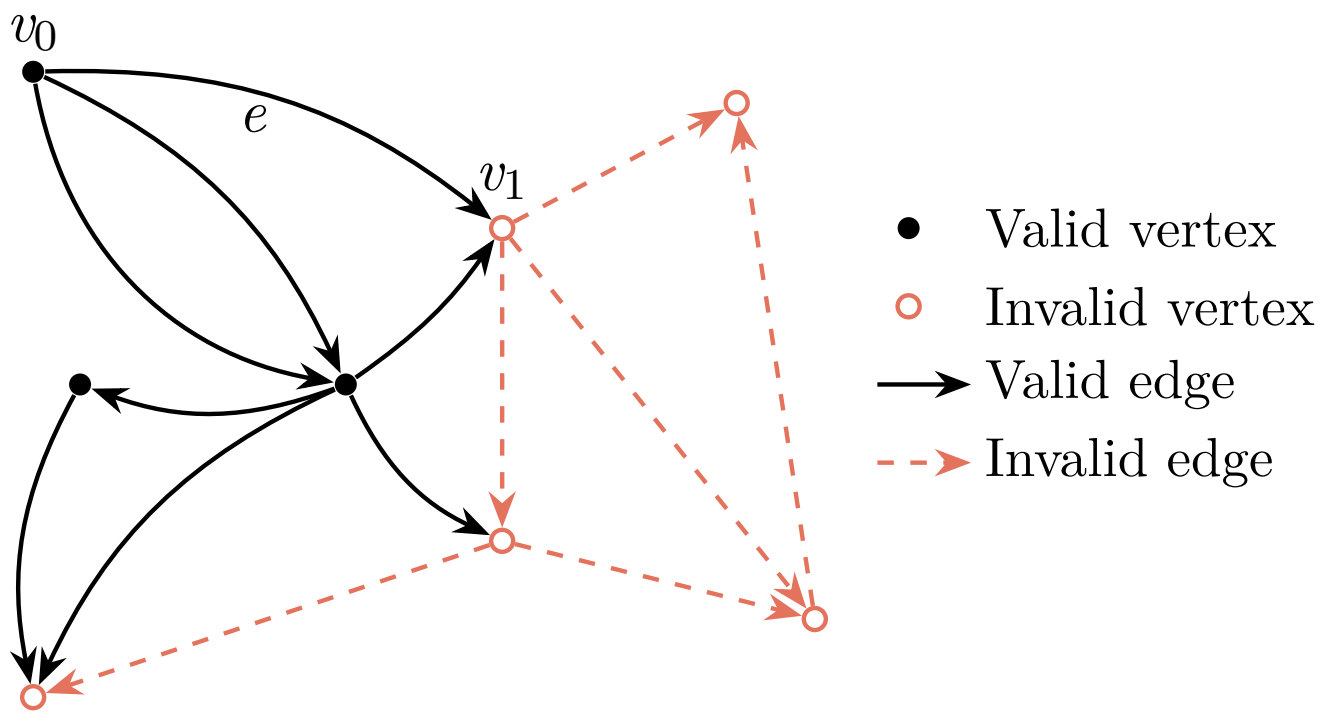
Sources of Complexity
- variable-length objects
- disambiguate int/ptr
- determine v's gen
- determine gen size
- what if `malloc` fails?



Instantiating GC_Graph

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



Instantiating GC_Graph

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

GC_PreGraph: `VType := nat * nat`

`EType := VType * nat`

`src := fst`

`dst :=` *unrestricted*

$\forall v.$ `vvalid`$(\gamma, v) \Leftrightarrow$ `graph_has_v`(γ, v)

$\forall v, out.$ `evalid`$(\gamma, (v, out)) \Leftrightarrow$

`vvalid`$(\gamma, v) \wedge$ `In` out (`get_edges`(γ, 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 everywhere!

```
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);
   if(hd == 0) {
    *p = Field(v,0);
   } else { /* elided */
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pointer? in from space?

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pointer? in `from` space? already forwarded?

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called on root set called on heap

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forward: a Deep Dive

$$\left\{ \begin{array}{l} \forall \gamma, from, to, v, n.\ \mathsf{gc\_graph}(\gamma) \wedge compat(\gamma, from, to) \wedge \\ \mathrm{s} = start(\gamma, from) \wedge \mathrm{l} = \mathrm{s} + gensz(\gamma, from) \wedge \\ \mathrm{n} = nxtaddr(to) \wedge \mathrm{p} = vaddr(\gamma, v) + n \end{array} \right\} \stackrel{\text{def}}{=} \phi_1$$

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

```
 }
```

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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$$\left\{ \begin{array}{l} \phi_1 \wedge \exists \gamma', v'.\ \mathsf{gc\_graph}(\gamma') \wedge v' = copied\_vertex(\gamma, to) \wedge \\ \gamma' = copy\_vertex(\gamma, to, v, v') \wedge compat(\gamma', from, to) \end{array} \right\} \stackrel{\text{def}}{=} \phi_2$$

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```
  Hd_val(v) = 0; Field(v, 0) = p2iop((void *)new);
  *p = p2iop((void *)new);
```

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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);
```

$$\left\{ \begin{array}{l} \phi_1 \wedge \exists \gamma', v'.\ \mathsf{gc\_graph}(\gamma') \wedge v' = copied\_vertex(\gamma, to) \wedge \\ \gamma' = copy\_vertex(\gamma, to, v, v') \wedge compat(\gamma', from, to) \end{array} \right\} \stackrel{\text{def}}{=} \phi_2$$

```
 Hd_val(v) = 0; Field(v, 0) = p2iop((void *)new);
 *p = p2iop((void *)new);
```

$$\left\{ \begin{array}{l} \phi_2 \wedge \exists \gamma''.\ \mathsf{gc\_graph}(\gamma'') \wedge \gamma'' = upd\_edge(\gamma', e, v') \wedge \\ compat(\gamma'', from, to) \wedge fwd\_relation(\gamma, \gamma'', from, to, v, n) \end{array} \right\}$$

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      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`
- `do_scan_relation`
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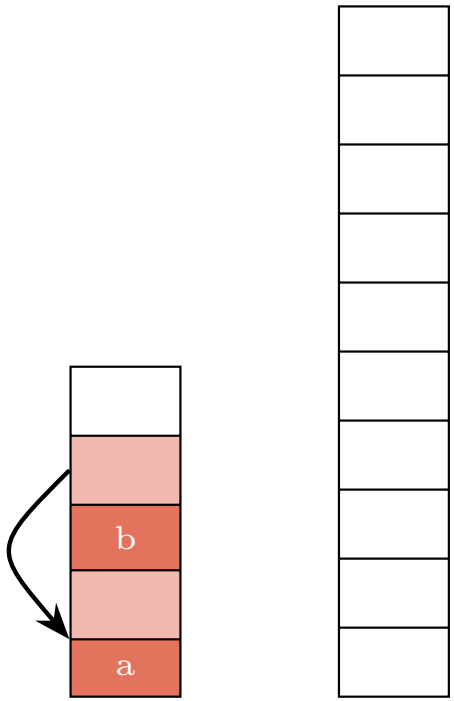
A composition of these gives us our isomorphism

Moving Towards Isomorphism

But the journey is far from easy!

A brief look at `semi_iso`:



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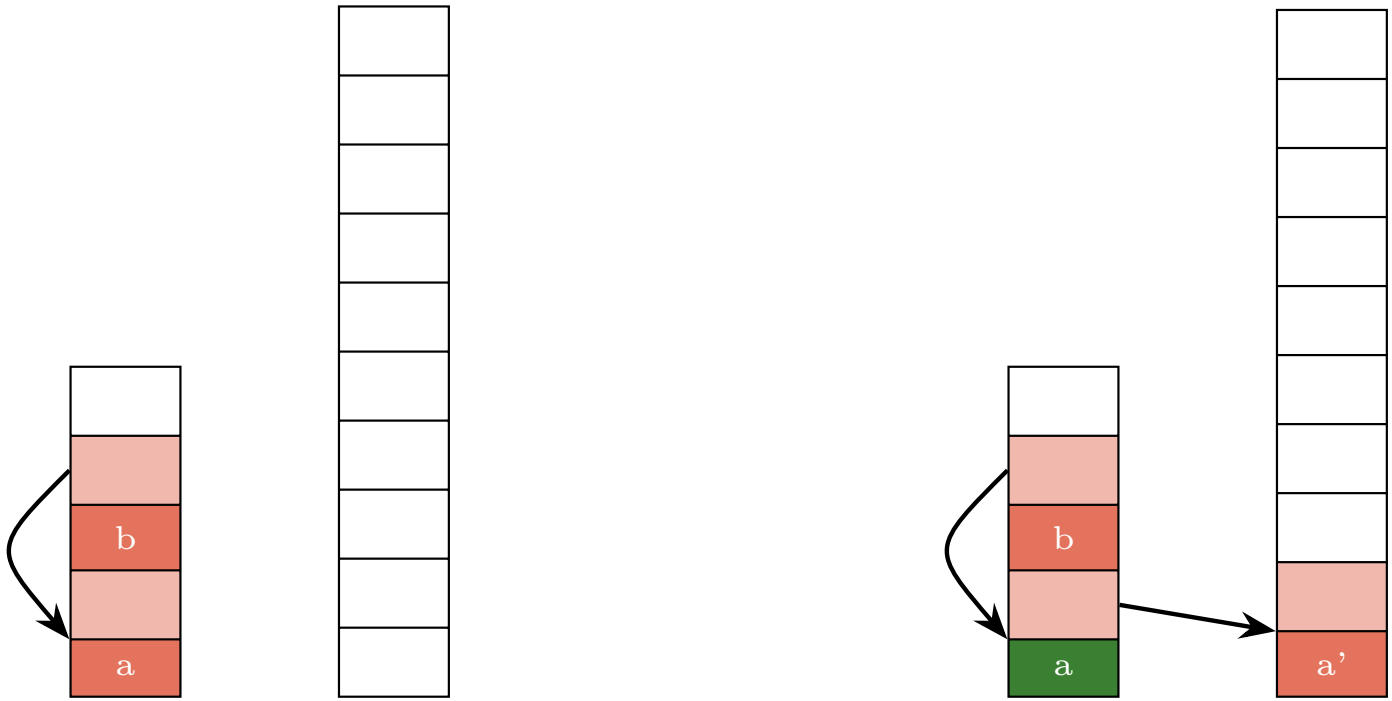

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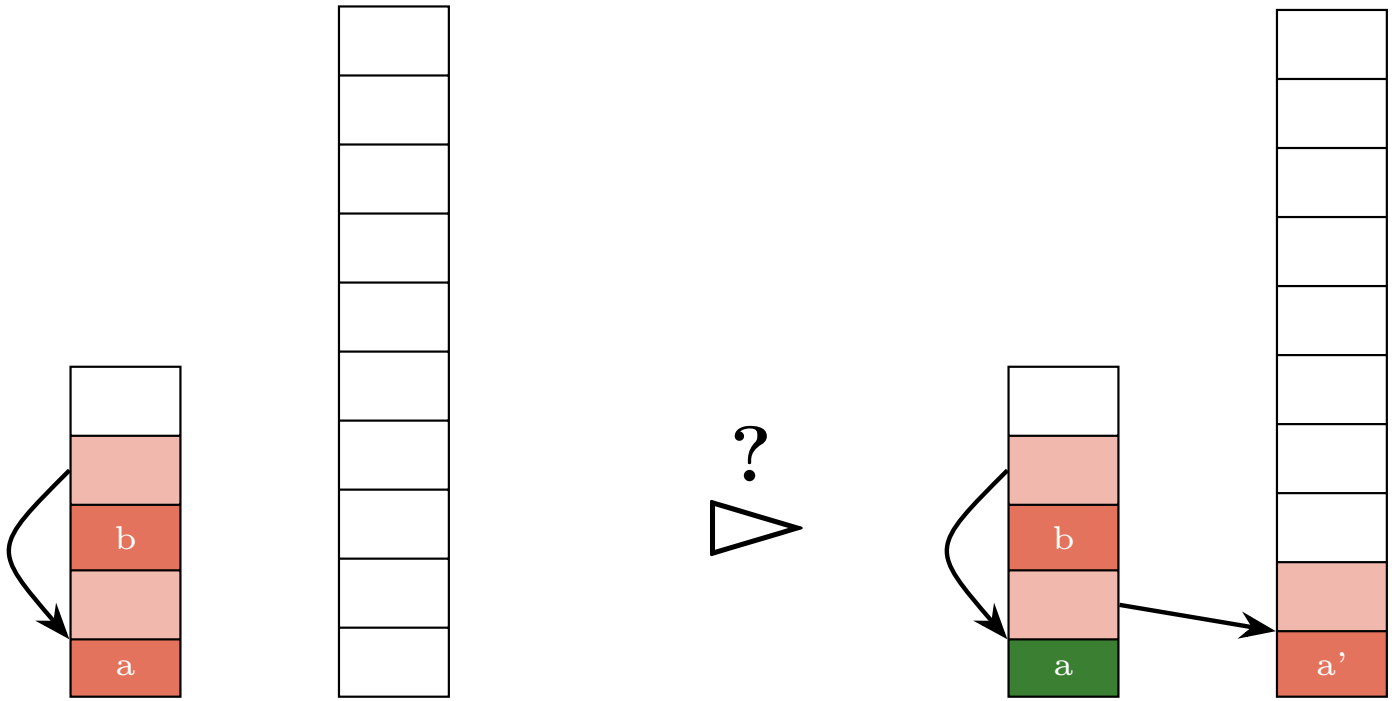

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Lemma fwd_rel_semi_iso:
  forall from to p g1 g2 g3 roots,
    semi_iso g1 g2 from to l1 ->
    forward_relation from to p g2 g3 ->
    semi_iso g1 g3 from to
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Moving Towards Isomorphism

And eventually,

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Theorem garbage_collect_iso: forall roots1 roots2 g1 g2,
  ...
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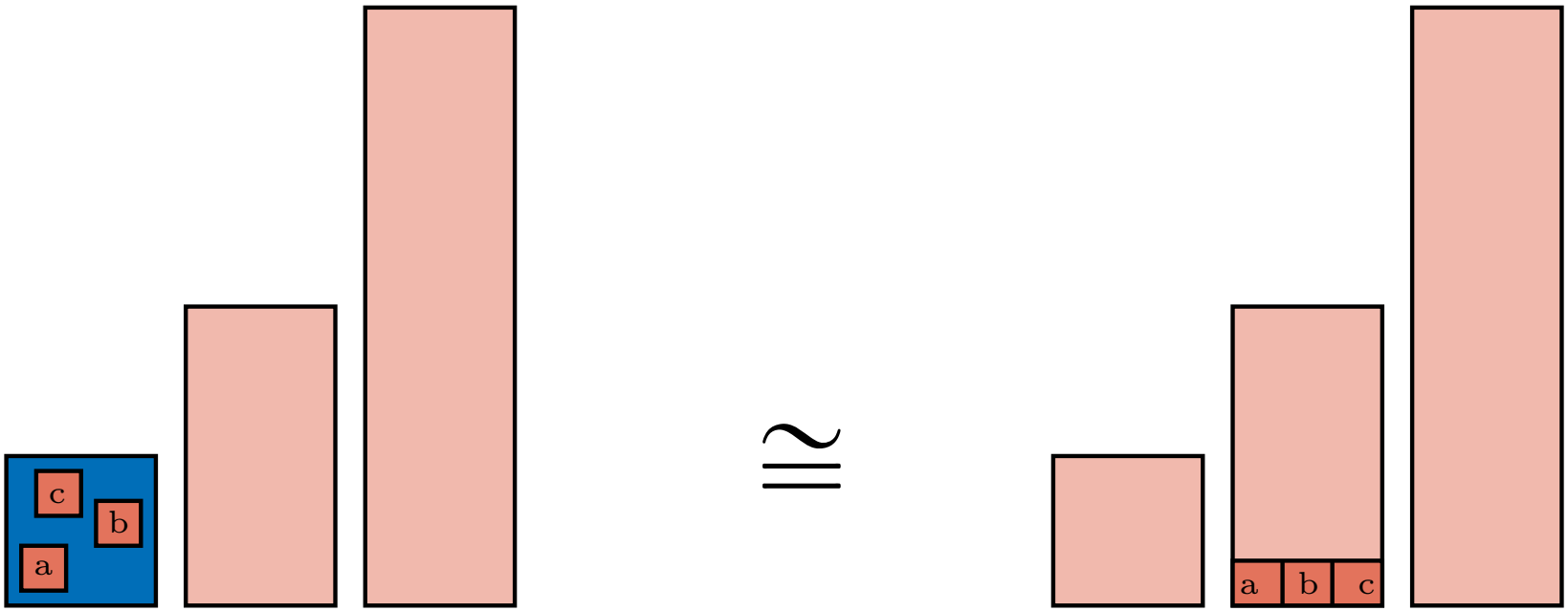
    and may even grow to accommodate new generations

Recap: Intuitive Specification

Primum non nocere: first, do no harm



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  Fixed by adjusting nursery size

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Double-bounded pointer comparisons:

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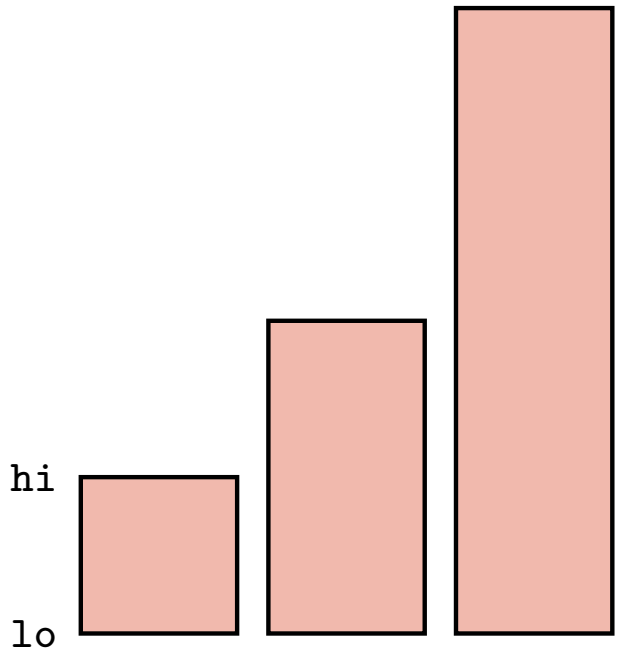

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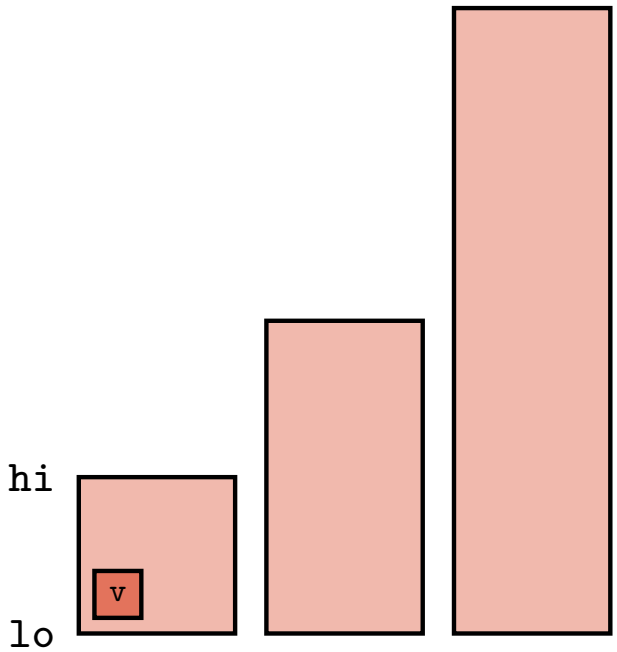

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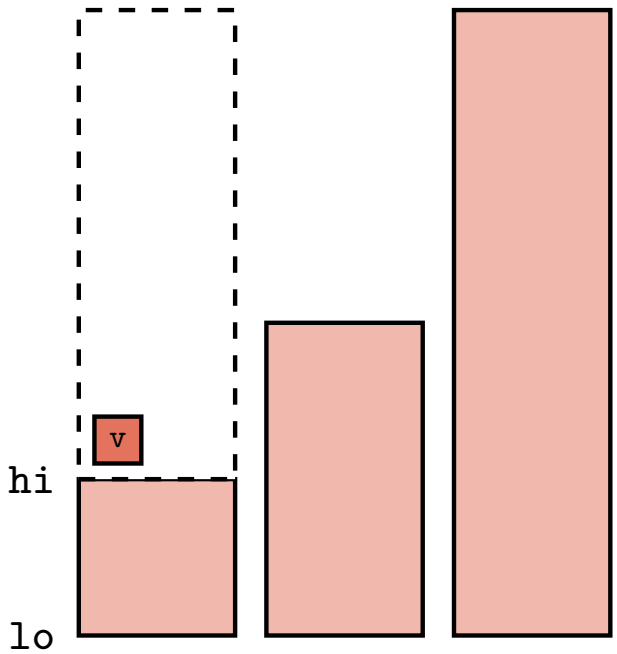

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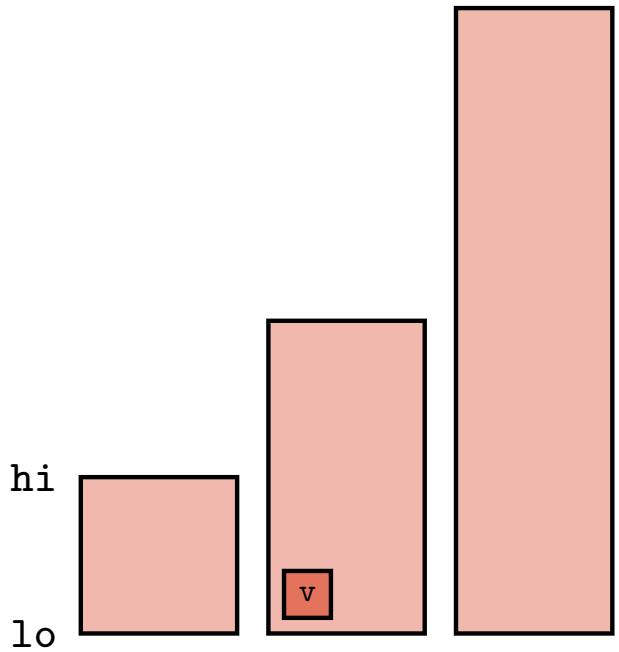

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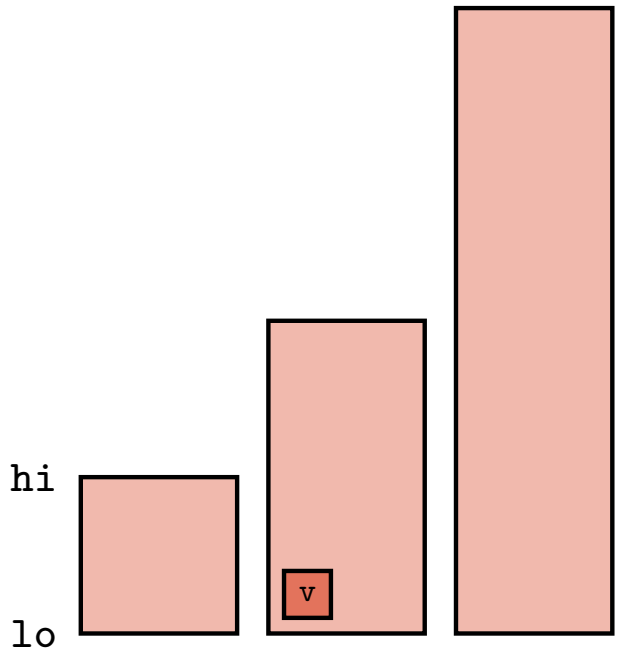

Resolved using CompCert's `extcall_properties`

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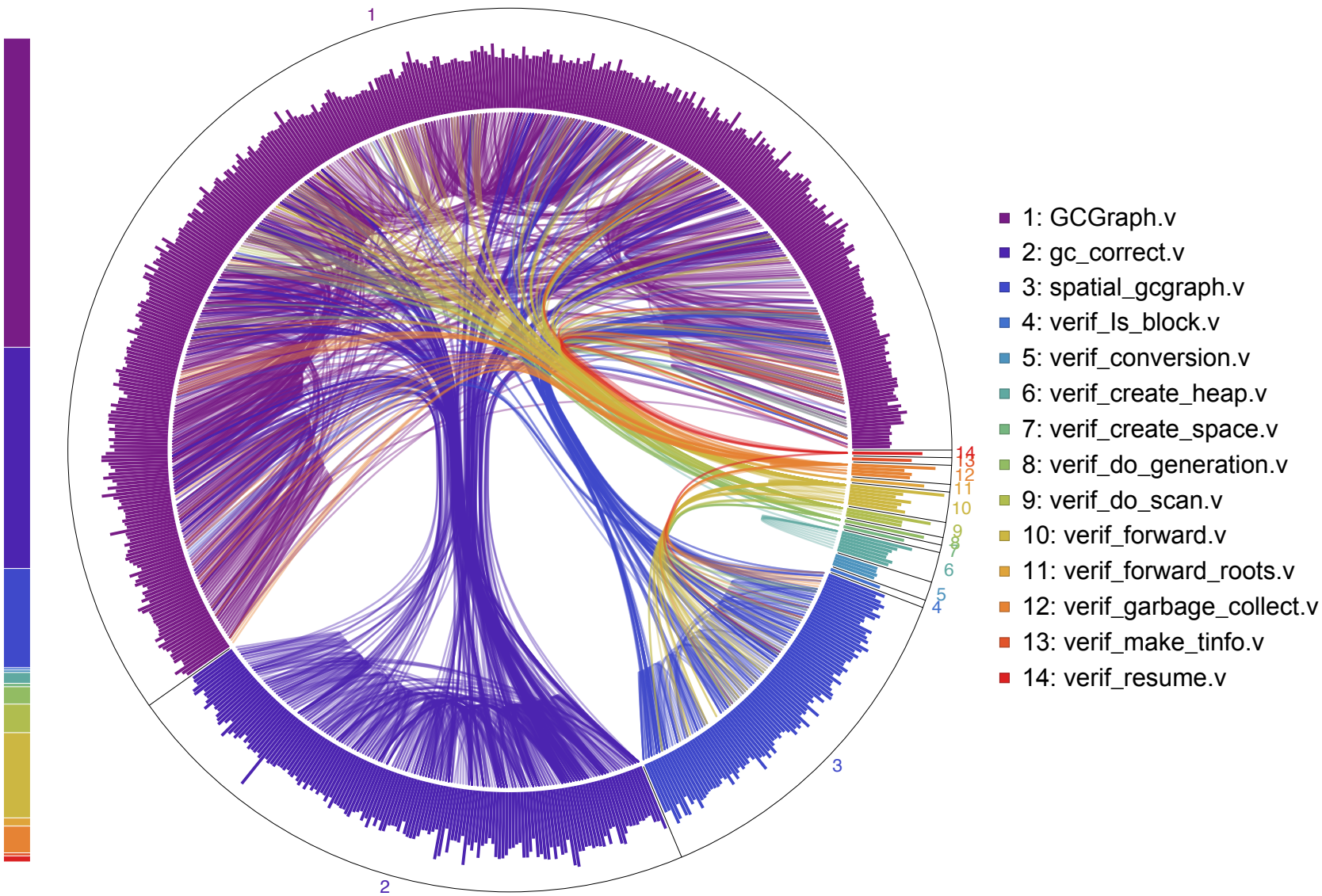
Discussing `char` alignment issues with CompCert

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?