A Verified Garbage Collector for Gallina

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APLAS NIER
December 1, 2019

Broad Problem

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

Hard, but ubiquitous in critical areas

Broad Solution

Verified
Software
Toolchain

Certifying Graph-Manipulating C Programs via Localizations within Data Structures

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VST + CompCert + 25000 LOC library

Powerful enough to verify executable code
against realistic specifications
expressed with mathematical graphs

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

This Talk

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

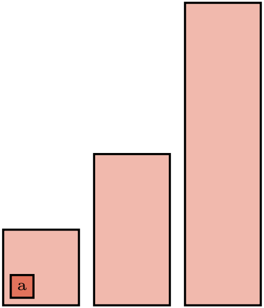
Gallina assumes infinite memory
but CompCert C has a finite heap

Solution: garbage collect the CompCert C code

New problem: verify the garbage collector

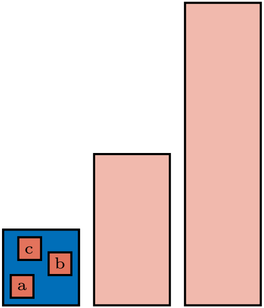
GC has jurisdiction over the heap

Mutator `allocs` in special subheap



GC has jurisdiction over the heap

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

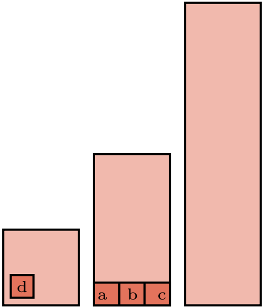


Our Garbage Collector

GC has jurisdiction over the heap

Mutator `allocs` in special subheap

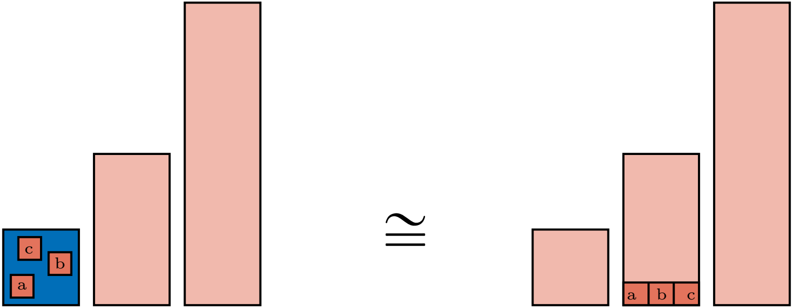
If subheap is full call GC and try again



Our Garbage Collector

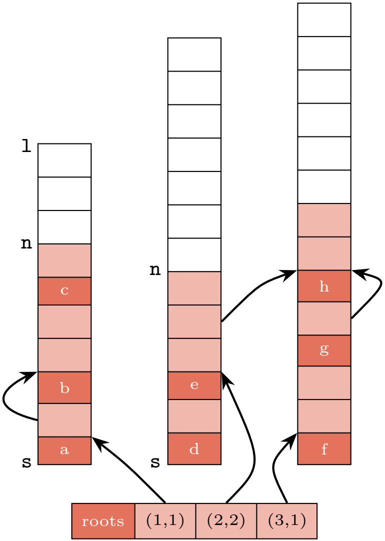
- 12 generations, doubling in size
- Functional mutator: no back pointers
- Cheney's mark-and-copy collects gen to next
- Potentially triggers cascade of pairwise collections
- Three key functions:
  `forward` copies individual objects
  `do_scan` repairs copied objects
  `forward_roots` kick-starts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

Primum non nocere: first, do no harm



Overview of Operations

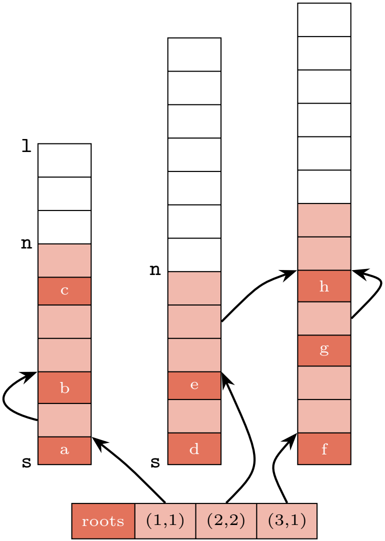
Nursery cannot fit `alloc`



Overview of Operations

Nursery cannot fit `alloc`

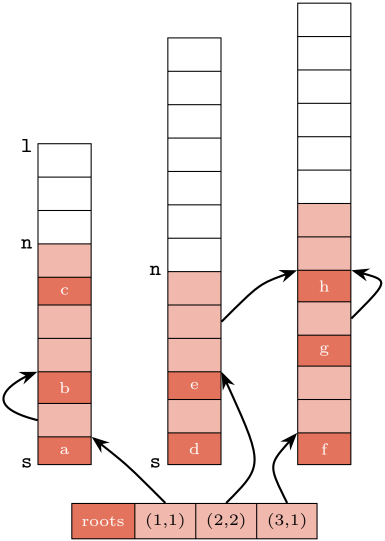
`do_gen`



Overview of Operations

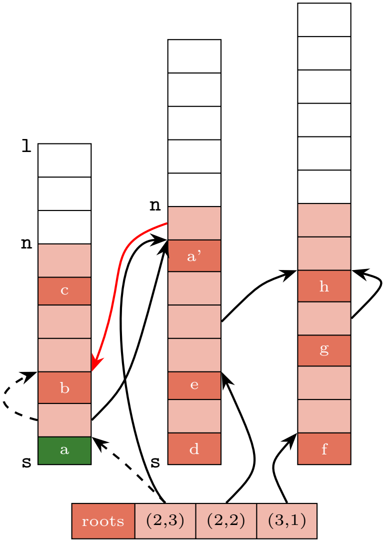
Nursery cannot fit `alloc`

```
  do_gen
    forward_roots
```



Nursery cannot fit `alloc`

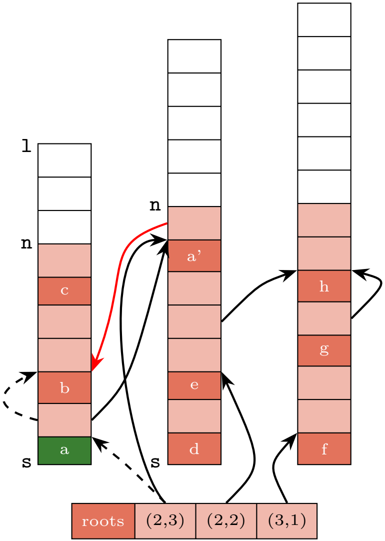
```
do_gen
  forward_roots
    forward
```



Overview of Operations

Nursery cannot fit `alloc`

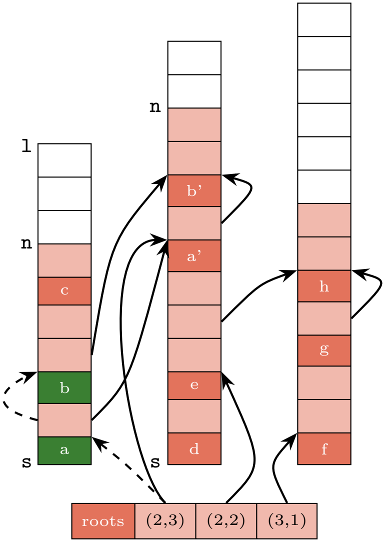
```
  do_gen
    forward_roots
      forward
    do_scan
```



Overview of Operations

Nursery cannot fit `alloc`

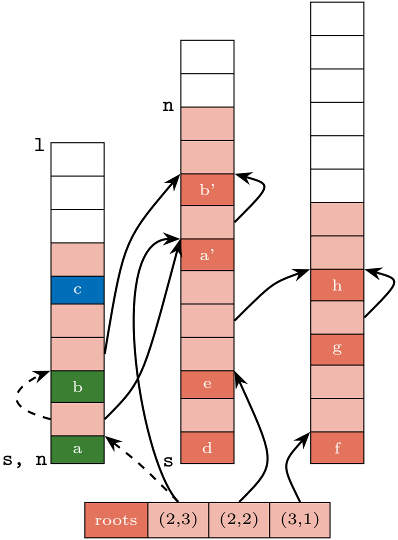
```
do_gen
  forward_roots
    forward
  do_scan
    forward
```



Overview of Operations

Nursery cannot fit `alloc`

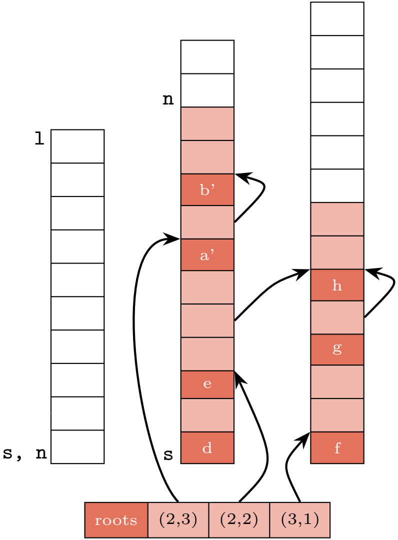
```
do_gen
  forward_roots
    forward
  do_scan
    forward
  reset_gen
```



Overview of Operations

Nursery cannot fit `alloc`

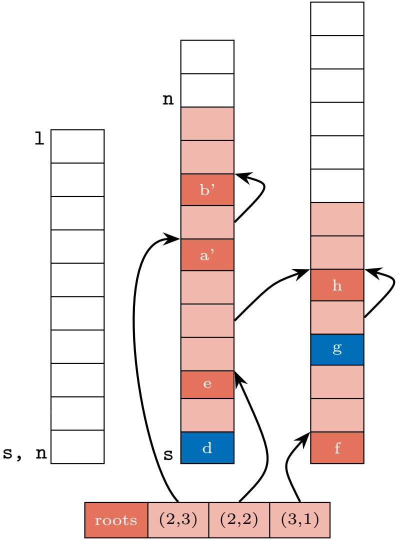
```
do_gen
  forward_roots
    forward
  do_scan
    forward
  reset_gen
```



Overview of Operations

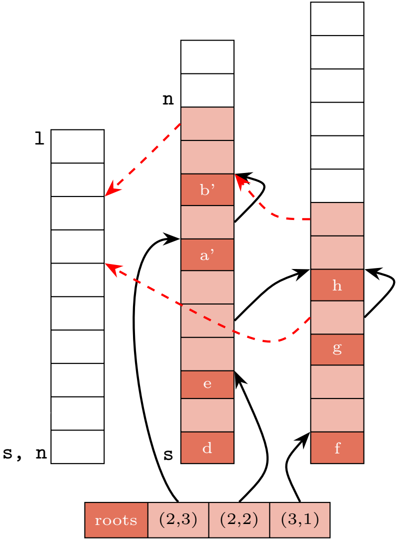
Non-Concerns

more garbage



Non-Concerns

- more garbage
- backward pointers



Overview of Operations

Non-Concerns

more garbage

backward pointers

Sources of Complexity

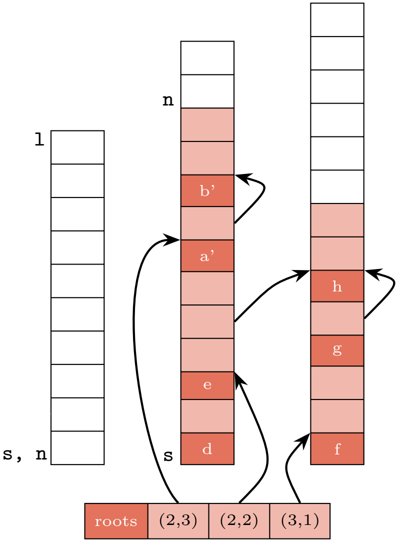
variable-length objects

disambiguate int/ptr

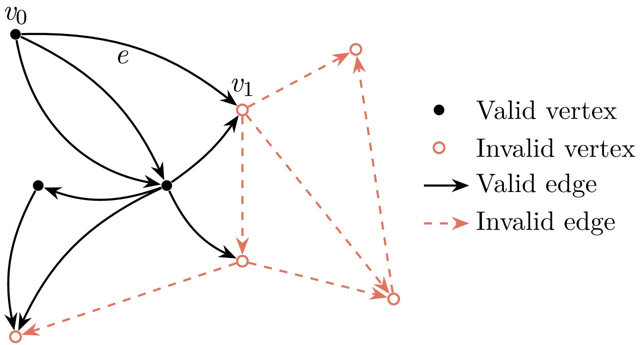
determine `v`'s gen

determine gen size

what if `malloc` fails?



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



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

GC_PreGraph:
```
VType := nat * nat
EType := VType * nat
src := fst
dst := unrestricted
```
$\forall v.\ \texttt{vvalid}(\gamma, v) \Leftrightarrow \texttt{graph\_has\_v}(\gamma, v)$

$\forall v, out.\ \texttt{evalid}(\gamma, (v, out)) \Leftrightarrow$
$\texttt{vvalid}(\gamma, v) \wedge \texttt{In}\ \ out\ \ (\texttt{get\_edges}(\gamma, v))$

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
```

```
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 is everywhere!

forward is robust

pointer? in from space? already forwarded?

and versatile

called on root set called on heap

```
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 */
```

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

```
void forward (value *s, *l, **n, *p) {
 /* elided */
 if(hd == 0) {
  *p = Field(v,0);
```

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

```
 }
```

```
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);
```

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

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

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

```
}
```

```
Inductive fwd_relation from to :
  forward_t -> LGraph -> LGraph -> Prop :=
| fr_v_not_in : forall v g,
  vgen v <> from ->
  fwd_relation from to (inl (inr v)) g g
| fr_e_to_fwded : forall e g,
  vgen (dst g e) = from ->
  raw_mark (vlabel g (dst g e)) = true ->
  let new_g := lgraph_gen_dst g e
    (copied_vertex (vlabel g (dst g e))) in
  fwd_relation from to (inr e) g new_g
```

```
| fr_e_to_not_fwded_Sn : forall e g g',
  vgen (dst g e) = from ->
  raw_mark (vlabel g (dst g e)) = false ->
  let new_g :=
    lgraph_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' ->
  fwd_relation from to (inr e) g g'
```

Specification

Similar to `forward_relation`, we have

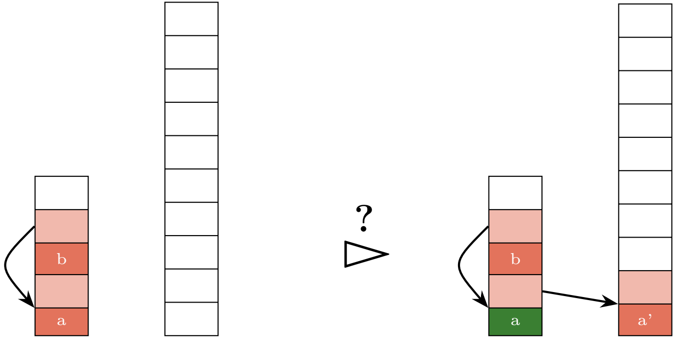
```
forward_roots_relation
do_scan_relation
do_generation_relation
garbage_collect_relation
```

A composition of these gives us our isomorphism

Moving Towards Isomorphism

But the journey is far from easy!

A brief look at `semi_iso`:



The general iterative strategy:

$$\dfrac{\dfrac{}{\gamma \rhd \gamma} \qquad \dfrac{\gamma \rhd \gamma_i \qquad \gamma_i \rightsquigarrow \gamma_{i+1}}{\gamma \rhd \gamma_{i+1}}}{\gamma_\alpha \rhd \gamma_\omega}$$

A specific example:

```
Lemma semi_iso_refl: forall g from to,
  sound_gc_graph g -> semi_iso g g from to nil.

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
```

And eventually,

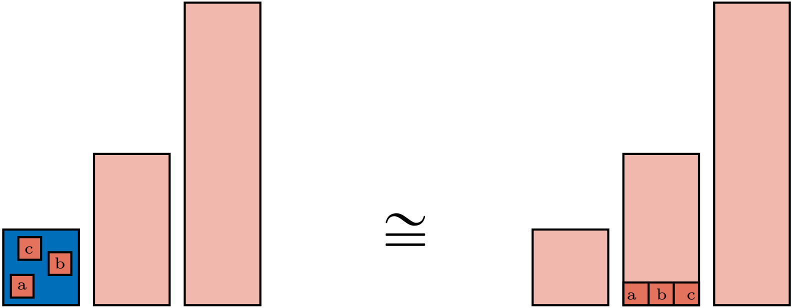
```
Theorem garbage_collect_iso: forall roots1 roots2 g1 g2,
  ...
  garbage_collect_relation roots1 roots2 g1 g2 ->
  gc_graph_iso g1 roots1 g2 roots2.
```

The graphs are isomorphic
  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 may change to register new vertices
    and may even grow to accommodate new generations

Recap: Intuitive Specification

Primum non nocere: first, do no harm



Bugs in the source C code

- Cheney implemented too conservatively:
  only part of `to` space needs to be
  scanned during `do_scan`
  Performance doubled

- Overflow in the following calculation:

```
int space_size =
    h->spaces[i].limit - h->spaces[i].start;
```

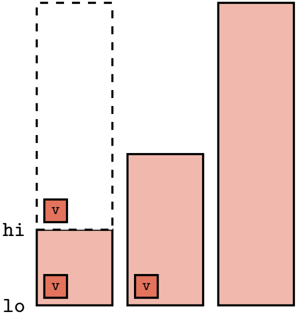
  if difference $> 2^{31}$

  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); }
```



Resolved using CompCert's `extcall_properties`

A classic OCaml trick to disambiguate int/ptr:

```
int test_int_or_ptr (value x) {
    return (int)(((intnat)x)&1); }
```

Essentially, assume that pointers are even-aligned.

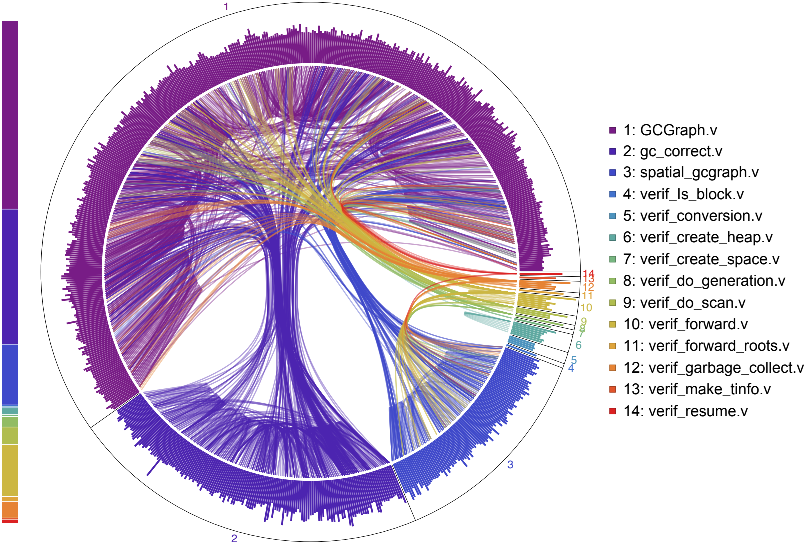
Consider:

```
void foo() {
  char a; char b; char* pa = &a; char* pb = &b;
  if ((pa&1 == 0) && (pb&1 == 0)) { /* elided */ } }
```

True in C, false in exec!

Discussing `char` alignment issues with CompCert

Reusability: separation between pure and spatial reasoning



Future Work

Problems of a similar shape
- serialization
- other collectors

Towards a verified GC for OCaml
- mutability
- calculate root set
- allow other datatypes

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