A Verified Garbage Collector for Gallina

Shengyi Wang, Anshuman Mohan, Aquinas Hobor

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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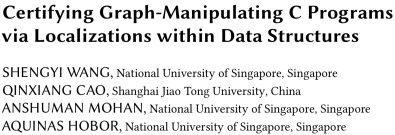
Ubiquitous in critical areas

Broad Solution

Verified
Software
Toolchain



Certifying Graph-Manipulating C Programs via Localizations within Data Structures

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VST + CompCert + 40000 LOC library

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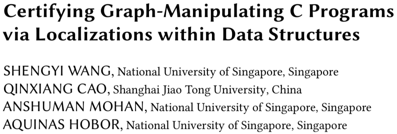

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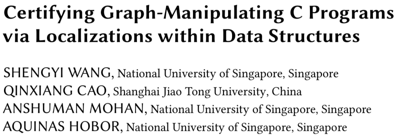

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[Wang *et. al.*, PACMPL OOPSLA 2019]

This Talk

Gallina ⇝ CompCert C ⇝ Assembly

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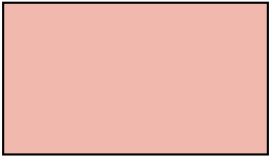
New problem: verify the garbage collector

Garbage Collection: an Introduction

GC has jurisdiction over the heap



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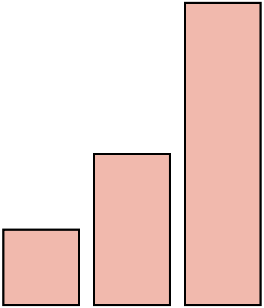

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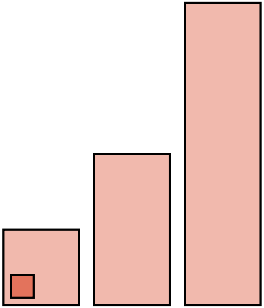
Mutator `mallocs` in special subheap



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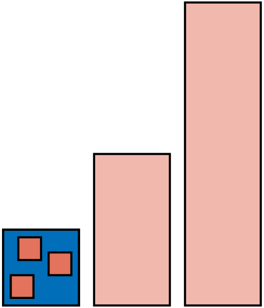

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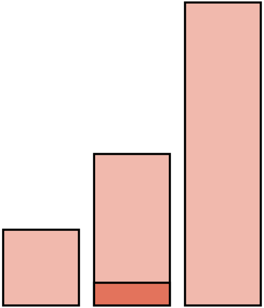
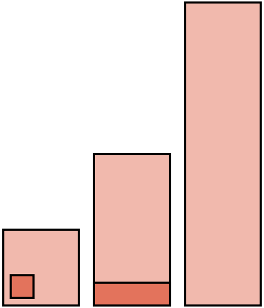
  - If subheap is full call GC



Garbage Collection: an Introduction

GC has jurisdiction over the heap

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



Intuitive Specification

Primum non nocere: first, do no harm

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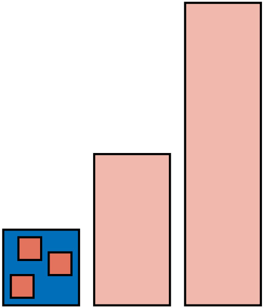

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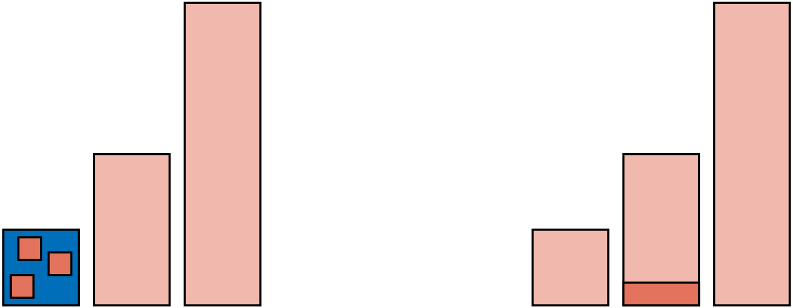

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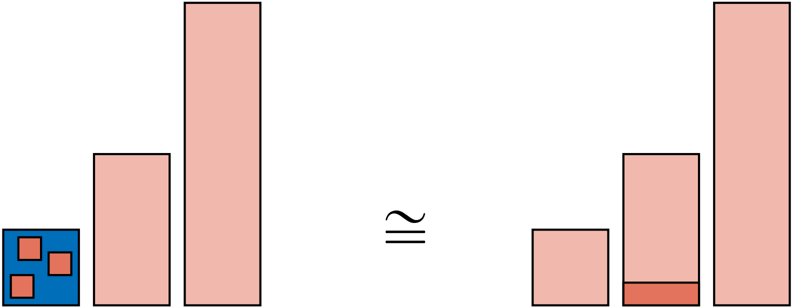

Our Garbage Collector

- 12 generations, doubling in size
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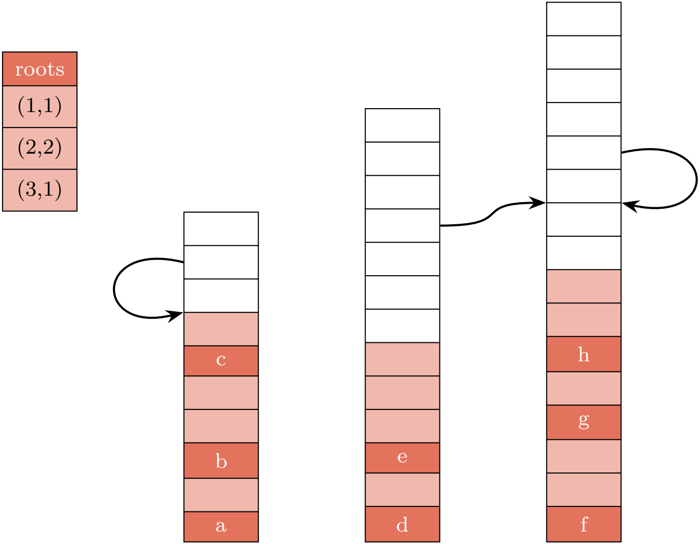
- 12 generations, doubling in size
- Functional mutator: no back pointers
- Cheney's mark-and-copy collects gen to next
- Potentially triggers cascade of pairwise collections
- Three key functions:

  `forward` copies individual objects

  `do_scan` repairs copied objects

  `forward_roots` kick-starts the collection

Overview of Operation’



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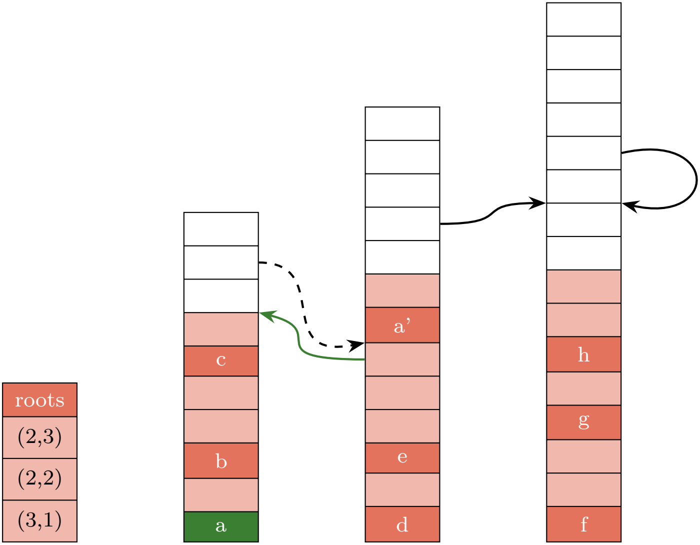

forward ✓

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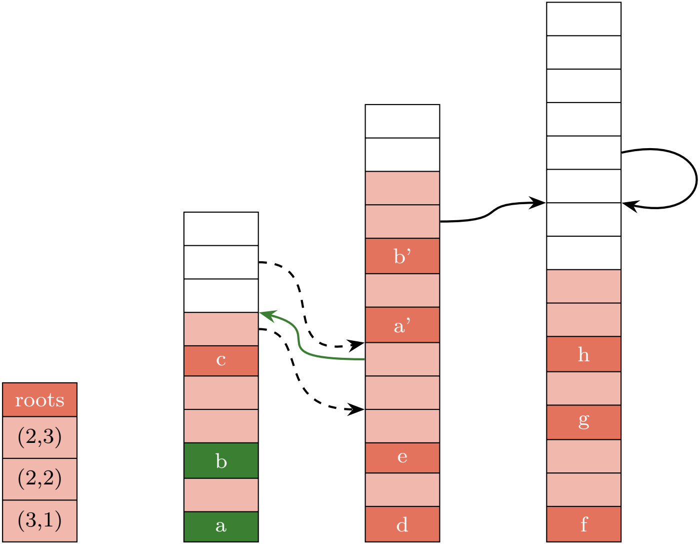

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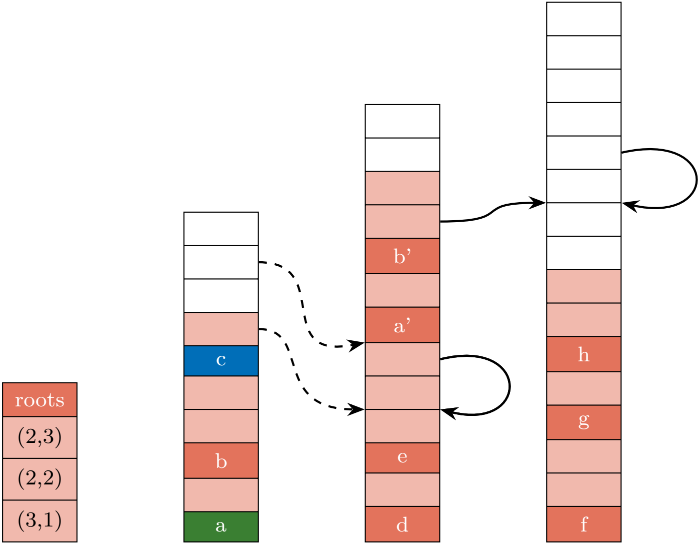

forward ✓ do_scan ✓

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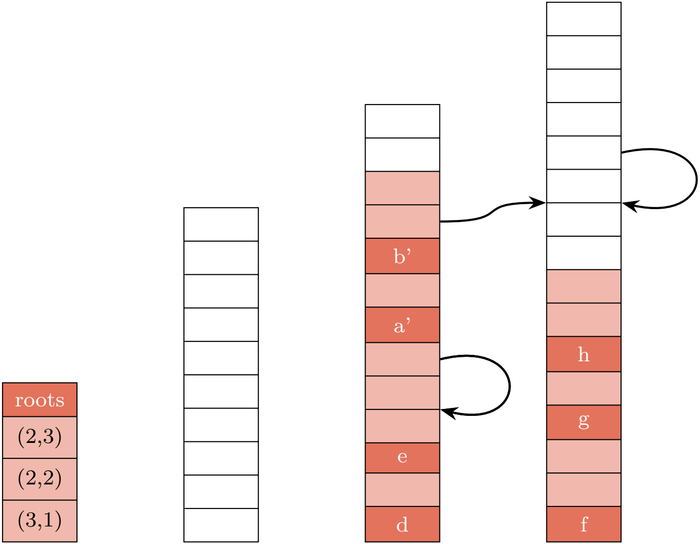
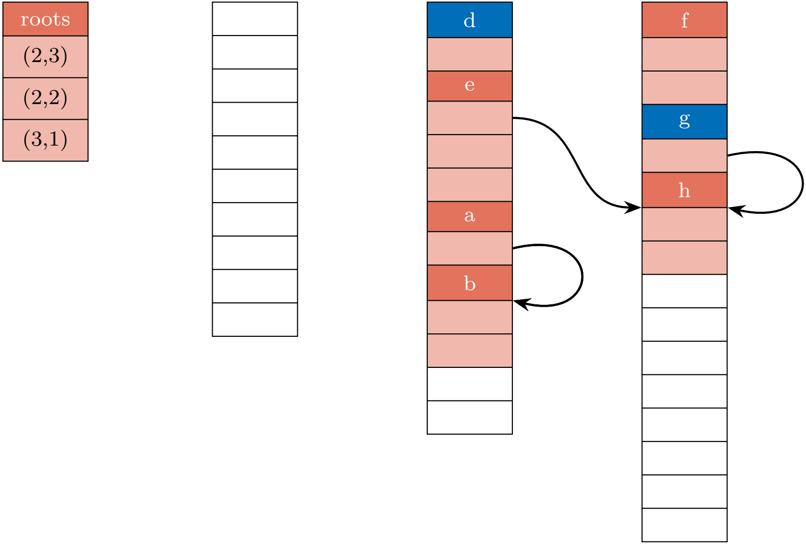


roots
(2,3)
(2,2)
(3,1)

forward ✓ do_scan ✓ do_gen ✓

Non-Concerns



more garbage? ✗

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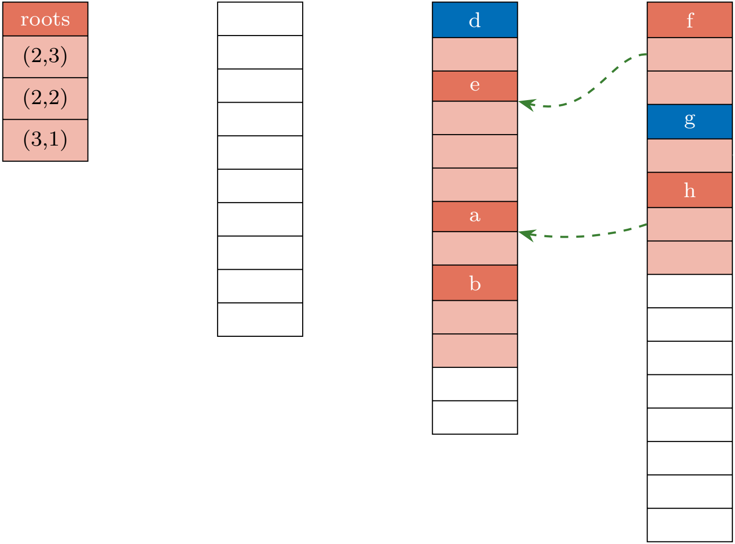
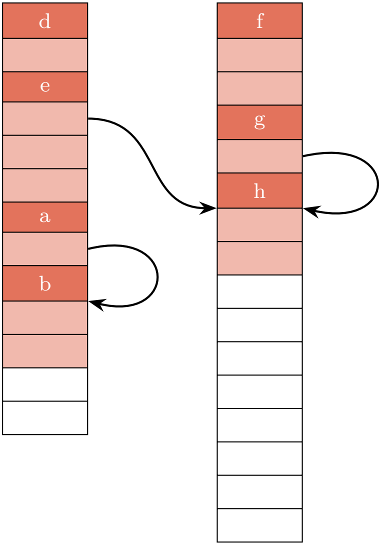


more garbage? ✗ back pointers? ✗

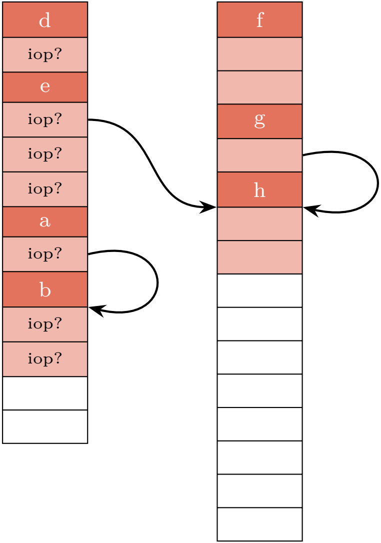
Sources of Complexity

variable-length objects



Sources of Complexity

variable-length objects
on-the-fly int/ptr disambiguation



Forward: a Deep Dive

forward is robust

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  pointer?

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Specifying `forward` *functionally* is too hard

`Forward`: a Deep Dive

`forward` is robust and versatile

pointer?	called on root set
in `from` space?	called on heap
already forwarded?	

Specifying `forward` *functionally* is too hard

`forward_relation` explains how
the graph may change because of `forward`

forward_relation

```
Inductive forward_relation (from to : nat) :
    forward_t -> LGraph -> LGraph -> Prop :=
```

forward_relation

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Inductive forward_relation (from to : nat) :
    forward_t -> LGraph -> LGraph -> Prop :=
| fr_v_not_in : forall (v : VType) (g : LGraph),
    vgeneration v <> from ->
    forward_relation from to (inl (inr v)) g g
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| fr_e_to_fwded : forall (e : EType) (g : LGraph),
    vgeneration (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
    forward_relation from to (inr e) g new_g
```

forward_relation, *cont.*

```
| fr_e_to_not_fwded_Sn : forall (e : EType) (g g' : LGraph),
    vgeneration (dst g e) = from ->
    raw_mark (vlabel g (dst g e)) = false ->
    let new_g :=
      labeledgraph_gen_dst (lgraph_copy1v g (dst g e) to)
      e (copy1v_new_v g to) in forward_loop from to
      (make_fields new_g (copy1v_new_v g to)) new_g g' ->
      forward_relation from to (inr e) g g'
```

forward_relation, *cont.*

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  with forward_loop (from to : nat) :
    list field_t -> LGraph -> LGraph -> Prop :=
| fl_nil : forall (g : LGraph), forward_loop from to  [] g g
| fl_cons : forall (g1 g2 g3 : LGraph)
                   (f : field_t) (fl : list field_t),
      forward_relation from to  (field2forward f) g1 g2 ->
      forward_loop from to  fl g2 g3 ->
      forward_loop from to  (f :: fl) g1 g3
```

Specification

Similar to `forward_relation`, we have

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

More Meat and Potatoes

Bugs in the source C code

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  Fixed by adjusting nursery size

Undefined behavior in C

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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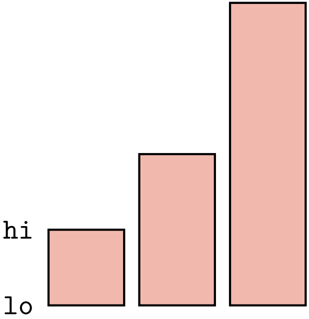

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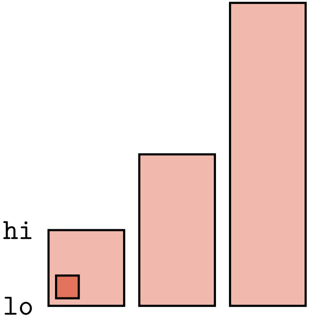

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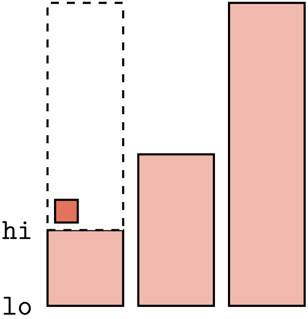

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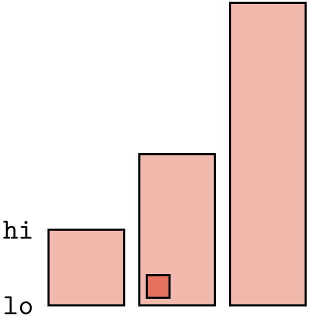

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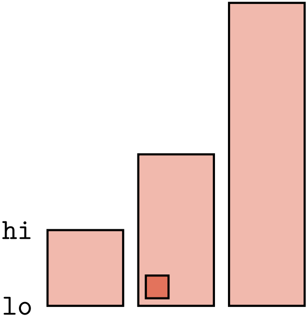

Resolved using CompCert's `extcall_properties`

Undefined behavior in C, *cont.*

A classic OCaml trick:

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int test_int_or_ptr (value x) {
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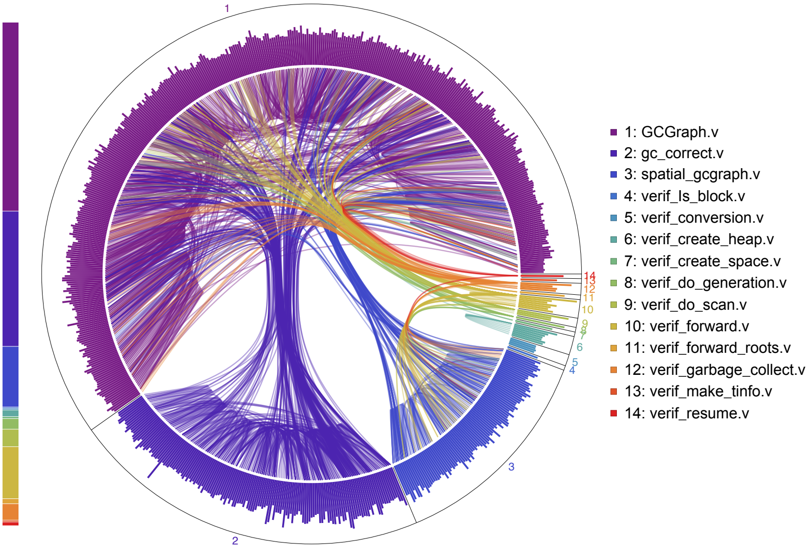
Discussing `char` alignment issues with CompCert

Reusability: separation between pure and spatial reasoning



Future Work

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serialization

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Towards a verified GC for OCaml

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- other collectors

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Further refinements required in C semantics

- before we can specify and verify OCaml's GC?