Run-time Systems for High-Assurance Systems Programming

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Vision

- A tool-chain for developing robust, reliable, and secure systems software that spans the full range of concerns:
  - From high-level analysis and verification
  - To low-level, performance-sensitive implementation

Focus: Systems Software

Examples: Operating system kernels, Hypervisors, VMMs, Device Drivers, etc…

- **Essential**: key components in any computer system
- **Critical**: failures can compromise higher-level, "secure" application layers

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Current Practices

Industry practices for developing systems software typically rely on fairly low-level languages and tools (e.g., C)

+ Enables programmers to address low-level issues & performance concerns

- Harder to reason formally about the code

Using a Functional Language ...

- Functional languages can provide:
  - Improved productivity
  - Memory safety
  - Type safety
  - Formal semantics
  - Connections to proof assistants, etc…
- But can you build systems software in a functional language?

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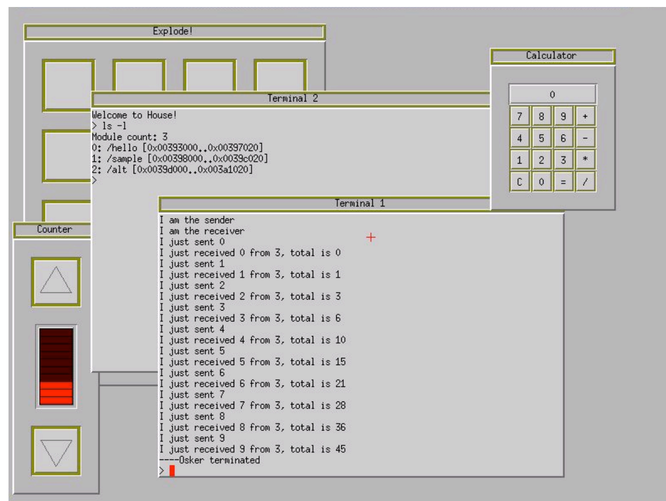
Welcome to our House

- House is a proof-of-concept OS, written in Haskell:
  - Kernel + basic drivers (~5KLOC)
  - Network driver (~2KLOC)
  - GUI (~6KLOC)
  - Apps
  - User programs
- A starting point for the Galois HaLVM



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A Credibility Gap

- House relies on services provided by the "GHC run-time system":
  - a general purpose software component
  - currently around 35-50KLOC of C code

- Any assurance argument that we might make about House requires a corresponding argument about the run-time system

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How to Bridge the Gap

- Reduce code size:
  - Eliminate functionality that we don't need
  - Eliminate accidental/historical complexity

- Implement in a framework that supports formal verification

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Feasibility

Example: Garbage Collection (GC)

- A simple, verifiable GC can be written in 100-300 lines
- There are fielded, production-quality GC implementations with good performance and support for a rich set of language features in 2KLOC

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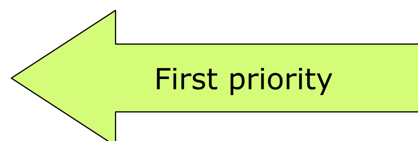
HARTS

High-**A**ssurance **RTS** for Haskell, Java, …

- Design Philosophy:
  - "As simple as possible"
  - Modular
  - Formal verification
- Services:
  - Garbage collection
  - Concurrency
  - Interfacing to untrusted languages



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Memory Allocation

- Languages like C provide run-time libraries for allocating and freeing memory
- It is notoriously difficult to use these functions correctly:
  - Freeing memory too early can result in corruption and crashes
  - Freeing memory too late can result in space leaks and denial of service
- Memory allocation bugs are very hard to find

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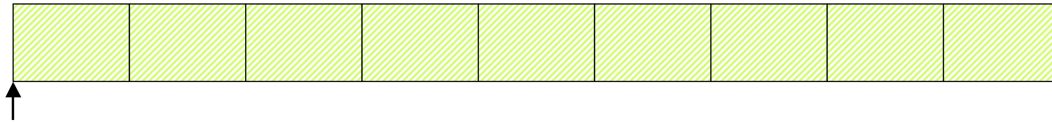
Garbage Collection

- A mechanism for reclaiming and reusing unused memory automatically
- Many different approaches:
  - Reference Counting, Mark-sweep, Stop-and-copy, Generational, Incremental, Real-time, …
- Programmer doesn't free memory by hand:
  - Less code to write
  - Fewer memory allocation bugs

Stop-and-copy Garbage Collection



Allocate memory from a "heap"

Stop-and-copy Garbage Collection

Allocate memory from a "heap"

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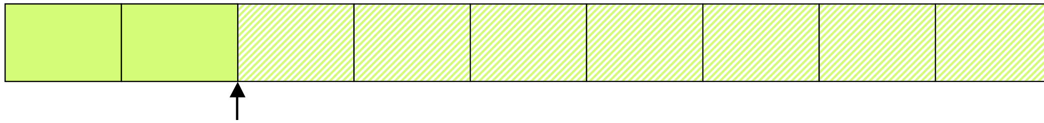
Stop-and-copy Garbage Collection



Allocate memory from a "heap"

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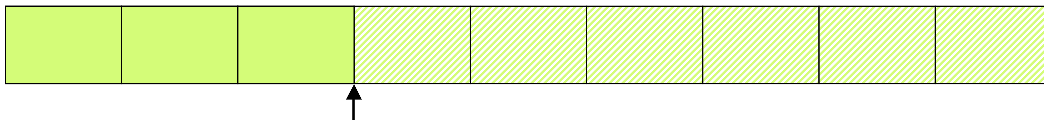
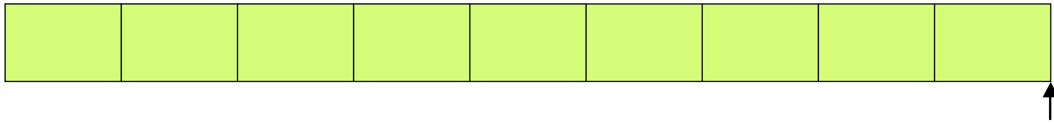
Stop-and-copy Garbage Collection



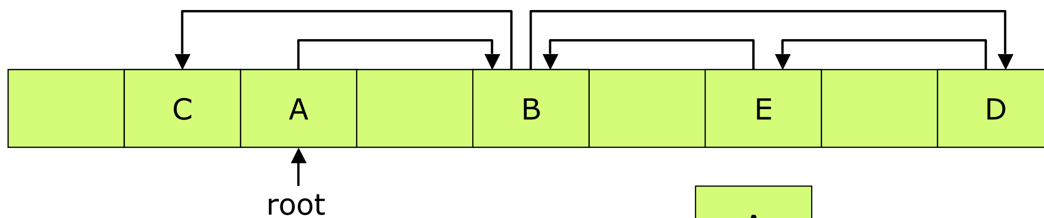
Allocate memory from a "heap"

Stop-and-copy Garbage Collection

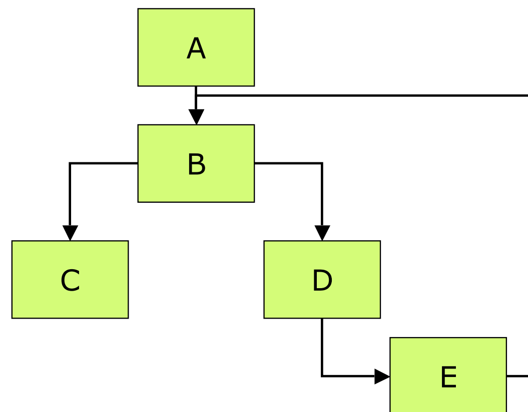


Eventually, the heap is full!

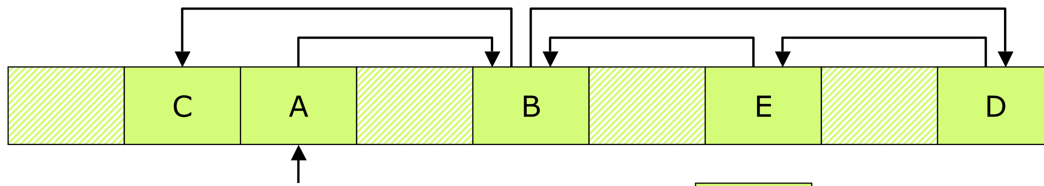
Stop-and-copy Garbage Collection

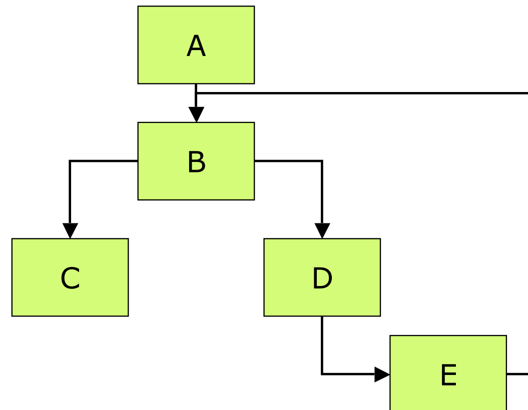


But we may only be using
a part of this …



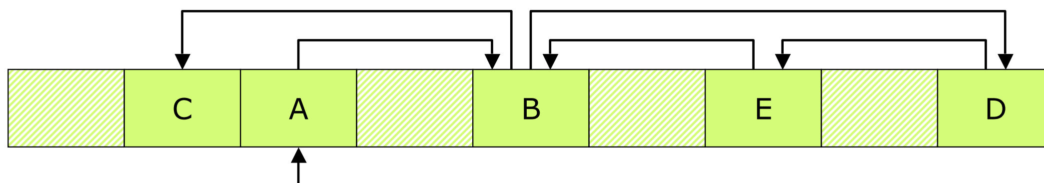
Stop-and-copy Garbage Collection





Everything else is "garbage"

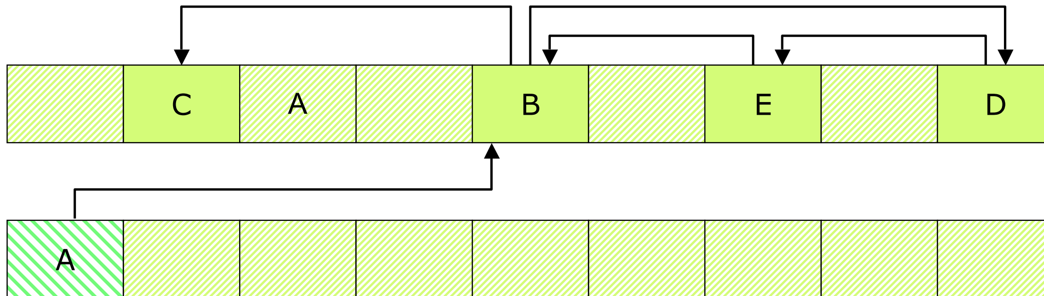
Stop-and-copy Garbage Collection



Assume that we have a second block of memory that we can use as a new heap

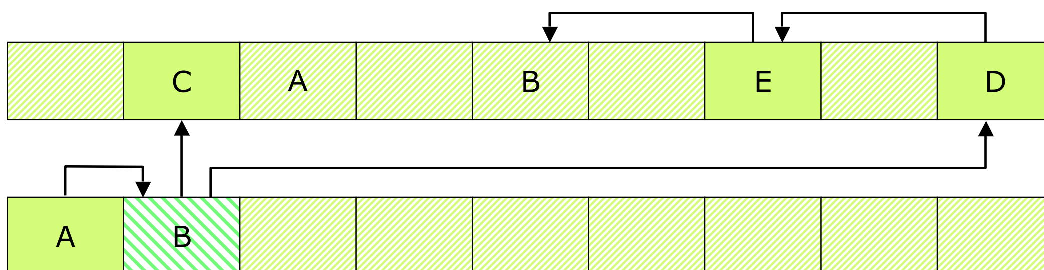
(Algorithm due to Cheney, 1970)

Stop-and-copy Garbage Collection



Copy A into the new heap

Stop-and-copy Garbage Collection



Scavenge A (copy B into the new heap)

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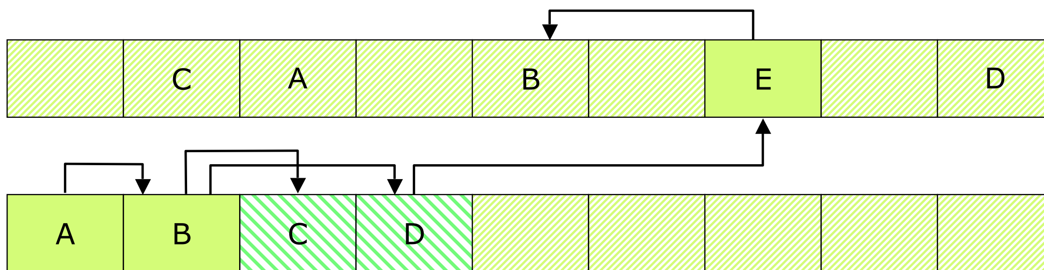
Stop-and-copy Garbage Collection



Scavenge B (copy C and D into the new heap)

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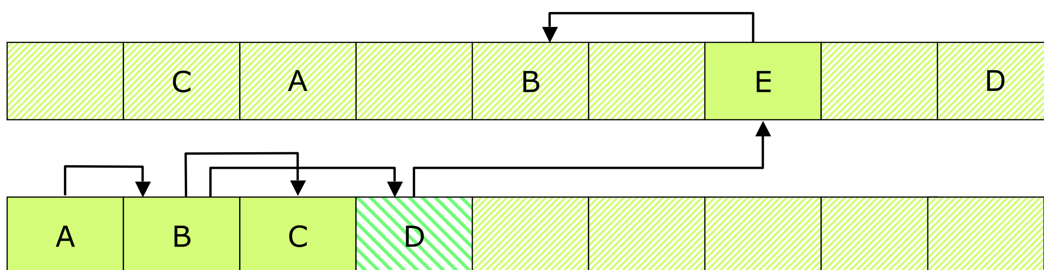
Stop-and-copy Garbage Collection



Scavenge C (no objects copied)

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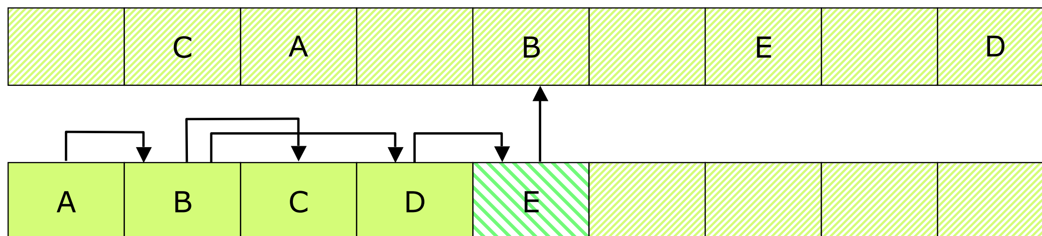
Stop-and-copy Garbage Collection



Scavenge D (copy E into the new heap)

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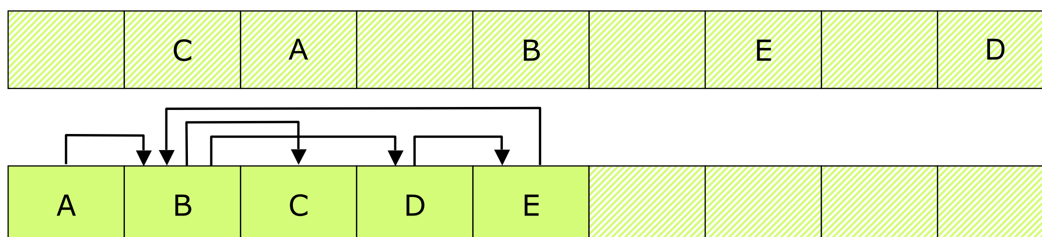
Stop-and-copy Garbage Collection



Scavenge E (B is already in the new heap)

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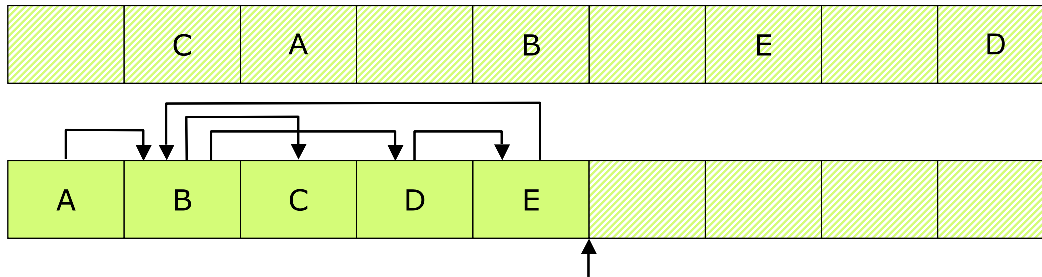
Stop-and-copy Garbage Collection



- All live data has been copied to the new heap;
- The original data structure has been preserved;
- Unused memory reorganized in a single block.

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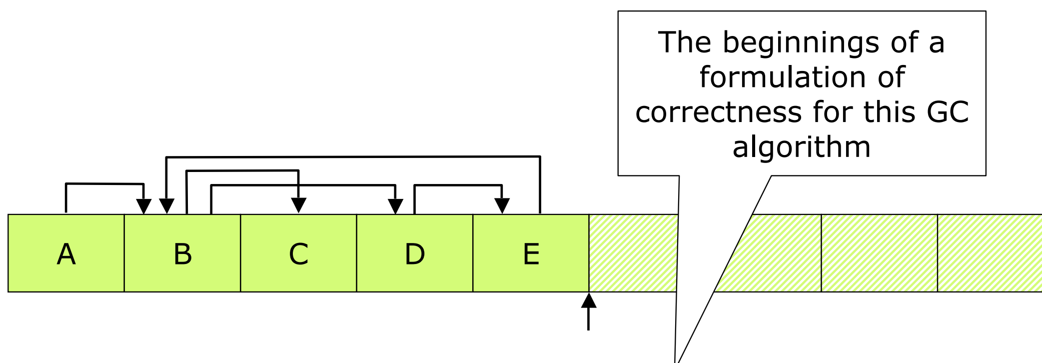
Stop-and-copy Garbage Collection



- All live data has been copied to the new heap;
- The original data structure has been preserved;
- Unused memory reorganized in a single block.

Garbage Collectors have Bugs Too!

- GC bugs show up regularly in public bug and vulnerability databases
- **Example**: Widely used browsers (IE, Firefox, Safari), have all suffered from JavaScript engine GC bugs that can lead to:
  - browser crashes
  - denial of service attacks
  - execution of arbitrary code

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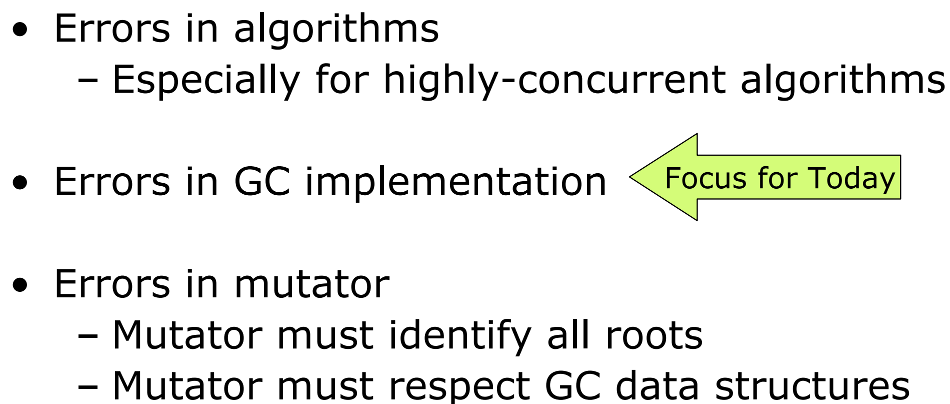
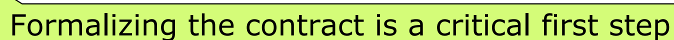
Where Do GC Bugs Come From?

- Errors in algorithms
  - Especially for highly-concurrent algorithms
- Errors in GC implementation
- Errors in mutator
  - Mutator must identify all roots
  - Mutator must respect GC data structures





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Principles for Verified GC

- Insist on machine-checked proofs
- Verify the actual implementation
- Amortize the cost of verification over all uses
- Engineer a re-usable framework for future verifications of similar style
- Amortize the cost of building the framework over multiple GCs
- Leverage existing work
  - INRIA (Leroy *et al*)
  - Yale (Shao, McCreight, *et al*)

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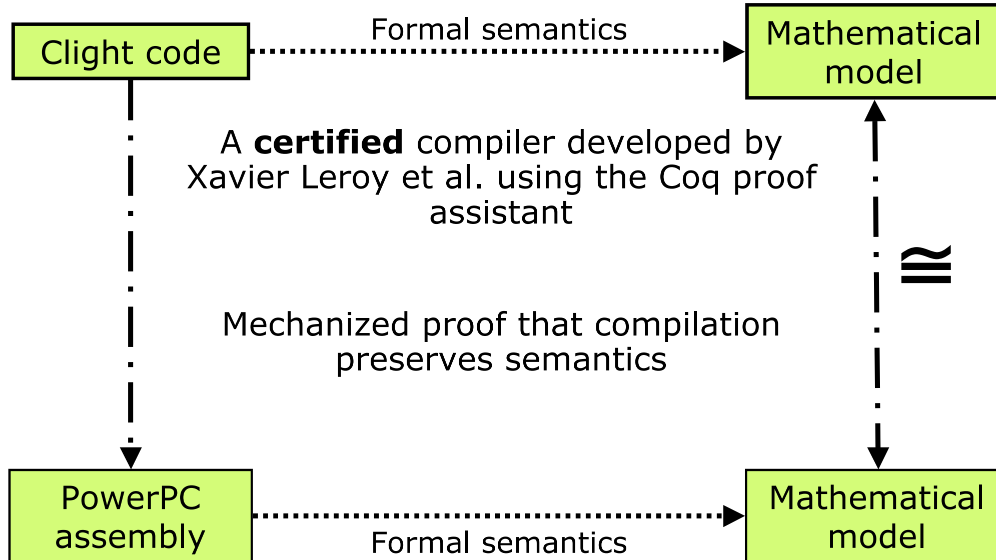
Typed Garbage Collection?

- Long-standing goal: define a type system rich enough to express a GC
  - Proposals to date are complex and only guarantee safety
- We propose a different path using general-purpose provers (e.g. Coq, Isabelle, etc.)
- Type-based approach may still be good choice for mutator

The Compcert Framework



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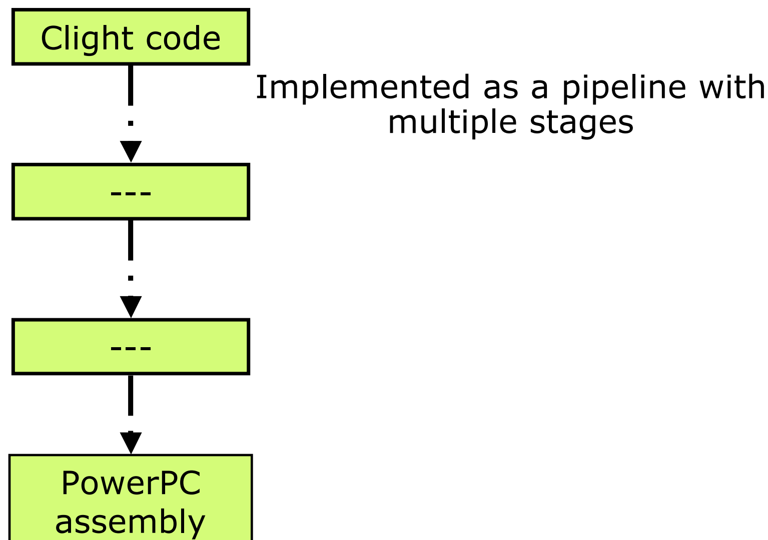
The Compcert Framework



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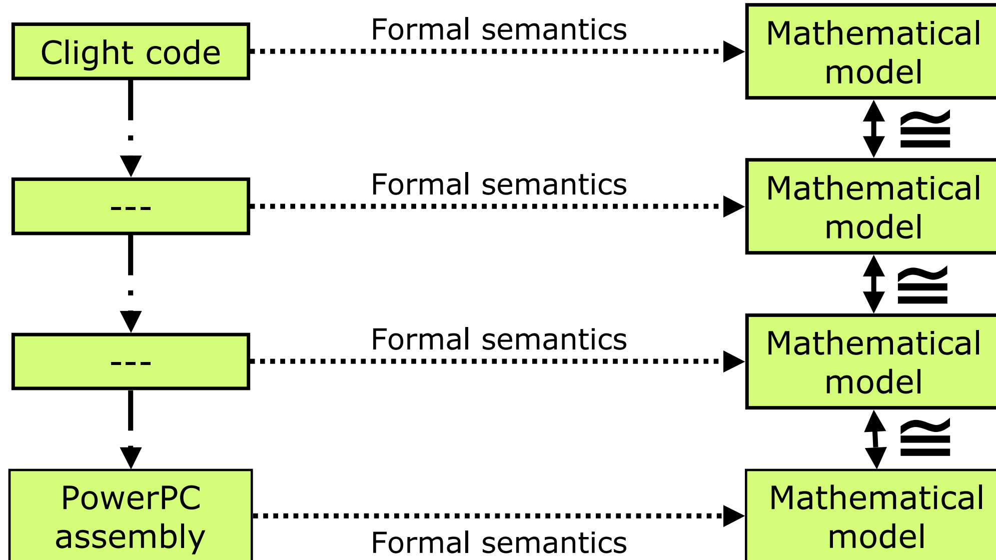

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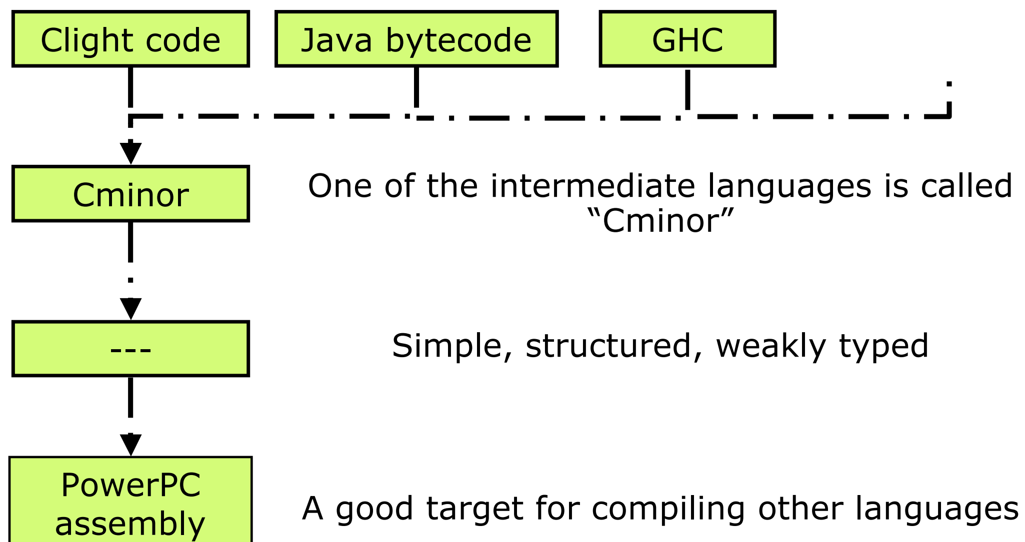

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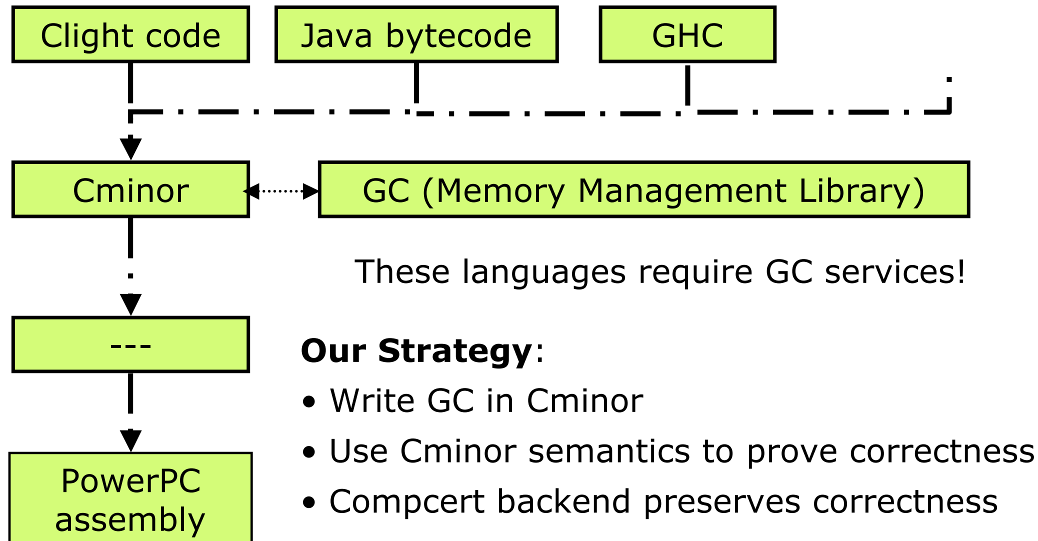

Stop-and-copy GC code (1)

```
#define NULL_PTR 0

var "freep"[4]
var "toStartp"[4]
var "toEndp"[4]
var "frStartp"[4]
var "frEndp"[4]

"numFields" (x) : int -> int
{ return int32[x]; }

"fieldIsPointer" (x,k) : int -> int -> int
{ return int32[x+4] <= k; }

"memCopy" (src,dst,len) : int -> int -> int -> void
{ var i;
  i = 0;
  while (I < len) {
     int32[dst + 4 * i] = int32[src + 4 * i];
     i = i + 1;
  }
}
```

```
"scanPtrField" (xp,free) : int -> int -> int
{
    var x, len, hdr;

    x = int32[xp];
    if (x == NULL_PTR)
      return free;
    hdr = int32[x - 4];
    if (hdr != NULL_PTR) {
      len = "numFields"(hdr) : int -> int;
      "memCopy"(x - 4, free, len + 1) : int -> int -> int -> void;
      int32[x] = free + 4;
      int32[x - 4] = NULL_PTR;
      free = free + 4 * len + 4;
    }
    int32[xp] = int32[x];
    return free;
}

"cheneyCollect" (rootp) : int -> int  {
    var hdr,len,toStart,toEnd,root,free,frStart,frEnd,scan,i,isPtr;

    frStart = int32["toStartp"];
    toStart = int32["frStartp"];
```

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Stop-and-copy GC code (2)

```
    int32["toStartp"] = toStart;
    int32["frStartp"] = frStart;
    toEnd = int32["frEndp"];
    frEnd = int32["toEndp"];
    int32["toEndp"] = toEnd;
    int32["frEndp"] = frEnd;

    free = "scanPtrField"(root, toStart) : int -> int -> int;
    scan = toStart;
    while (scan != free) {
      hdr = int32[scan];
      scan = scan + 4;
      len = "numFields"(hdr) : int -> int;
      i = 0;
     while (I < len) {
         isPtr = "fieldIsPointer"(hdr,i) : int -> int -> int;
         if (isPtr)
           free = "scanPtrField"(scan,free) : int -> int -> int;
         scan = scan + 4;
         i = i + 1;
     }
    }
}
```

```
"cheneyAlloc"(hdr,root) : int -> int -> int
{
  var free,len;

  free = int32["freep"];
  len = "numFields"(hdr) : int -> int;
  len = len * 4;
  if (len == 0)
    return 0;
  if (free + len + 4 >= int32["toEndp"]) {
    free = "cheneyCollect"(root) : int -> int;
    if (free + len + 4 >= int32["toEndp"])
      return 0;
  }
  int32["freep"] = free + len + 4;
  int32[free] = hdr;
  return (free + 4);
}
```

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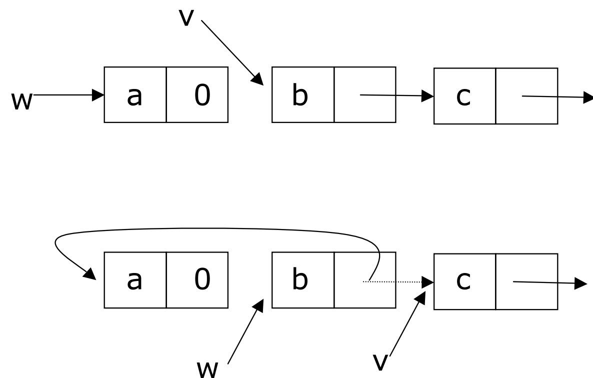
Example: in-place list reversal

```
"reverse" (v) : int -> int {
  var w,t;
  w = 0;
  {{ loop {
     if (v == 0)
       exit 0;
     t = int32[v + 4];
     int32[v + 4] = w;
     w = v;
     v = t;
  } }}
  return w;
}
```



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Proving Cminor Programs

- Proving correctness of imperative pointer-based programs is a hot research topic
- (Different from Compcert's goal, which is about proving compiler correctness)
- Our current direction:
  - Construct proofs on a **deep embedding** of the Cminor semantics in Coq
  - Use **separation logic** to describe the heap

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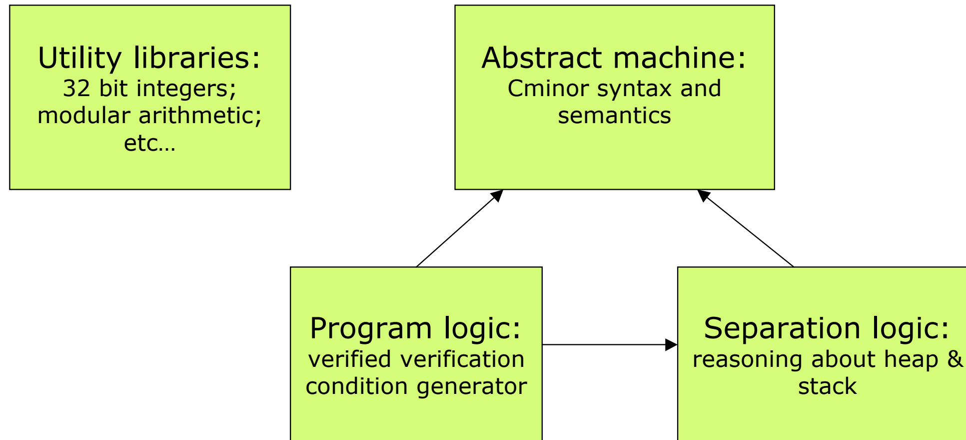
Shallow vs. Deep Embeddings

- In a shallow embedding, the program is represented by a term in the prover's logic
  + Can reason directly using full power of prover
  – Hard to formalize connection with actual code
- In a deep embedding, the program is represented as a syntactic object (AST):
  + Compcert gives operational semantics for this already
  – But reasoning requires lots of tactic support

Framework Overview



Everything is implemented in the Coq proof assistant

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Separation Logic

- Logic for reasoning about heaps [Reynolds, O'Hearn, …]
- Key predicates:

P * Q	Heap is split into two *disjoint* parts P holds on one part, Q on the other
$x \mapsto v$	Holds on a heap containing *only* address x that contains value v

- Neatly encapsulates complexities of reasoning about pointer-based programming (aliasing, etc.)

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Example: Linked Lists

- Relating list values to in-memory representation:

```
Fixpoint plist (x:val) (xs:list val) :=
 match xs with
 | nil        => !(x = null_ptr)
 | (x'::ys) =>
     !(x = x') * lexists v, lexists y,
                    (x ↦ v) * ((x+4) ↦ y) * plist y ys
end.
```

- Separating conjunction enforces that elements are disjoint (and hence lists are acyclic)

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Separation Logic Implementation

- Definitions and properties of predicates
  - Commutativity, associativity, etc.

- Tactics are critical:
  - Simplification
  - Rearranging
  - Matching

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Program Logic

- Hoare-style reasoning using pre- and post-conditions
- Similar to prog logic of [Appel Blazy 07]
- Verified verification condition generation
  - Generator calculates a verification condition (VC) for each statement
  - Resulting semantics consistent with original Cminor semantics

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Verification Conditions

precondition of next statement

initial state

- Example: vc (x := e) Q s
  $= \exists$ v. s $\vdash$ e $\rightarrow$ v
  $\wedge$ Q(s{x:=v})
- Extra predicate arguments are added for return, call, and jump
- Infrastructure provides tools for helping to prove VCs automatically

Proof Example: List Reverse

```
Lemma reverseOk : fdefOk reversePre reversePost reverseDef.
```

Pre-condition:

```
Definition
  reversePre is args:=
    lexists i, !(args=i::nil) *
                          plist i is.
```

Post-condition:

```
Definition
  reversePost is result :=
      plist result (rev is).
```

Loop Invariant:

```
Definition inv is (s:cstate) :=
  exists w, exists v,
    (vfEqv (xv :: xw :: xt :: nil) ((xw,w) :: (xv, v) :: nil) (cvfOf s) /\
      (lexists vl, lexists wl,
        plist v vl * plist w wl * !(rev vl ++ wl = rev is)) (cmemOf s)).
```

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Proof Details:

- Main proof: ~ 45 lines
- Comparable length to our proof of the same result using a shallow-embedding of Cminor semantics
- Program logic and Separation logic tactics make this possible.

```
Lemma reverseOk : fdefOk P0 reverseTy reversePre reversePost
                              reverseDef.
Proof.
  fdefBegin.
  unfold reversePre. intros is args m sp Hp. sle Hp. subst args.
  split. reflexivity.
  intros vf VFE.  simpl in VFE.
  vcSteps.

  exists (inv is). split.

  (* establish loop invariant *)
  unfold inv.
  exists null_ptr. exists x. split; auto.
  exists is. exists (@nil val).
  simpl. sli.
  auto with datatypes.

  (* loop entry *)
  clear VFE Hp.
  intros.  destruct s'. destruct H as [w [v0 [VFE Hp]]].
  vcSteps.
  branchStep.

  (* true branch: establish postcondition *)
  sli. unfold reversePost.
  subst v0. sle Hp.
  srewrite plist_null in Hp. sle Hp.
  subst x0. simpl in H. subst x1.
  apply Hp.

  (* false case: do loop body *)
  sle Hp.
  srewrite plist_non_null in Hp; [sle Hp | auto].
  vcSteps.
  (* bottom of loop body: re-establish invariant *)
  rewrite H0 in H; simpl in H; rewrite app_ass in H; simpl in H.
  unfold inv.
  exists v0. exists x3. split.
  vfEqvSolver.
  exists (tail x0). exists (v0::x1).
  simpl; sli.
  searchMatch.

  (* undefined case : impossible *)
  subst v0; sle Hp.
  srewrite plist_not_undef in Hp. sle Hp. auto.
Qed.
```

Infrastructure Line Counts

Utility libraries: ~3,300

Abstract machine: ~5,750

Program logic: ~1,550

Separation logic ~4,100

Garbage Collector: 5,000

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Stop-and-copy GC Proof

Lemma cheneyCollectorOk :
fdefOk cheneyCollectorPre cheneyCollectorPost cheneyCollectorDef.

```
Definition cheneyCollectorPre objs fields cmap (rootp:addr) root C cl
  (frStart frEnd toStart toEnd:addr) (vv:list val) :=
  let objsAddrs := objs_addrs objs cl cmap in
    !(vv = (rootp:val)::nil /\
      (root = null_ptr \/ ptr_In root objs) /\
      contiguous frStart objsAddrs /\
      (Z_of_nat (AS.cardinal objsAddrs) < indexBound)%Z) **
  rootp |-> root **
  clDescrs C cmap ** gcInfo toStart toEnd frStart frEnd **
  okObjHp C cmap objs objs cl fields **
  buffer toStart (AS.cardinal objsAddrs).
```

Pre-condition

```
Definition cheneyCollectorPost (objs:AS.t) (fields:addr->list val) cmap
  rootp root C (cl:addr->addr) (frStart frEnd toStart toEnd:addr) (v:val) :=
  lexists M, lexists phi,
    let objs' := AASetMap.map phi M in
    let cl' := seq (inv M phi) cl in
    let fields' := seq (inv M phi) fields in
    let objsAddrs := objs_addrs objs cl cmap in
    let objs'Addrs := objs_addrs objs' cl' cmap in
    let free := toStart + 4 * AS.cardinal objs'Addrs in
      !(map_inj M phi /\
        (forall x, AS.In x M -> vaReachable cmap cl fields root x) /\
        (root = null_ptr \/ ptr_In root M) /\
        AS.Subset M objs /\
        contiguous toStart objs'Addrs /\
        v = free) **
      rootp |-> fwd_ptr phi root **
      okObjHp C cmap objs' objs' cl' (fwd_objs_fields cmap cl' phi fields') **
      buffer frStart (AS.cardinal objsAddrs) **
      clDescrs C cmap ** gcInfo frStart frEnd toStart toEnd **
      buffer free (AS.cardinal objsAddrs - AS.cardinal objs'Addrs).
```

Post-condition

Definition

```
#define NULL_PTR 0

var "freep"[4]
var "toStartp"[4]
var "toEndp"[4]
var "frStartp"[4]
var "frEndp"[4]

"numFields" (x) : int -> int
{ return int32[x]; }

"fieldIsPointer" (x,k) : int -> int -> int
{ return int32[x+4] <= k; }

"memCopy" (src,dst,len) : int -> int -> int -> void
{ var i;
  i = 0;
  while (I < len) {
     int32[dst + 4 * i] = int32[src + 4 * i];
     i = i + 1;
  }
}

"scanPtrField" (xp,free) : int -> int -> int
{
   var x, len, hdr;

   x = int32[xp];
   if (x == NULL_PTR)
     return free;
   hdr = int32[x - 4];
   if (hdr != NULL_PTR) {
     len = "numFields"(hdr) : int -> int;
     "memCopy"(x - 4, free, len + 1) : int -> int -> int -> void;
     int32[x] = free + 4;
     int32[x - 4] = NULL_PTR;
     free = free + 4 * len + 4;
   }
   int32[xp] = int32[x];
   return free;
}

"cheneyCollect" (rootp) : int -> int  {
   var hdr,len,toStart,toEnd,root,free,frStart,frEnd,scan,i,isPtr;

   frStart = int32["toStartp"];
   toStart = int32["frStartp"];
   int32["toStartp"] = toStart;
   int32["frStartp"] = frStart;
   toEnd = int32["frEndp"];
   frEnd = int32["toEndp"];
   int32["toEndp"] = toEnd;
   int32["frEndp"] = frEnd;

   free = "scanPtrField"(root, toStart) : int -> int -> int;
   scan = toStart;
   while (scan != free) {
      hdr = int32[scan];
      scan = scan + 4;
      len = "numFields"(hdr) : int -> int;
      i = 0;
     while (I < len) {
          isPtr = "fieldIsPointer"(hdr,i) : int -> int -> int;
          if (isPtr)
            free = "scanPtrField"(scan,free) : int -> int -> int;
          scan = scan + 4;
          i = i + 1;
      }
   }
}

"cheneyAlloc"(hdr,root) : int -> int -> int
{
   var free,len;

   free = int32["freep"];
   len = "numFields"(hdr) : int -> int;
   len = len * 4;
   if (len == 0)
     return 0;
   if (free + len + 4 >= int32["toEndp"]) {
     free = "cheneyCollect"(root) : int -> int;
     if (free + len + 4 >= int32["toEndp"])
       return 0;
   }
   int32["freep"] = free + len + 4;
   int32[free] = hdr;
   return (free + 4);
}
```

Key Points

- We've proved correctness of a realistic GC implementation written in Cminor
  - One remaining technical lemma to prove
- Advances on our previous work:
  - **Uses true machine arithmetic**
  - Supports arbitrary record sizes
  - Supports precise pointer information
- Next steps: Proof of generational collector
- Next steps: Must ensure that mutator keeps to its part of the GC contract …

Conclusions

- Assurance of programs written in high-level languages requires assurance of underlying run-time systems
- Results described today:
  - A verified implementation of realistic GC
  - A general verification infrastructure for GCs and other code that manipulates the heap
  - Essential use of tactics to automate reasoning
- An enabling step towards the use of high-level languages for high-assurance applications.