Lecture 25

CIS 341: COMPILERS

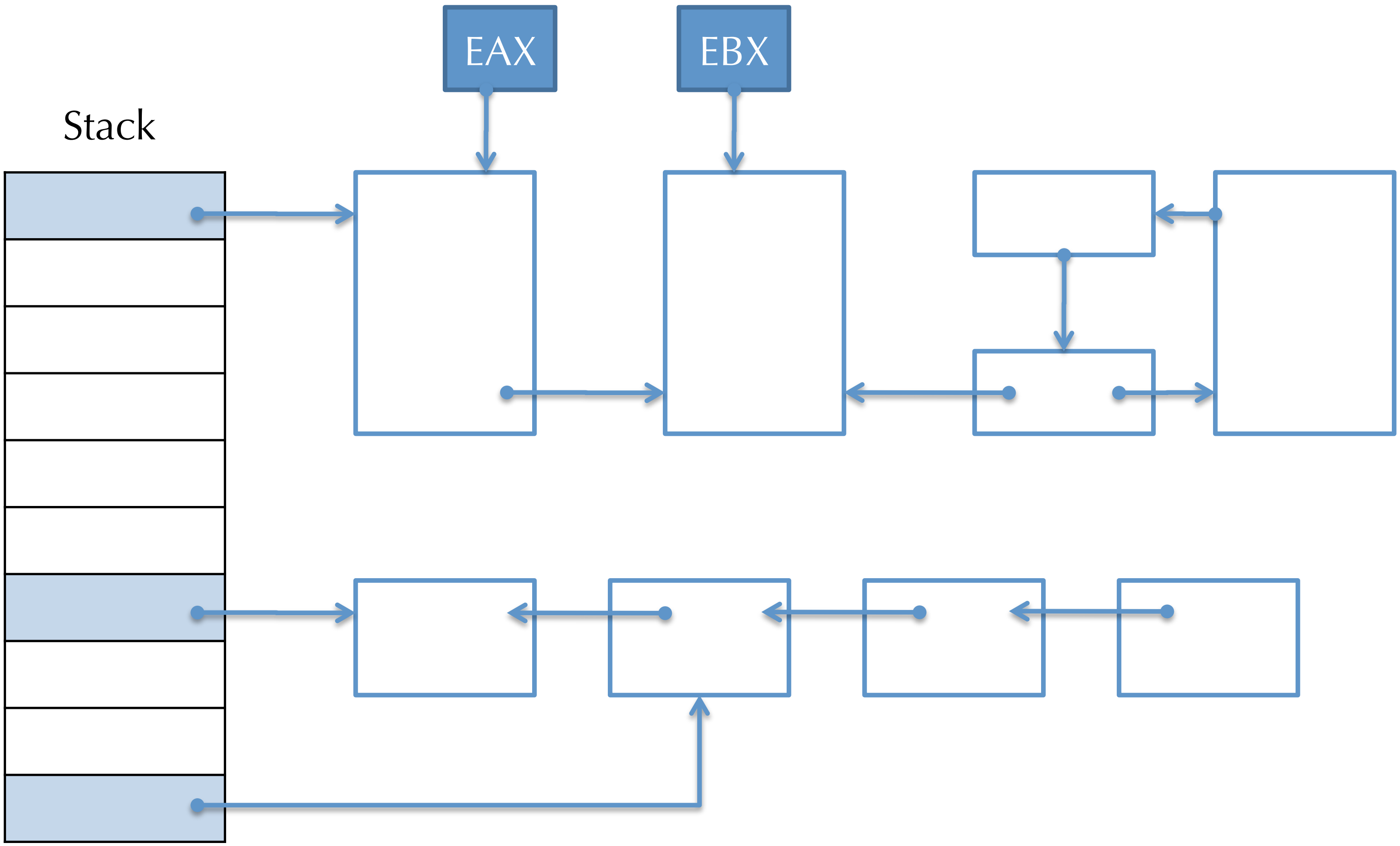
Announcements

- HW 7: Optimization & Experiments
  - Available now
  - Due: April 29th
- My office hours today are *cancelled*.
- Final Exam:
  - Thursday, May 7th
  - 9:00AM
  - Moore 216

MARK & SWEEP GC

Example Object Graph

- Pointers in the stack, registers, and globals are *roots*



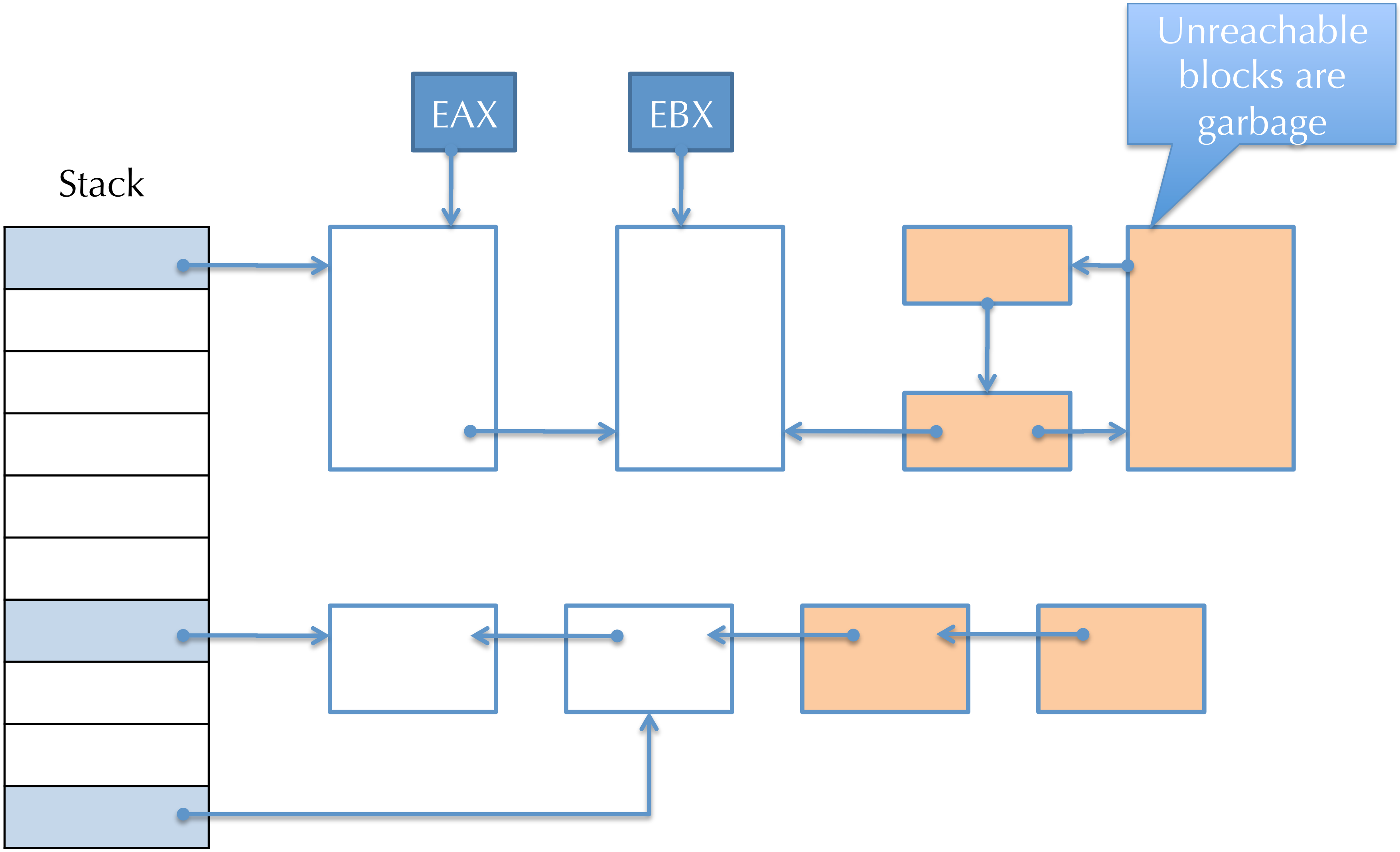
Mark and Sweep Garbage Collection

- Classic algorithm with two phases:

- Phase 1: Mark
  - Start from the roots
  - Do depth-first traversal, marking every object reached.

- Phase 2: Sweep
  - Walk over *all* allocated objects and check for marks.
  - Unmarked objects are reclaimed.
  - Marked objects have their marks cleared.
  - Optional: compact all live objects in heap by moving them adjacent to one another. (needs extra work & indirection to "patch up" pointers)

Results of Marking Graph



Costs & Implications

- Need to generalize to account for objects that have multiple outgoing pointers.
- Depth-first traversal terminates when there are no children pointers or all children are already marked.
  - Accounts for cycles in the object graph.
- The Deutsch-Schorr-Waite algorithm breaks objects during the traversal.
  - All computation must be halted during the mark phase. (Bad for concurrent programs!)
- Mark & Sweep algorithm reads all memory in use by the program (even if it's garbage!)
  - Running time is proportional to the total amount of allocated memory (both live and garbage).
  - Can pause the programs for long times during garbage collection.

COPYING COLLECTION

Copying Garbage Collection

- Like mark & sweep: collects all garbage.
- Basic idea: use *two* regions of memory
  - One region is the memory in use by the program. New allocation happens in this region.
  - Other region is idle until the GC requires it.

- Garbage collection algorithm:
  - Traverse over live objects in the active region (called the "*from- space*"), copying them to the idle region (called the "*to-space*").
  - After copying all reachable data, switch the roles of the from-space and to-space.
  - All dead objects in the (old) from-space are discarded en masse.
  - A side effect of copying is that all live objects are compacted together.

Cheney's Algorithm (1)

- Idea: maintain two pointers into the to-space
  - *Scan* – points to the next piece of data to be examined
  - *Free* – points to the next available word of memory
  - Invariant: data pointed to by values between the scan and free pointers might need to be copied to the to-space
  - Leave behind "*forwarding pointers*" to the new copies.

- Crucial subroutine: (note implicit use of type information)

```
pointer copy-forward(pointer p)
```

  - If structure pointed to by `p` has already been copied, return the corresponding forwarding pointer.
  - Otherwise:
    - Copy the structure pointed to by `p` into the to-space. (Incrementing the free pointer)
    - Mark the structure in from-space as copied and put a forwarding pointer in from-space to the copy in to-space
    - Return the pointer to the new copy in to-space

Cheney's Algorithm (2)

- When garbage collection is triggered:
  - Initialize the free pointer to be beginning of to-space
- For each root R containing a pointer ptr:

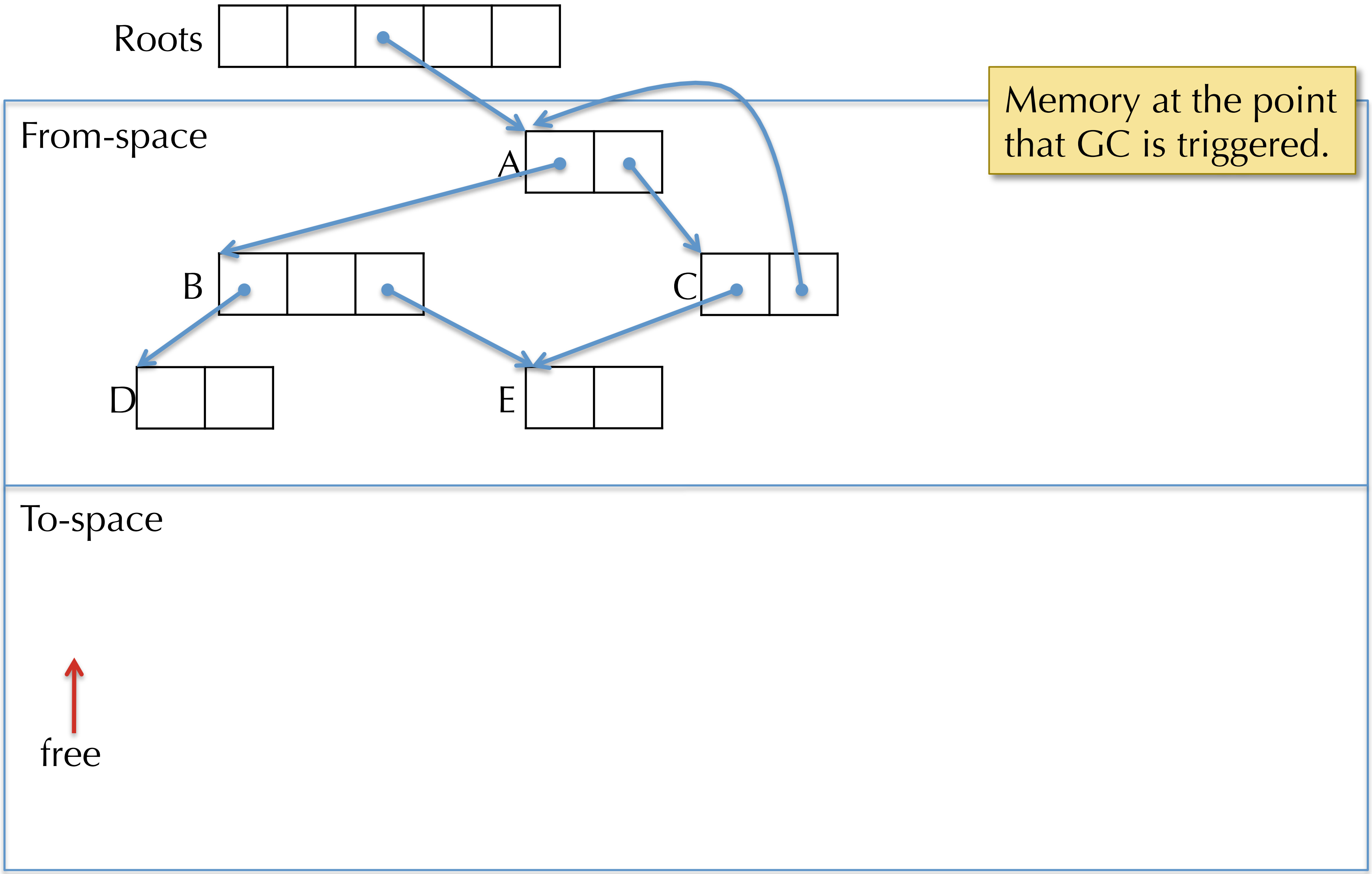
  Set ptr′ = copy-forward(ptr)

  Set R := ptr′

  Set the scan pointer to ptr′.

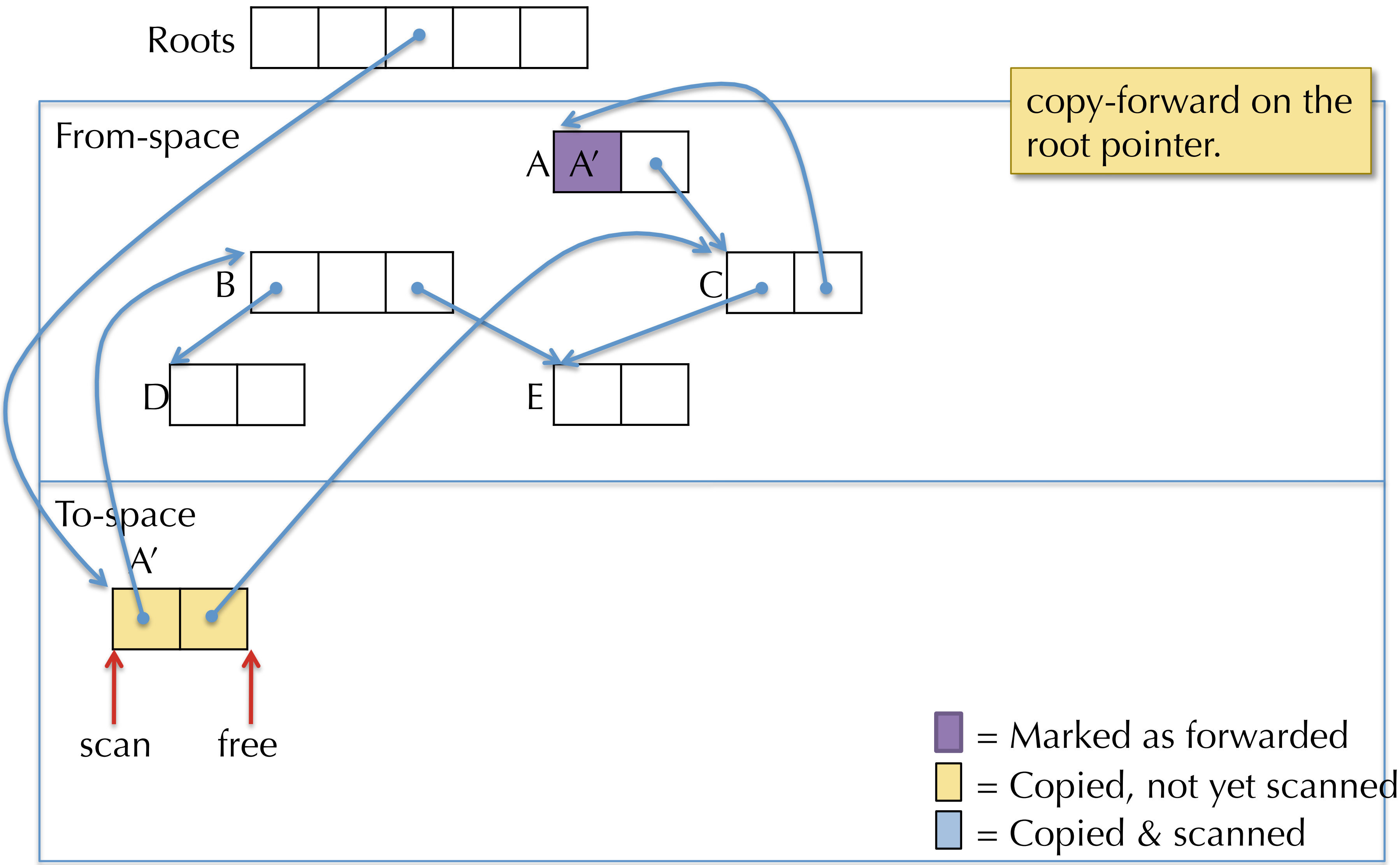
  While (scan != free)
  - Increment the scan pointer (element-wise according to types of the fields in the underlying structure)
  - If the scan pointer points to a pointer ptr
    - Set `*scan := copy-forward(ptr)`

Run of Cheney's Algorithm

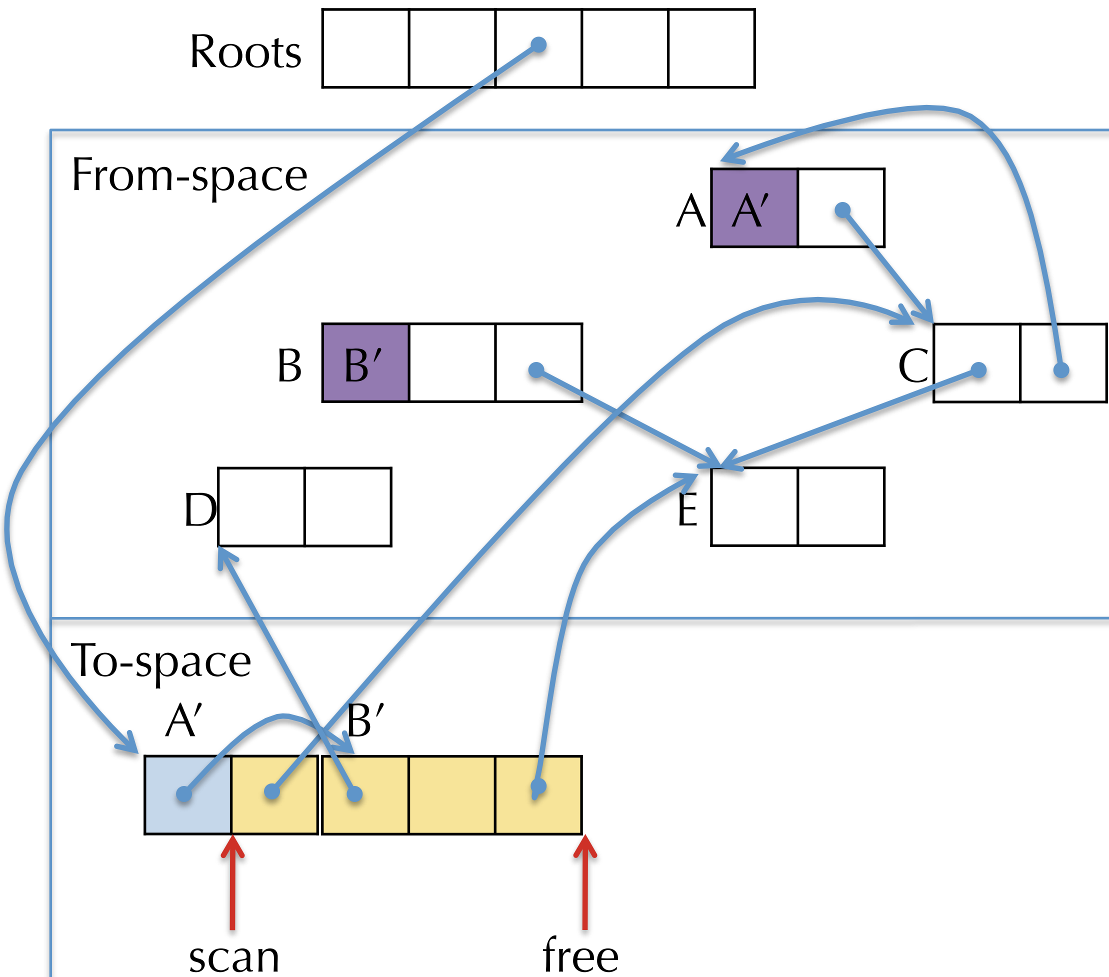


Memory at the point that GC is triggered.

Run of Cheney's Algorithm



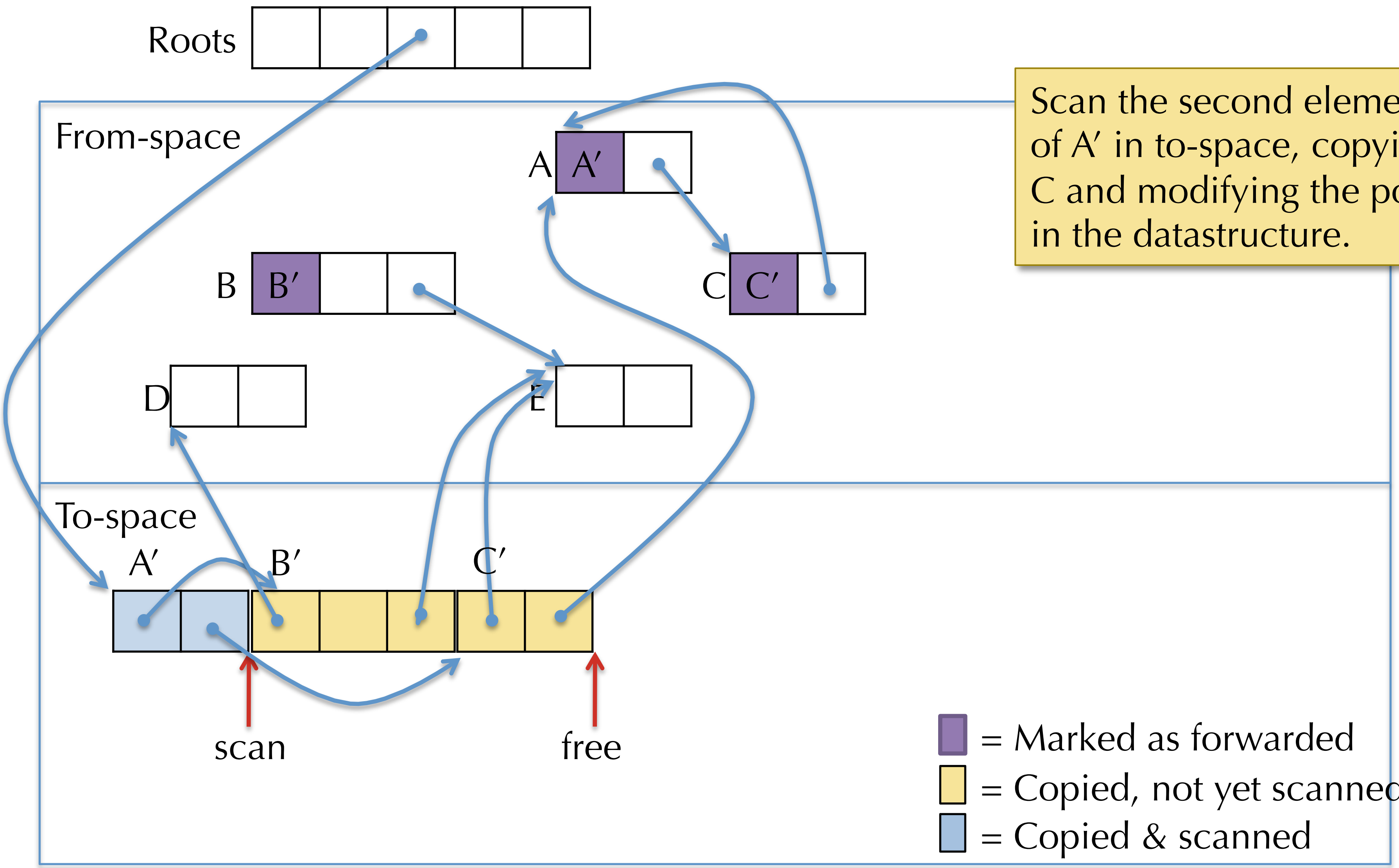
Run of Cheney's Algorithm



Scan the first element of A′ in to-space, copying B and modifying the pointe in the datastructure.

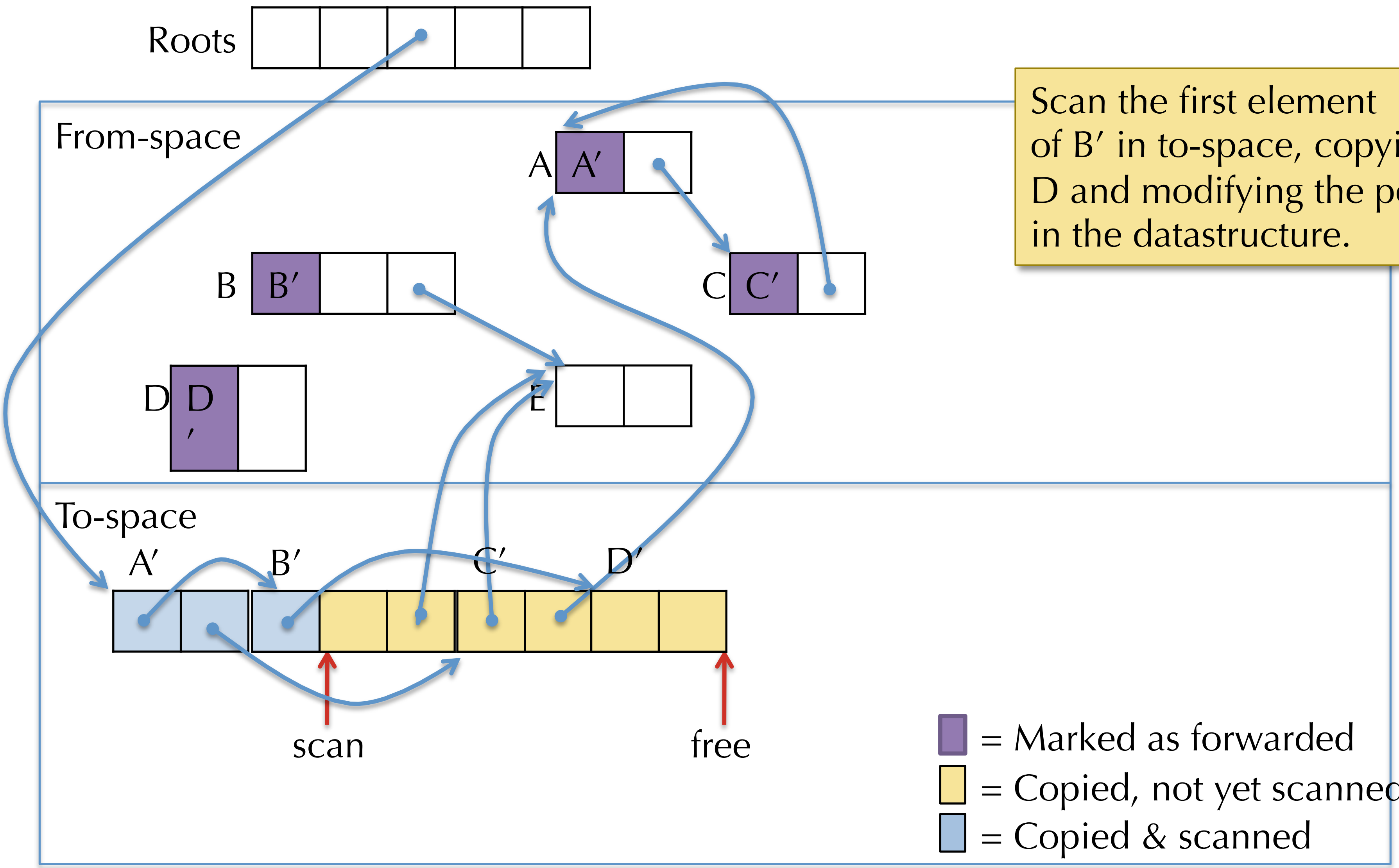
= Marked as forwarded
= Copied, not yet scanned
= Copied & scanned

Run of Cheney's Algorithm



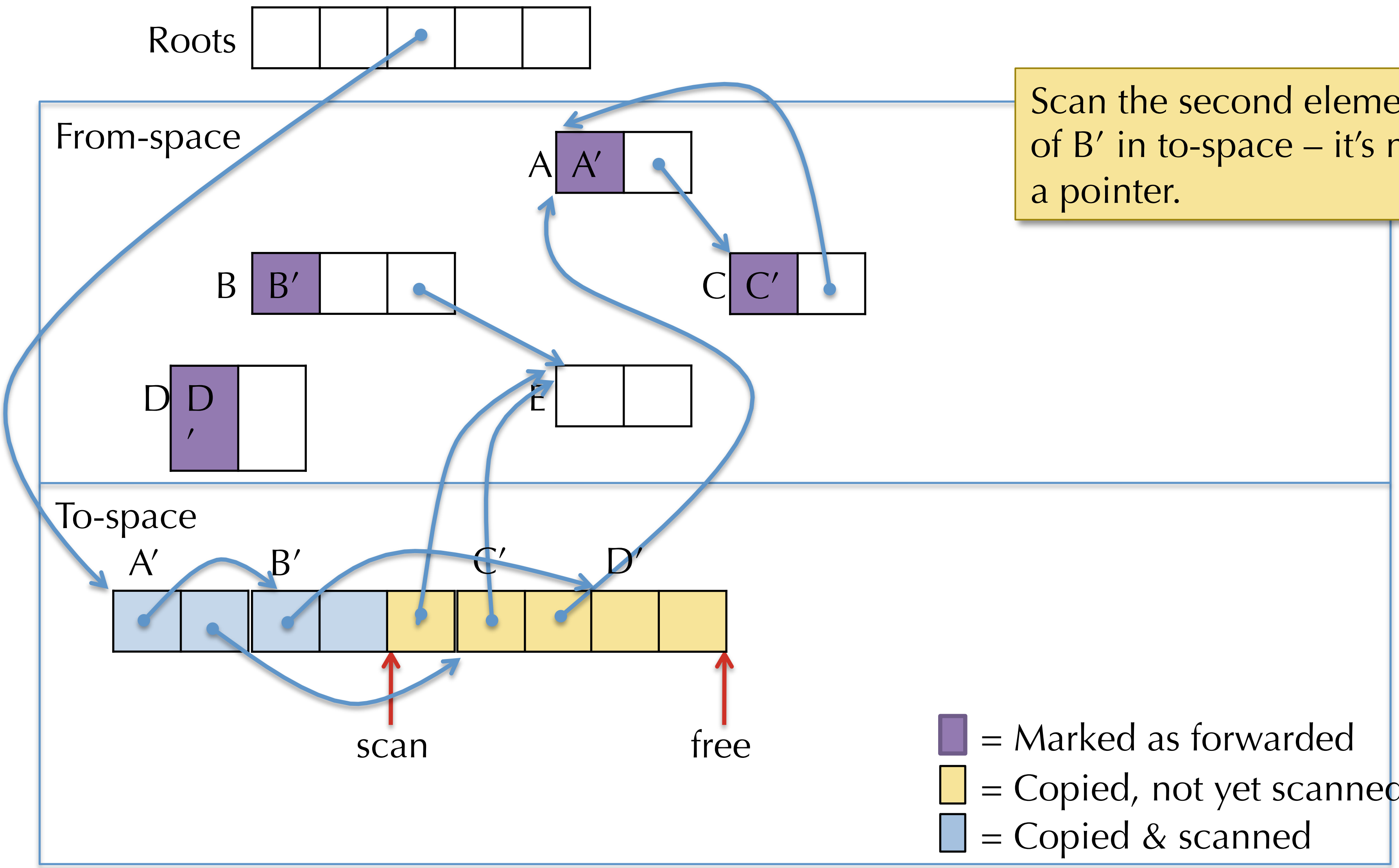
Scan the second element of A′ in to-space, copying C and modifying the pointer in the datastructure.

Run of Cheney's Algorithm



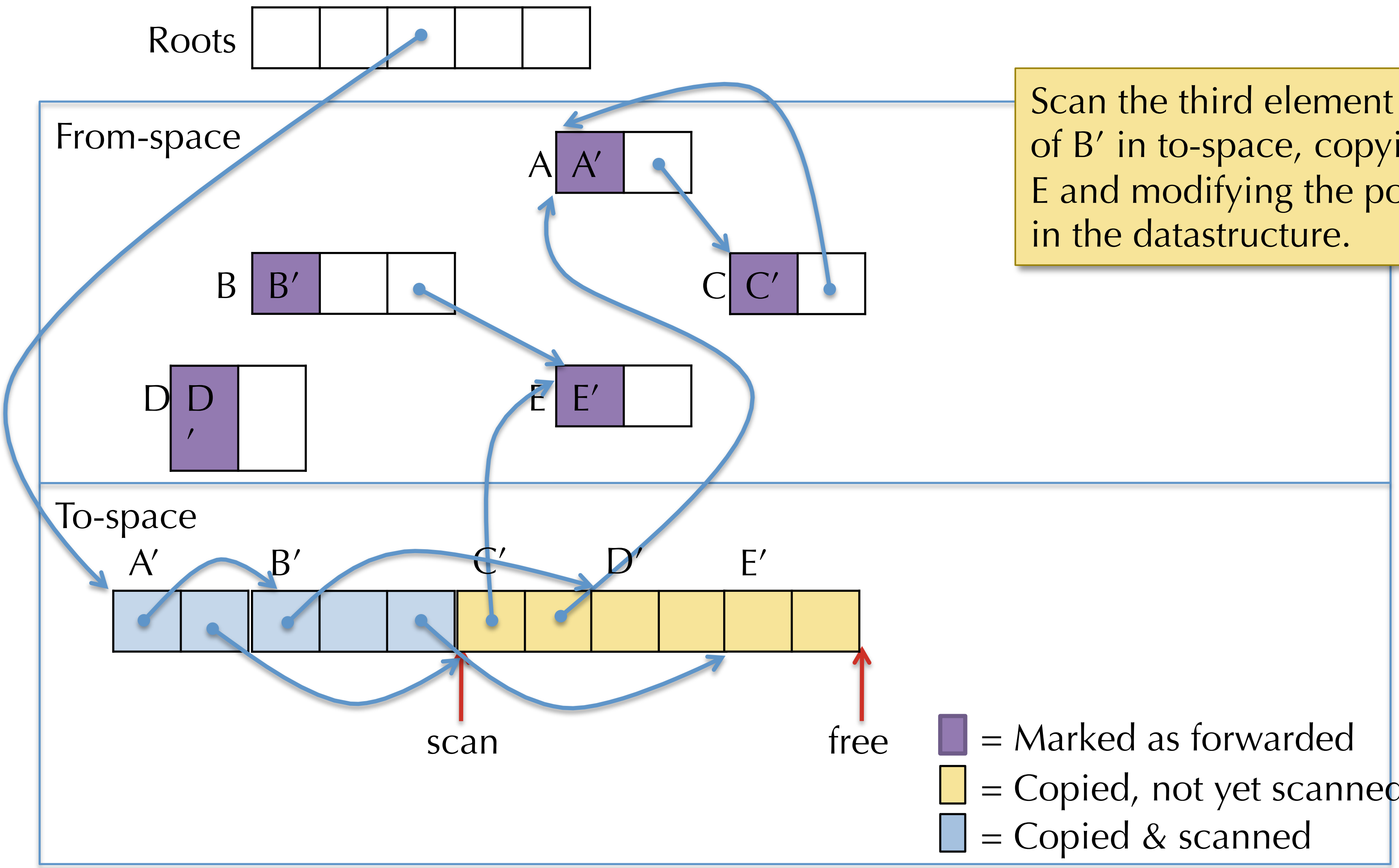
Scan the first element of B′ in to-space, copying D and modifying the pointer in the datastructure.

Run of Cheney's Algorithm



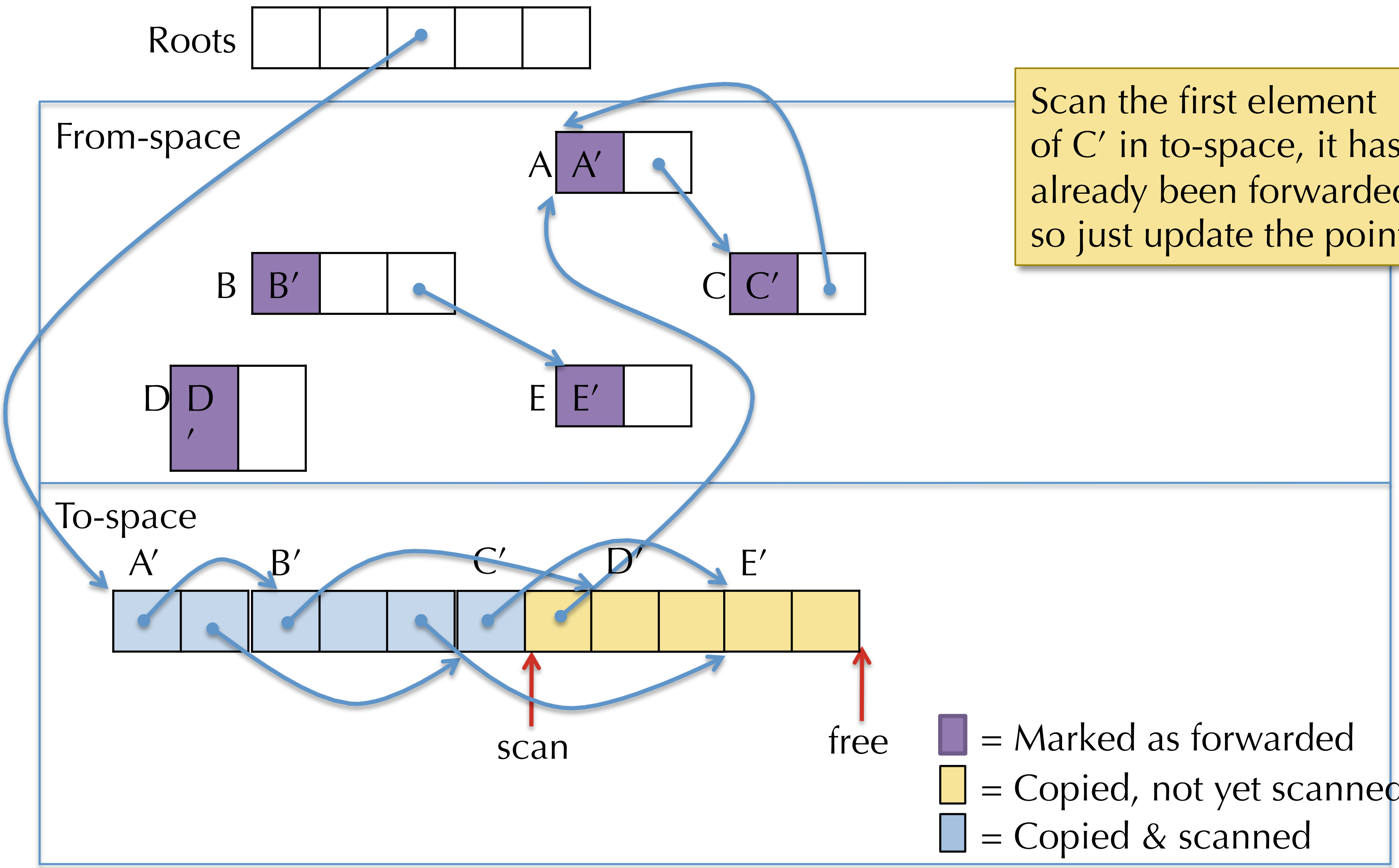
Scan the second element of B′ in to-space – it's not a pointer.

Run of Cheney's Algorithm



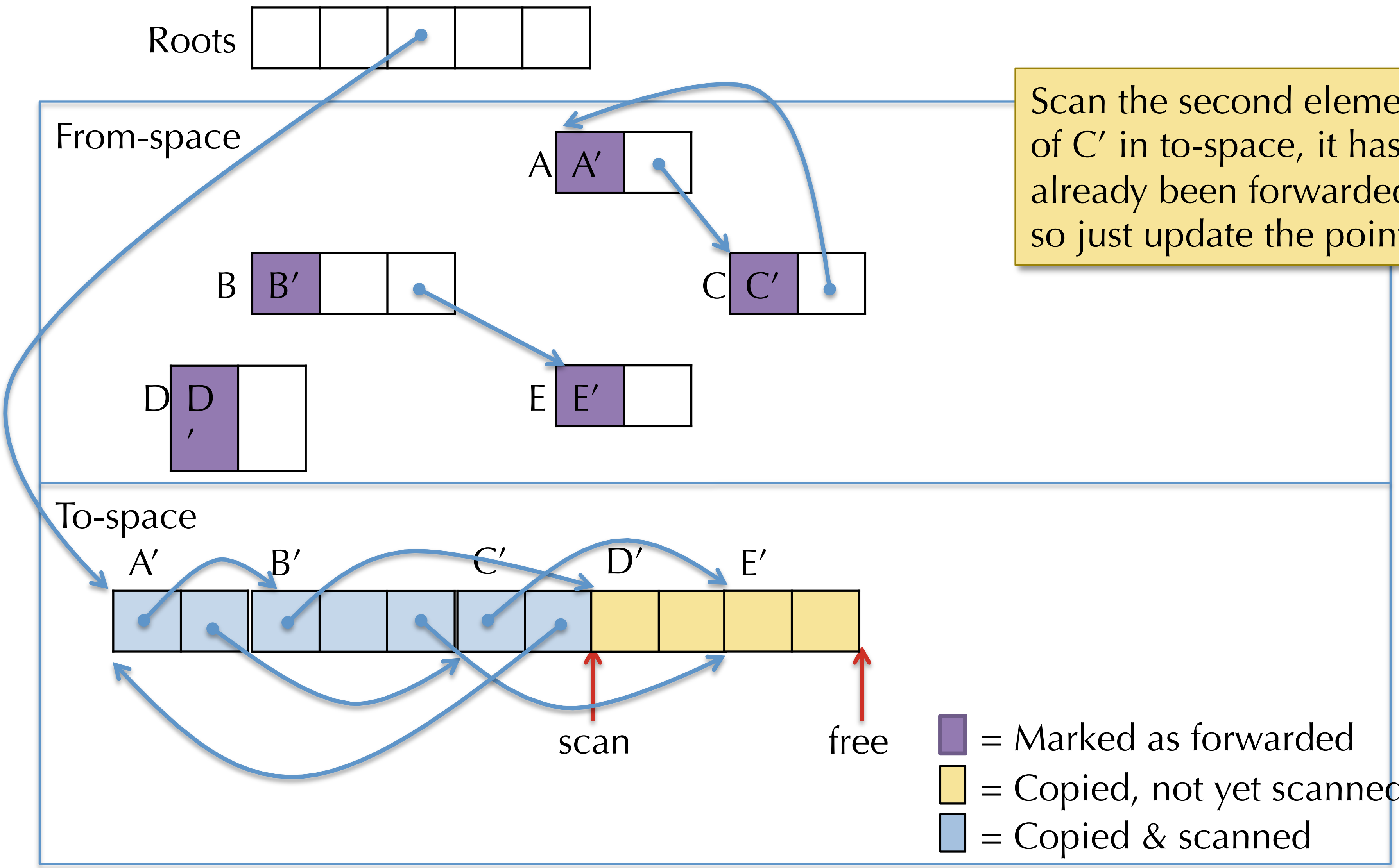
Scan the third element of B′ in to-space, copying E and modifying the pointe in the datastructure.

Run of Cheney's Algorithm



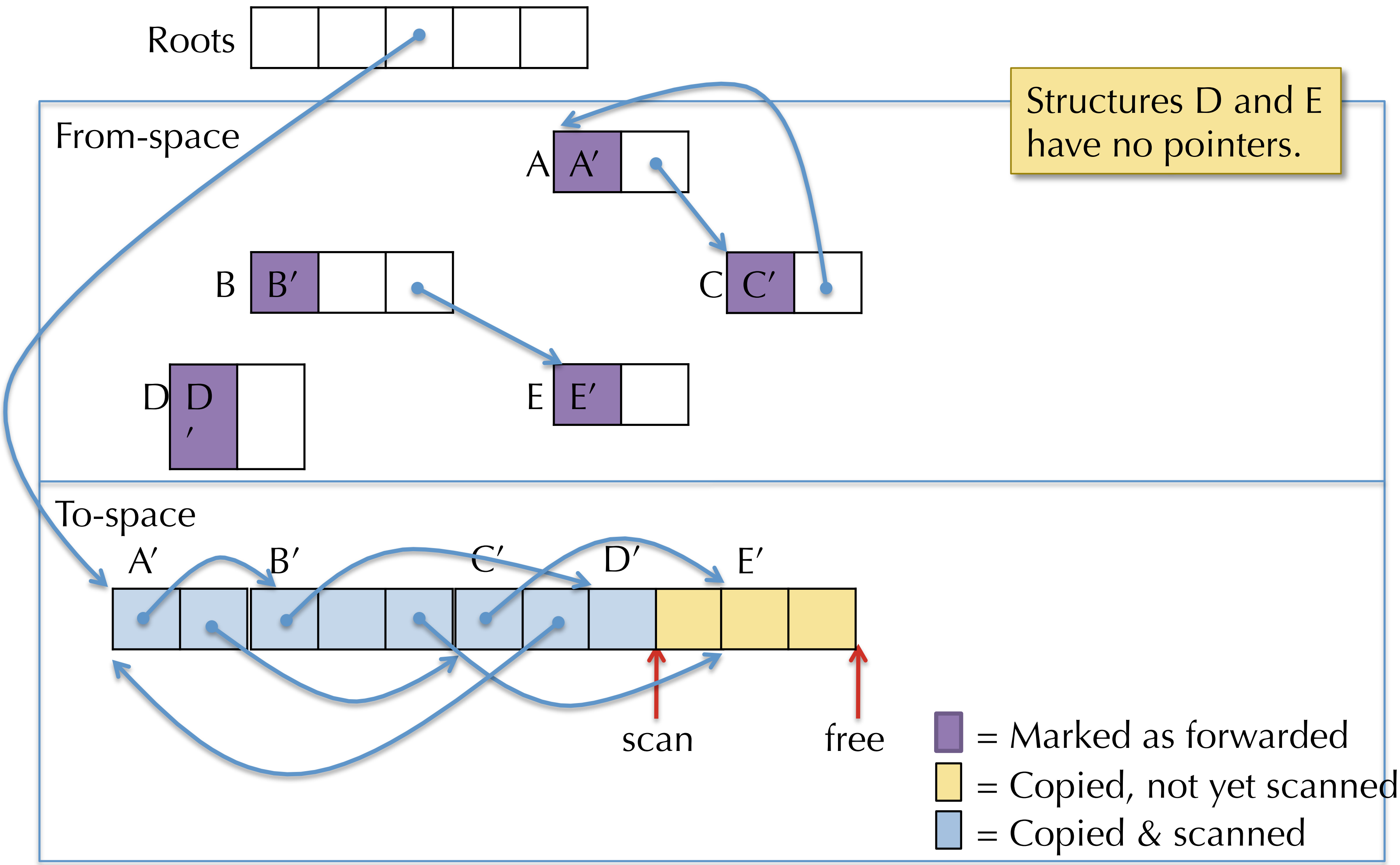
Scan the first element of C′ in to-space, it has already been forwarded so just update the pointer.

Run of Cheney's Algorithm

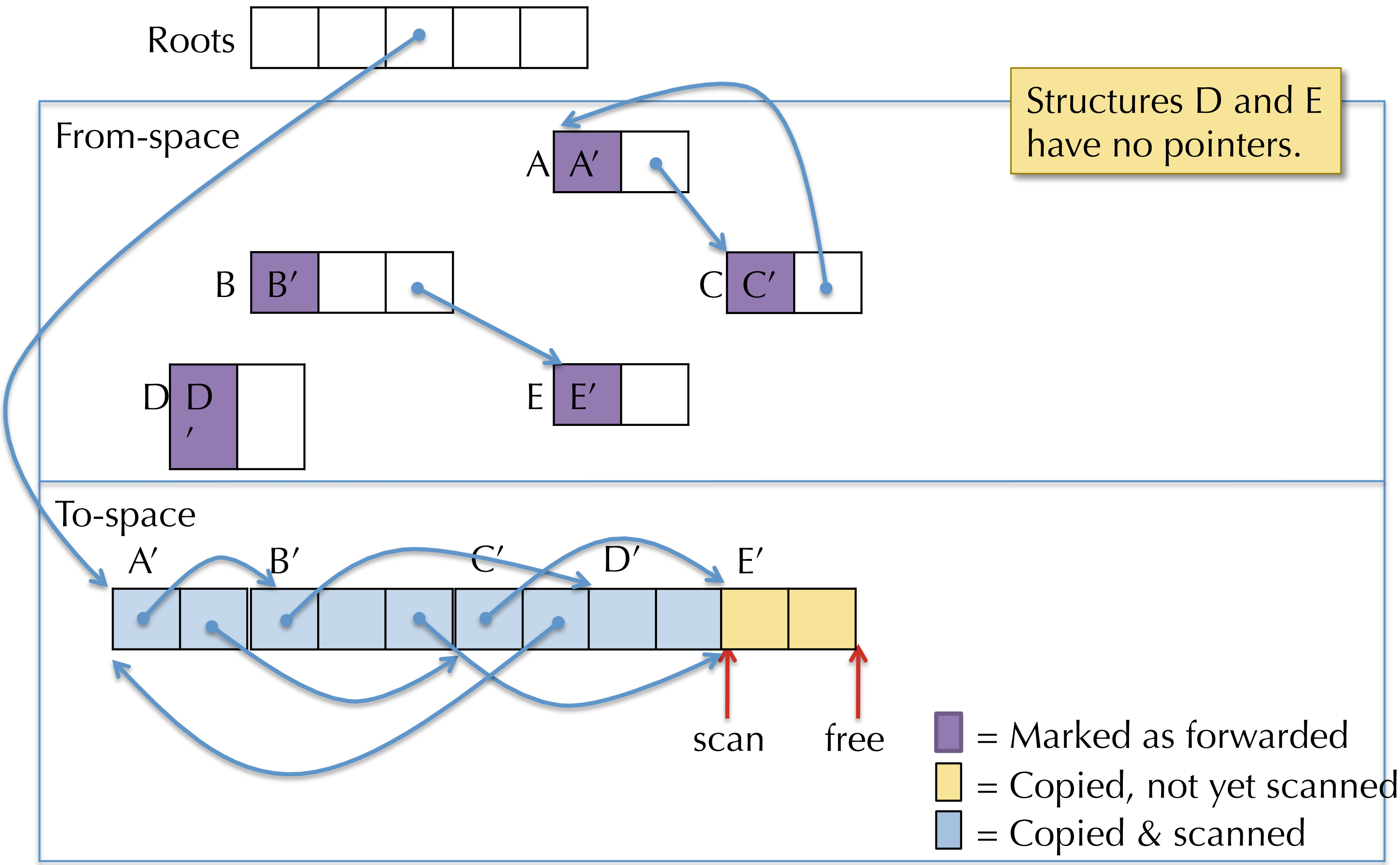


Scan the second element of C′ in to-space, it has already been forwarded so just update the pointer.

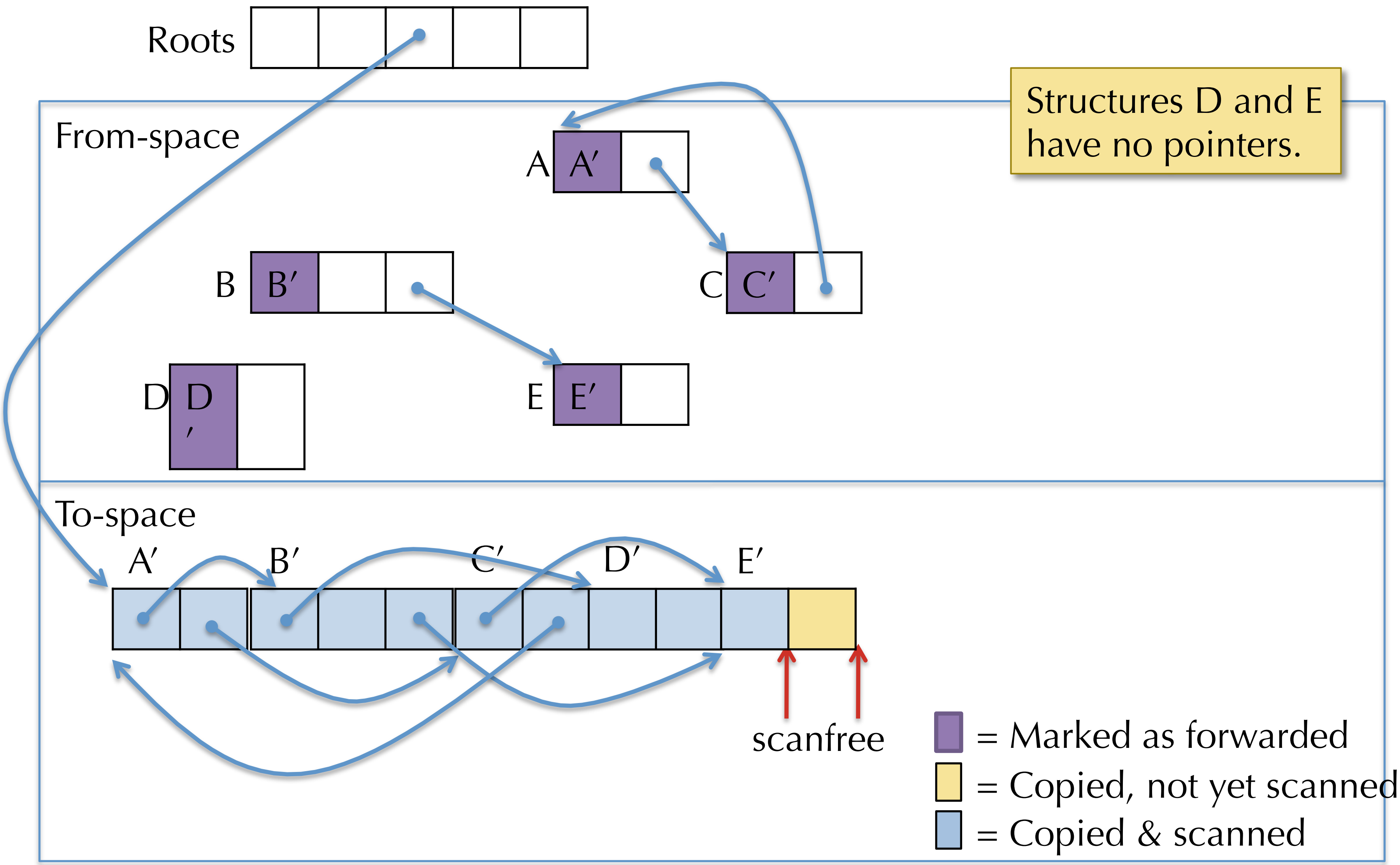
Run of Cheney's Algorithm



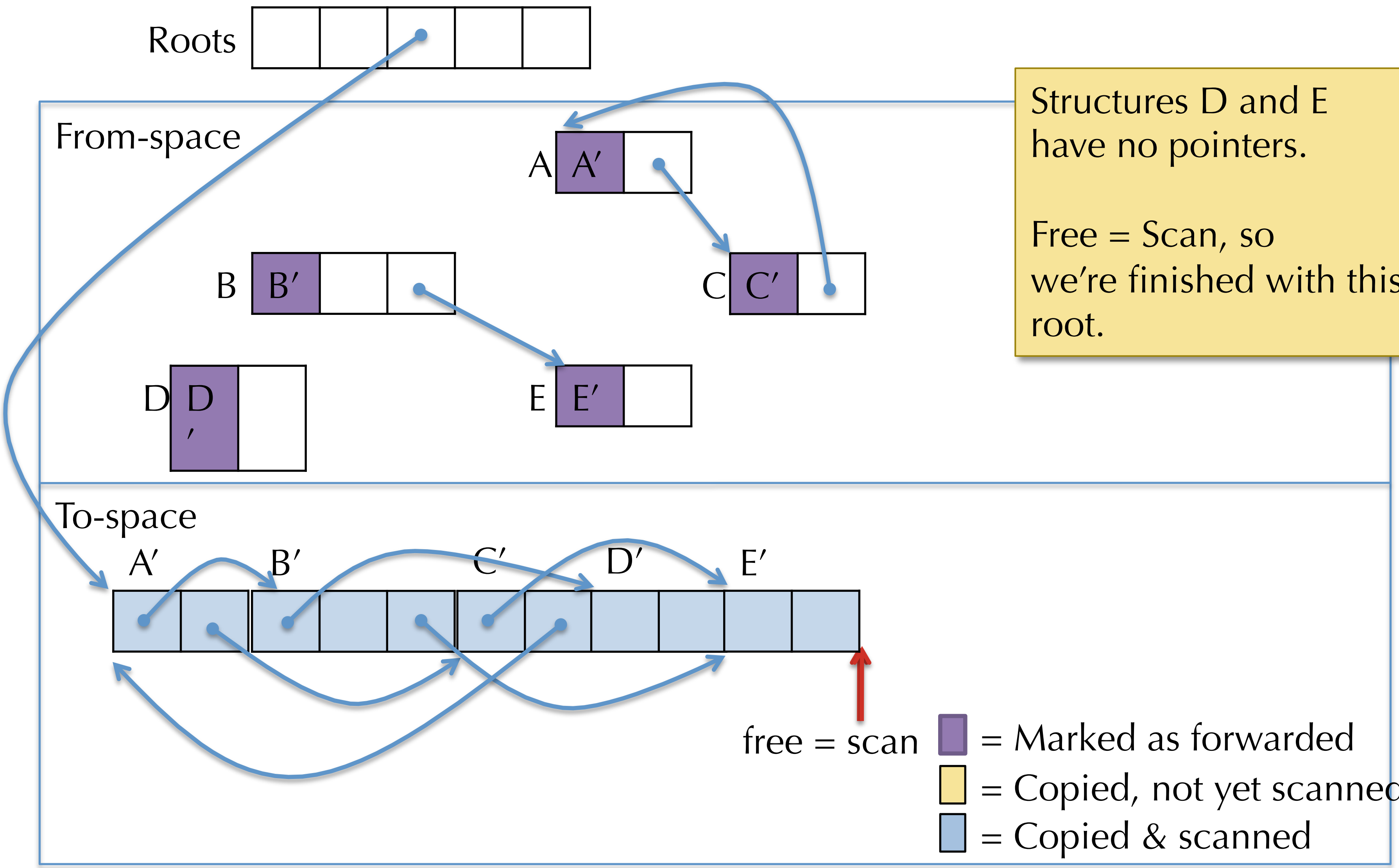
Run of Cheney's Algorithm



Run of Cheney's Algorithm



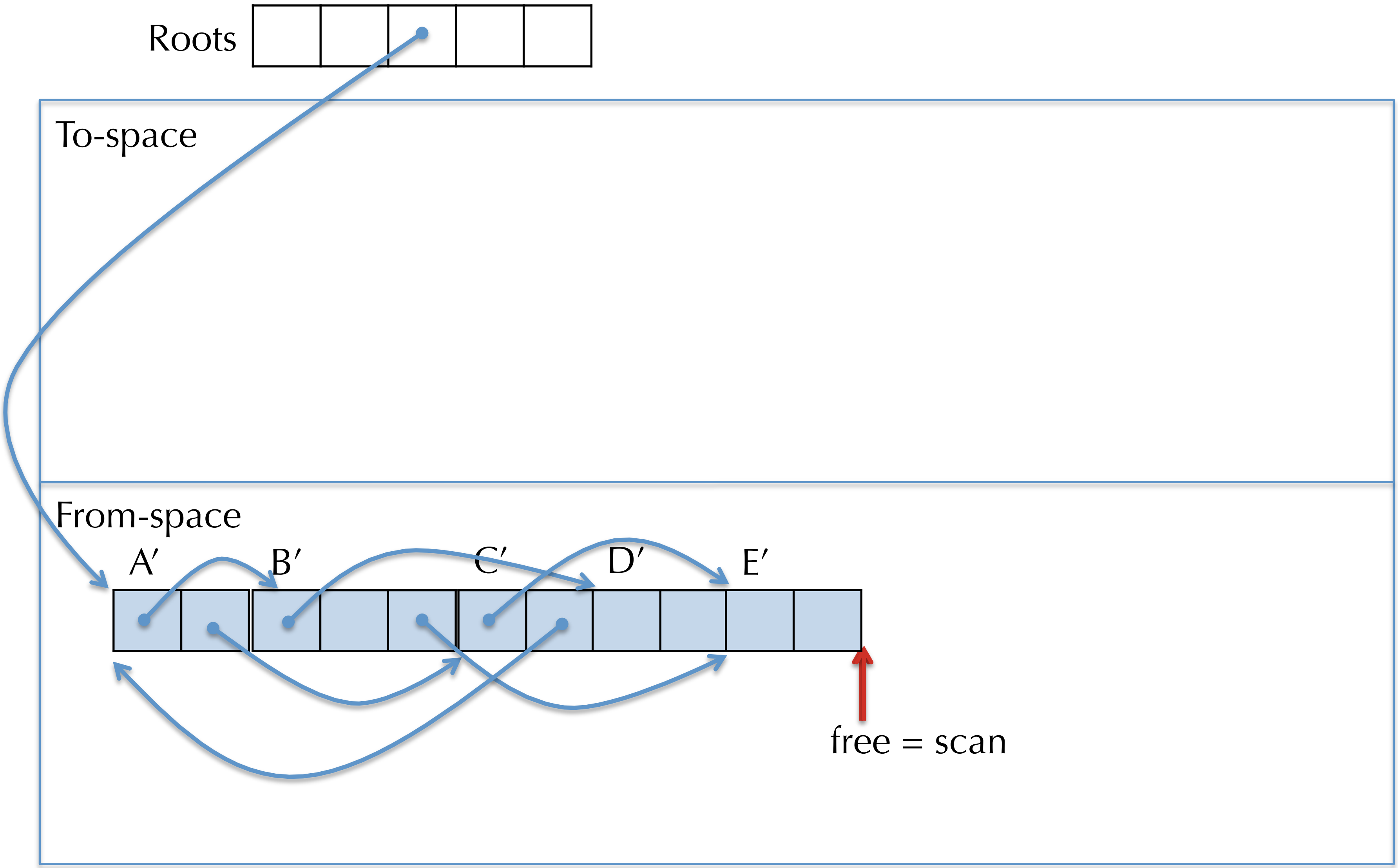
Run of Cheney's Algorithm



Structures D and E have no pointers.

Free = Scan, so we're finished with this root.

Run of Cheney's Algorithm



Tradeoffs of Copying Collection

- Benefits:
  - Simple, no stack space needed to implement the algorithm.
  - Running time is proportional to the number of reachable objects (not all allocated objects)
  - Automatically eliminates fragmentation by compacting memory during copy phase.
  - `malloc(n)` is implemented by `free := free + n`

- Drawbacks:
  - Twice as much memory is needed
  - Lots of memory traffic
  - Precise pointer/type information is required for traversal
  - Still can have long pauses

Baker's Concurrent GC

- Variant of copying collection in which the program and the garbage collector run concurrently.
- Program holds only pointers to to-space
- On field-fetch operation, if the pointer is in from-space, run `copy-forward` instead of directly fetching.
  - Moves the structure to to-space to maintain the invariant
  - Incrementally garbage collects as the program touches data.
- When the to-space fills up, swap to/from by copying the roots and fixing up the stack and registers.
- Avoids long pauses due to copying

Generational Garbage Collection

- Observation: If an object has been reachable for a long time, it is likely to remain so.
- In long-running programs, mark & sweep and copying collection waste time and cache by scanning/copying old objects.
- Idea: Assign objects to different *generations* G_0, G_1, G_2, …
  - Generation G_0 contains newest objects, most likely to become garbage (< 10% live)
  - Younger generations scanned for garbage much more frequently than older generations.
  - New object eventually given tenure (promoted to the next generation) if they last long enough.
  - Roots of garbage collection for G_0 include objects in G_1
- *Remembered sets*:
  - Avoid scanning all tenured objects by keeping track of pointers from old objects to new objects. Compiler emits extra code to keep track of such pointer updates.
  - Pointers from old generations to new generations are uncommon

GC in Practice

- Combination of generational and incremental GC techniques reduce delay
  - Millisecond pause times
- Very large objects (e.g. big arrays) can be copied in a “virtual” fashion without doing a physical copy
  - Complicates the book keeping
- Some systems combine copying collection (for young data) with mark & sweep (for old data)
- Challenging to scale to server-scale systems with terabytes of memory
- Interactions with OS matter a lot
  - It can be cheaper to do GC than it is to start paging
- GC is here to stay (thanks to Java, C#, etc.)

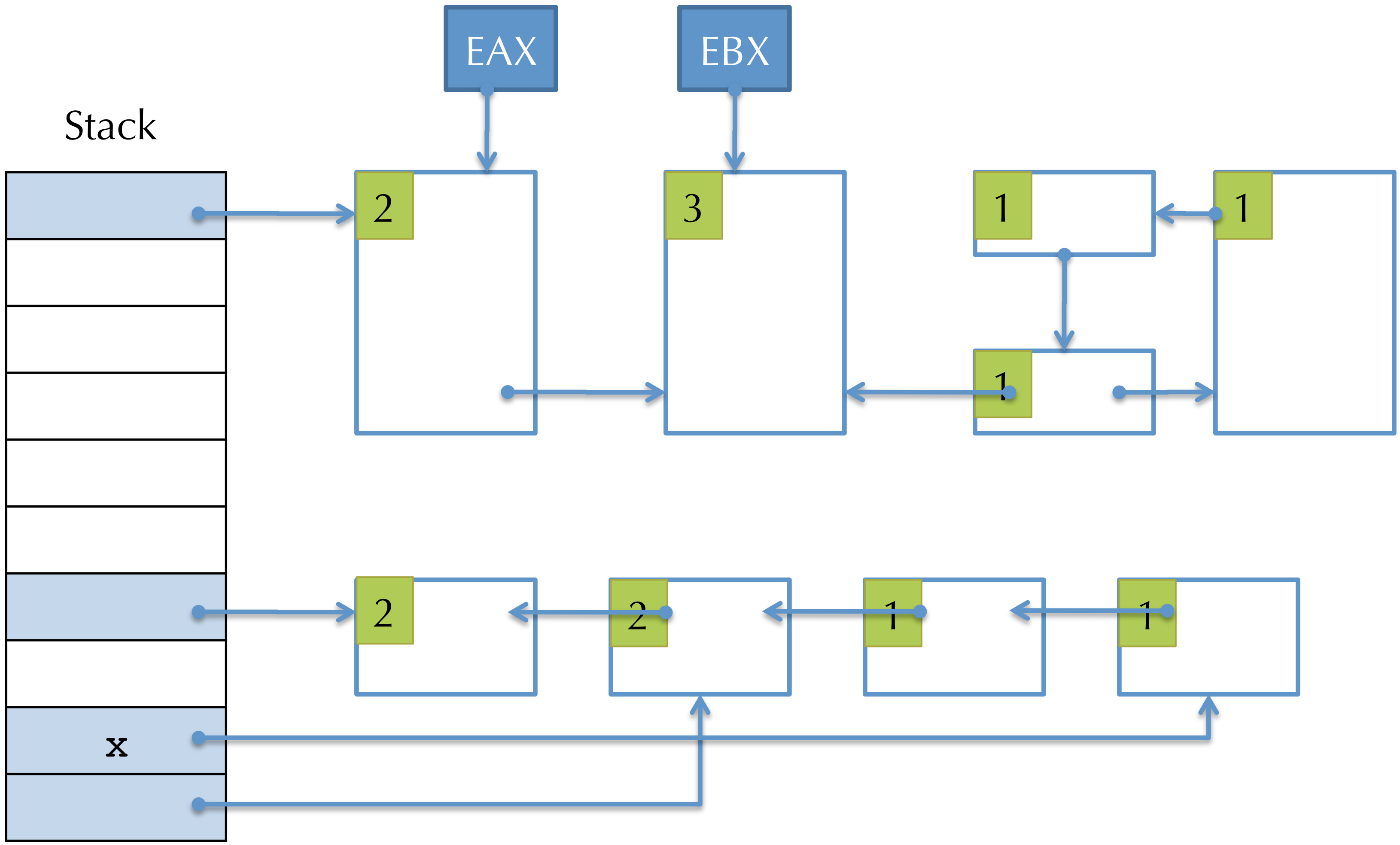
REFERENCE COUNTING

Reference Counting

- Idea: Keep track of the number of references to a given object.
  - When creating a new reference to the object, increase the reference count
  - On a call to `free`, decrement the reference count
  - If the reference count is 0, the object can be deallocated immediately
- Deallocating an object will decrement reference counts of objects it points to
  - Deallocations can "cascade," causing lots of objects to be deallocated
- Benefit: immediate reclamation of the space (no need to wait for garbage collector)
- Challenges:
  - Tracking reference counts efficiently
  - Cyclic data structures

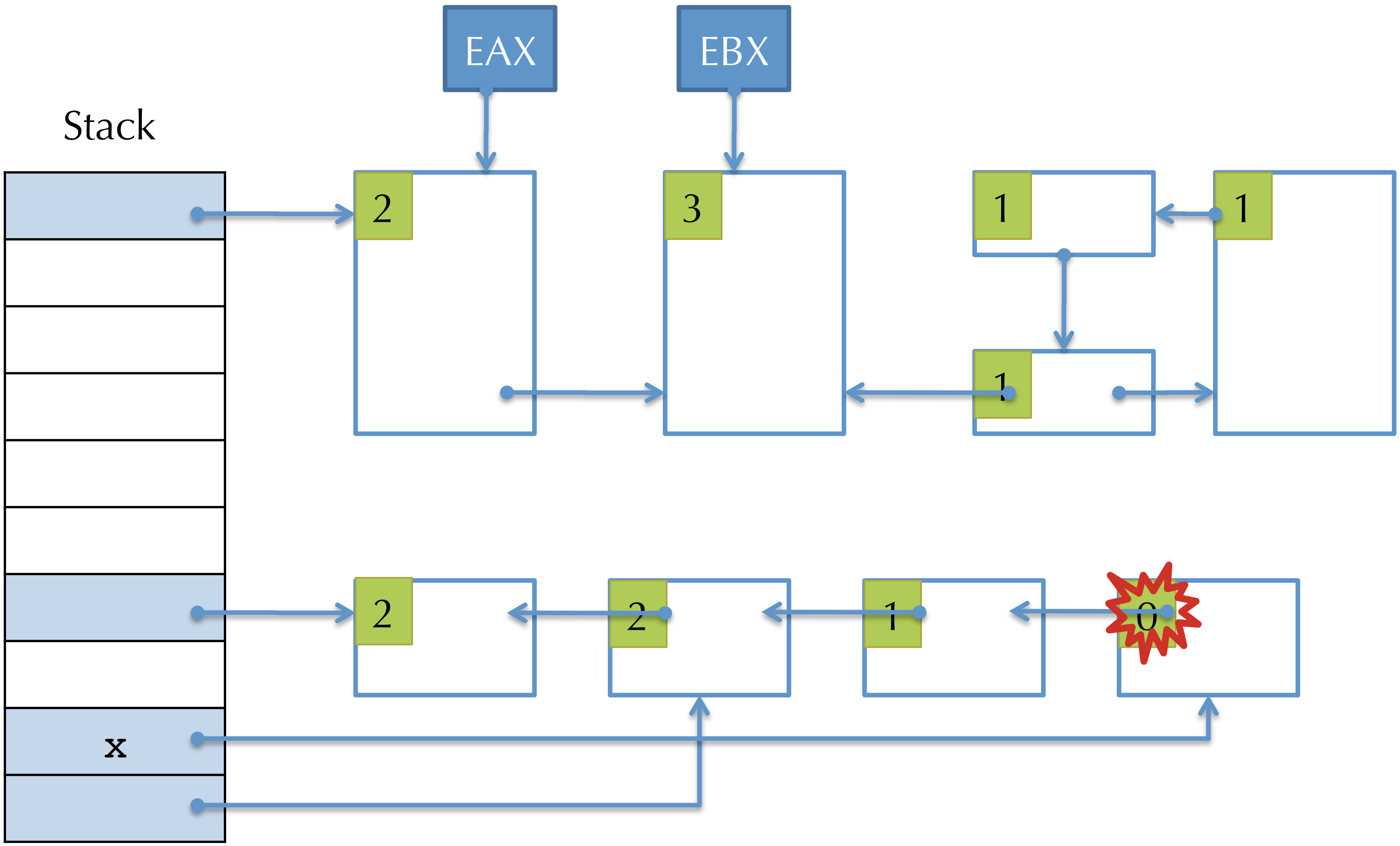
Example Reference Counts

- Objects track reference counts.



Example Reference Counts

- On `free(x)`



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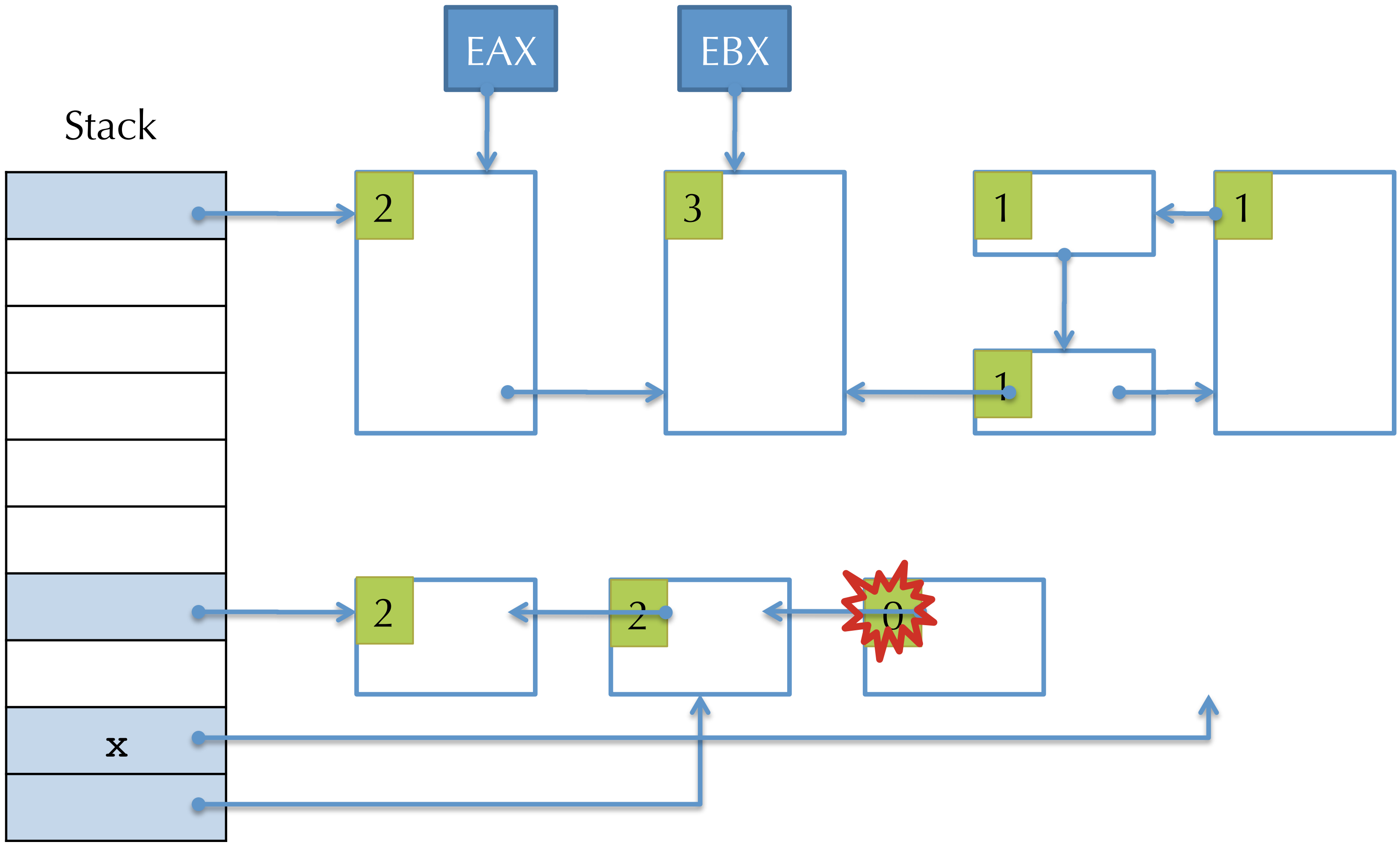
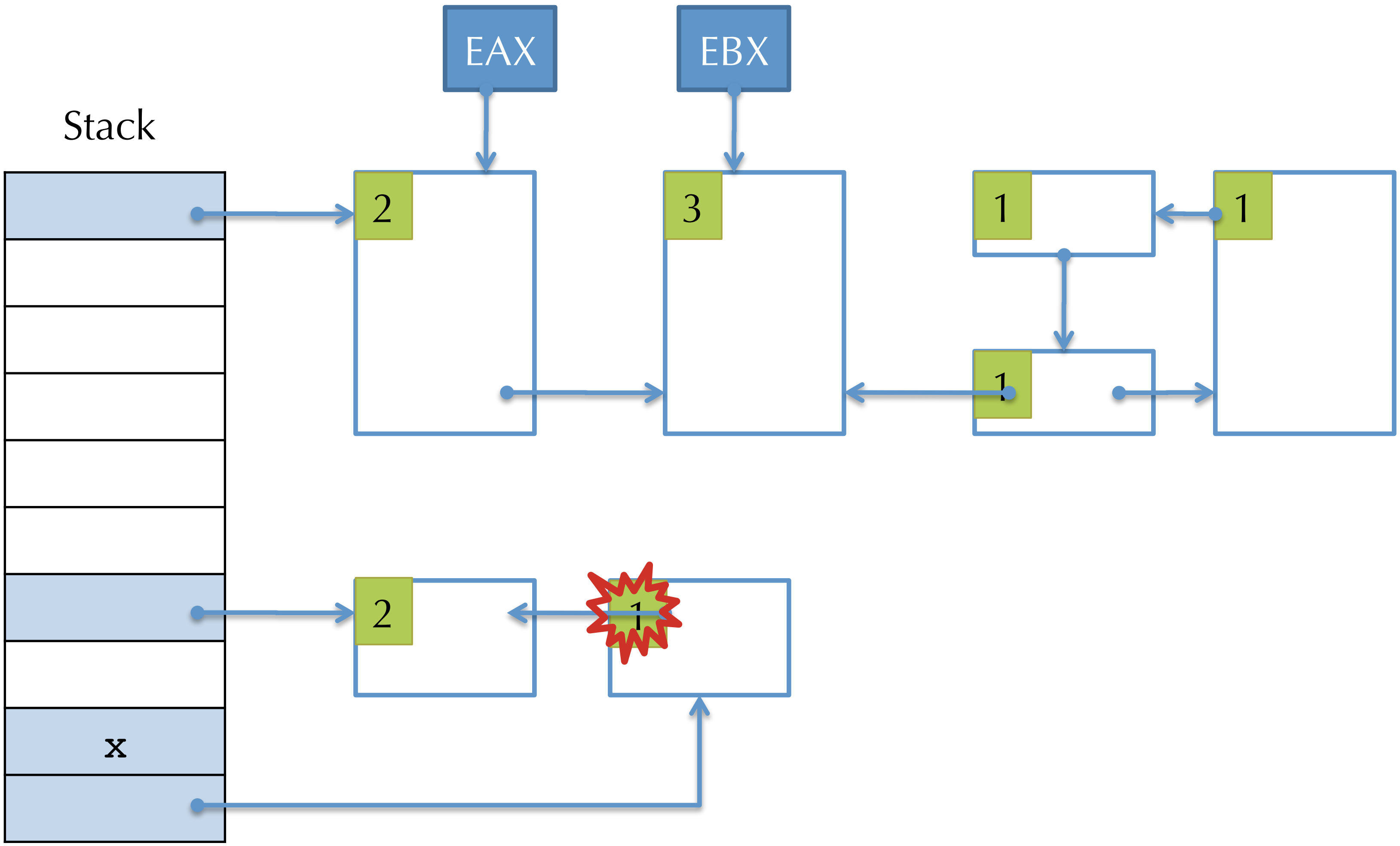
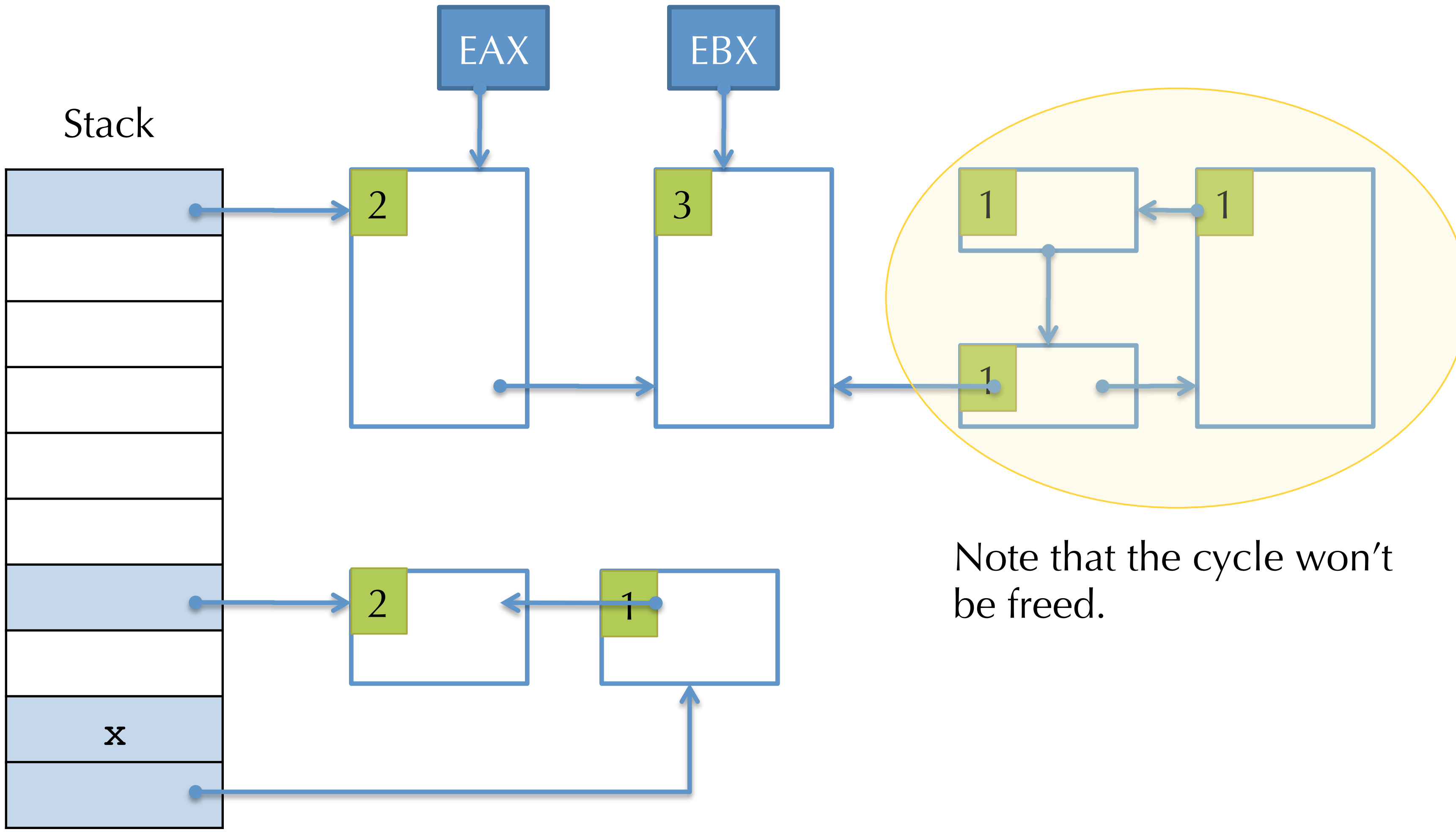


Example Reference Counts

- On `free(x)`



Example Reference Counts



Note that the cycle won't be freed.

Dealing with Cycles

- Option 1: Require programmers to explicitly null-out references to break cycles.
- Option 2: Periodically run GC to collect cycles
- Option 3: Require programmers to distinguish "weak pointers" from "strong pointers"
  - *weak pointers*: if all references to an object are "weak" then the object can be freed even with non-zero reference count.
  - "Back edges" in the object graph should be designated as weak
  - (Aside: weak pointers useful in GC settings too.)
- In practice: Reference counts
  - Apples Cocoa framework used ref counts, recent versions use GC
  - iOS supports "automatic reference counting"

COMPILER VERIFICATION

Compiler Verification

- 1967: Correctness of a Compiler for Arithmetic Expressions [McCarthy, Painter]
- 1972: Proving Compiler Correctness in a Mechanized Logic
  [Milner, Weyhrauch]
- … many interesting developments

See: Compiler Verification, A Bibliography [Dave, 2003]

- 2006-present: CompCert [Leroy, et al.]
  - (Nearly!) fully verified compiler from C to Power PC, ARM, etc.
- Others:
  - Verified Software Toolchain [Appel, et al.]
  - Vellvm: Verified LLVM [Zdancewic, et a.]

Motivation: Safety-critical Software

- How do you know that the program you are running is correct?

- Aircraft flight control software
- Automobile engine controllers
- Pacemakers
- Autonomous vehicles
- Embedded systems

- Formal verification is expensive and time consuming, but sometimes warranted…

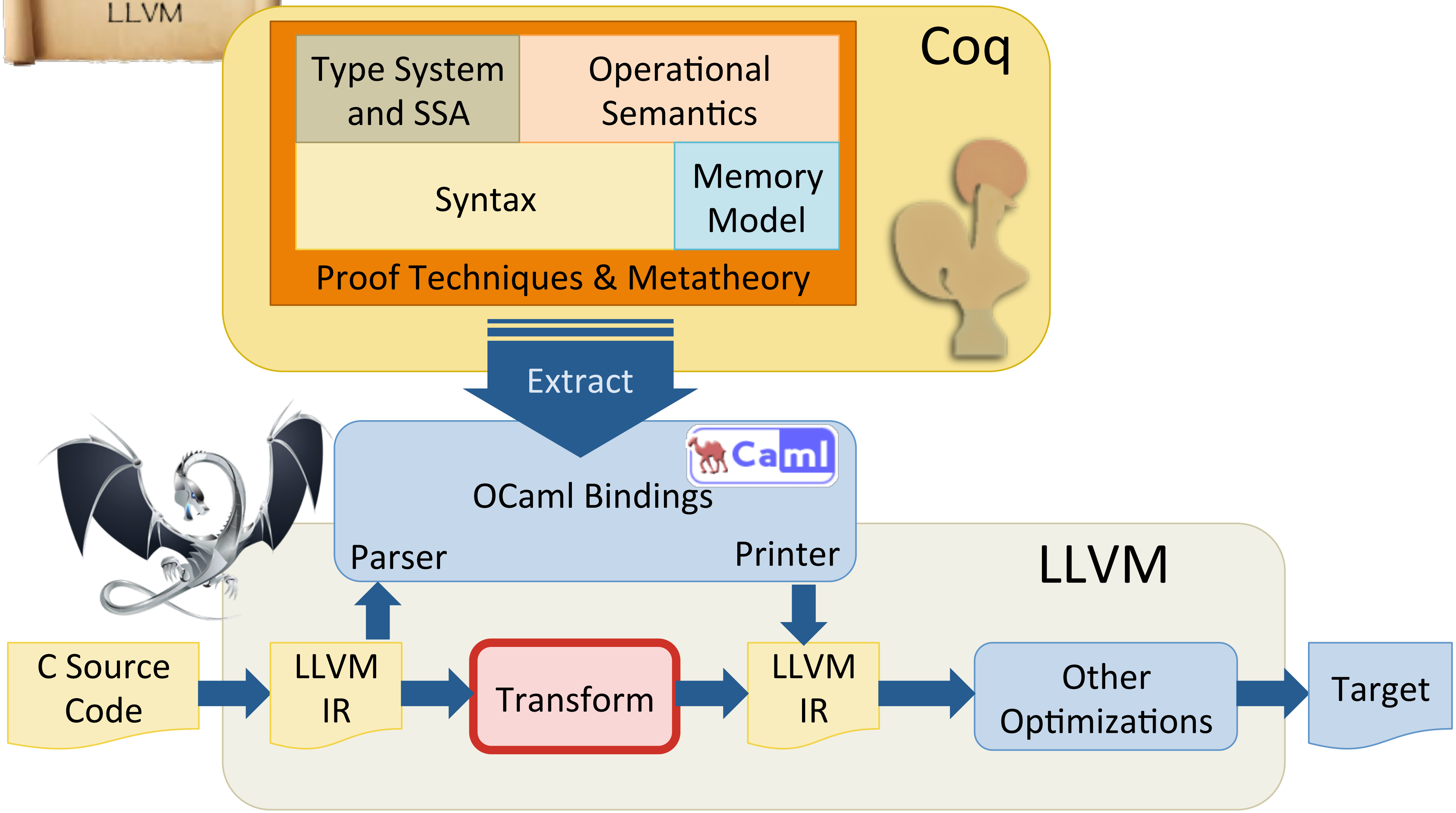
Motivation: SoftBound/CETS

[Nagarakatte, et al. *PLDI '09, ISMM '10*]

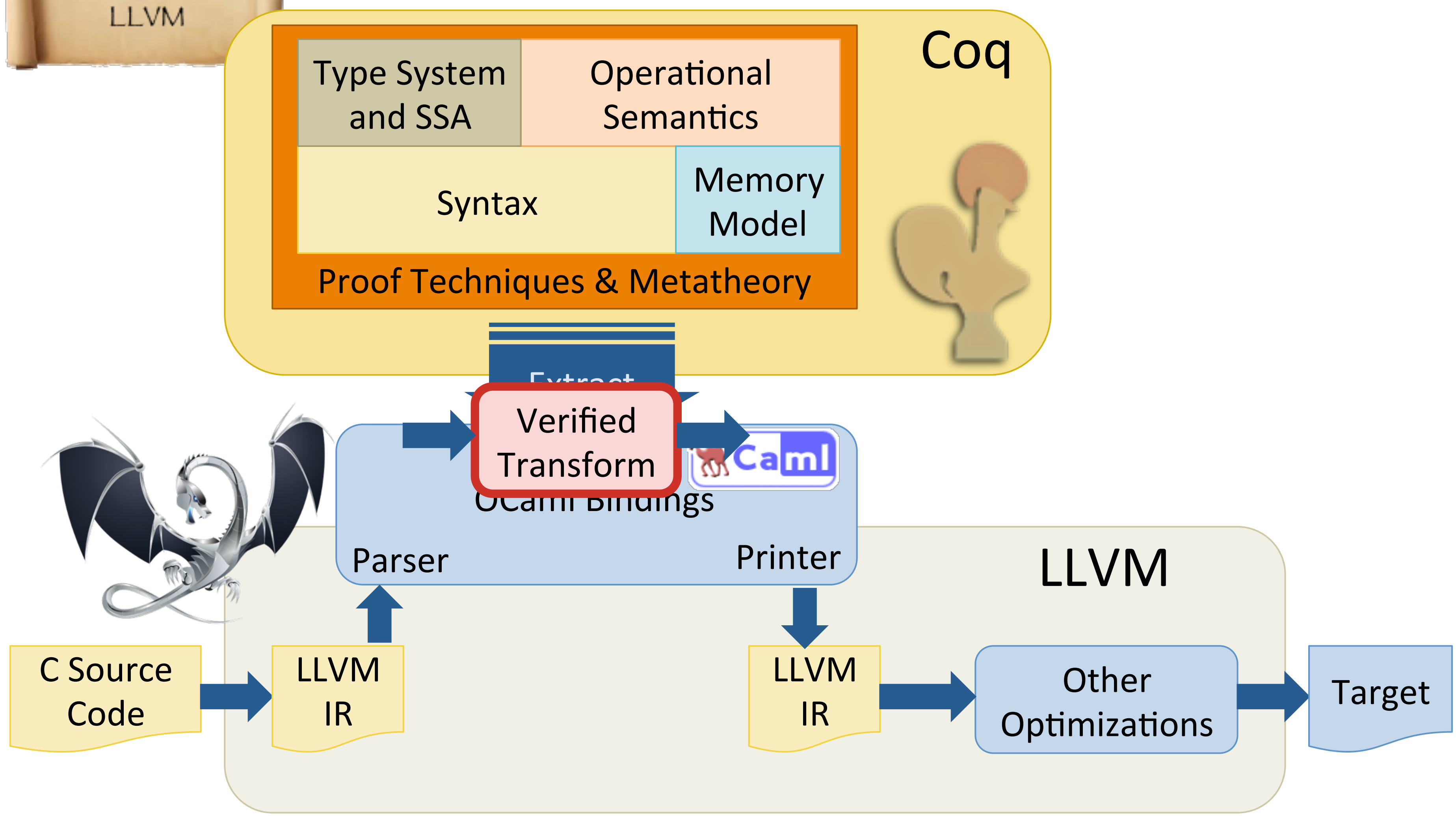
- Buffer overflow vulnerabilities.
- Detect spatial/temporal memory safety violations in legacy C code.
- Implemented as an LLVM pass.
- What about correctness?

http://www.cis.upenn.edu/acg/softbound/

Vellvm Framework

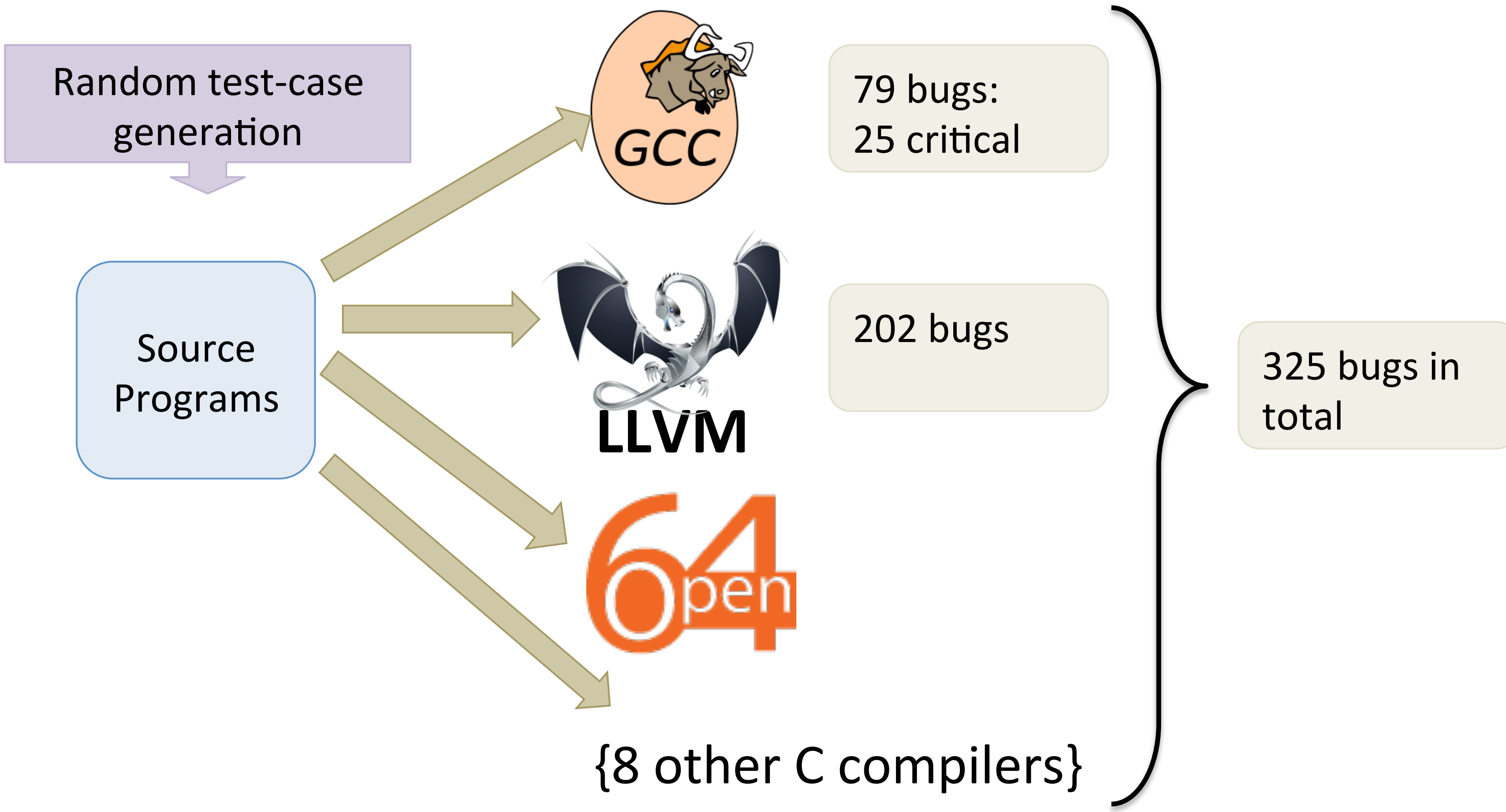


Vellvm Framework



Motivation:Compiler Bugs

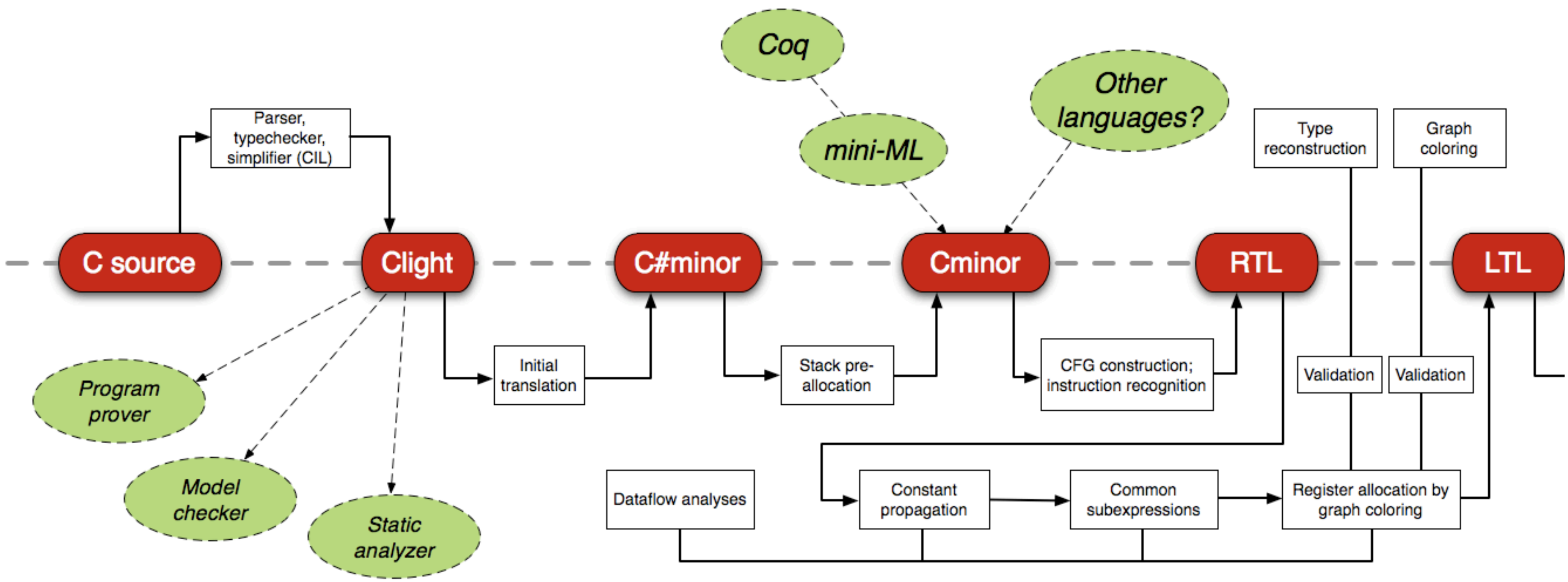
[Yang et al. PLDI 2011]



Csmith – compiler testing infrastructure

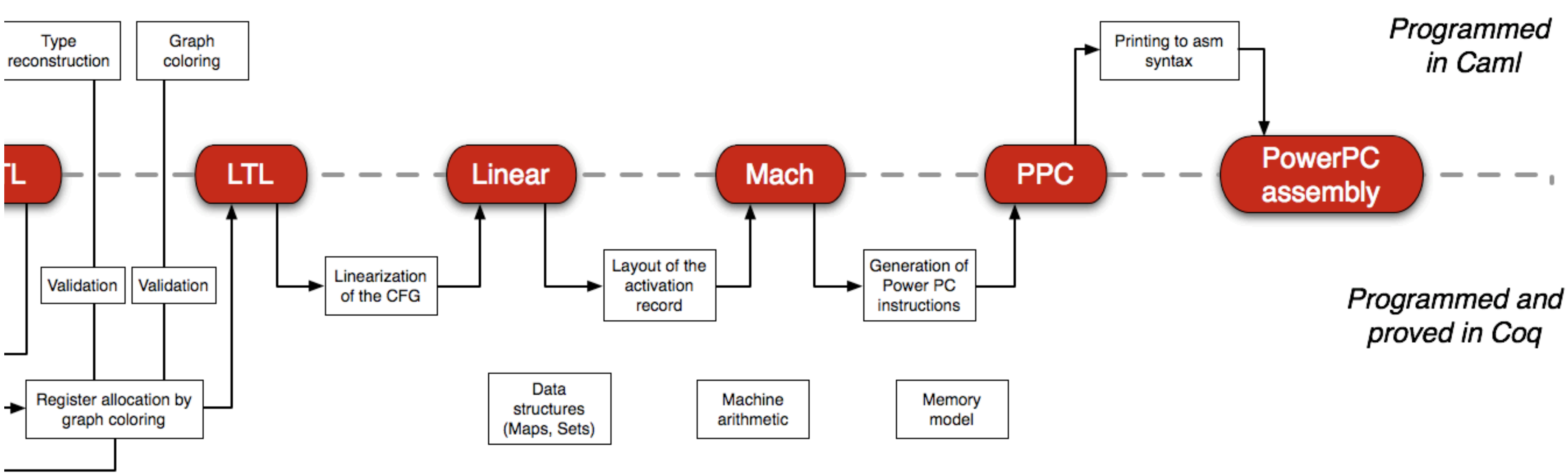
CompCert

- Initiated by Xavier Leroy of INRIA in 2006.
- Idea: Build a compiler using an interactive theorem prover.
  - Prove formally that each compilation translation pass is correct.



CompCert

- Initiated by Xavier Leroy of INRIA in 2006.
- Idea: Build a compiler using an interactive theorem prover.
  - Prove formally that each compilation translation pass is correct.
  - Implemented in Coq



CompCert – does it work?

The striking thing about our CompCert results is that the middle-end bugs we found in all other compilers are absent. As of early 2011, the under-development version of *CompCert is the only compiler we have tested for which Csmith cannot find wrong-code errors.*

This is not for lack of trying: *we have devoted about six CPU-years to the task*. The apparent unbreakability of CompCert supports a strong argument that developing compiler optimizations within a proof framework, where safety checks are explicit and machine-checked, has tangible benefits for compiler users.

Finding and understanding bugs in C compilers
Yang et al. PLDI 2011

FORMALLY SPECIFYING SEMANTICS

Execution Models

- Interpretation:
  - program represented by abstract syntax
  - tree traversed by interpreter
- Compilation to native code:
  - program translated to machine instructions
  - executed by hardware
- Compilation to virtual machine code:
  - program translated to “virtual machine” instructions
  - interpreted (efficiently)
  - further translated to machine code
  - just-in-time compiled to machine code

Simple Imperative Language

```
id     := X|Y|Z|…                                     Variables

aexp   := n | id | aexp + aexp |                      Arithmetic Expressions
              aexp – aexp | aexp * aexp

bexp   := true | false | aexp = aexp                  Boolean Expressions
              !bexp | bexp && bexp

cmd :=
   | SKIP                                             Do nothing
   | id ::= aexp                                      Assignment
   | cmd ;; cmd                                       Sequence
   | IFB bexp THEN cmd ELSE cmd FI                    Conditional
   | WHILE bexp DO cmd END                            Loop
```

See Vminus/Imp.v for the Coq formalism

Formal Semantics

- Basic idea: implement interpreters or simulators
  - Just as in the earliest 341 projects

- "small step": cmd / st $\longmapsto$ cmd′ / st′
  - say how a single step of computation affects the state

    `x ::= 3` / {x=0} $\longmapsto$ `skip` / {x=3}
  - Implementation as an interpreter:
    ```
    step : (cmd * state) -> (cmd * state)
    ```

- "large step": cmd / st $\Downarrow$ st′
  - say how a command runs to completion to produce a final state
  - Implementation as an interpreter:
    ```
    eval: (cmd * state) -> state
    ```

Correct Execution?

- What does it mean for such a program to be executed correctly?

- Even at the interpreter level we could show *equivalence* between the small-step and the large-step operational semantics:

$$\text{cmd} \,/\, \text{st} \longmapsto^{*} \texttt{SKIP} \,/\, \text{st}'$$

iff

$$\text{cmd} \,/\, \text{st} \Downarrow \text{st}'$$