Garbage Collection: Basics

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Contents

Introduction

Two ways memory management goes wrong

- **premature free:** reclaim/reuse space for data when it may still be used in future
- **memory leak:** do not reclaim/reuse space for date when it is no longer used

- GC automates memory management, by identifying when data becomes *"never used in future"*
  - ▸ or, conversely, by identifying which data *"may be"* used in future

```
int * s, * t;
void h() { ... }

void g() {
  ...
  h();
  ... = p->x ... }

void f() {
  ...
  g()
  ... = q->y ... }

int main() {
  ...
  f()
  ... = r->z ... }
```

- global variables
- local variables of active function calls (calls that have started but have not finished)
- and …

active function calls
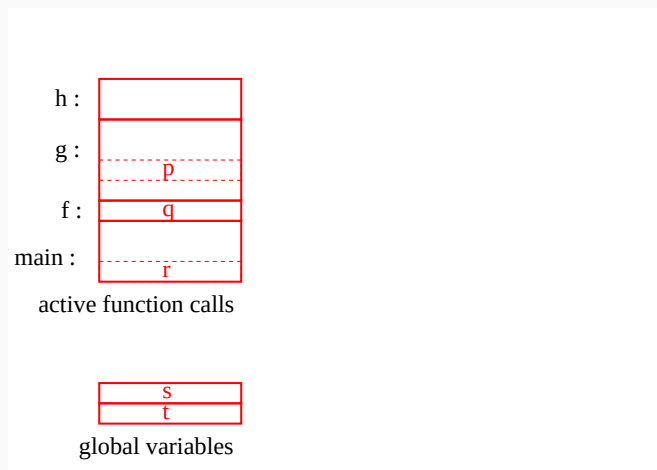
global variables

Data that "may be" used in future ?

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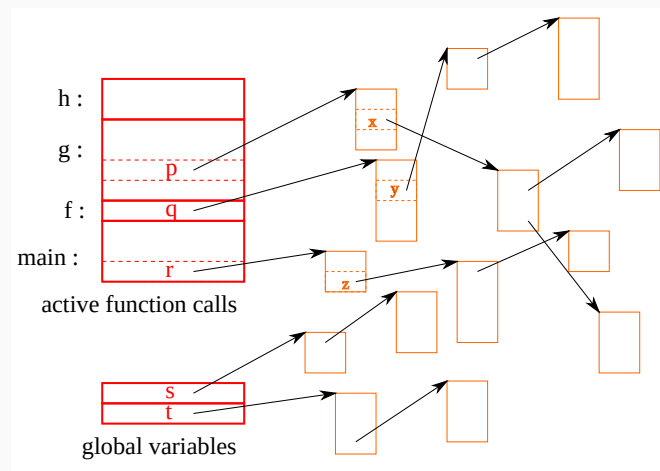
- global variables
- local variables of active function calls (calls that have started but have not finished)
- objects reachable from them by pointers

How GC basically works

Terminologies and the basic principle

- *an object:* the unit of data subject to memory allocation/release (malloc in C; objects in Java; etc.)
- *the root:* objects accessible without traversing pointers, such as global variables and local variables of active function calls
- *(un)reachable objects:* objects (un)reachable from the root by traversing pointers
- *live objects:* objects that may be accessed in future
- *dead objects* or *garbage:* objects that are never accessed in future

Terminologies and the basic principle

- *collector:* the program (or the thread/process) doing GC
- *mutator:* the user program
  - ▸ very GC-centric terminology, viewing the user program as someone simply "mutating" the graph of objects

the basic principle of GC:

objects unreachable from the root are dead

The two major GC methods (traversing GC and reference counting)

- simply traverses pointers from the root, to find (or *visit*) objects *reachable from the root*
- reclaim objects not visited
- two basic traversing methods
  - ▸ *mark&sweep* GC
  - ▸ *copying* GC

- during execution, *maintain the number of pointers* pointing to each object *(reference count)*
- *reclaim an object when its reference count drops to zero*
  - ▸ *∵ an object's reference count is zero → it's unreachable from the root*
- note: "GC" sometimes narrowly refers to the traversing GC only
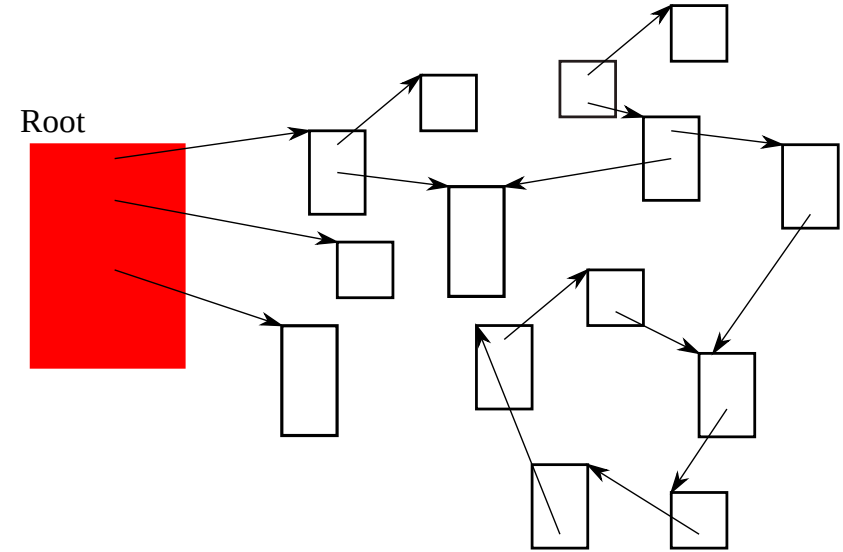
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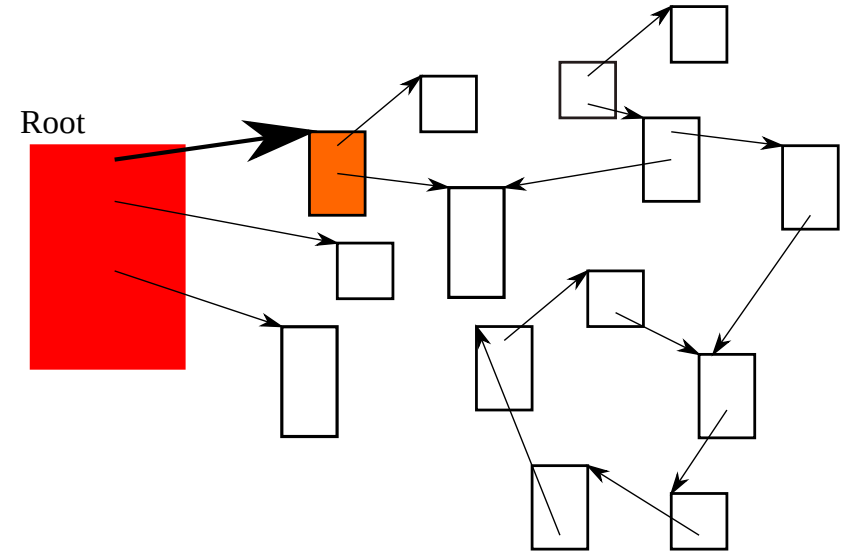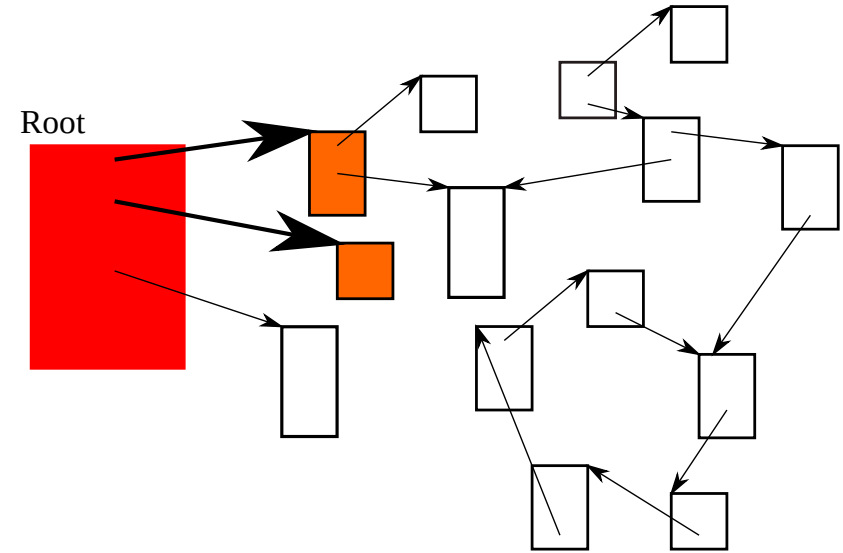- note: the difference between mark&sweep and copying is covered later

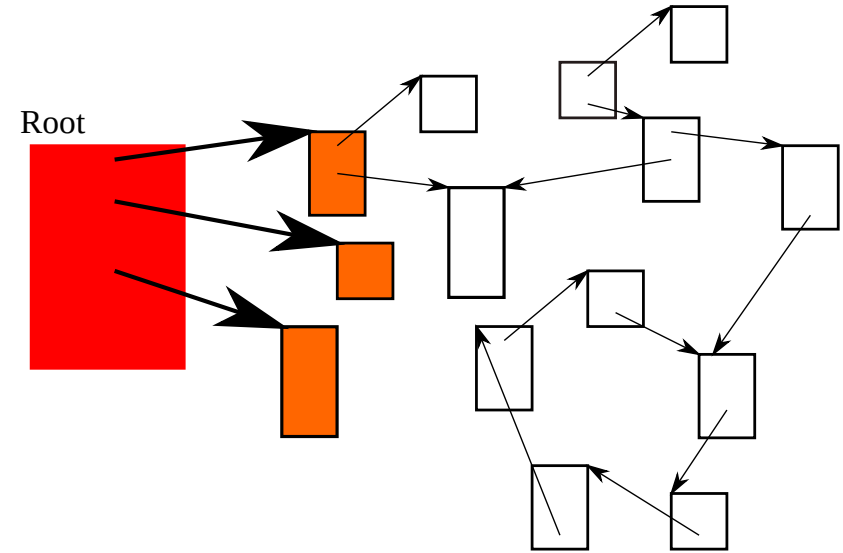- traverse pointers from the root

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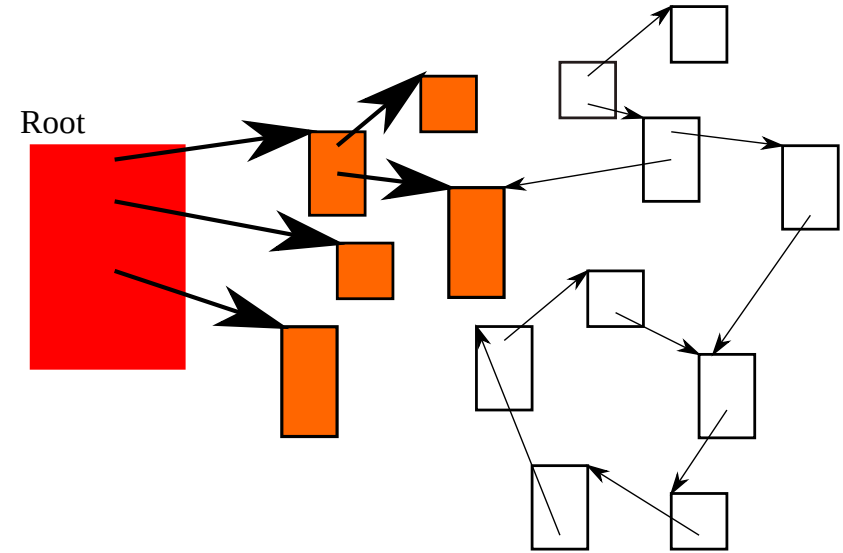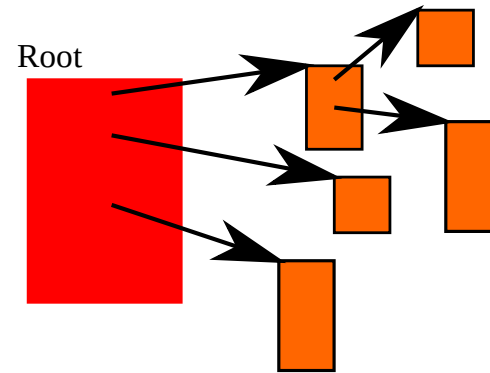
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How traversing GC works

- traverse pointers from the root
- when no more "visited $\rightarrow$ unvisited" pointers are found, objects that have not been visited are garbage
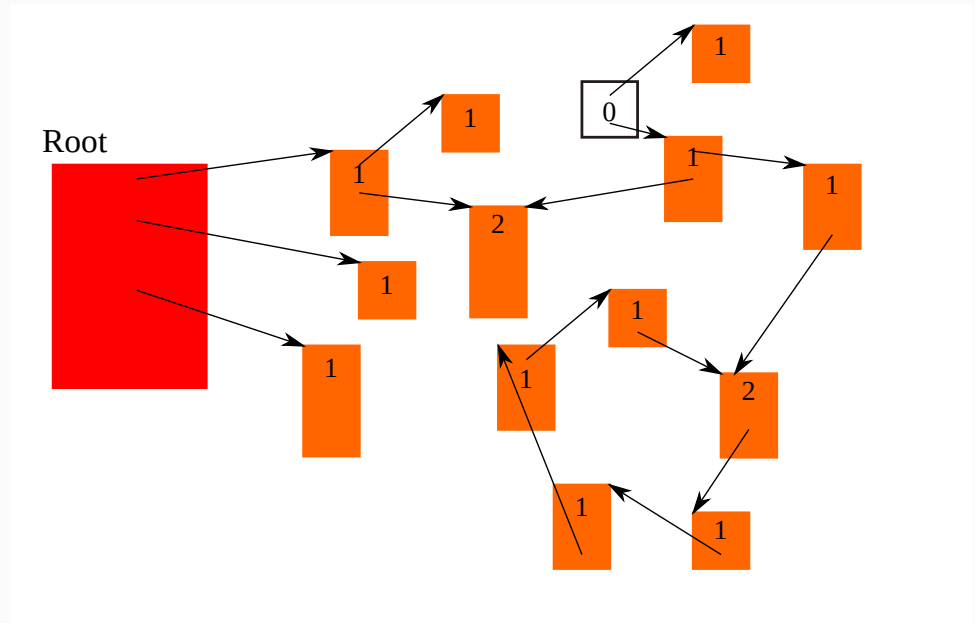

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How reference counting works

- each object has a ***reference count (RC)***, the number of pointers referencing it
- update RCs during execution; e.g., upon p = q
  - ‣ the RC of the object p points to `-= 1`
  - ‣ the RC of the object q points to `+= 1`

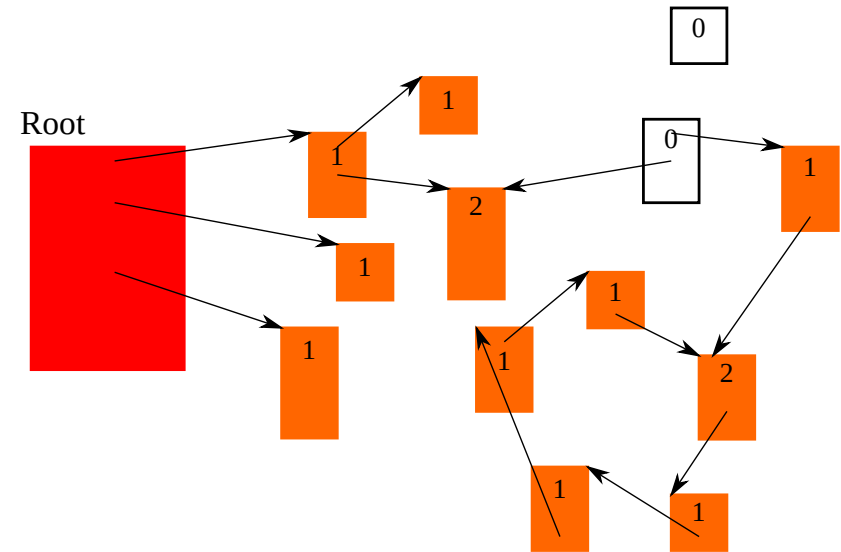- reclaim an object when its RC drops to zero

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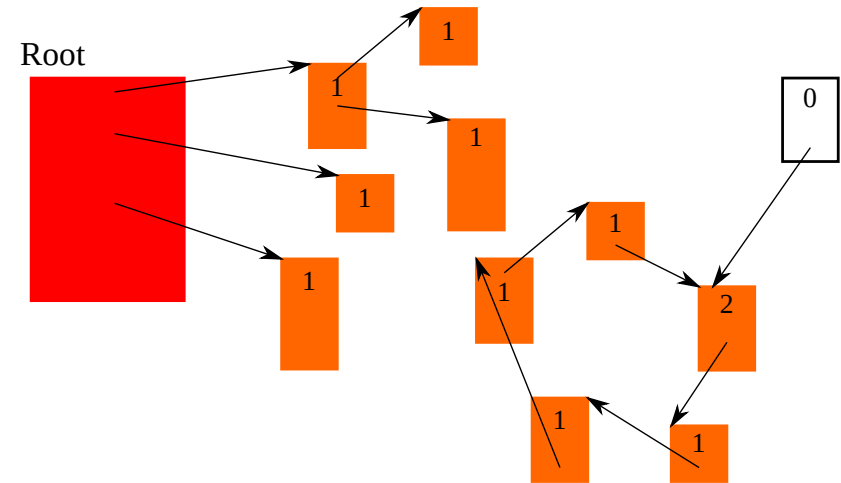
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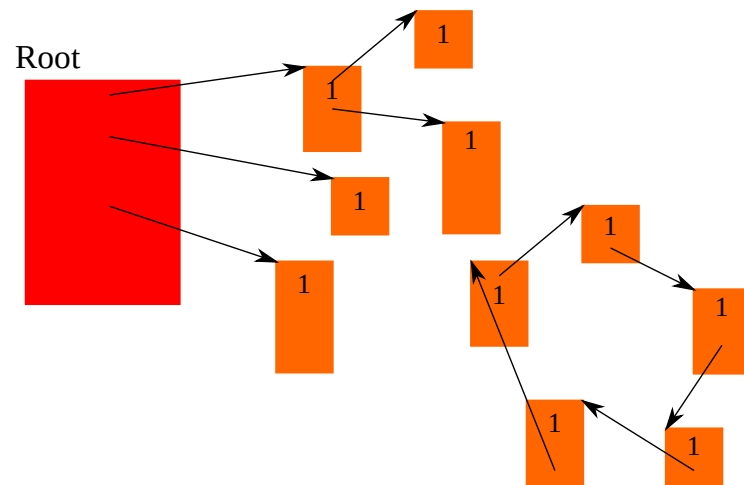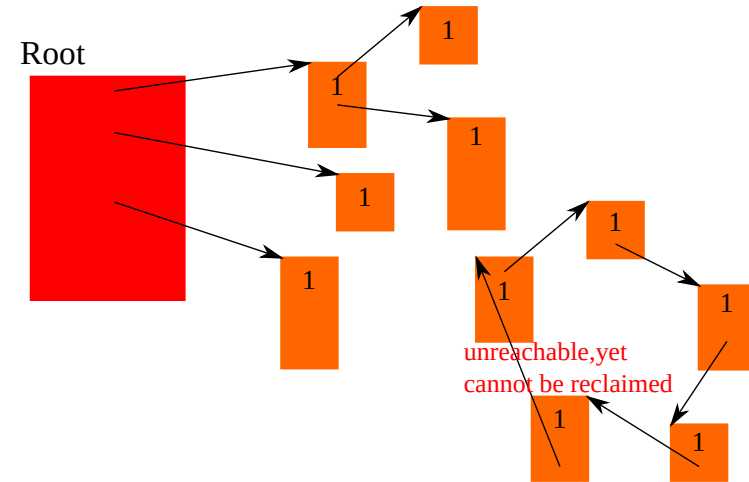- RCs of objects pointed to by the reclaimed object decrease, which may result in reclaiming them too

Root

1
1
1
1
1
1
1
1
1
1
1

unreachable,yet
cannot be reclaimed

- **note:** unreachable cycles cannot be reclaimed (RC = 0 $\Rightarrow$ unreachable, but *not vice versa*)

When an RC changes

- a pointer variable is updated

- a reference is passed to a function

- a variable goes out of scope or a function returns

- ≈ any point when pointers get copied / dropped

- summary: *expensive*

```
p = q; p->f = q; etc.

int main() {
  object * q = ...;
  f(q); /* rc of q += 1 */
}

void f(object * p) {
  ...
  {
    object * r = ...;

  } /* RC of r -= 1 */
  ...
  return ...; /* RC of p -= 1 */
}
```

Evaluating GCs

Evaluating GCs

- preciseness:
  - ▸ garbage that can be collected
- memory allocation cost:
  - ▸ the work (including GC) required to allocate memory
- pause time:
  - ▸ the (worst case) time the mutator has to (temporarily) suspend for GC to function
- mutator overhead:
  - ▸ the overhead imposed on the mutator for GC to function

Criteria 1: preciseness

- *reference counting cannot reclaim cyclic garbage*
- reference counting $<$ traversing GC (better)
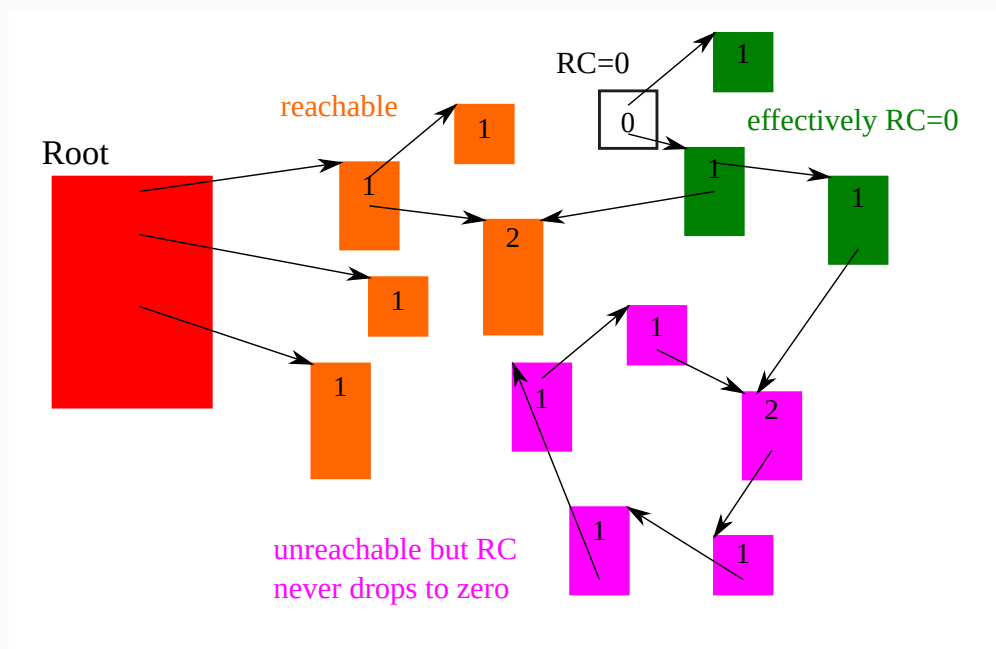
Criteria 2: memory allocation cost (details ahead)

- traversing GC:
  - ▸ determined by the ratio "reachable objects" / "unreachable (reclaimed) objects" (later)
  - ▸ an advanced technique: *generational GC*
- reference counting:
  - ▸ the cost of reclaiming an object once its RC drops to zero is small and constant
  - ▸ constant even if memory is scarce (good)

Criteria 3: pause time

- (better) reference counting $<$ traversing GC
- traversing GC:
  - ▸ stop the user program while it is traversing live objects
    - – traverse *all* live objects, *en masse*, and reclaim *all* unreached objects
  - ▸ why so? troubled if the mutator runs (= changes the graph of objects) during traversing
    - – a solution: ***incremental GC***
    - – generational GCs mitigate it too
- reference counting:
  - ▸ when an object's RC drops to zero (as a result of mutator's action), it can be reclaimed *immediately*
  - ▸ reclaim garbage as they arise

Criteria 4: mutator overhead

- (better) traversing $<$ reference counting
- reference counting has a large overhead for updating RCs
- e.g.,

```
object * p, * q;
p = q;
```

will perform:

```
if (p) p->rc--;
if (q) q->rc++;
p = q;
```

- moreover,

Criteria 4: mutator overhead

- ▸ what if it is multithreaded?
- ▸ what if the counter overflows (how to check it)?
- techniques: *deferred reference counting, sticky reference counting, 1 bit reference counting*
- remark: some traversing GCs (e.g., generational and incremental) add overhead to pointer updates too

Summary

	traversing GC	reference counting
preciseness	$+$	$-$
allocation cost	? ($*$)	?
pause time	$-$ (†)	$+$
mutator overhead	$+$ (‡)	$-$

- ($*$) depends on size of reachable graph and memory; *generational* GC helps
- (†) *incremental* GC helps
- (‡) both *generational* and *incremental* GC impose some mutator overheads
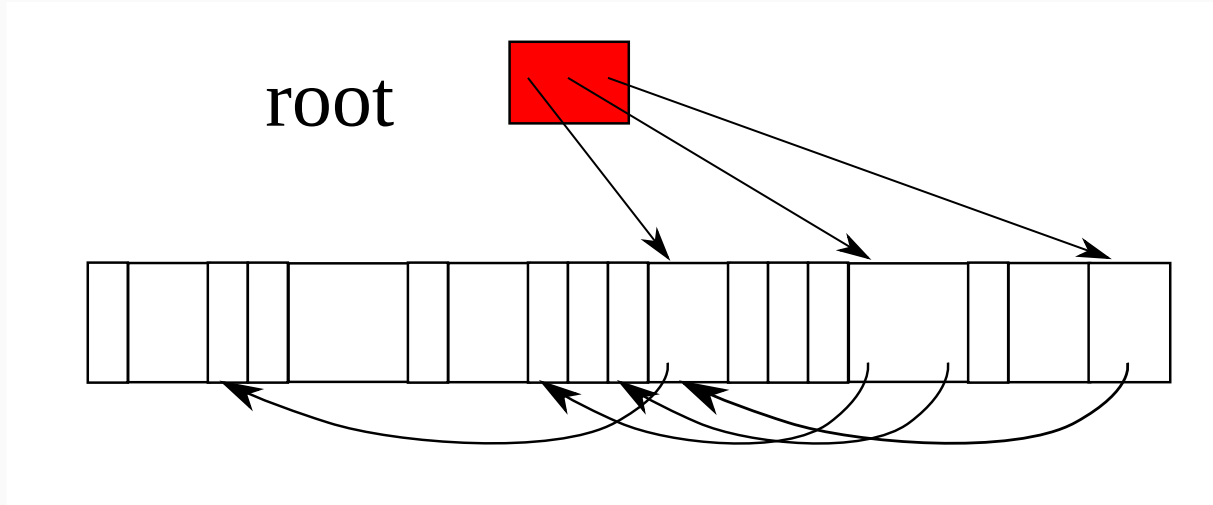
they differ in what to do on reachable objects

- mark&sweep GC: mark them as "visited"
- copying GC: copy them into a distinct (contiguous) region

Mark&sweep GC

- *mark-phase:*
  - ▸ traverses objects from the root, *marking* encountered objects as *visited*
  - ▸ maintains *mark stack*, the set of objects marked but whose children may have not been marked
- *sweep phase:*
  - ▸ reclaims all memory blocks not visited in the mark phase
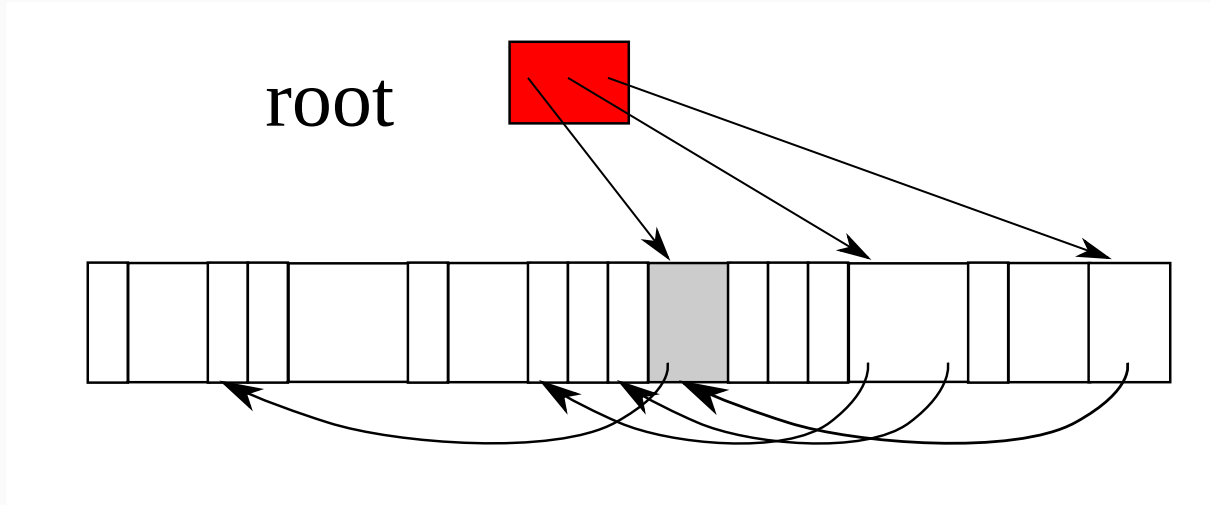 - ▸ free memory blocks are not contiguous, so must be managed by an appropriate data structure **(*free lists*)**

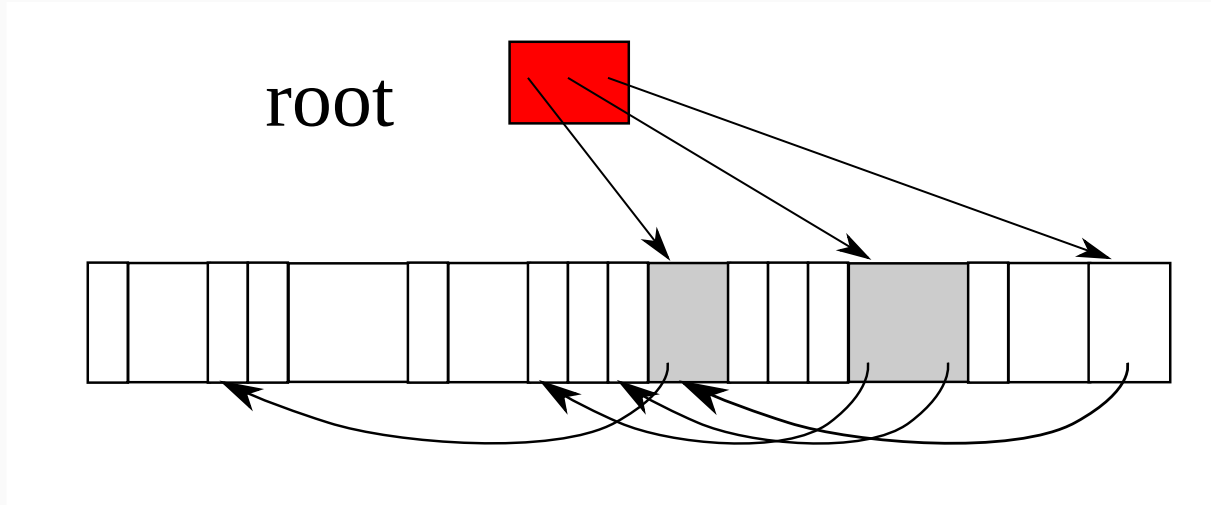- mark stack (not shown in the figure) = light gray objects

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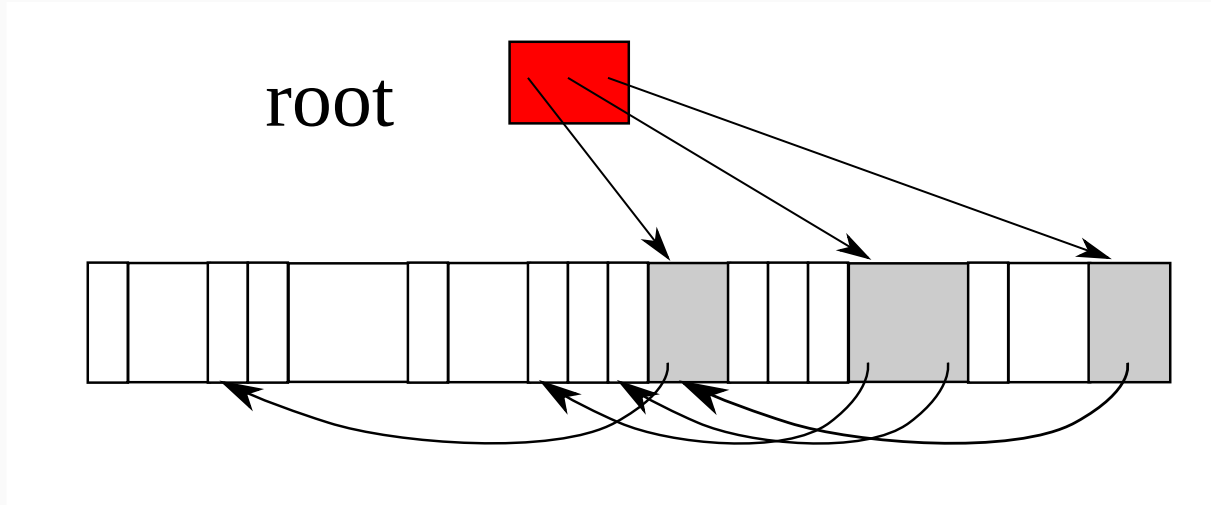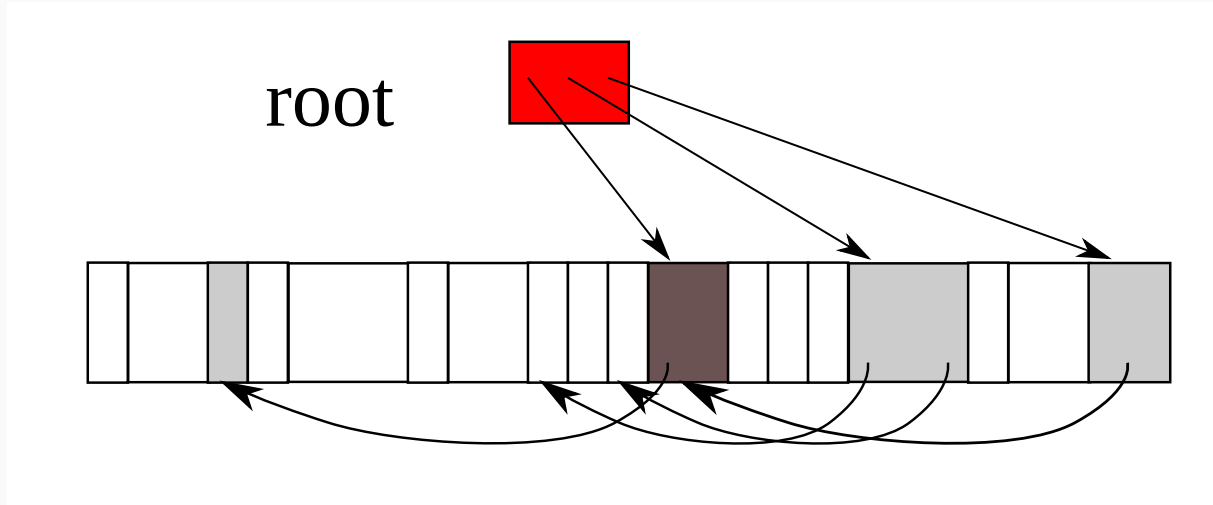- mark stack (not shown in the figure) = light gray objects

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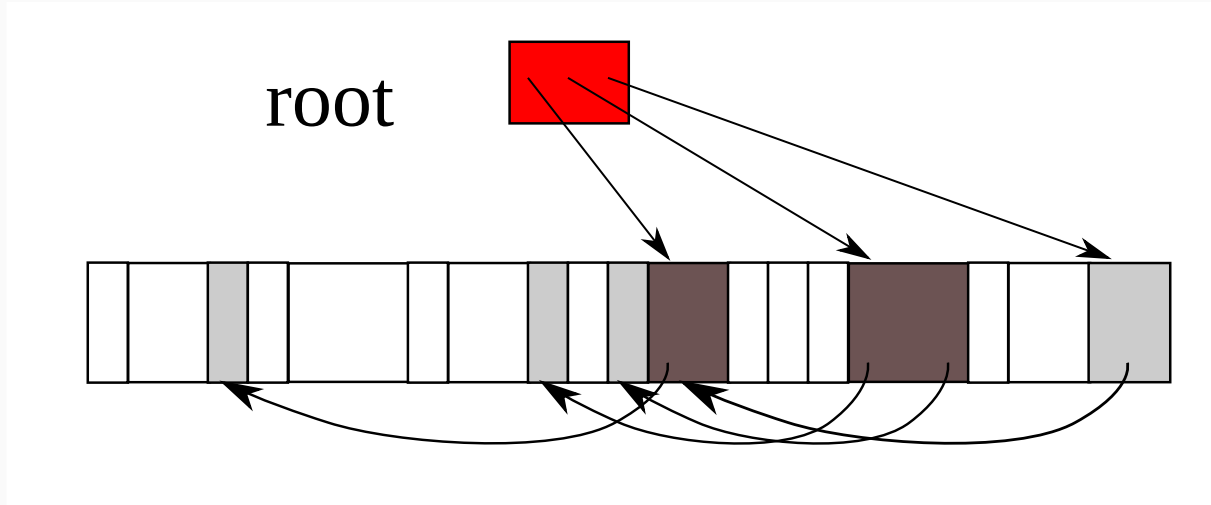- mark stack (not shown in the figure) = light gray objects

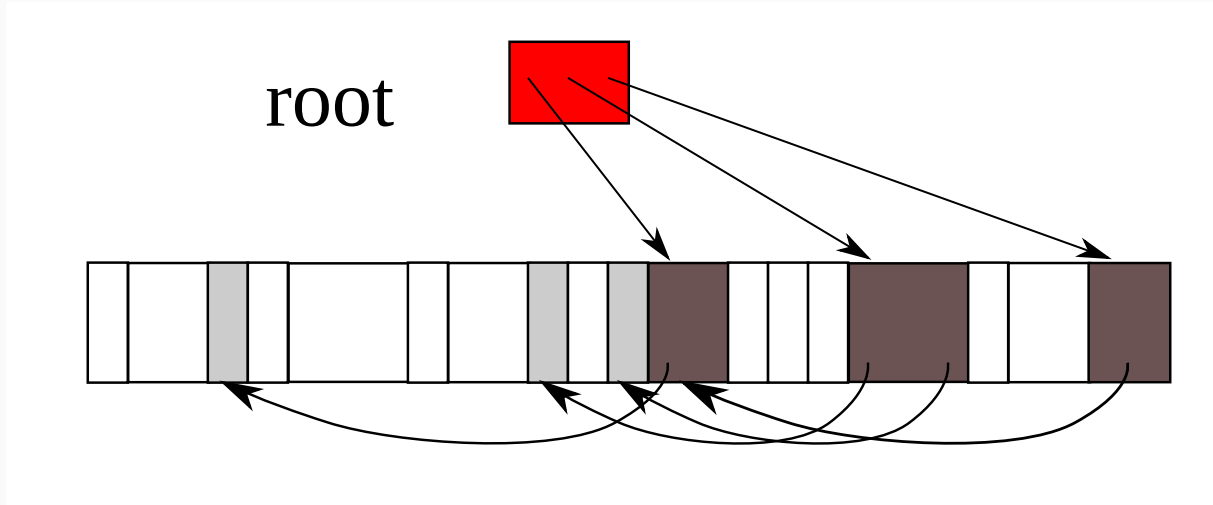- mark stack (not shown in the figure) = light gray objects

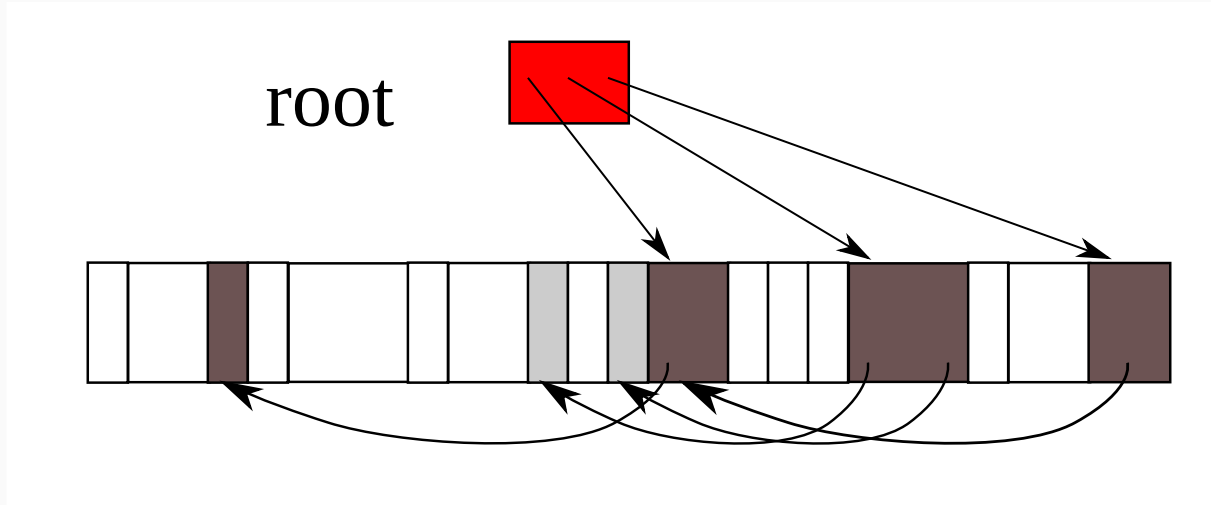- mark stack (not shown in the figure) = light gray objects

Copying GC

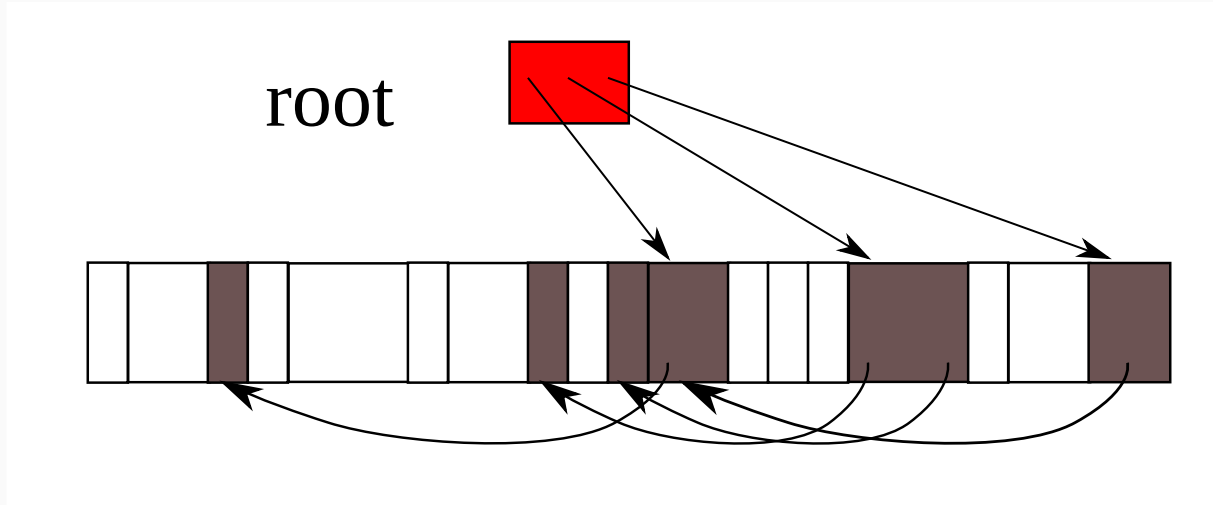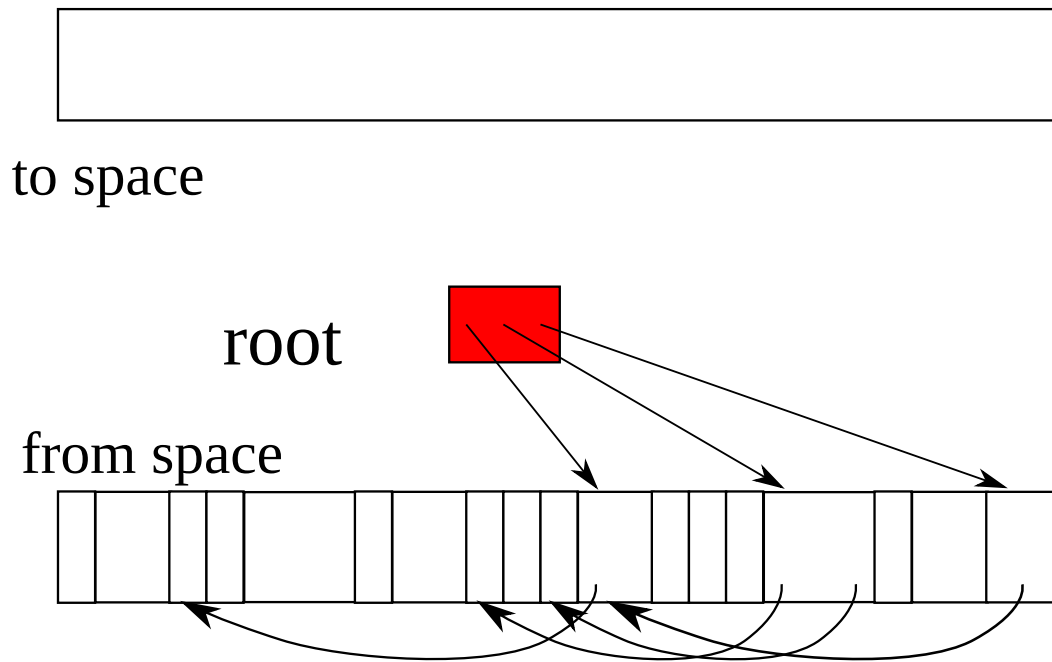- $\approx$ copying a graph (possibly with merges and cycles)
- the crux : *pointers to the same object must remain the same after copy*
- ***semi-space GC:*** splits the available memory into equal-sized two spaces
  - ‣ when one space fills up, copy all reachable objects to the other

```
void *free, *scan;
void copy_gc() {
 free = scan = to_space;
 redirect_ptrs(root);
 while (scan < free) {
  redirect_ptrs(scan);
  scan += the size of object scan points to;
 }
 swap to_space and from_space;
}
void redirect_ptrs(void * o) {
 for (f : pointer fields of o) {
  if ([o->f] has been copied) {
   o->f = [o->f]'s forward pointer;
  } else {
   copy [o->f] to to free;
   [o->f]'s forward pointer = free;
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 } } }
```

- [p] is the object p points to (at address p)

Simi-space copying GC in action

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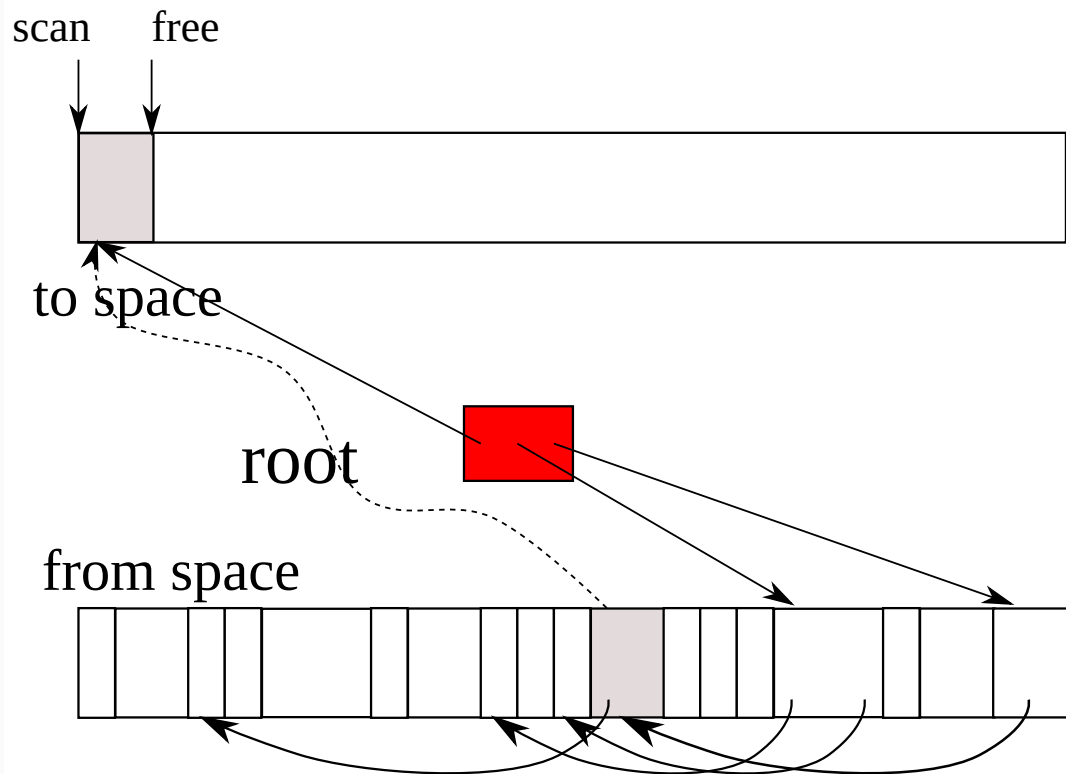
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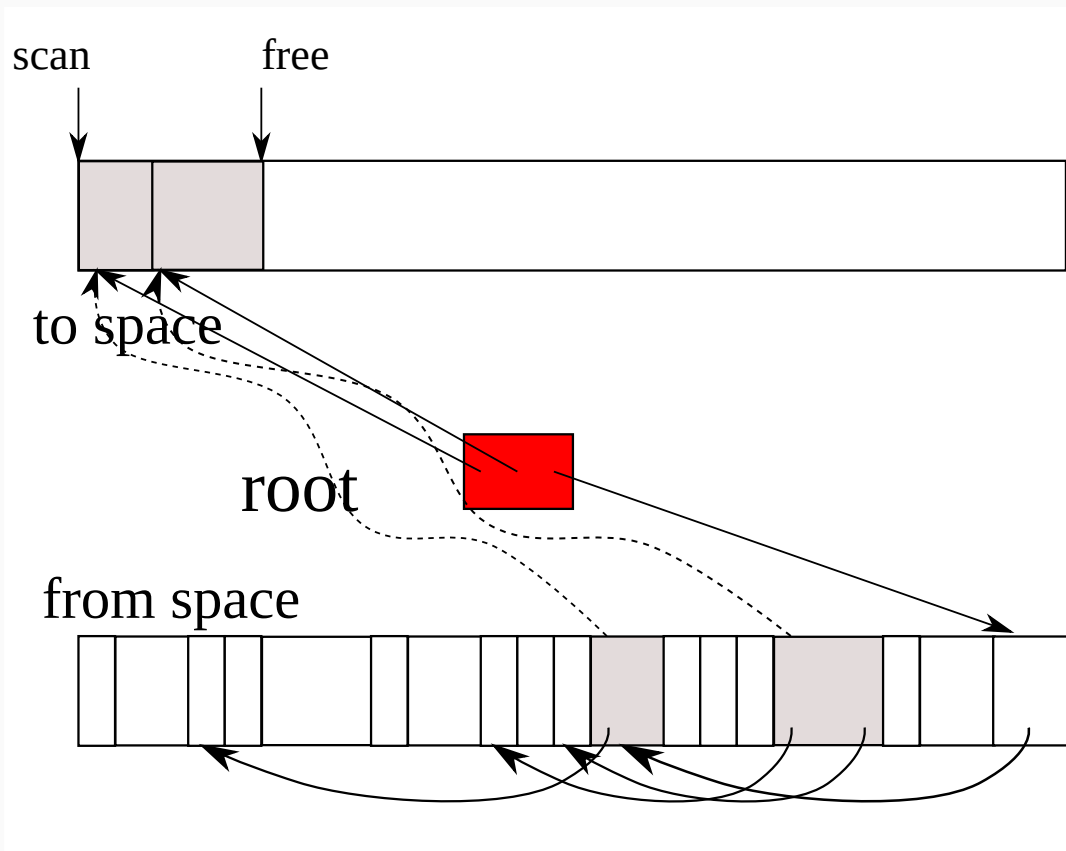- [p] is the object p points to (at address p)

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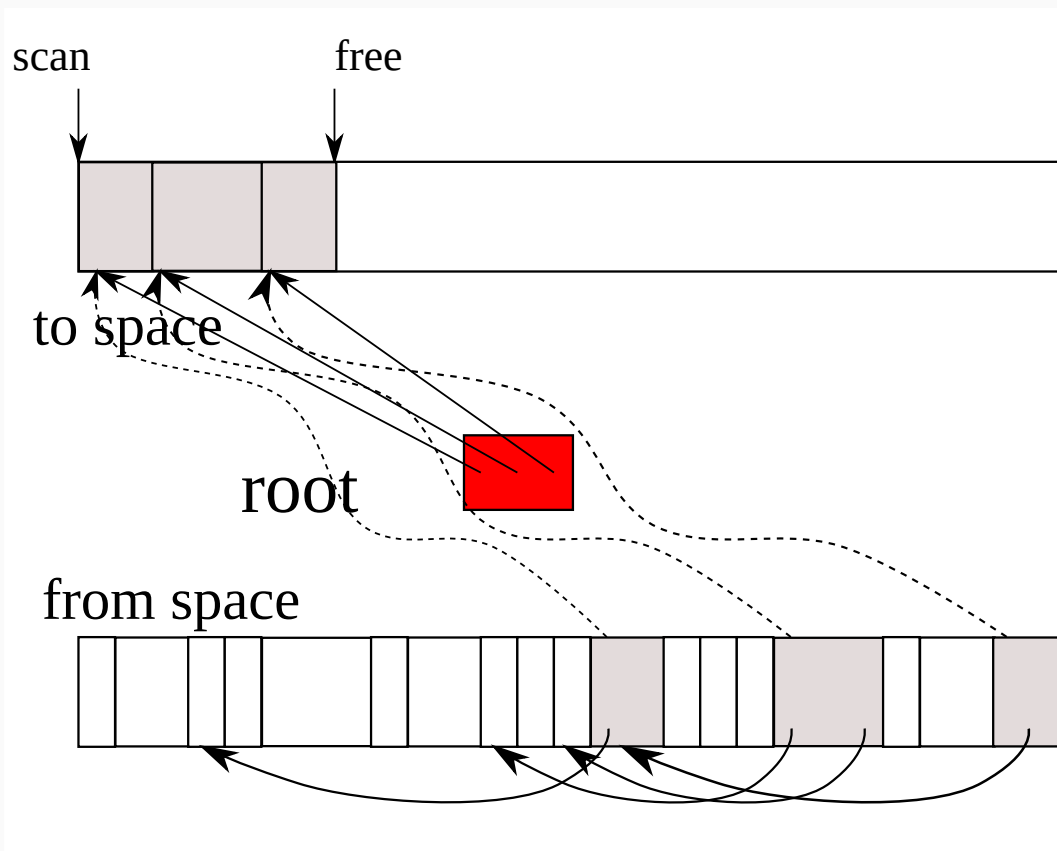
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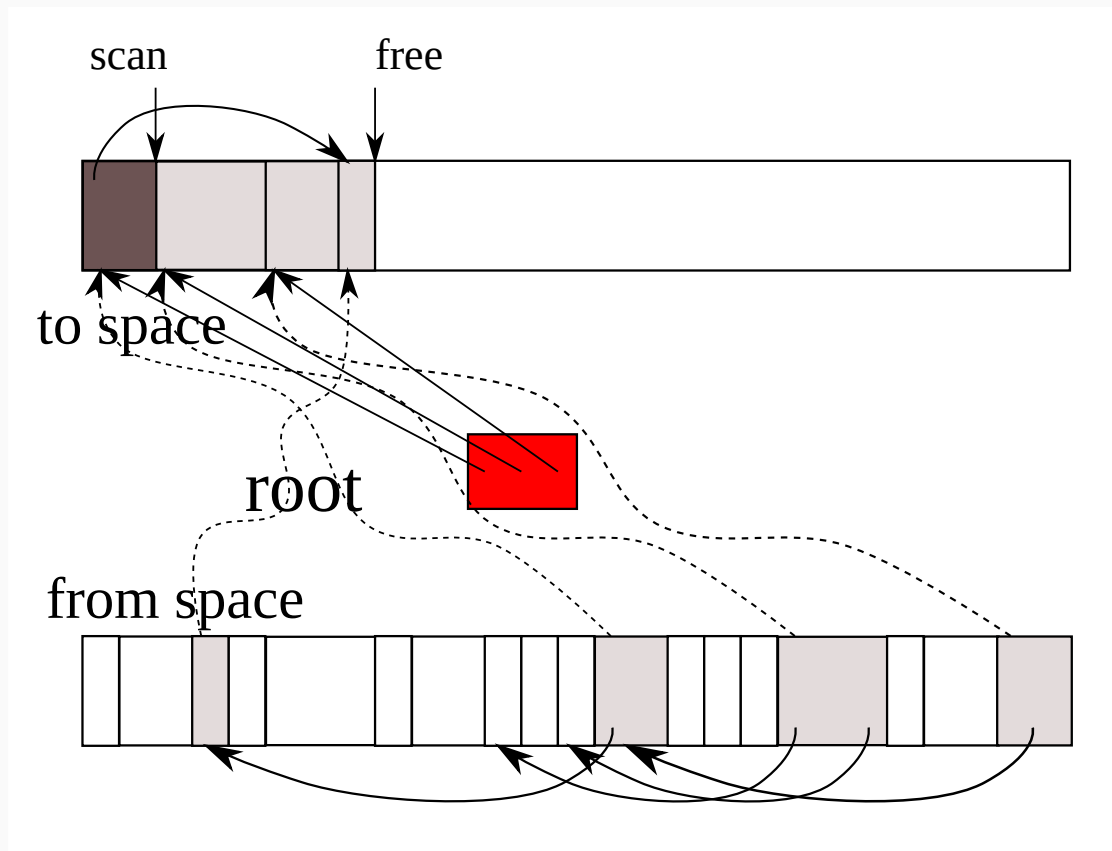
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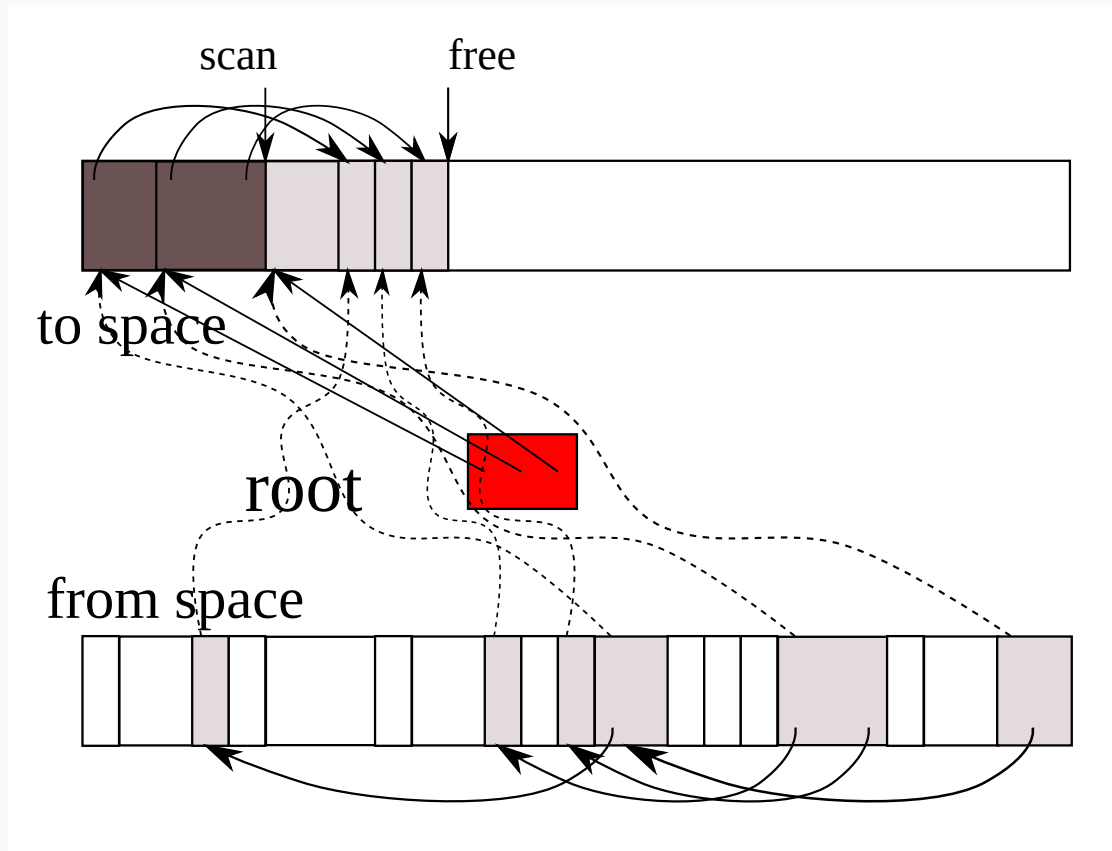

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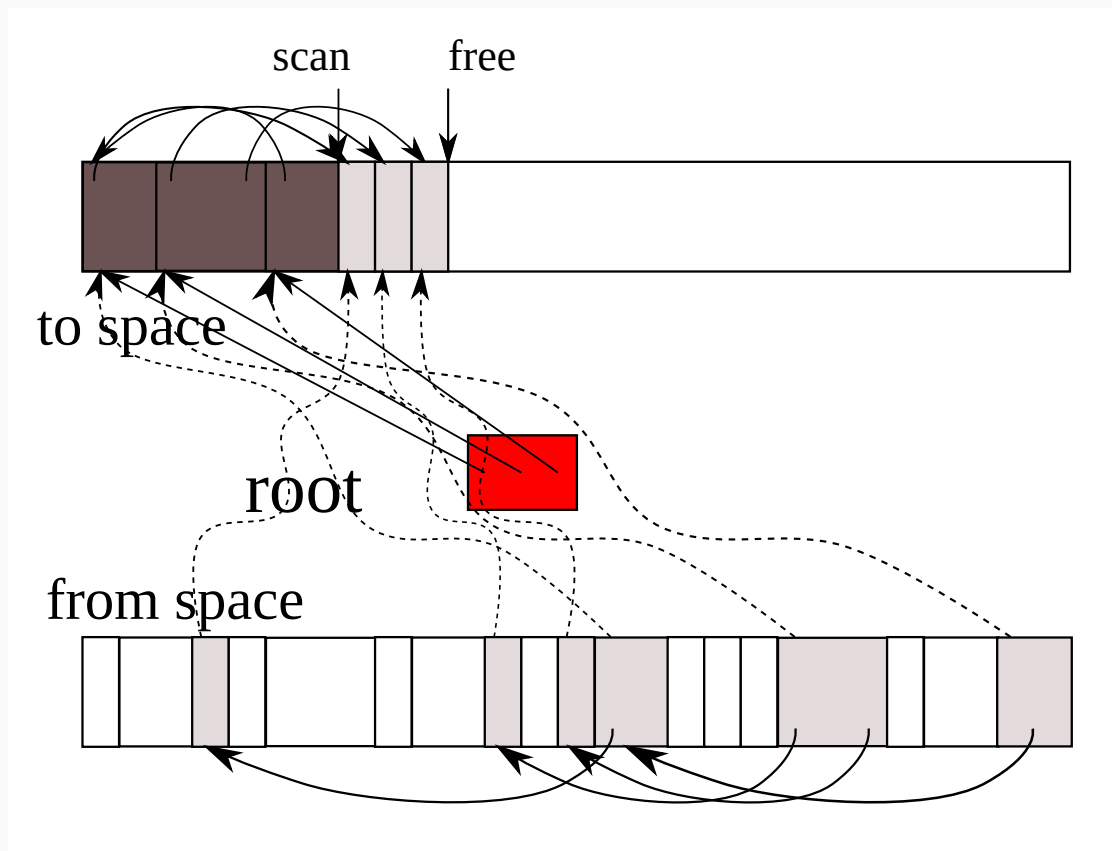
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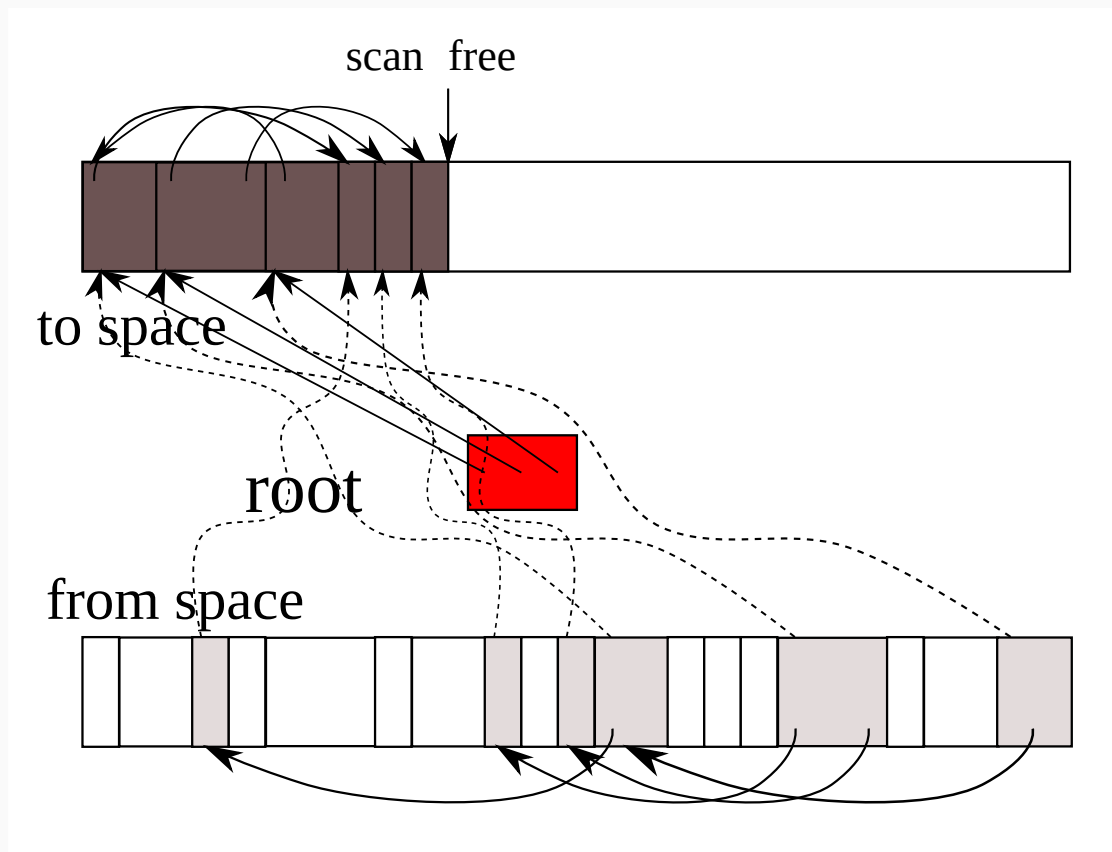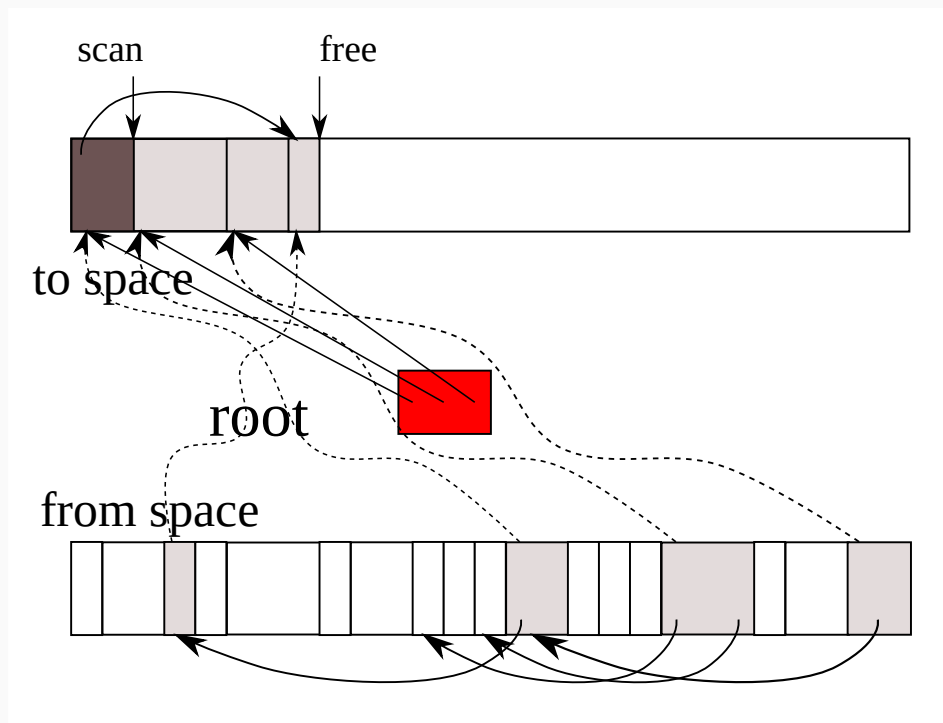

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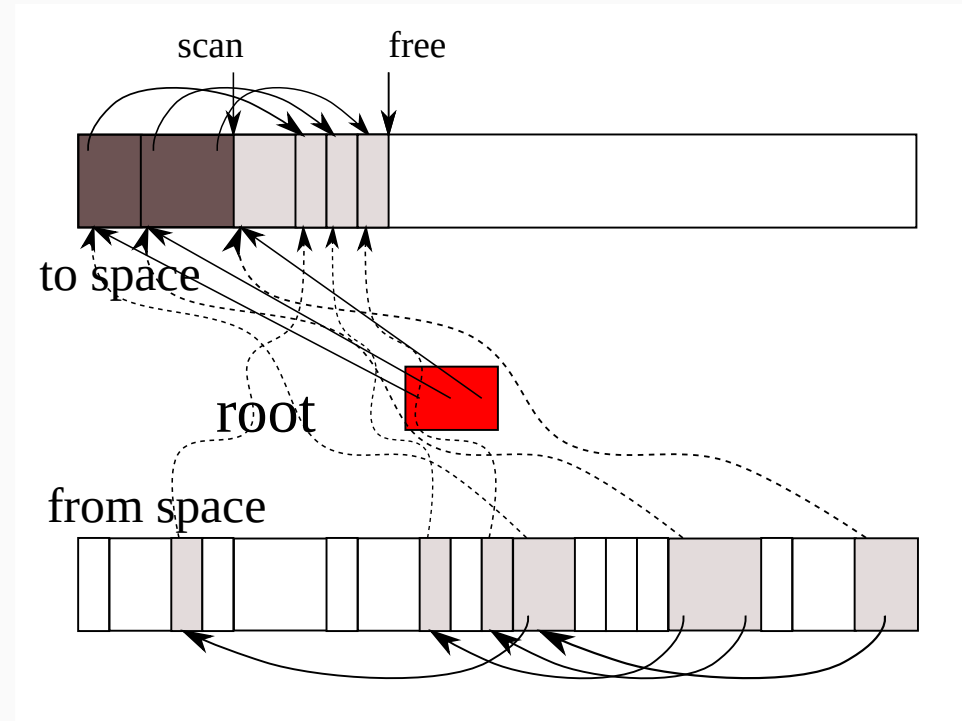
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Mark&sweep vs. copying GC

- copying GC pros:
  - ‣ live objects occupy a contiguous region after a GC
  - ‣ $\rightarrow$ the free region becomes contiguous too
  - ‣ $\rightarrow$ *the overhead for memory allocation is small* (no need to "search" the free region)

Mark&sweep vs. copying GC

- copying GC cons:
  - ▸ *copying is more expensive than marking*, obviously
  - ▸ *the free region must be reserved* to accommodate objects copied (low memory utilization)
    - – must ensure "size of objects that may be copied" $\leq$ "size of the region to copy them into"
    - – $\rightarrow$ "from space" = "to space" (semi-space)
  - ▸ pointers must be "precisely" distinguished from non-pointers (*ambiguous pointers are not allowed*)
    - – ∵ pointers are updated to the destinations of copies
    - – a disaster occurs if you update non-pointers