Programming Language (7)
Garbage Collection

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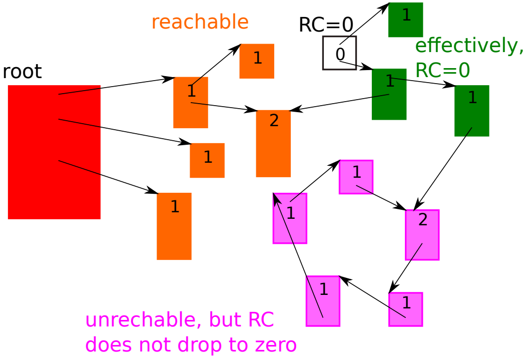
Evaluating GCs

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

Criteria #1: preciseness

- *reference counting cannot reclaim cyclic garbage*
- reference count < traversing GC (traversing GC is better)



Criteria #2: memory allocation cost

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  - *the cost is determined by the ratio "reachable objects" / "unreachable (reclaimed) objects"* (later)
  - totally depending on apps and memory size, it can be anywhere from the minimum to infinity
  - an advanced technique: generational GC

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  - totally depending on apps and memory size, it can be anywhere from the minimum to infinity
  - an advanced technique: generational GC
- reference counting:
  - the cost of reclaiming an object once its RC drop to zero is small and constant
  - it is constant even if memory is scarce (good)

Criteria #3: pause time

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  - why so? troubled if the mutator runs (= changes the graph of objects) during traversing
    - a solution: incremental GC
    - generational GCs mitigate it too

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  - 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

- traversing < reference counting (traversing GC is better)
- reference counting has a large overhead for updating RCs

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

will do:

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

Moreover,

  - what about multithreaded programs?
  - 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	reference counting
preciseness	$+$	$-$
allocation cost	? $(*)$	$+$
pause time	$-$ $(\dagger)$	$+$
mutator overhead	$+$ $(\ddagger)$	$-$

$(*)$ depends on size of reachable graph and memory; generational garbage collector helps

$(\dagger)$ incremental garbage collector helps

$(\ddagger)$ both generational and incremental garbage collectors impose some mutator overheads

Contents

mark&sweep GC vs. copying GC

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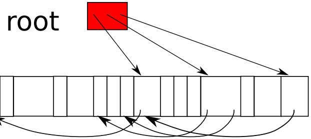
mark&sweep GC vs. copying GC

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

1. mark-phase:
   - traverses objects from the root, *marking* objects it encounters
   - maintains *mark stack (not shown in the figure)*, marked objects whose children may have not been marked (= light gray objects)
2. sweep phase:
   - reclaims all memory blocks that were not visited
   - free memory blocks are not contiguous, so must be managed by an appropriate data structure *(free lists)*



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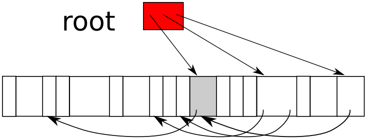

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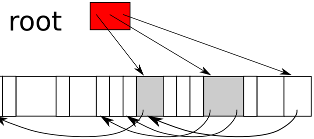

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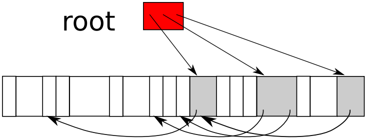

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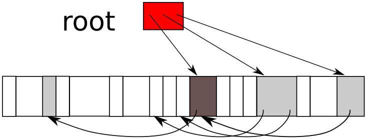

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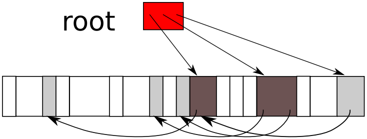

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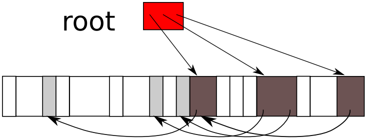

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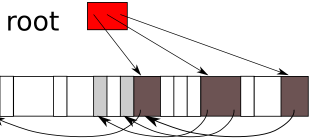

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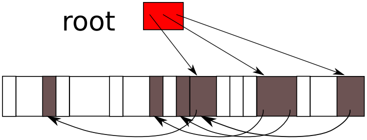
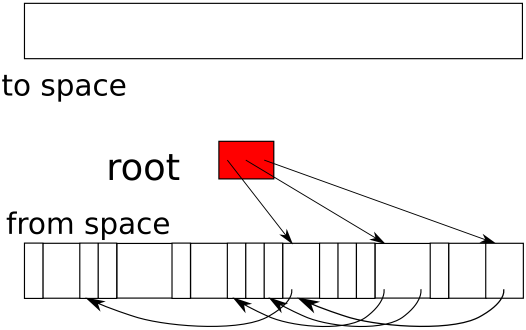


Copying GC

- in essence, ≈ copying a graph (≈ serialization)
  - the same pointers must remain the same after the copy
- semi-space GC (copy all objects reachable from the root into another space)



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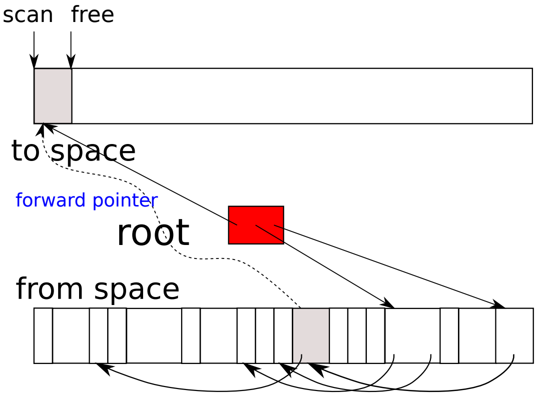

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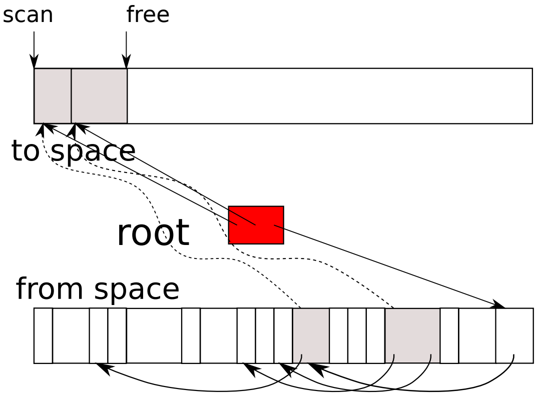

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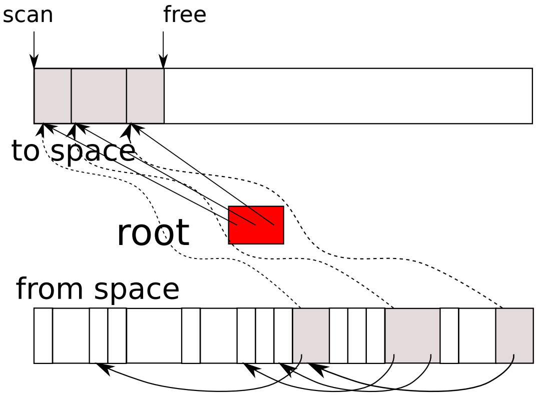

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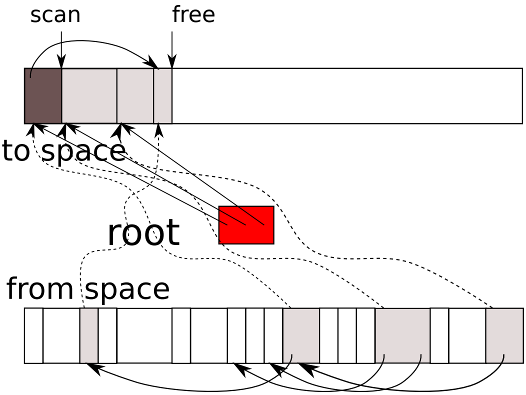

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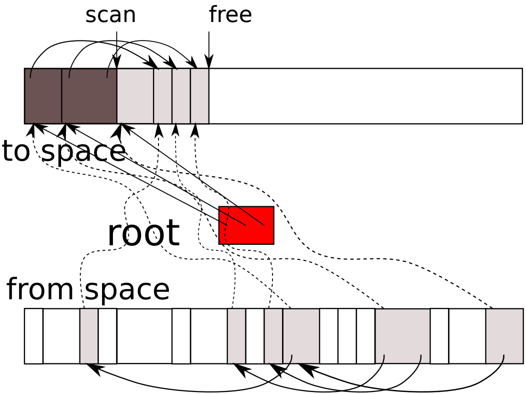

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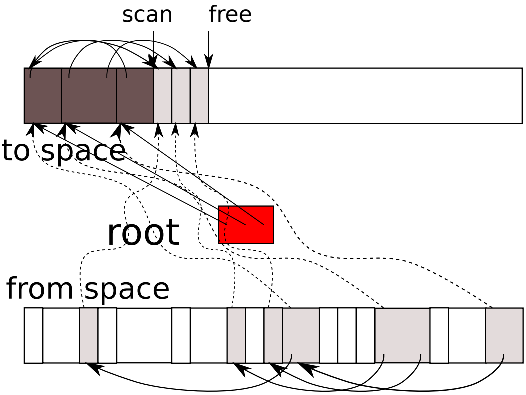

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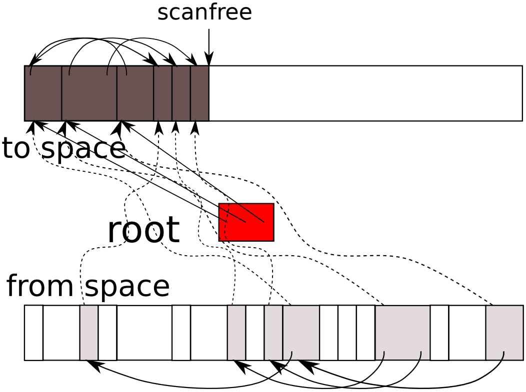

Copying GC: algorithm

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void *free, *scan;
copy_gc() {
  free = scan = to_space;
  redirect_ptrs(root);
  while (scan < free) {
    redirect_ptrs(scan);
    scan += the size of object scan points to;
  }
}
redirect_ptrs(void * o) {
  for (p ∈ pointers in o) {
    if (p has been copied) {
      p = p's forward pointer;
    } else {
      copy p to free;
      p = free;
      p's forward pointer = free;
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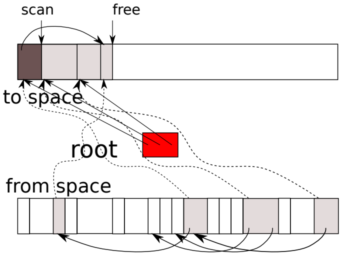
invariant

- $p <$ `scan` $\Rightarrow p$ has been reached; so has its direct children
- $p <$ `free` $\Rightarrow p$ has been reached; but its children may not



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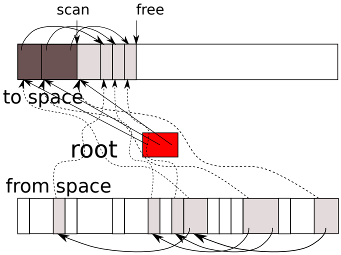


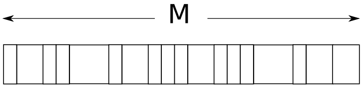
Mark&sweep vs. copying GC

- copying GC pros:
  - live objects occupy a contiguous region after a GC
  - → the free region becomes contiguous too
  - → the overhead for memory allocation is small (no need to "search" the free region)
- copying GC cons:
  - copy is expensive, obviously
  - the free region must be reserved to accommodate objects copied (low memory utilization)
    - must ensure "size of objects that may be copied" ≤ "size of the region to copy them into"
    - → "from space" = "to 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

Contents

Memory allocation cost of traversing GCs

- let's quantify the cost of allocating a byte including GC's work
- assume:
  - heap size (size of a semi-space in case of copying GC) = M
  - reached objects = r
  - assume for the sake of argument it's *always* r



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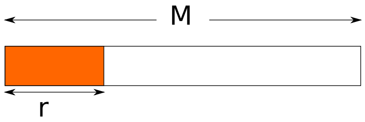

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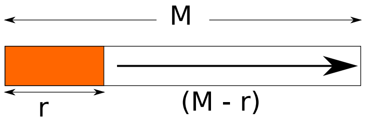

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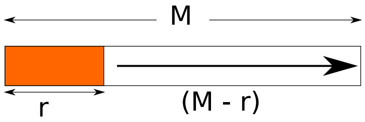
- a key observation

  the time (cost) of a single GC is roughly proportional to the amount of reached objects (i.e., $\propto r$)



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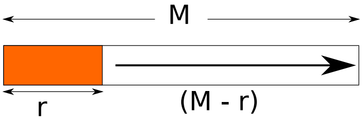

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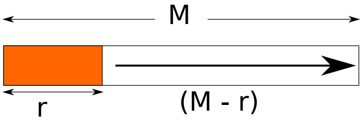
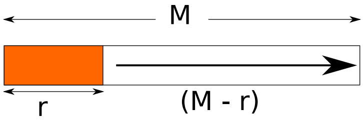


$\therefore$ the cost of allocating a byte

Memory allocation cost of traversing GCs



$$
\begin{aligned}
\therefore \quad & \text{the cost of allocating a byte} \\
= \quad & \alpha + \frac{\text{the amount of time spent on a GC}}{\text{the amount of space reclaimed by a GC}}
\end{aligned}
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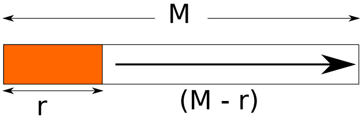
- α : a constant cost needed anyway, even if you don't need to reclaim memory at all

Memory allocation cost of traversing GCs



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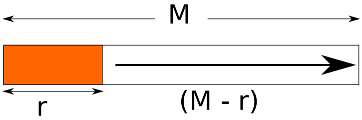

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= & \quad \alpha + \beta \frac{\text{the amount of space visited by a GC}}{\text{the amount of space reclaimed by a GC}} \\
= & \quad \alpha + \beta \frac{r}{M - r}
\end{aligned}
$$

- α : a constant cost needed anyway, even if you don't need to reclaim memory at all
- β : an average cost to examine a single byte
  - copy it (in a copying GC)
  - see if it is a pointer to an unvisited object

Note on copying GC vs mark-sweep GC

- the key observation

  the time (cost) of a single GC is roughly proportional to the amount of reached objects (i.e., $\propto r$)

  ignores the cost of so-called "sweep phase"
- a more accurate quantification will be

$$\text{the time (cost) of a single GC} \approx \beta r + \gamma(M - r),$$

  which adds a constant (γ) to an allocation cost per byte, which any memory allocator will incur anyway
- i.e., the cost will be

$$\begin{aligned} & \alpha + \frac{\beta r + \gamma(M - r)}{M - r} \\ = \; & \alpha + \gamma + \beta \frac{r}{M - r} \end{aligned}$$

Memory allocation cost of traversing GCs

- important formula:

$$\text{allocation cost per byte} \propto \text{const.} + \frac{r}{M - r}$$

- $r/(M-1)$ is often called *mark-cons ratio*. its origin:
  - mark : the amount of work to *mark* reachable objects
  - cons : the synonym of memory allocation in the ancient Lisp language =`(cons x y)`

Memory allocation cost of traversing GCs

$$\text{cost per byte} \propto \text{const.} + \frac{r}{M - r}$$

- r (primarily) depends only on app (not dependent of GCs)
  - remark: r may fluctuate depending on "when" GCs occur
- M is an adjustable parameter (up to GC's choice)
- M is large $\rightarrow$ the cost is small
- $\rightarrow$ you can reduce the cost by making M (memory usage) larger
- may sound obvious, but remember that what is important is the cost *per allocation (byte)*, not the frequency of GCs

How large do we make M (memory usage)?

- alright, the larger we make M, the smaller the cost becomes
  - $\rightarrow$ why don't we make it arbitrarily large (up to physical memory)?
- we normally set M "modestly", like:

  $$M \propto r$$

  e.g., choose a constant $k > 1$ and set:

  $$M = kr$$

- a GC measures the amount of reachable objects to get r and set M according to the above formula

How large do we make M (memory usage)?

- in this setting,
  - cost:

$$\text{mark-cons ratio} = \frac{r}{kr - r} = \frac{1}{k-1}$$

  - memory usage

$$\propto \text{the size of reachable objects at a point during execution}$$

  both are "reasonable"
- most GCs allow you to set k (or M directly)
- normally, $k = 1.5 \sim 2$, but it is worth knowing that you can reduce the cost by setting it large

Contents

Generational GC: introduction

- objective: reduce *mark-cons ratio* in traversing GCs
- how: traverse and reclaim only *recently created objects (young generation)*
  - traverse only young generations often
  - traverse the entire heap occasionally when it does not reclaim enough space
- why does it work?

mark-cons ratio (review)

$$\begin{aligned} & \text{GC overhead} \\ \equiv\ & \text{GC's work per allocating a byte} \end{aligned}$$

mark-cons ratio (review)

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\begin{aligned}
& \text{GC overhead} \\
\equiv\ & \text{GC's work per allocating a byte} \\
=\ & \frac{\text{GC's work}}{\text{memory allocated}}
\end{aligned}
$$

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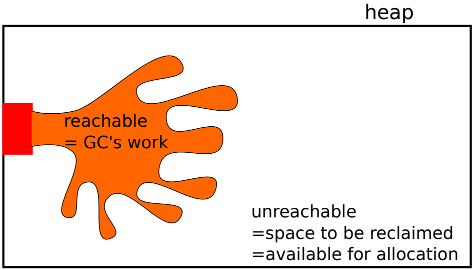
- *the less reachable space there are, the smaller it becomes*
- below, we simply say an object is "alive" when it is "reachable from the root" (strictly, not a correct usage)

Generational GC: the basic idea

- basic idea: traverse (collect) only *a region that has a lesser live object ratio*



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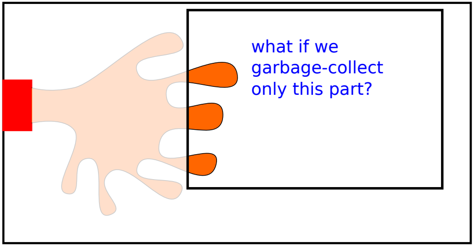

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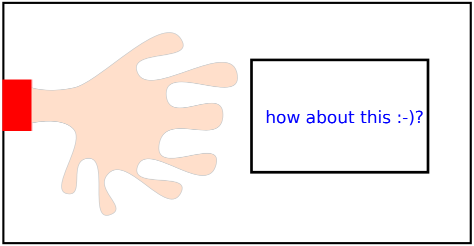

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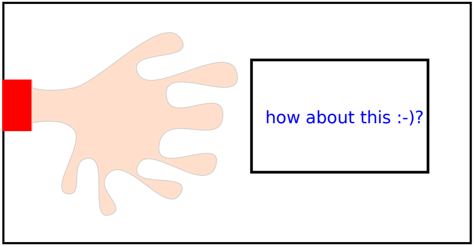

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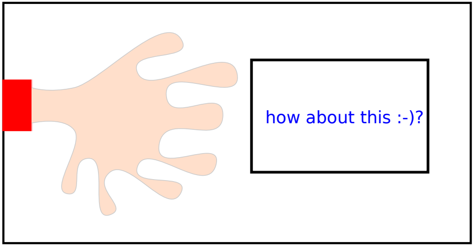

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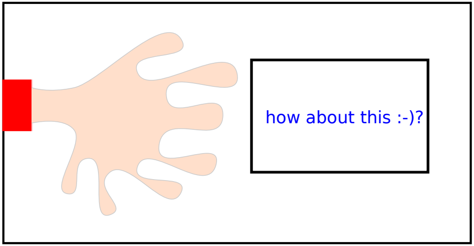

- two problems:
  1. where to target: *which region has a lesser live object ratio?*
  2. correctness: how to find all live objects in a region, *by traversing "only" that region?*

Problem 1: where generational GC targets

a region holding young (recently created) objects

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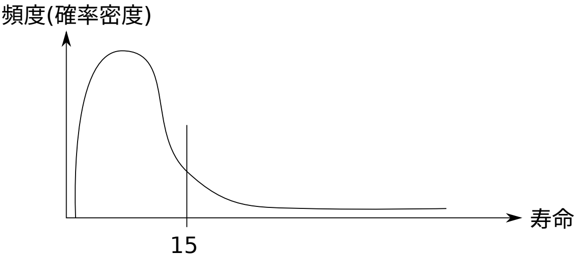
a region holding young (recently created) objects

Q: why (or when) is this effective?

(Weak) generational hypothesis

- *"most objects die young"*
- it seems to hold in most languages (where all memory allocations are served from the heap)



Studies on (weak) generational hypothesis

- studies show *"a (large) fraction d of objects die before a (young) age y"* in various languages
  - note: an "age" of an object o = the total size of memory allocated after o is created (that is, *the time is measured by the amount of memory allocation*)

authors	lang.	mortality rate (d)	age (y)
Zorn	Common Lisp	50-90%	10KB
Sanson and Jones	Haskell	75-95%	10KB
Hayes	Cedar	99%	721KB
Appel	SML/NJ	98%	varies
Barret and Zorn	C	50%	10KB
	C	90%	32KB

source: Richard Jones and Rafael Lins. "Garbage Collection. Algorithms for Automatic Memory Management" Chapter 7.1

“most objects die young” and a rational of generational GCs

- say 90% die younger than 10KB, then

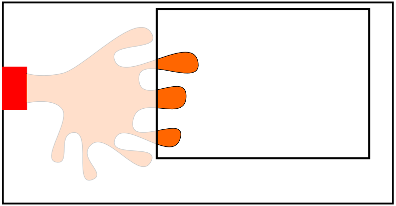
  mark-cons ratio when traversing most recent 10KB ≈ 0.1

- if we use heap 2-3 times larger than the live objects,

  the ratio when traversing the entire heap $\approx 1/3 \sim 1/2 > 0.1$

Problem 2: how to make it correct?

- we need to find all young objects reachable from the root, through "*all pointers, young or old*"
- simply ignoring old objects won't work



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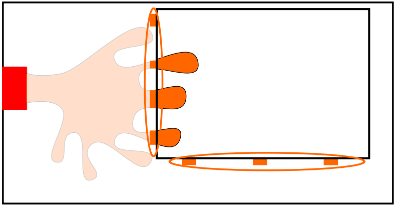

- solution: *record "all" pointers from "old → young"* during the execution and consider them as part of the root

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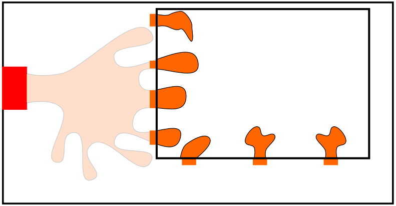


- solution: *record "all" pointers from "old → young"* during the execution and consider them as part of the root
- note: some may not be reclaimed, despite being unreachable from the root

Write barrier

- an intervention in mutator actions to capture all "old $\to$ young" pointers
- mutator actions that need an intervention: assignments:

(possibly) old object's field $\leftarrow$ (possibly) young object

- in OCaml,

expression	description	need intervention?
`o.x <- a`	update a mutable field	yes
`{ x = ...; ...}`	create a record etc.	no
`let b = o.x`	initialize a variable	no

- hopefully they rarely occur in "mostly functional" languages

Implementing Write Barrier (1) Remembered Set

- given

```
o.x <- a;
```

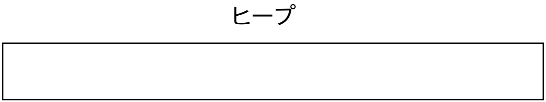
we do

```
if (generation(a) < generation(o)) {
  if (o ∉ R) add(R, o)
}
```

- the overhead is large
  - obtain **generation(·)** (address comparison in copying GC)
  - check if `o` $\in$ `R`
  - manage `R`

Implementing Write Barrier (2) Card Marking

- basic idea: unconditionally record addresses pointers are written to
- partition the heap into constant-sized "cards"
  - a card: a region whose addresses share a number of most significant bits
    - e.g., share the highest 57 of 64 bit addresses
    - $\rightarrow$ a single card $2^7 = 128$ bytes



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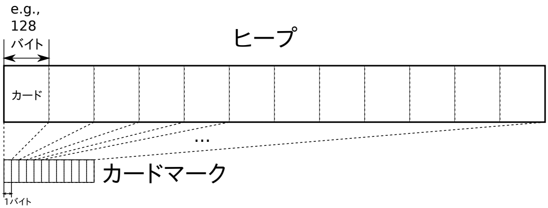

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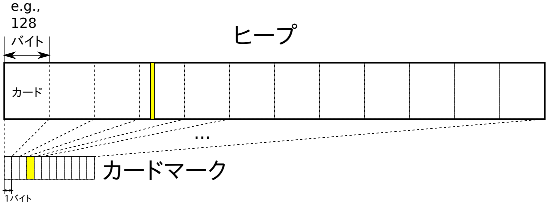


- record only whether each card receives any pointer write (1 byte/card; card mark)

The overhead of card-marking

- e.g.: given the following pointer update,

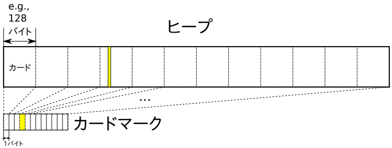
```
o->x <- y;
```

unconditionally record "a card containing `&o->x` is written"

```
C[(&o->x) >> 9] = 1;
```

C is the base address to obtain the card address. that is,

```
C[heap >> 9] == card
```



Card-marking : Pros and Cons

- a small write barrier overhead (if you hold C in a register, it takes three RISC instructions)

```
C[(&o->x) >> 9] = 1;
```

- memory overhead adjustable by adjusting card size (e.g. a card is 128 bytes $\rightarrow$ 1/128)
- you cannot efficiently list written cards; you must check all cards ($\propto$ heap)
- when any address of a card is written, we must consider all addresses of the card a root

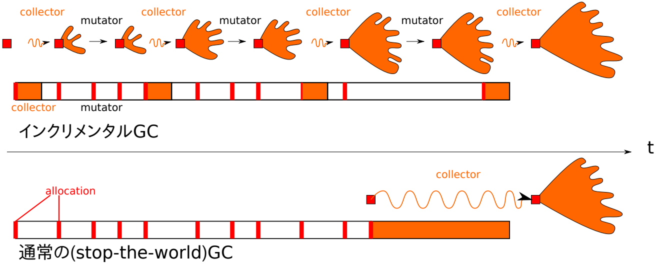
Contents

Incremental GC

- objective: *reduce the "pause time"* of traversing GC
  - good for applications that need real time or interactive responses
- recall that pause time $\approx$ time to traverse all reachable objects

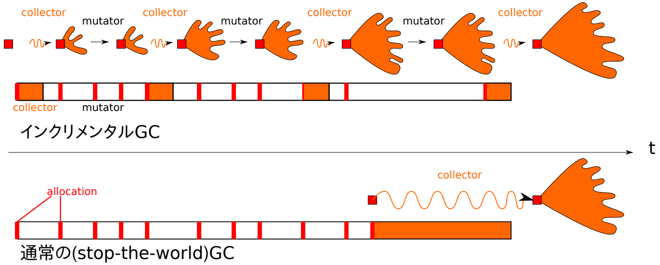
Incremental GC

- objective: *reduce the "pause time"* of traversing GC
  - good for applications that need real time or interactive responses
- recall that pause time ≈ time to traverse all reachable objects
- how: by traversing reachable objects *"a little bit at a time"*
  - instead of traversing 1 GB in one stroke, traverse 10 MB at a time, 100 times



Challenges in incremental GC

- (from GC's view point) *the object graph changes while GC is traversing it*



- how to guarantee it does not miss any reachable object?
- ⇒ we'll get back to the basics of graph traversal

Assumptions for later discussions

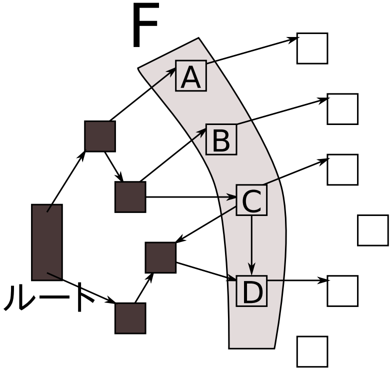
- only a single mutator (the app is single-threaded)
- the mutator and the collector run *"alternately" (not at the same time)*
  - the collector does a little bit of its work upon a memory allocation
- i.e., we do not consider race conditions that would happen when they are truly concurrent

Graph traversal : basics

- traversing GC ≈ graph traversal
- the principle is the same whether it's mark&sweep or copying

- omitting details, it is:

```
F = { root };
while (F is not empty) {
  o = pop(F);
  for (all pointers p in o)
    if (!marked(p)) {
      mark(p);
      add(F, p);
    }
}
```



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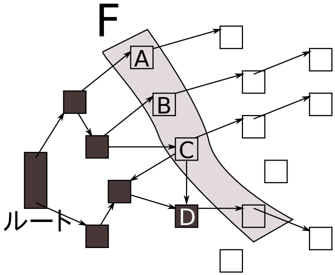
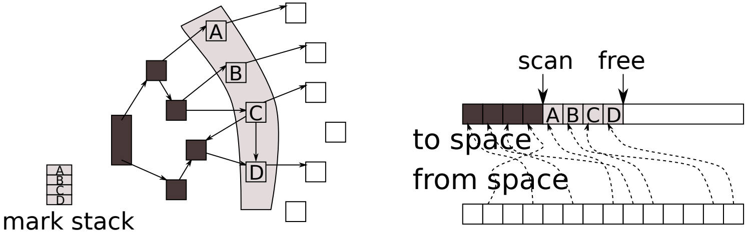


Key data : the frontier

- F : frontier
- the set of objects that have been visited but whose children may have not
- the actual data structure
  - mark&sweep : mark stack
  - copying : a part of the to space



mark&sweep copying

The issue that an incremental GC must address

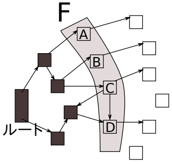
```
F = { root };
while (F is not empty) {
  o = pop(F);
  for (all pointers p in o)
    if (!marked(p)) {
      mark(p);
      add(F, p);
    }
  if (has iterated a few times)
    // the graph changes below
    resume_mutator();
}
```

- ordinary GC: the while loop runs until the end keeping the mutator stopped → the object graph does not change during the loop
- incremental GC:
  - *the collector gets interrupted by the mutator every once in a while*
  - … and continues after a while
  - that is, the issues is how to do with the fact that *the graph may change between iterations of the while loop*

The tri-color abstraction

- likens a graph traversal to coloring its nodes
- visiting an object ≈ coloring an object
  - black: the object and its children have been visited
  - gray: it has been visited but its children may not
  - white: it has not been visited
- the graph traversal using the tri-color abstraction

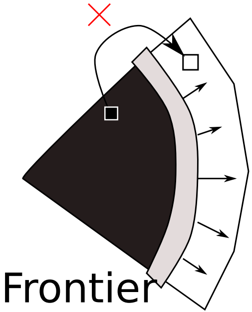
```
gray the root;
while (there is a gray object) {
  o = pick a gray object and blacken it;
  for (all pointers in o)
    if (p points to a white object)
      gray it;
  the mutator changes the graph;  }
```



- correctness of the algorithm: *when there are no gray objects, all objects reachable from the root are black (i.e., white objects are unreachable)*

A problematic mutation to the graph

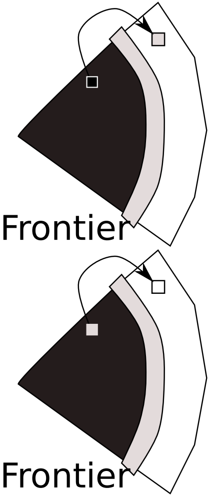
- intuitively, *the issue seems the mutator may create "black → white" pointers*
  - black: GC thinks it has "done" with it
  - white: going to be reclaimed, unless found in other paths
- ⇒ prevent "black → white pointers" from being created



Two approaches to preventing black→white

capture the point where " black → white " is about to be created

1. approach #1: gray the white (make black → gray)
   - pros: the frontier always progresses
   - pros: easier to work with for copying GCs
   - cons: reclaim less objects. if p becomes unreachable due to another update to o, it won't be reclaimed (by the current GC)
2. approach #2: get the black back to gray (make gray → white)
   - pros: reclaim more objects
   - cons: the frontier retreats



Mutator actions that need to be captured

naively all pointer movements must be captured

- write a pointer into an object field (write barrier)

```
o->x = p
```

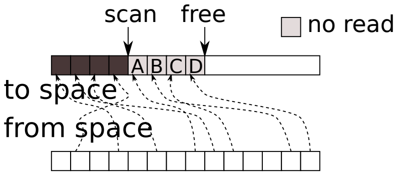
- write a pointer into a root ≡ write a pointer to a variable (read barrier)

```
p = o->x
```

the latter is so frequent that some approaches avoid them (example #2: Boehm GC)

Example #1: Appel-Ellis-Li

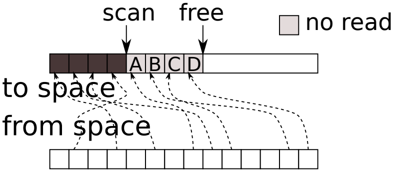
- copying GC + incremental
- based on the approach # 1. more precisely, maintain the following invariant
  the mutator never sees a pointer to white
- how?
  - intervene in reading a field from gray objects (read barrier)
- read-protect the region of gray objects ⊂ scan ∼ free, by the virtual memory primitive of operating systems



Appel-Ellis-Li : the read barrier in action

- when a field of a gray object is read, blacken objects in the page containing it (= scan those objects → they become gray)

```
trap_read_from_grey(a) {
  page = the page including a;
  for (all objects o in the page) {
    scan(o); // copy o's children
  }
  unprotect(page);
}
```



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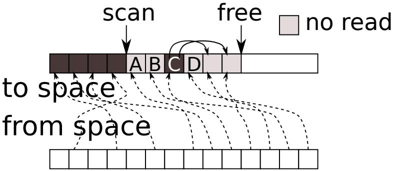
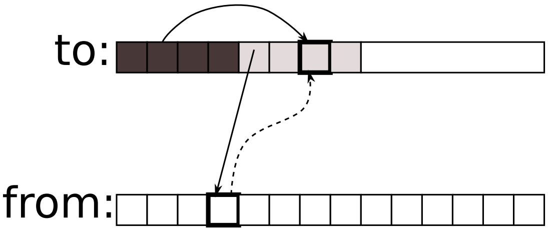


Remark : it's easier for copying GC

- during a copying GC, there are two versions of each visited object (one in the from space and the other in the to space)
- immutable objects do not care which one the mutator sees, but mutable ones do
- it will eventually see the one in to space anyways, so it's natural to maintain "it never sees the one in the from space"
- $\rightarrow$ it's natural to let the mutator never see (get a pointer to) a white object



Example #2: Boehm GC

- conservative GC (→ mark&sweep) + incremental
- invariants:
  - "non-root black → white" pointers never exist
- how?
  - capture *"writing to an object field" (write barrier)*
- remark: "root → white" pointers *may* exist
  - prevention requires us to capture writing to the root → *reading* from an object
  - the overhead is so large that it deserves a separate treatment (covered later)

Write barrier in Boehm GC

- capture writing into objects by virtual memory (the only choice in C/C++)
- gray the "written-to" object
  - push it onto the mark stack
- no read barriers → "root (black) → white" pointers are allowed
- at the end of a mark phase, it traverses from the root again
- during this second traversal, the mutator is stopped → it may cause a long pause time

Appendix: a more rigorous correctness proof

- while it is clear "black→white" pointers cause a problem, it is not trivial that preventing them is sufficient to solve the problem
- the proposition to prove: after the following algorithm finished,

  reachable from the root → black

```
gray the root;
while (there are gray objects) {
  o = pick and blacken a gray object;
  for (pointers p in o)
    if (p points to a white object)
      gray it;
  the mutator changes the graph;
}
```

The key invariant

- the following "always" holds during the execution (GC or mutator)
  (I): all "white" objects reachable from the root are reachable from some "gray" objects

- if this is true,

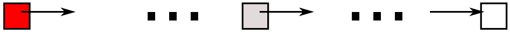
  (I) and the termination condition (i.e. there are no grays)
  $\rightarrow$ no white objects are reachable from the root
  $\rightarrow$ white objects can be reclaimed

  and we are done. the only remaining task is to prove (I).

Proof of (I)

- say w is a white object reachable from the root

- since the root is always black or gray and there are no "black $\to$ white" pointers $(*)$, there must be a gray object on each path P from the root to w (QED).



- $(*)$: you need to show that not only the mutator but also the collector never creates "black $\to$ white" pointers. it's easy and left as an exercise.