

Programming Language (9)

Garbage Collection

田浦

Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

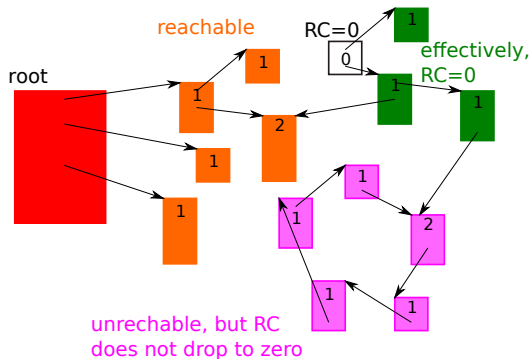
Conservative GC

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

- ▶ difficult to say in a few words (more details ahead)

Criteria #2: memory allocation cost

- ▶ difficult to say in a few words (more details ahead)
- ▶ traversing GC:
 - ▶ *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**

Criteria #2: memory allocation cost

- ▶ difficult to say in a few words (more details ahead)
- ▶ traversing GC:
 - ▶ *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**
- ▶ **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

- ▶ reference counting < traversing GC (reference counting is better)

Criteria #3: pause time

- ▶ reference counting < traversing GC (reference counting is better)
- ▶ traversing GC:
 - ▶ traverse *all* live objects, *en masse*, and reclaim *all* unreachable objects, *en masse*
 - ▶ do a whole bunch of work and get a whole bunch of free blocks

Criteria #3: pause time

- ▶ reference counting < traversing GC (reference counting is better)
- ▶ traversing GC:
 - ▶ traverse *all* live objects, *en masse*, and reclaim *all* unreachable objects, *en masse*
 - ▶ do a whole bunch of work and get a whole bunch of free blocks
 - ▶ why so? troubled if the mutator runs (= changes the graph of objects) during traversing
 - ▶ a solution: [incremental GC](#)
 - ▶ generational GCs mitigate it too

Criteria #3: pause time

- ▶ reference counting < traversing GC (reference counting is better)
- ▶ traversing GC:
 - ▶ traverse *all* live objects, *en masse*, and reclaim *all* unreachable objects, *en masse*
 - ▶ do a whole bunch of work and get a whole bunch of free blocks
 - ▶ 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

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

will do:

```
1 if (p) p->rc--;  
2 if (q) q->rc++;  
3 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	— (†)	+
mutator overhead	+ (‡)	—

- (*) depends on size of reachable graph and memory;
generational garbage collector helps
- (†) incremental garbage collector helps
- (‡) both generational and incremental garbage collectors
impose some mutator overheads

Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

mark&sweep GC vs. copying GC

they differ in what to do on reachable objects

- ▶ mark&sweep GC: mark them as “visited”

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

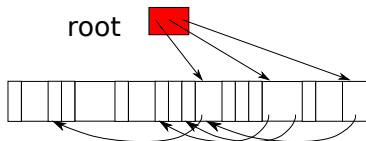
Mark&sweep GC

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*)



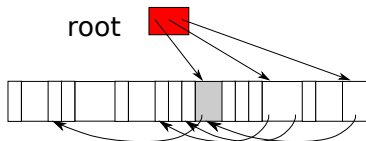
Mark&sweep GC

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*)



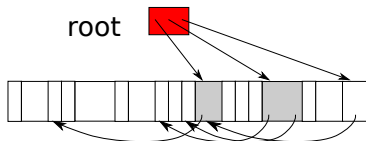
Mark&sweep GC

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*)



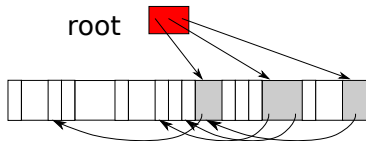
Mark&sweep GC

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*)



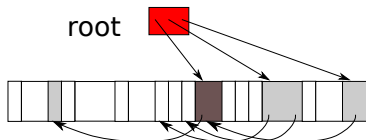
Mark&sweep GC

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*)



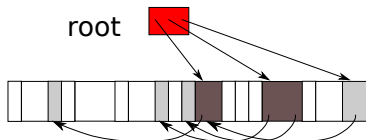
Mark&sweep GC

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*)



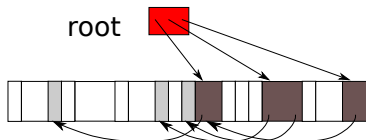
Mark&sweep GC

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*)



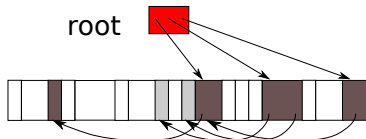
Mark&sweep GC

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*)



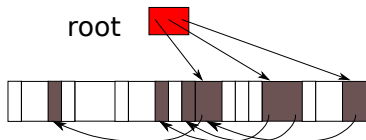
Mark&sweep GC

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)

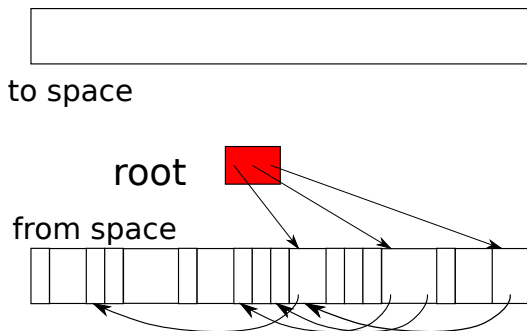
2. sweep phase:

- ▶ 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*)



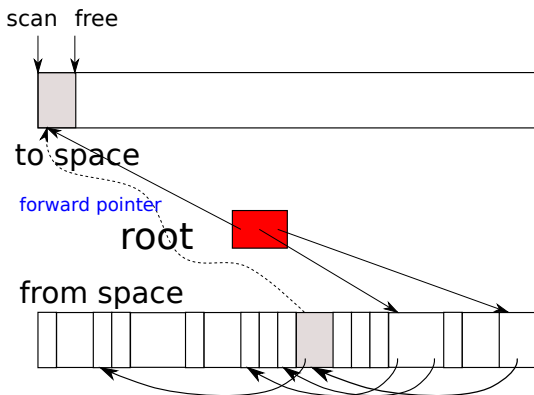
Copying GC

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



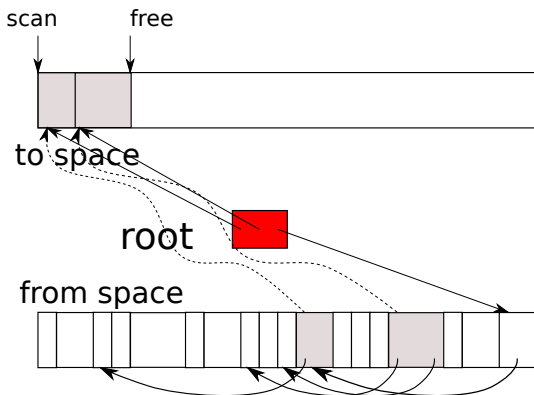
Copying GC

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



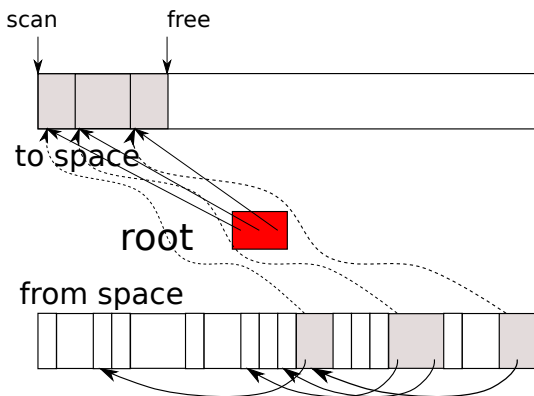
Copying GC

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



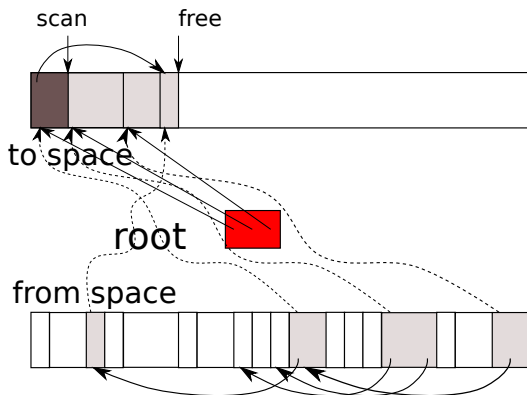
Copying GC

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



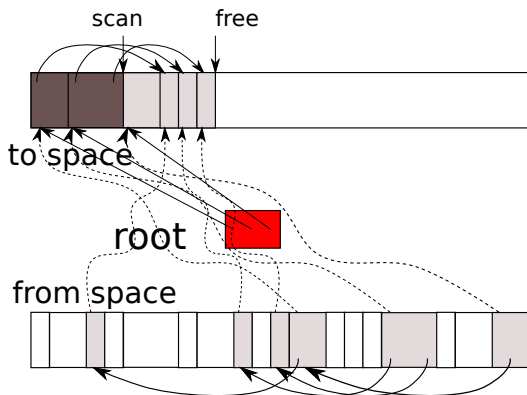
Copying GC

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



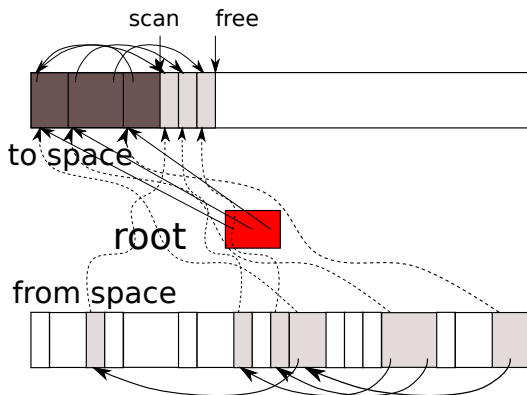
Copying GC

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



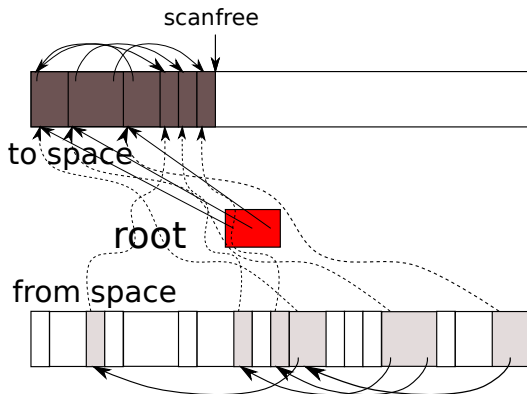
Copying GC

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



Copying GC

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

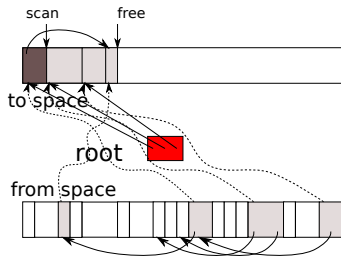


Copying GC: algorithm

```
1 void *free, *scan;
2 copy_gc() {
3     free = scan = to_space;
4     redirect_ptrs(root);
5     while (scan < free) {
6         redirect_ptrs(scan);
7         scan += the size of object scan points to;
8     }
9 }
10 redirect_ptrs(void * o) {
11     for (p ∈ pointers in o) {
12         if (p has been copied) {
13             p = p's forward pointer;
14         } else {
15             copy p to free;
16             p = free;
17             p's forward pointer = free;
18             free += the size of object p points to;
19         }
20     }
21 }
```

invariant

- ▶ $p < \text{scan} \Rightarrow p$ has been reached; so has its direct children
- ▶ $p < \text{free} \Rightarrow p$ has been reached; but its children may not

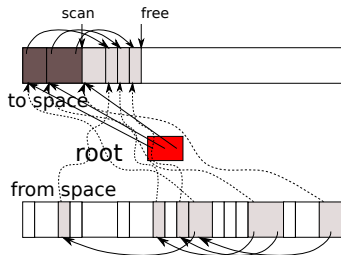


Copying GC: algorithm

```
1 void *free, *scan;
2 copy_gc() {
3     free = scan = to_space;
4     redirect_ptrs(root);
5     while (scan < free) {
6         redirect_ptrs(scan);
7         scan += the size of object scan points to;
8     }
9 }
10 redirect_ptrs(void * o) {
11     for (p ∈ pointers in o) {
12         if (p has been copied) {
13             p = p's forward pointer;
14         } else {
15             copy p to free;
16             p = free;
17             p's forward pointer = free;
18             free += the size of object p points to;
19         }
20     }
21 }
```

invariant

- ▶ $p < \text{scan} \Rightarrow p$ has been reached; so has its direct children
- ▶ $p < \text{free} \Rightarrow p$ has been reached; but its children may not



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” \leq “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

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

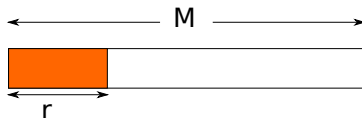
Memory allocation cost of traversing GCs

- ▶ 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



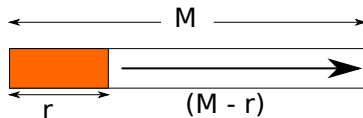
Memory allocation cost of traversing GCs

- ▶ 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



Memory allocation cost of traversing GCs

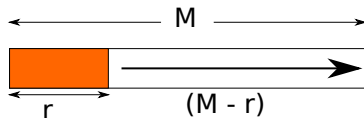
- ▶ let's quantify the cost of allocating a byte including GC's work
- ▶ assume:
 - ▶ heap size (size of a semi-space in case of copying GC) = M
 - ▶ reached objects = r
 - ▶ assume for the sake of argument it's *always* r
- ▶ behavior at equilibrium: the program repeats:
 1. a GC occurs \rightarrow scan (or copy) r bytes, to make a free space of $(M - r)$ bytes
 2. allocate $(M - r)$ bytes without triggering a GC



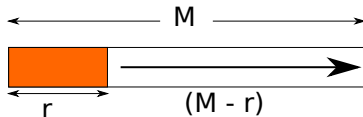
Memory allocation cost of traversing GCs

- ▶ 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
- ▶ behavior at equilibrium: the program repeats:
 1. a GC occurs \rightarrow scan (or copy) r bytes, to make a free space of $(M - r)$ bytes
 2. allocate $(M - r)$ bytes without triggering a GC
- ▶ a key observation

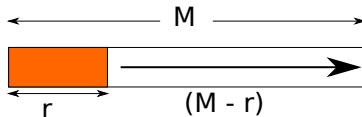
the time (cost) of a single GC is roughly proportional to the amount of reached objects (i.e., $\propto r$)



Memory allocation cost of traversing GCs

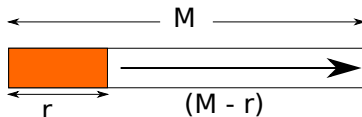


Memory allocation cost of traversing GCs



\therefore the cost of allocating a byte

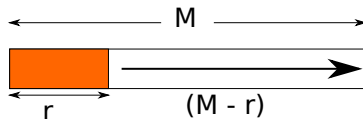
Memory allocation cost of traversing GCs



$$\begin{aligned} \therefore & \quad \text{the cost of allocating a byte} \\ = & \quad \alpha + \frac{\text{the amount of time spent on a GC}}{\text{the amount of space reclaimed by a GC}} \end{aligned}$$

- ▶ α : a constant cost needed anyway, even if you don't need to reclaim memory at all

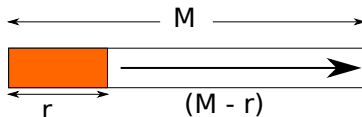
Memory allocation cost of traversing GCs



$$\begin{aligned} \therefore & \text{the cost of allocating a byte} \\ = & \alpha + \frac{\text{the amount of time spent on a GC}}{\text{the amount of space reclaimed by a GC}} \\ = & \alpha + \beta \frac{\text{the amount of space visited by a GC}}{\text{the amount of space reclaimed by a GC}} \end{aligned}$$

- ▶ α : a constant cost needed anyway, even if you don't need to reclaim memory at all

Memory allocation cost of traversing GCs



$$\begin{aligned} \therefore & \text{the cost of allocating a byte} \\ = & \alpha + \frac{\text{the amount of time spent on a GC}}{\text{the amount of space reclaimed by a GC}} \\ = & \alpha + \beta \frac{\text{the amount of space visited by a GC}}{\text{the amount of space reclaimed by a GC}} \\ = & \alpha + \beta \frac{r}{M - r} \end{aligned}$$

- ▶ 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

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:

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

- ▶ $r/(M - r)$ 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

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

- ▶ memory usage

\propto 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

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

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?

GC overhead

\equiv GC's work per allocating a byte

mark-cons ratio (review)

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

mark-cons ratio (review)

$$\begin{aligned} & \text{GC overhead} \\ \equiv & \text{GC's work per allocating a byte} \\ = & \frac{\text{GC's work}}{\text{memory allocated}} \\ & (\text{assume a traversing GC; look at a specific GC}) \end{aligned}$$

mark-cons ratio (review)

$$\begin{aligned} & \text{GC overhead} \\ \equiv & \text{GC's work per allocating a byte} \\ = & \frac{\text{GC's work}}{\text{memory allocated}} \\ & (\text{assume a traversing GC; look at a specific GC}) \\ \propto & \frac{\text{space reachable from the root}}{\text{space reclaimed}} \end{aligned}$$

mark-cons ratio (review)

$$\begin{aligned} & \text{GC overhead} \\ \equiv & \text{GC's work per allocating a byte} \\ = & \frac{\text{GC's work}}{\text{memory allocated}} \\ & (\text{assume a traversing GC; look at a specific GC}) \\ \propto & \frac{\text{space reachable from the root}}{\text{space reclaimed}} \\ = & \frac{\text{space reachable from the root}}{\text{space unreachable from the root}} \end{aligned}$$

mark-cons ratio (review)

$$\begin{aligned} & \text{GC overhead} \\ \equiv & \text{GC's work per allocating a byte} \\ = & \frac{\text{GC's work}}{\text{memory allocated}} \\ & (\text{assume a traversing GC; look at a specific GC}) \\ \propto & \frac{\text{space reachable from the root}}{\text{space reclaimed}} \\ = & \frac{\text{space reachable from the root}}{\text{space unreachable from the root}} \end{aligned}$$

► *the less reachable space there are, the smaller it becomes*

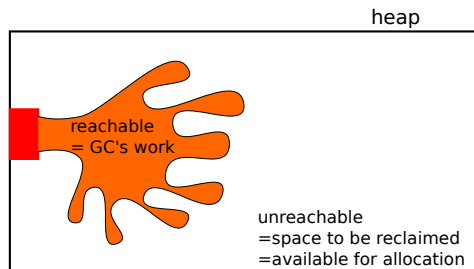
mark-cons ratio (review)

$$\begin{aligned} & \text{GC overhead} \\ \equiv & \text{GC's work per allocating a byte} \\ = & \frac{\text{GC's work}}{\text{memory allocated}} \\ & (\text{assume a traversing GC; look at a specific GC}) \\ \propto & \frac{\text{space reachable from the root}}{\text{space reclaimed}} \\ = & \frac{\text{space reachable from the root}}{\text{space unreachable from the root}} \end{aligned}$$

- ▶ *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)

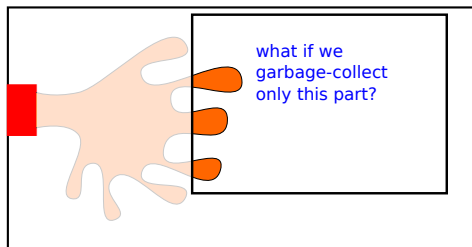
Generational GC: the basic idea

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



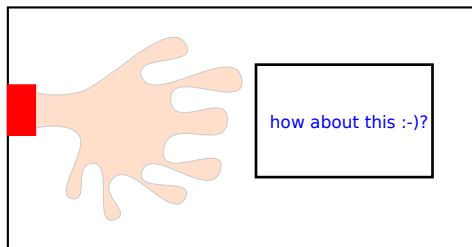
Generational GC: the basic idea

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



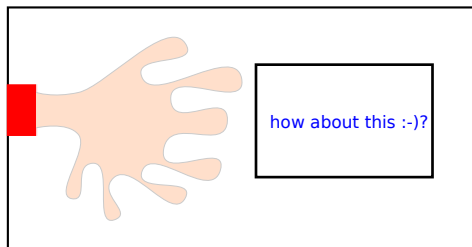
Generational GC: the basic idea

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



Generational GC: the basic idea

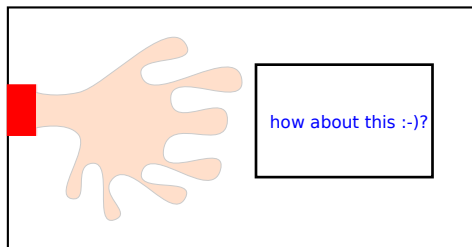
- ▶ basic idea: traverse (collect) only *a region that has a lesser live object ratio*



- ▶ two problems:

Generational GC: the basic idea

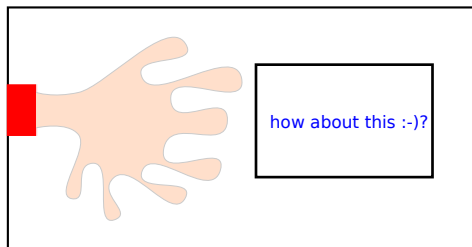
- ▶ basic idea: traverse (collect) only *a region that has a lesser live object ratio*



- ▶ two problems:
 1. where to target: *which region has a lesser live object ratio?*

Generational GC: the basic idea

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



- ▶ 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

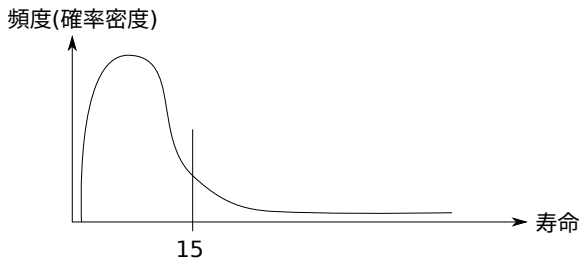
Problem 1: where generational GC targets

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 rationale of generational GCs

- ▶ say 90% die younger than 10KB, then

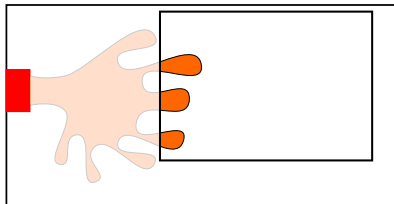
mark-cons ratio when traversing most recent 10KB ≈ 0.1

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

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

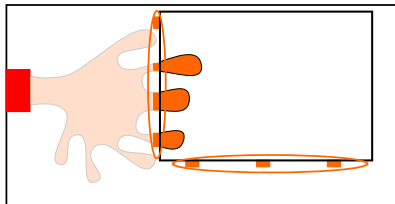
Problem 2: how to make it correct?

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



Problem 2: how to make it correct?

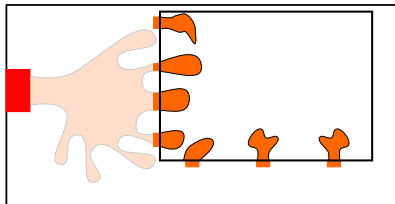
- ▶ we need to find all young objects reachable from the root, through “*all pointers, young or old*”
- ▶ simply ignoring old objects won't work



- ▶ solution: *record “all” pointers from “old \rightarrow young”* during the execution and consider them as part of the root

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



- ▶ solution: *record “all” pointers from “old \rightarrow 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 \rightarrow young” pointers
- ▶ mutator actions that need an intervention: assignments:

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

- ▶ in OCaml,

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

- ▶ hopefully they rarely occur in “mostly functional” languages

Implementing Write Barrier (1) Remembered Set

▶ given

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

we do

```
1 if (generation(a) < generation(o)) {  
2   if (o ∉ R) add(R, o)  
3 }
```

▶ the overhead is large

- ▶ obtain `generation(·)` (address comparison in copying GC)
- ▶ check if $o \in R$
- ▶ manage R

Implementing Write Barrier (2) Card Marking

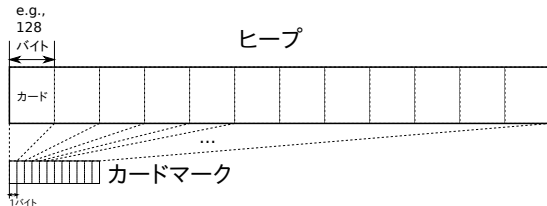
- ▶ basic idea: unconditionally record addresses pointers are written to
- ▶ partition the heap into constant-sized “cards”
 - ▶ a card: a region whose addresses share a number of most significant bits
 - ▶ e.g., share the highest 57 of 64 bit addresses
 - ▶ \rightarrow a single card $2^7 = 128$ bytes

ヒープ



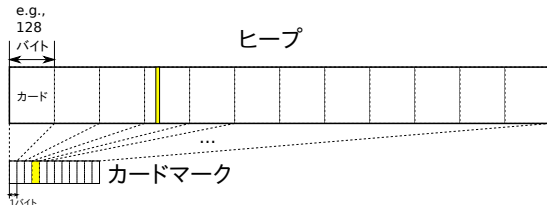
Implementing Write Barrier (2) Card Marking

- ▶ 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
 - ▶ → a single card $2^7 = 128$ bytes



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
 - ▶ → a single card $2^7 = 128$ bytes



- ▶ 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,

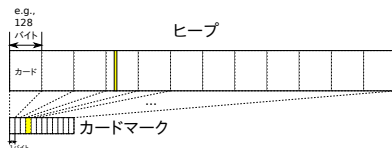
```
1 o->x <- y;
```

unconditionally record “a card containing $\&o \rightarrow x$ is written”

```
1 C[( $\&o \rightarrow x$ ) >> 9] = 1;
```

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

```
1 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)

```
1 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

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

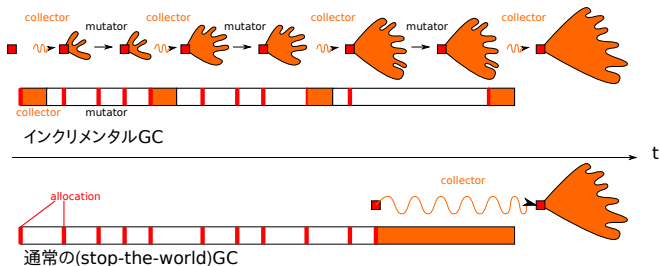
Conservative GC

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

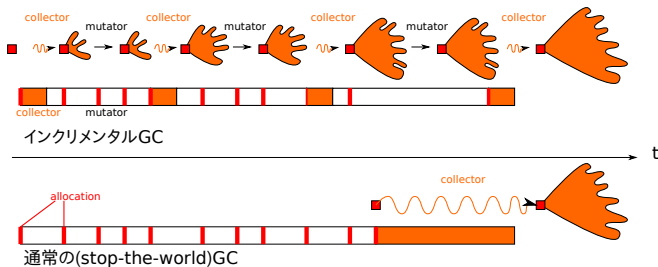
Incremental GC

- ▶ objective: *reduce the “pause time”* of traversing GC
 - ▶ good for applications that need real time or interactive responses
- ▶ recall that pause time \approx 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?
- ▶ \Rightarrow we'll get back to the basics of graph traversal

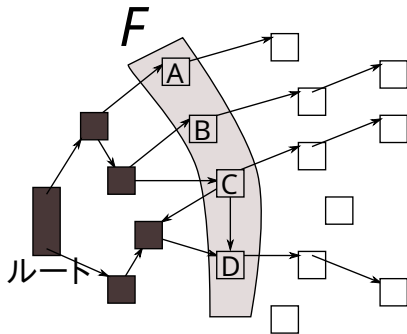
Assumptions for later discussions

- ▶ 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 \approx graph traversal
- ▶ the principle is the same whether it's mark&sweep or copying
- ▶ omitting details, it is:

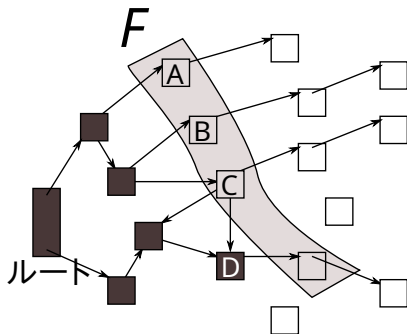
```
1  F = { root };  
2  while (F is not empty) {  
3    o = pop(F);  
4    for (all pointers p in o)  
5      if (!marked(p)) {  
6        mark(p);  
7        add(F, p);  
8      }  
9  }
```



Graph traversal : basics

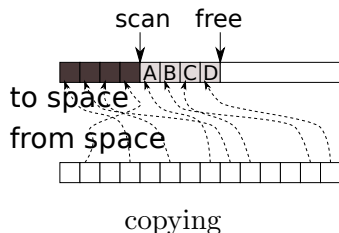
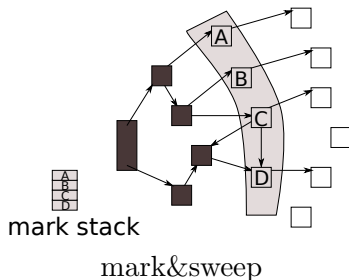
- ▶ traversing GC \approx graph traversal
- ▶ the principle is the same whether it's mark&sweep or copying
- ▶ omitting details, it is:

```
1  F = { root };  
2  while (F is not empty) {  
3    o = pop(F);  
4    for (all pointers p in o)  
5      if (!marked(p)) {  
6        mark(p);  
7        add(F, p);  
8      }  
9  }
```



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



The issue that an incremental GC must address

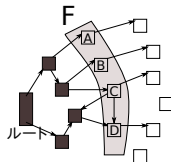
```
1 F = { root };
2 while (F is not empty) {
3   o = pop(F);
4   for (all pointers p in o)
5     if (!marked(p)) {
6       mark(p);
7       add(F, p);
8     }
9   if (has iterated a few times)
10    // the graph changes below
11    resume_mutator();
12 }
```

- ▶ **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 \approx 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

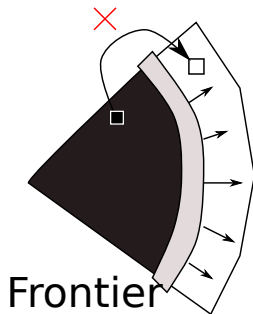
```
1 gray the root;  
2 while (there is a gray object) {  
3   o = pick a gray object and blacken it;  
4   for (all pointers in o)  
5     if (p points to a white object)  
6       gray it;  
7   the mutator changes the graph; }
```



- ▶ 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

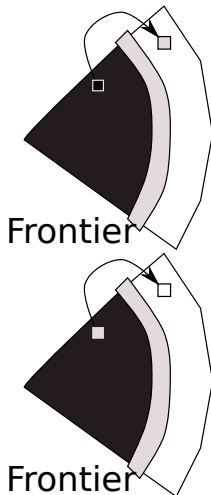
- ▶ intuitively, *the issue seems the mutator may create “black \rightarrow white” pointers*
 - ▶ **black**: GC thinks it has “done” with it
 - ▶ **white**: going to be reclaimed, unless found in other paths
- ▶ \Rightarrow prevent “black \rightarrow white pointers” from being created



Two approaches to preventing black \rightarrow white

capture the point where “**black** \rightarrow **white**” is about to be created

1. approach #1: gray the **white** (make **black** \rightarrow **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** \rightarrow **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)

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

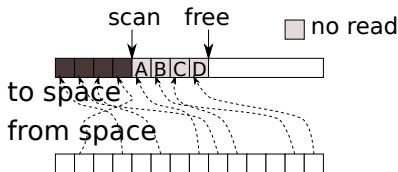
- ▶ write a pointer into a root \equiv write a pointer to a variable (read barrier)

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

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

Example #1: Appel-Ellis-Li

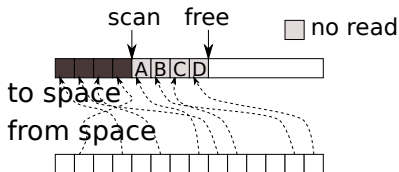
- ▶ copying GC + incremental
- ▶ based on the approach # 1. more precisely, maintain the following invariant
the mutator never sees a pointer to white
- ▶ how?
 - ▶ intervene in reading a field from gray objects (read barrier)
- ▶ read-protect the region of gray objects \subset scan \sim free, by the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

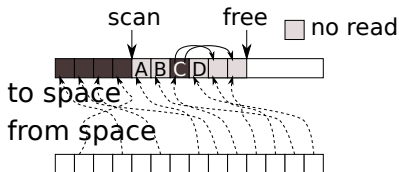
```
1 trap_read_from_grey(a) {  
2   page = the page including a;  
3   for (all objects o in the page) {  
4     scan(o); // copy o's children  
5   }  
6   unprotect(page);  
7 }
```



Appel-Ellis-Li : the read barrier in action

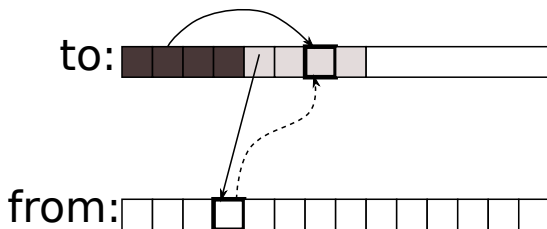
- ▶ when a field of a gray object is read, blacken objects in the page containing it (= scan those objects → they become gray)

```
1 trap_read_from_grey(a) {  
2   page = the page including a;  
3   for (all objects o in the page) {  
4     scan(o); // copy o's children  
5   }  
6   unprotect(page);  
7 }
```



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”
- ▶ → it's natural to let the mutator never see (get a pointer to) a white object



Example #2: Boehm GC

- ▶ conservative GC (\rightarrow mark&sweep) + incremental
- ▶ invariants:
 - ▶ “non-root **black** \rightarrow white” pointers never exist
- ▶ how?
 - ▶ capture “*writing to an object field*” (*write barrier*)
- ▶ remark: “**root** \rightarrow **white**” pointers *may* exist
 - ▶ prevention requires us to capture writing to the root \rightarrow *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 \rightarrow 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 \rightarrow black

```
1 gray the root;  
2 while (there are gray objects) {  
3     o = pick and blacken a gray object;  
4     for (pointers p in o)  
5         if (p points to a white object)  
6             gray it;  
7     the mutator changes the graph;  
8 }
```

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)
 - no white objects are reachable from the root
 - white objects can be reclaimedand 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 \rightarrow 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 \rightarrow white” pointers. it’s easy and left as an exercise.

Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

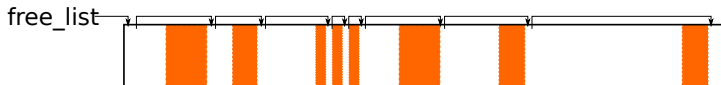
Managing and finding free space

- ▶ in any method except for copying GC (mark&sweep GC, reference counting, malloc/free), free space are not contiguous
- ▶ → tracking and managing free blocks is required
- ▶ goal:
 - ▶ good allocation speed: quickly find a region that fits the request size
 - ▶ good memory utilization: do not waste available space
- ▶ basic data structure: free list (list of free blocks)



Managing and finding free space

- ▶ in any method except for copying GC (mark&sweep GC, reference counting, malloc/free), free space are not contiguous
- ▶ → tracking and managing free blocks is required
- ▶ goal:
 - ▶ good allocation speed: quickly find a region that fits the request size
 - ▶ good memory utilization: do not waste available space
- ▶ basic data structure: free list (list of free blocks)



Free list

- ▶ list of free blocks (or cells)

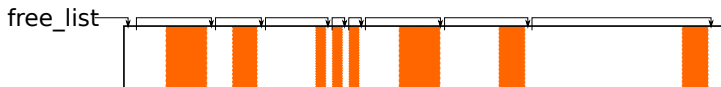
```
1 typedef struct cell {  
2     struct cell * next;  
3     size_t sz;  
4     /* other info as necessary */  
5 } cell;  
6 cell * free_list;
```

- ▶ allocation (malloc) \approx

1. (linearly) search for a cell large enough for the requested size
2. if a free space remains in the cell, put it back to the free list

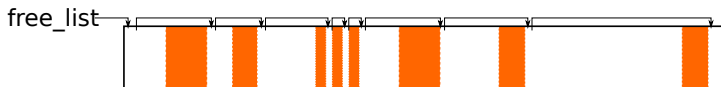
- ▶ reclamation (free) \approx

1. put it back to the free list (issue: how to know its size?)
2. if the cell just freed is adjacent to another free cell, merge them (coalescing)



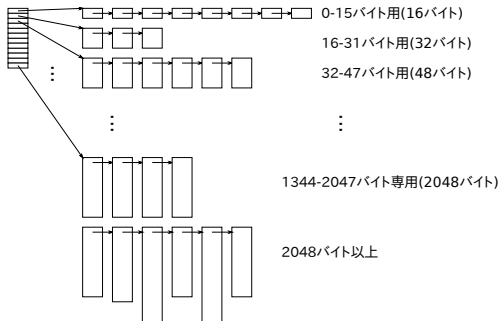
Issues in the simple method

- ▶ allocation:
 - ▶ needs to traverse a fair amount of cells (until you find a cell that fits)
 - ▶ → make many free lists, one for a fixed size (*segregated free lists*)
- ▶ reclamation:
 - ▶ needs to check if coalescing is possible
 - ▶ needs to know the size of the freed cell
 - ▶ → manage memory in a larger unit (*page*) and dedicate a page to a single size (*Big Bags of Pages; BiBOP*)



Segregated free lists

- ▶ for small sizes (e.g., < 2KB), make a free list for various representative sizes
- ▶ a single list for large sizes
- ▶ ex:
 - ▶ 16, 32, 48, 64, ..., 448, 512, 672, 800, 1024, 1344, 2048
 - ▶ 2048 bytes or larger



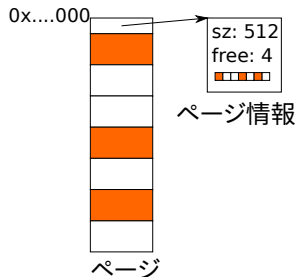
Allocation sequence

- ▶ **Colored**: a fast path for small objects
- ▶ **blue**: the overhead removable if the size (*sz*) is a compile-time constant
- ▶ **red**: the essential cost. traverse a list once (6-7 instructions)
- ▶ note: in multithreaded programs, we either have to
 - ▶ let each thread have its own `free_lists`, or
 - ▶ atomically perform **the read-modify-write on `free_lists`** (this hinders scalability)

```
1 void ** free_lists;
2
3 void * malloc(size_t sz) {
4     if (SMALL(sz)) {
5         size_t idx =
6             bytes_to_idx(sz);
7         cell * a =
8             free_lists[idx];
9         if (a) {
10             free_lists[idx] =
11                 a->next;
12             return a;
13         } else {
14             return malloc_slow(sz);
15         }
16     }
17 }
```


Big Bags of Pages

- ▶ manage the heap by dividing it into constant-sized blocks (page)
 - ▶ a page: a set of addresses sharing a number of highest bits
 - ▶ e.g. 64 bit addresses, sharing the highest 52 bits $\rightarrow 2^{12} = 4096$ bytes/page
- ▶ each page is either
 - ▶ completely free or
 - ▶ used only for a single size (e.g., only for 48 bytes)
- ▶ Coalescing: repurpose a page only when the page becomes completely empty
 - ▶ \rightarrow only need to count the number of free cells in the page
- ▶ does not require per-object size field either



Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

Improving performance of mark&sweep GC

- ▶ overall structure:
 1. **mark phase**: traverses pointers from the root, **marking** reached objects along the way
 2. **sweep phase**: reclaims unmarked objects → **pushes them back to an appropriate free list**
- ▶ basics:
 - ▶ segregated free lists
 - ▶ BiBOP
 - ▶ **mark bits separated from objects**
 - ▶ **lazy sweep**

Separated mark bits

- ▶ question: where do you put the mark bit of an object?
- ▶ Method 1: use a word within an object
- ▶ Method 2: use a separate space dedicated for mark-bits outside objects
 - ▶ where is the separate space, exactly? → page header; holds mark bits of all the objects in the page together (1 byte/object)

```
1 mark(void * o) {  
2     page * page = o & 0xFFF...000; /* page header address */  
3     page->header->mark[(o & 0x000...FFF) >> 4] = 1;  
4 }
```

- ▶ point: gather spaces that are written

Lazy sweep

- ▶ why do we need to sweep: reclaim space that has become free
- ▶ naturally, you would put them back to an appropriate free list (cf. BiBOP)
- ▶ **lazy sweep**: defer this operation until you need to allocate them

Overview of the sweep phase

- ▶ after a mark phase is finished, a page is either
 - ▶ empty: zero objects have been reached
 - ▶ partial: > 0 objects have been reached, > 0 objects have not been reached
 - ▶ full: zero objects have not been reached
- ▶ a naive implementation of a sweep phase:

```
1  for (all pages p) {  
2      if (p is empty) {  
3          put p in the empty page list;  
4          /* can be repurposed for any size */  
5      } else if (p is partial) {  
6          sz = the size of objects in the page;  
7          put free cells in p to the free list fo sz bytes;  
8      }  
9  }
```

Lazy sweep

- ▶ does not rebuild free lists immediately
- ▶ instead puts the page into the list of “to-reclaim” pages

```
1 for (all pages p) {  
2   if (p is empty) {  
3     put p in the empty page list;  
4     /* can be repurposed for any size */  
5   } else if (p is partial) {  
6     sz = the size of objects in the page;  
7     put p into the reclaim list for sz bytes;  
8   }  
9 }
```

Reclaim list

- ▶ list of pages that have at least one free cell
- ▶ like free lists, there is a list per size
- ▶ when an allocation finds the free list empty, look at the reclaim list and if there is any page, move free cells of a page into the free list

What's the point?

- ▶ simply deferring the task you need to do anyway? not exactly so
- ▶ make more coalescing opportunities:
 - ▶ after a few GCs, a page may become empty before it needs to be reused for allocation
- ▶ improve temporal locality of references:
 - ▶ by touching free cells to put them back to free list, closely before they are used by the mutator
- ▶ shorten the pause time due to the sweep phase

Contents

Criteria of evaluating GCs (RC vs. traversing)

Two traversing GCs (mark&sweep vs. copying)

Memory allocation cost of traversing GCs (mark-cons ratio)

Generational GC

Incremental GC

Topics on Mark&Sweep GCs

- Free Area Management

- Improving mark&sweep GCs

 - Separated Mark Bits

 - Lazy Sweep

Conservative GC

Conservative GC

- ▶ *conservative* GC
 - ▶ \approx GC for languages designed without assuming GC, such as C/C++

Conservative GC

- ▶ *conservative* GC
 - ▶ \approx GC for languages designed without assuming GC, such as C/C++
 - ▶ \approx GC in the presence of words that may or may not be pointers (conservatively assumed to be pointers)

Conservative GC

- ▶ *conservative* GC
 - ▶ \approx GC for languages designed without assuming GC, such as C/C++
 - ▶ \approx GC in the presence of words that may or may not be pointers (conservatively assumed to be pointers)
- ▶ antonym: *accurate* GC
 - ▶ does not necessarily reclaim all dead (no longer used) objects
 - ▶ *accurate* or *conservative* refers to whether “pointer identifications” are accurate or not
 - ▶ languages that implement an accurate GC normally use a data representation in which looking at a single word can tell you whether it is a pointer or not
 - ▶ ex: the last bit = 0 (pointer), = 1 (non-pointer)

A challenge in C/C++: pointer ambiguity

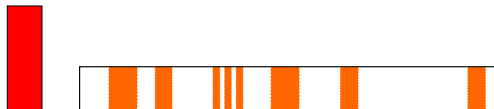
- ▶ a pointer and a non-pointers cannot be told apart; a word “7596272344674820427 (10110100101101011011...011000010100101₂)” can be any of the following
 - ▶ a pointer to an object at address 7596272344674820427,
 - ▶ an integer 7596272344674820427,
 - ▶ a part of a string (“Kawasaki”),
 - ▶ a double precision floating point number $(6.549545 \dots \times 10^{199})$,
 - ▶ ...

A challenge in C/C++: pointer ambiguity

- ▶ a pointer and a non-pointers cannot be told apart; a word “7596272344674820427 (10110100101101011011...011000010100101₂)” can be any of the following
 - ▶ a pointer to an object at address 7596272344674820427,
 - ▶ an integer 7596272344674820427,
 - ▶ a part of a string (“Kawasaki”),
 - ▶ a double precision floating point number (6.549545... $\times 10^{199}$),
 - ▶ ...
- ▶ the basic principle:
 - ▶ *if a word is an address of a block being used, it is assumed to be the pointer to it*
 - ▶ a non-pointer may be misidentified as a pointer
 - ▶ a method to minimize the loss (leak) caused by misidentified pointers → [blacklisting](#)

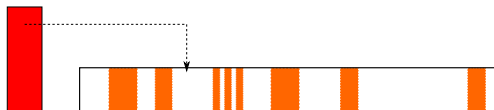
Blacklisting

- ▶ during marking, record (“blacklist”) words p (suspicious addresses) satisfying:



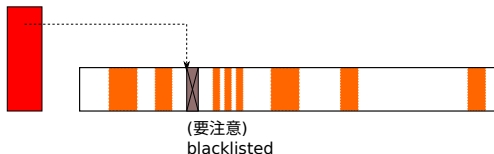
Blacklisting

- ▶ during marking, record (“blacklist”) words p (suspicious addresses) satisfying:
 - ▶ address p is currently *not* used and
 - ▶ p is a subject of future allocation (i.e., an address within the current heap)



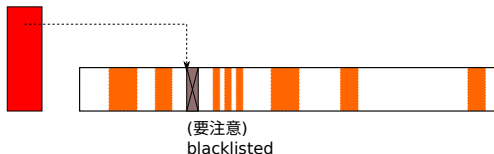
Blacklisting

- ▶ during marking, record (“blacklist”) words p (suspicious addresses) satisfying:
 - ▶ address p is currently *not* used and
 - ▶ p is a subject of future allocation (i.e., an address within the current heap)
- ▶ do not use such p 's for *future allocation*



Blacklisting

- ▶ during marking, record (“blacklist”) words p (suspicious addresses) satisfying:
 - ▶ address p is currently *not* used and
 - ▶ p is a subject of future allocation (i.e., an address within the current heap)
- ▶ do not use such p ’s for *future allocation*
- ▶ note that we already lose (a memory associated with) p , but it would be much worse and devastating to allocate p and make *p and all objects reachable from p* uncollectable (*the domino effect*)

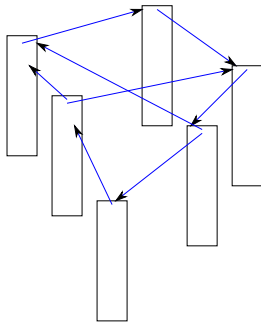
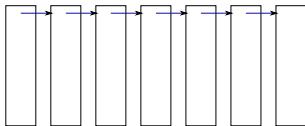


Other tips in conservative GC

1. see <http://hboehm.info/gc/gcinterface.html>
2. `GC_MALLOC_ATOMIC` :
 - ▶ same as `GC_MALLOC`, except you indicate (declare) you never put pointers in it (good for strings and numerical arrays)
 - ▶ reduce the probability of pointer misidentification
 - ▶ reduce the space that must be traversed
3. `GC_MALLOC_IGNORE_OFF_PAGE` : declares “you never put pointers except in the first 512 bytes”
4. clear pointers no longer necessary with NULL
 - ▶ pointers within a data structure
 - ▶ prevent the domino effect when a single object is mistakenly kept alive
5. tips in how you link data structures
 - ▶ data structures less prone to the domino effect due to a pointer misidentification

Data structure (not) prone to the domino effect

- ▶ suppose you make link lists, trees and graphs
- ▶ **(NG)**: directly link large nodes with payload
- ▶ **(GOOD)**: separate the structure linking nodes (*the spine*) and the payloads → misidentifying a payload does not lead to another object



Data structure (not) prone to the domino effect

- ▶ suppose you make link lists, trees and graphs
- ▶ **(NG)**: directly link large nodes with payload
- ▶ **(GOOD)**: separate the structure linking nodes (*the spine*) and the payloads → misidentifying a payload does not lead to another object

