Garbage Collection

Concepts, Algorithms and Java Case-Study

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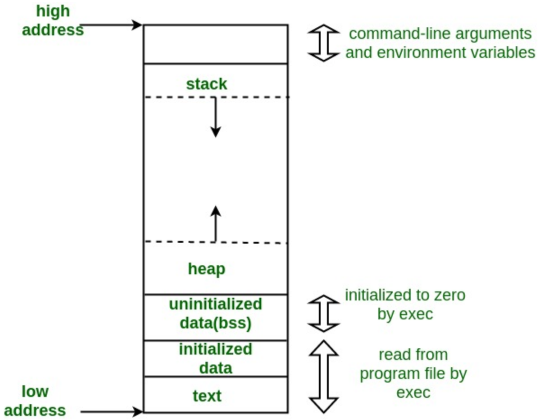
Overview

1. programming without garbage collection
2. basic concepts of garbage collection
3. garbage collection algorithms
4. garbage collection in Java

Programming without Garbage Collection

- C program memory layout:



Programming without Garbage Collection

- static space: `.text`, `.data` and `.bss`
- dynamic space: `stack` and `heap`
- stack keeps track of function calls
- data stored in the stack is ephemeral
- heap used to store longer-lived data
- variables in the stack keep pointers to heap data

Programming without Garbage Collection

- heap management is done by the programmer:
- `void* malloc(size_t size)`
- `void* calloc(size_t count, size_t size)`
- `void* realloc(void *ptr, size_t size)`
- `void  free(void *ptr)`
- functions available from `libc`;
- C keeps information on allocated blocks
- is the block used? what is the size of the block?
- freed blocks are reused in further `malloc()` calls
- blocks have different sizes, hence fragmentation of heap

Programming without Garbage Collection

- problem: heap size is limited
- hence, from application or libraries
- at some point `malloc()` may fail
- heap size can be extended
- usually this resorts to calls that change size of data segment:
- `void* brk(const void* addr)` (mostly deprecated)
- `void* mmap(void* addr, ...)` (current implementations)
- ultimately, the operating system limits heap growth

Some Languages *without* Garbage Collection

- C
- C++
- Objective-C
- Rust

Some Languages *with* Garbage Collection

- Java
- Python
- Haskell
- Go

Basic Concepts

- concept attributed to John McCarthy (LISP, 1959)
- main idea: the heap is automatically managed
- no interference from programmer
- automatic identification of items no longer in use
- reuse the space freed by these items
- eventually optimize layout (e.g., compaction)

Basic Concepts

- but why use garbage collection?
- manual heap management is prone to error:
- e.g., memory leaks
- e.g., memory corruption
- it is especially hard for inexperienced programmers
- therefore:
- most modern programming languages use garbage collection

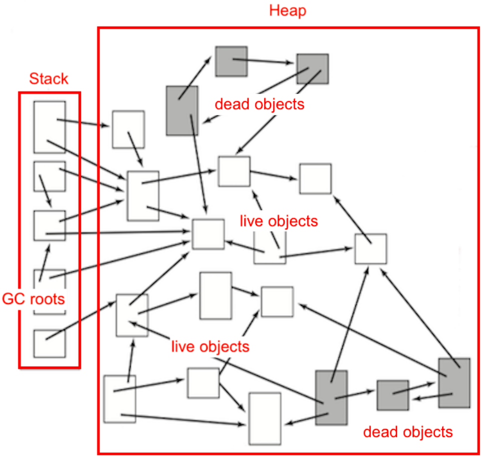
Basic Concepts > Heap

- Heap (H): the region of memory where objects reside
- $|H|$: size of Heap in bytes
- $\#H$: number of objects in Heap

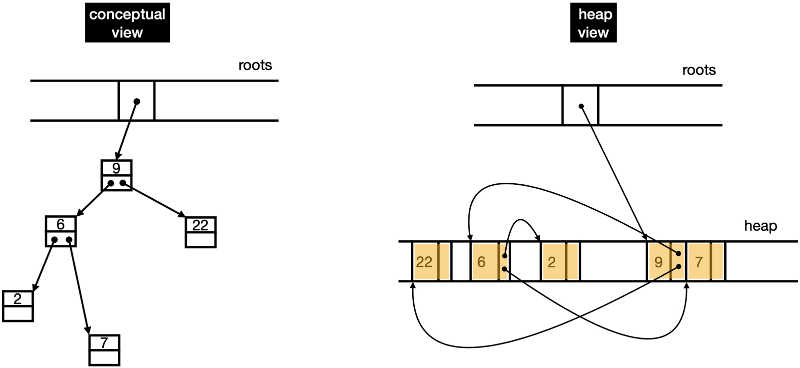
Basic Concepts > Roots & Live Set

- GC Root: any object referenced from outside the Heap
- e.g., a variable in the Stack
- Live Set (LS): all objects in Heap reachable from GC roots
- objects may be reachable via long chains of references
- $|LS|$: size of Live Set in bytes
- $\#LS$: number of objects in Live Set

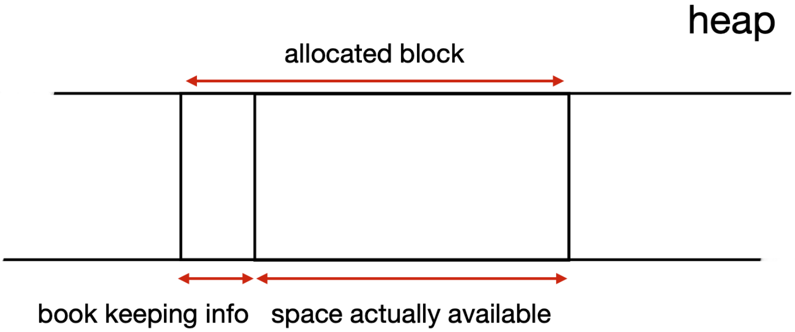
Basic Concepts > Roots & Live Set



Basic Concepts > Roots & Live Set



Basic Concepts > Roots & Live Set



Basic Concepts > Mutator

- Mutators: application threads that change the Heap
- mutation rate: frequency of Heap changes by application
- e.g., by changing references, chains, eventually deleting objects
- allocation rate: frequency of object allocation by application

Basic Concepts > Collector

- Collector: thread that collects dead objects in Heap
- there can be multiple threads
- typically part of the run-time system
- types:
- “pauseless” (runs concurrently with application)
- “stop the world” (stops the application)
- “serial” (one thread)
- “parallel” (multiple threads)

Basic Concepts > GC Safepoint

- GC Safepoint: an execution state for which it is safe to GC
- consider an application thread
- if thread at a GC Safepoint then GC *can* be performed
- thread cannot leave GC Safepoint until after GC ends
- GC Safepoints should be frequent during application execution
- (otherwise, few opportunities for GC)

Basic Concepts > GC Trigger

- usually, GC is triggered when the heap is full
- e.g., an allocation returns `null`
- or, when a given threshold is exceeded
- e.g., only 5% of space in the heap is still available

Some Algorithms

- Reference Counting
- Mark & Sweep
- Mark & Compact
- Copy Collection
- Generational Garbage Collection

Algorithms > Reference Counting

- for every object in Heap there is a counter
- new reference to the object, counter incremented
- e.g., local var assignment
- reference to the object removed, counter decremented
- e.g., local var on returning function
- when counter = 0, space allocated to object is reclaimed
- reclaimed space is reused for new objects
- $+$ lightweight, real-time GC
- $-$ cyclic references are a problem

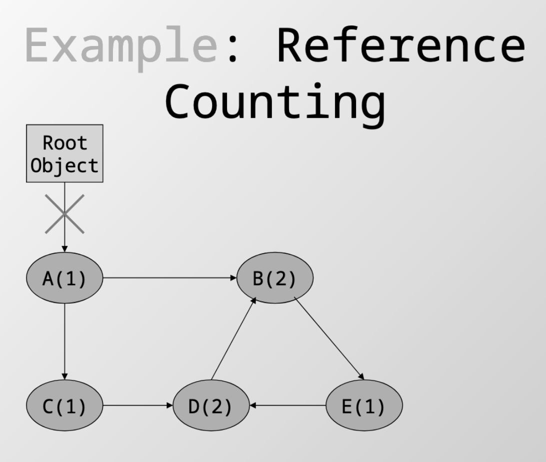
Algorithms > Reference Counting

- reference counting preserves the following invariant:
- an object A is alive iff rc(A) > 0

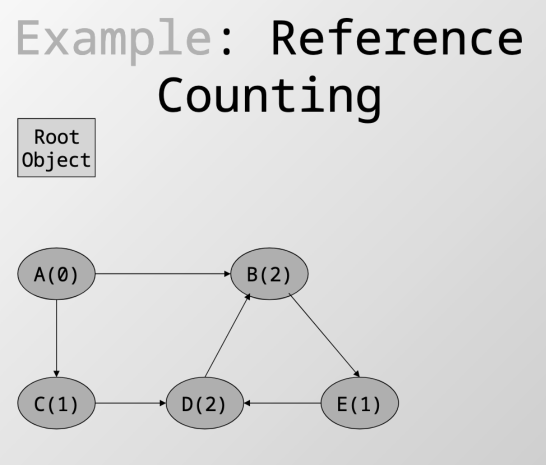
Algorithms > Reference Counting

- object A has rc(A)
- if rc(A) = 0, A is collected
- reference counting also applied to object B referenced from A
- if rc(B) = 0, B is collected
- and so on...
- collecting an object may induce a cascade of collections
- cyclic references are a problem however
- objects that should be collected will never be so

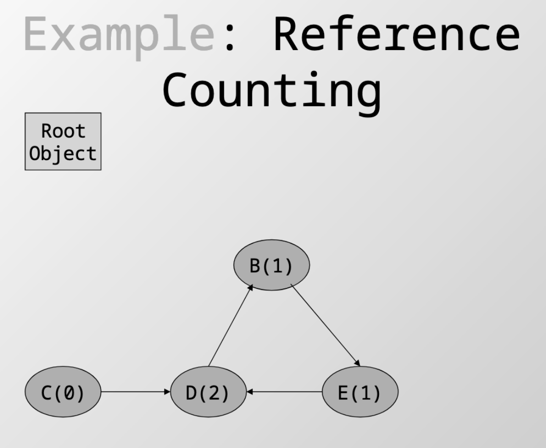
Algorithms > Reference Counting



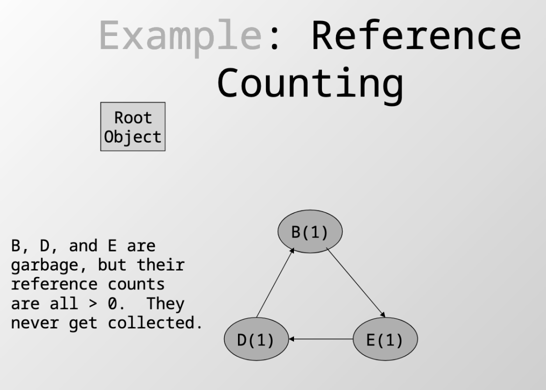
Algorithms > Reference Counting



Algorithms > Reference Counting



Algorithms > Reference Counting



Algorithms > Reference Counting

```
new():
  ref <- allocate()
  if ref = null
    error "Out␣of␣Memory"
  rc(ref) <- 0
  return ref
```

Algorithms > Reference Counting

```
atomic write(src, ref):
  addReference(ref)
  deleteReference(src)
  src <- ref
```

Algorithms > Reference Counting

```
addReference(ref):
  if ref <> null
    rc(ref) <- rc(ref) + 1
```

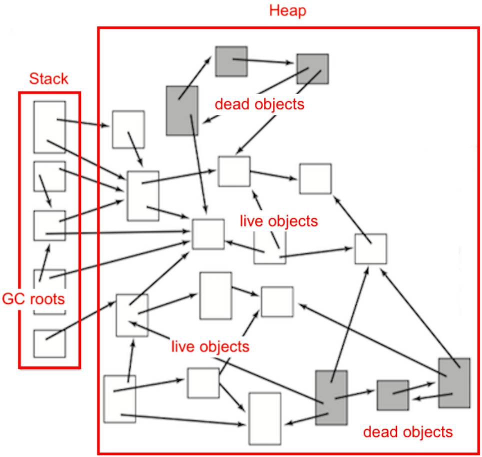
Algorithms > Reference Counting

```
deleteReference(ref):
  if ref <> null
    rc(ref) <- rc(ref) - 1
    if rc(ref) = 0
      for field in Pointers(ref)
        deleteReference(*field)
      free(ref)
```

Algorithms > Mark & Sweep

- Mark phase:
- every object has live bit set to 0
- start from GC roots
- traverse graph, set bit to 1 for every object visited
- Sweep phase:
- linear traversal of heap, bit 0 objects added to free list
- Mark: $\mathcal{O}(\#LS)$
- Sweep: $\mathcal{O}(|H|)$
- $+$ simple, references do not change
- $-$ external fragmentation

Algorithms > Mark & Sweep



Algorithms > Mark & Sweep

Algorithms > Mark & Sweep

```
new():
  ref <- allocate()
  if ref = null
    collect()
    ref <- allocate()
    if ref = null
      error "Out of Memory"
  return ref
```

Algorithms > Mark & Sweep

```
atomic collect():
  markFromRoots();
  sweep(heapStart, heapEnd);
```

Algorithms > Mark & Sweep

```
initialise():
  workList <- empty
```

Algorithms > Mark & Sweep

```
markFromRoots():
  initialise(workList)
  for field in Roots
    ref <- *field
    if ref <> null && not isMarked(ref)
      setMarked(ref)
      add(workList, ref)
      mark()
```

Algorithms > Mark & Sweep

```
mark():
  while not isEmpty(workList)
    ref <- remove(workList)
    for field in Pointers(ref)
      child <- *field
      if child <> null && not isMarked(child)
        setMarked(child)
        add(workList, child)
```

Algorithms > Mark & Sweep

```
sweep(start, end):
  scan <- start
  while scan < end
    if isMarked(scan)
      unsetMarked(scan)
    else
      free(scan)
    scan <- nextObject(scan)
```

Algorithms > Mark & Compact

- Mark phase:
- same as above
- $\mathcal{O}(\#LS)$
- Compact phase:
- move objects (in same Heap space)
- fix references
- $\mathcal{O}(|H| + |LS|)$
- $+$ no free list
- $+$ no external fragmentation
- $-$ delicate compact operation, references change

Algorithms > Mark & Compact

Algorithms > Mark & Compact

```
new(): /* same as M&S */
  ref <- allocate()
  if ref = null
    collect()
    ref <- allocate()
    if ref = null
      error "Out␣of␣Memory"
  return ref
```

Algorithms > Mark & Compact

```
atomic collect():
  markFromRoots() /* same as M&S */
  compact(heapStart, heapEnd)
```

Algorithms > Mark & Compact

```
/* e.g., Lisp 2 algorithm */
compact(heapStart, heapEnd):
  computeLocations(heapStart, heapEnd, heapStart)
  updateReferences(heapStart, heapEnd)
  relocate(heapStart, heapEnd)
```

Algorithms > Mark & Compact

```
computeLocations(start, end, toRegion)
  scan <- start
  free <- toRegion
  while scan < end
    if isMarked(scan)
      forwardingAddress(scan) <- free
      free <- free + size(scan)
    scan <- scan + size(scan)
```

Algorithms > Mark & Compact

```
updateReferences(start, end):
  /* first update only roots */
  for field in Roots
    ref <- *field
    if ref <> null
      *field <- forwardingAddress(ref)
  /* now update internal references */
  scan <- start
  while scan < end
    if isMarked(scan)
    for field in Pointers(scan)
      if *field = null
        *field <- forwardingAddress(*field)
      scan <- scan + size(scan)
```

Algorithms > Mark & Compact

```
relocate(start, end):
  scan <- start
  while scan < end
    if isMarked(scan)
      dest <- forwardingAddress(scan)
      move(scan, dest)
      unsetMasked(dest)
    scan <- scan + size(scan)
```

Algorithms > Copy Collector

- Heap divided into “fromSpace” and “toSpace”
- Mark phase:
- same as above, with objects in ”fromSpace”
- Copy phase:
- all live objects (bit = 1) copied to “toSpace”
- “toSpace” becomes “fromSpace” and vice versa
- “stop the world”, copy operation expensive
- naturally compact, no fragmentation
- twice the amount of heap required
- Mark: $\mathcal{O}(\#LS)$, Copy: $\mathcal{O}(|LS|) = \mathcal{O}(\#LS)$

Algorithms > Copy Collection

```
createSemiSpace()
  fromSpace <- heapStart
  extent <- (heapEnd - heapStart) / 2
  toSpace <- heapStart + extent
  top <- toSpace
  free <- fromSpace
```

Algorithms > Copy Collection

```
flip():
  fromSpace, toSpace <- toSpace, fromSpace
  top <- fromSpace + extent
  free <- fromSpace
```

Algorithms > Copy & Collection

```
new(): /* same as M&S */
  ref <- allocate()
  if ref = null
    collect()
    ref <- allocate()
    if ref = null
      error "Out␣of␣Memory"
  return ref
```

Algorithms > Copy Collection

```
atomic allocate(size):
  result <- free
  newfree <- result + size
  if newfree > top
    return null
  free <- newfree
  return result
```

Algorithms > Copy Collection

```
atomic collect():
  flip()
  initialise(workList)
  /* first copy the roots */
  for field in Roots
    process(field)
  /* then the internal references */
  while not isEmpy(workList)
    ref <- remove(workList)
    scan(ref)
```

Algorithms > Copy Collection

```
process(field):
  fromRef <- *field
  if fromRef <> null
    *field <- forward(fromRef)
```

```
scan(ref):
  for field in Pointers(ref)
    process(field)
```

Algorithms > Copy Collection

```
forward(fromRef):
  toRef <- forwardingAddress(fromRef)
  if toRef = null
    toRef = copy(fromRef)
  return toRef
```

Algorithms > Copy Collection

```
copy(fromRef):
  toRef <- free
  free <- free + size(fromRef)
  move(fromRef,toRef)
  forwardingAddress(fromRef) <- toRef
  add(worklist, toRef)
  return toRef
```

Algorithms > Generational Garbage Collection

- “Weak Generational Hypothesis”:
- most objects survive for short periods
- few references from older to new objects

Algorithms > Generational Garbage Collection

- idea:
- organize heap into regions of increasingly longer-lived objects
- the regions are called “generations”
- youngest generation is called “Eden”
- contains objects just created
- changes faster than all others

Algorithms > Generational Garbage Collection

- long-lived objects are moved to another “generation”
- a GGC is efficient because it spends most of its time at “Eden”
- memory recovered here is usually enough to keep app going
- ignore the other generations most of the time
- can use different GC algorithms for each generation

Performance

- which garbage collector to use?
- criteria:
- impact on application throughput
- memory footprint
- latency

Performance

- throughput:
- assume GC running α ms out of runtime β ms
- throughput = $\frac{(\beta-\alpha)}{\beta}$
- e.g., GC active 50ms every second ($\alpha = 50$ms, 1s$=1000$ms)
- e.g., throughput = $(1000 - 50)/1000 = 95\%$

Performance

- memory overhead:
- do you need extra memory to perform GC?
- e.g., Copy Collection
- latency:
- "real-time" (e.g., reference count)
- "stop world" (e.g., Mark&Sweep, Copy Collector)
- latency: Web app $\sim$ 1s, GUI $\sim$ 100ms, real-time $\sim$ 1μs

Garbage Collection in Java

- Java uses Generational Garbage Collection
- the memory used by JVM is divided as follows:
- non-Heap: loaded classes, “permanent generation” objects
- Heap: two regions for “young” and “tenured” objects
- “young” region divided into: “Eden”, S0 and S1
- objects start in “Eden”

Garbage Collection in Java

- when “Eden” is full, Java performs “minor GC”
- during “minor GC” objects copied between “Eden”/S0/S1
- (see detailed operations on “Eden”/S0/S1 during “minor GC”)
- objects that survive several “minor GC” promoted to “tenured”
- also promoted when “S0” and “S1” are filled

Garbage Collection in Java

- we can use different algorithms to GC these regions
- “minor GC” young objects (more frequent, needs to be faster)
- e.g., minor GC - Mark&Sweep
- “major GC” tenured objects (less frequent, ”stop the world”)
- e.g., major GC - Copy Collection

Garbage Collection in Java > Serial Collector

- serial collector:
- single-threaded
- “stop the world” / monolithic
- efficient (no need for synchronization with other threads)
- Java option `-XX:+UseSerialGC`

Garbage Collection in Java > Serial Collector

- serial collector (cont.):
- “young” collected when “Eden” full
- or when `System.gc()` is called
- “tenured” uses Mark & Sweep Compact
- triggered when no space in “tenured”
- or when `System.gc()` is called
- well suited for single-core processors
- good overall performance for 128MB $\leq |H| \leq$ 256MB

Garbage Collection in Java > Parallel Collector

- parallel collector:
- multithreaded
- "stop the world" / monolithic
- Java options: `-XX:+UseParallelGC`
- multiple parameters, e.g.
- number of threads: `-XX:ParallelGCThreads=<N>`

Garbage Collection in Java > Parallel Collector

- parallel collector (cont.):
- triggers are same as serial
- “Eden” is full triggers “minor GC”
- “tenured” is full triggers “major GC”
- or both if `System.gc()` is called
- best option for multicore processors
- best overall throughput
- works well for $|H| \leq 1$GB

Garbage Collection in Java $>$ CMS

- parallel collector variant:
- Concurrent Mark & Sweep (CMS)
- runs concurrently with application / not monolithic
- does not compact heap
- Java option: `-XX:+UseConcMarkSweepGC`
- works well for $|H| > 1\text{GB}$

Garbage Collection in Java $>$ CMS

- better when application responsiveness is important
- known issues:
- lower application throughput
- requires $\sim$ 20-30% extra memory

Garbage Collection in Java $>$ G1

- Garbage First Algorithm (G1):
- targeted for server-caliber multiprocessor machines
- scales for $|H| \sim$ tens of GBs or larger, more than 50% live
- some parts run concurrently with application
- tradeoff between more, but shorter, collection pauses
- application throughput also tends to be slightly lower
- G1 is the default collector for current JVM version (Java 18)

Garbage Collection in Java > G1

- partitions Heap into set of equally sized contiguous regions
- a region is the unit of memory (de)allocation
- regions are empty or assigned to “young” or “tenured”
- in general, “young” and “tenured” are not contiguous
- just before a collection, G1 knows which regions are mostly empty (low live %)
- it reclaims this memory first
- hence the name “G1” - “garbage first”
- memory reclaimed may be enough to resume app

References

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