

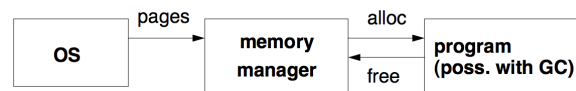
Lecture 17

Introduction to Garbage Collection

- I. Memory Management
- II. Why is Automatic GC Important and Hard?
- III. Reference Counting
- IV. Basic Trace-Based GC
- V. Copying Collectors

Readings: Chapter 7.4-7.6.4

I. Basic Memory Management



- **Tasks of memory manager:**
 - keep track of free space and respond to malloc and free
- **Starting point:** One large contiguous space

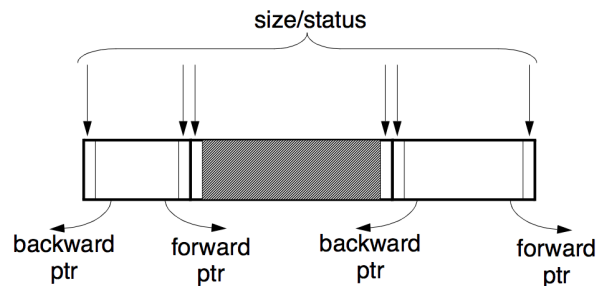
- **alloc:**
 - find big enough hole, get space from OS if necessary
 - decide where to allocate, creates small holes if not a perfect fit
- **free:**
 - coalesce adjacent free space to create larger space

Allocation Algorithm

- **Performance consideration**
 - **Space efficiency**
 - too many small holes that cannot be used
 - **Time**
 - dominated by allocations of small chunks
(cost of large chunk amortized by more computation)
 - **Spatial locality**
 - more compact is better (best if all space is coalesced)
- **Algorithms**
 - best fit: best utilization
 - next fit:
 - improves spatial locality because
consecutively allocated data tend to have similar life times

Two Data Structures

- **Boundary tags**
 - (for coalescing)
- **Doubly-linked embedded list**
 - (for keeping space in ascending-size order)



II. Why Automatic Memory Management?

- Perfect

| | live | dead |
|-------------|------|------|
| not deleted | ✓ | --- |
| deleted | --- | ✓ |

- Manual management

| | live | dead |
|-------------|------|------|
| not deleted | | |
| deleted | | |

- Assume for now the target language is Java

What is Garbage?

When is an Object not Reachable?

- **Mutator (the program)**
 - New / malloc: (creates objects)
 - Store p in a pointer variable or field in an object

- Load
- Procedure calls

- **Important property**
 - once an object becomes unreachable, stays unreachable!

How to Find Unreachable Nodes?

III. Reference Counting

- Free objects as they transition from "reachable" to "unreachable"
- Keep a count of pointers to each object
- Zero reference -> not reachable
 - When the reference count of an object = 0
 - delete object
 - subtract reference counts of objects it points to
 - recurse if necessary
- Not reachable -> zero reference?

- Cost
 - overhead for each statement that changes ref. counts

IV. Why is Trace-Based GC Hard?

- **Reasons**
 - Requires complementing the reachability set - that's a large set
 - Interacts with resource management: memory

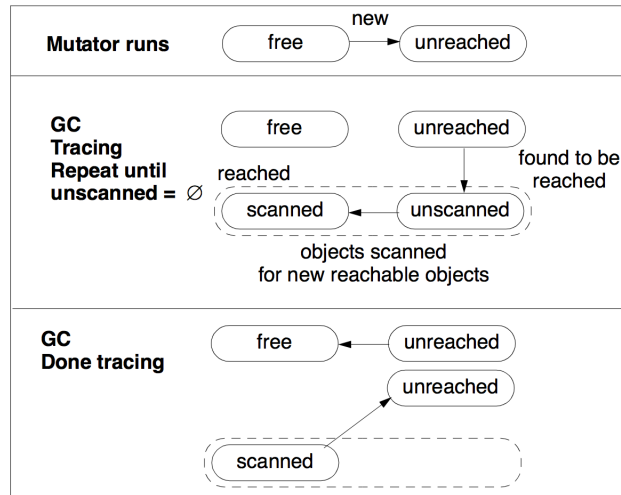
Trace-based GC

- **Reachable objects**
 - Root set: (directly accessible by prog. without deref'ing pointers)
 - objects on the stack, globals, static field members
 - + objects reached transitively from ptrs in the root set.
- **Complication due to compiler optimizations**
 - Registers may hold pointers
 - Optimizations (e.g. strength reduction, common subexpressions) may generate pointers to the middle of an object
 - Solutions
 - ensure that a "base pointer" is available in the root set
 - compiler writes out information to decipher registers and compiler-generated variables (may restrict the program points where GC is allowed)

Baker's Algorithm

- **Data structures**
 - Free: a list of free space
 - Unscanned: a work list
 - Unreached: a list of allocated objects
 - Scanned: a list of scanned objects
- **Algorithm**
 - Scanned = \emptyset
 - Move objects in root set from Unreached to Unscanned
 - While Unscanned $\neq \emptyset$
 - move object o from Unscanned to Scanned
 - scan o , move newly reached objects from Unreached to Unscanned
 - Free = Free \cup Unreached
 - Unreached = Scanned

Trace-Based GC: Memory Life-Cycle



When Should We GC?

Frequency of GC

- **How many objects?**
 - Language dependent, for example, Java:
 - all non-primitive objects are allocated on the heap
 - all elements in an array are individually allocated
 - "Escape" analysis is useful
 - object escapes if it is visible to caller
 - allocate object on the stack if it does not escape
- **How long do objects live?**
 - Objects die young
- **Cost of reachability analysis: depends on reachable objects**
 - Less frequent: faster overall, requires more memory

Performance Metric

| | Reference Counting | Trace Based |
|------------------------|--------------------|-------------|
| Space reclaimed | | |
| Overall execution time | | |
| Space usage | | |
| Pause time | | |
| Program locality | | |

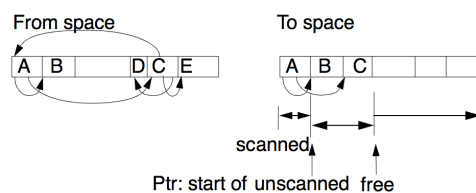
Copying Collector

- **To improve data locality**
 - place all live objects in contiguous locations
- **Memory separated into 2 (semi-)spaces: From and To**

- **Allocate objects in one**
- When (nearly) full, invoke *GC*, which copies reachable objects to the other space.
- Swap the roles of semi-spaces and repeat

Copying Collector (Continued)

- **Algorithm**



- $UnScanned = Free = \text{Start of To space}$
- Copy root set of objects space after *Free*, update *Free*;
- While $UnScanned \neq Free$
 - scan o, object at *UnScanned*
 - copy all newly reached objects to space after *Free*, update *Free*
 - update pointers in o
 - update *UnScanned*

Conclusions

- **Manual GC is error-prone**
 - Memory leaks & dangling pointers
- **Automatic GC: eliminate unreachable objects, not dead objects**
 - May still leak memory, if pointers to unused data exist
- **Reference counting**
 - Delete objects when their reference counts go to 0
 - Expensive
 - Cannot collect circular data structures
- **Trace-based GC**
 - Find all reachable objects, complement to get unreachable
 - 4 states: free, unreached unscanned, scanned
 - Stop-the-world GC: Baker's algorithm has a long pause time
 - Copying collector improves data locality