Virtual Memory

Explicit Memory Management

Freelists

Buddy System
Explicit Garbage Collection

- Java, C, C++ have new operator / malloc call that allocates new memory
- How do we get memory back when the object is not needed any longer?
- Explicit garbage collection (C, C++)
  - delete operator / free call destroys object, allows reuse of its memory; programmer decides how to collect garbage
  - makes modular programming difficult—have to know what code "owns" every object so that objects are deleted exactly once

Automatic Garbage Collection

- The other alternative: automatically collect garbage!
- Usually most complex part of the run-time environment
- Want to delete objects automatically if they won't be used again: undecidable
- Conservative: delete only objects that definitely won't be used again
- Reachability: objects definitely won't be used again if there is no way to reach them from root references that are always accessible (globals, stack, registers)

Object Graph

- Stack, registers are treated as the roots of the object graph. Anything not reachable from roots is garbage
- How can non-reachable objects be reclaimed efficiently?
  Compiler can help

Algorithm 1: Reference Counting

- Idea: associate a reference count with each allocated block (reference count = the number of references (pointers) pointing to the block)
- Keep track of reference counts
  - For an assignment x = Expr, increment the reference count of the new block x is pointing to
  - Also decrement the reference count of the block x was previously pointing to
- When number of incoming pointers is zero, object is unreachable: garbage

Reference Counts

- ... how about cycles?

Reference Counts

- Reference counting doesn't detect cycles!
Performance Problems

- Consider assignment: \( x.f = y \)
- Without ref-counts: \([tx += \text{off}] = ty\)
- With ref-counts:
  \( t_1 = (tx + f_.\text{off}) \); \( c = [t_1 + \text{refcnt}] \); \( c = c - 1 \); \( [t_1 + \text{refcnt}] = c \); if \( c == 0 \) goto L1 else goto L2; L1: call release Y_object(t1); L2: \( c = [ty + \text{refcnt}] \); \( c = c + 1 \); \( [ty + \text{refcnt}] = ty \);
- Data-flow analysis can be used to avoid unnecessary increments & decrements
- Large run-time overhead
- Result: reference counting not used much by real language implementations

Algorithm 2: Mark and Sweep

- Classic algorithm with two phases
- Phase 1: Mark all reachable objects
  - Start from roots and traverse graph forward marking every object reached
- Phase 2: Sweep up the garbage
  - Walk over all allocated objects and check for marks
  - Unmarked objects are reclaimed
  - Marked objects have their marks cleared
  - Optional: compact all live objects in heap

Traversing the Object Graph

Implementing Mark Phase

- Mark and sweep generally implemented as depth-first traversal of object graph
- Has natural recursive implementation
- What happens when we try to mark a long linked list recursively?

Pointer Reversal

- Idea: during DFS, each pointer only followed once. Can reverse pointers after following them -- no stack needed! (Deutsch-Waite-Schorr algorithm)
- Implication: objects are broken while being traversed; all computation over objects must be halted during mark phase (oops)

Cost of Mark and Sweep

- Mark and sweep accesses all memory in use by program
  - Mark phase reads only live (reachable) data
  - Sweep phase reads all of the data (live + garbage)
- Hence, run time proportional to total amount of data!
- Can pause program for long periods!
Conservative Mark and Sweep

- Allocated storage contains both pointers and non-pointers; integers may look like pointers
- Issues: precise versus conservative collection
- Treating a pointer as a non-pointer: objects may be garbage-collected even though they are still reachable and in use (unsafe)
- Treating a non-pointer as a pointer: objects are not garbage collected even though they are not pointed to (safe, but less precise)
- Conservative collection: assumes things are pointers unless they can't be; requires no language support (works for C!)

Algorithm 3: Copying Collection

- Like mark & sweep: collects all garbage
- Basic idea: use two memory heaps
  - one heap in use by program
  - other sits idle until GC requires it
- GC mechanism:
  - copy all live objects from active heap (from-space) to the other (to-space)
  - dead objects discarded during the copy process
  - heaps then switch roles
- Issue: must rewrite referencing relations between objects

Copying Collection (Cheney)

- Copy = move all root objects from from-space to to-space
- From space traversed breadth-first from roots, objects encountered are copied to top of to-space.

Benefits of Copying Collection

- Once scan=next, all uncopied objects are garbage. Root pointers (registers, stack) are swung to point into to-space, making it active
- Good:
  - Simple, no stack space needed
  - Run time proportional to # live objects
  - Automatically eliminates fragmentation by compacting memory
  - malloc(n) implemented as (top = top + n)
- Bad:
  - Precise pointer information required
  - Twice as much memory used

Incremental and Concurrent GC

- GC pauses avoided by doing GC incrementally; collector & program run at same time
- Program only holds pointers to to-space
- On field fetch, if pointer to from-space, copy object and fix pointer
- On swap, copy roots and fix stack/registers

Generational GC

- Observation: if an object has been reachable for a long time, it is likely to remain so
- In long-running system, mark & sweep, copying collection waste time, cache scanning/copying older objects
- Approach: assign heap objects to different generations \(G_0, G_1, G_2, \ldots\)
- Generation \(G_0\) contains newest objects, most likely to become garbage (<10% live)
Generations

- Consider a two-generation system. $G_0 =$ new objects, $G_1 =$ tenured objects
- New generation is scanned for garbage much more often than tenured objects
- New objects eventually given tenure if they last long enough
- Roots of garbage collection for collecting $G_0$ include all objects in $G_1$ (as well as stack, registers)

Remembered Set

- How to avoid scanning all tenured objects?
- In practice, few tenured objects will point to new objects; unusual for an object to point to a newer object
- Can only happen if older object is modified long after creation to point to new object
- Compiler inserts extra code on object field pointer writes to catch modifications to older objects—older objects are remembered set for scanning during GC, tiny fraction of $G_1$

Summary

- Garbage collection is an aspect of the program environment with implications for compilation
- Important language feature for writing modular code
- IC: Boehm/Demers/Weiser collector
    - conservative: no compiler support needed
    - generational: avoids touching lots of memory
    - incremental: avoids long pauses
    - true concurrent (multi-processor) extension exist