CS 412/413

Introduction to
Compilers and Translators
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Lecture 31: Garbage collection
17 April 00

Administration

- Prelim 2 graded
- Programming Assignment 5 due Friday

Schedule

Topics for remainder of course:

- Post-compiler support
  - Garbage collection
  - Linking and loading
  - Meta-objects
  - JITs and interpreters
- Advanced language support
  - First-class functions
  - Exceptions
  - Parametric polymorphism

Outline

- Overview of various garbage collection techniques and impact on compiled code:
  - Mark and sweep garbage collection
  - Reference counting GC
  - Copying GC
  - Generational GC
- More topics in Appel:
  - concurrent/incremental garbage collection
  - heap management

Garbage collection

- Garbage collection: the process of reclaiming memory unused by the program
- Usually most complex part of the run-time environment
- Implications for code generation

Problem

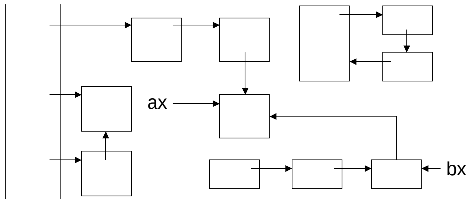
- Java, Iota$^+$, C++ have new operator that allocates new memory
- How do we get it back when the object is not needed any longer?
- C++: explicit memory management
  - delete operator destroys object, allows reuse of its memory -- programmer decides how to collect garbage
  - makes modular programming difficult—have to know what code “owns” every object so that objects are deleted exactly once

Automatic garbage collection

- 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

Object graph

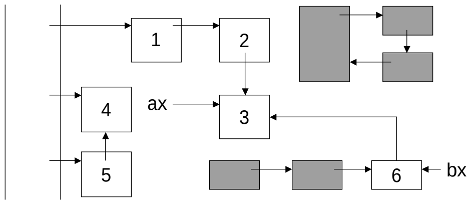
- Stack, registers are treated as the *roots* of the object graph. Anything not reachable from roots is garbage
- How can non-reachable objects can be reclaimed efficiently? Compiler can help



Mark and sweep collection

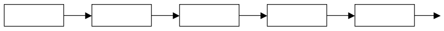
- Classic algorithm with two phases
- Phase 1: Mark all reachable objects
  - start from roots and traverse graph forward marking every object reached
- Phase 2: Sweep up the garbage
  - Walk over all allocated objects and check for marks
  - Unmarked objects are reclaimed
  - Marked objects have their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

Traversing the object graph



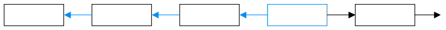
Implementing mark phase

- 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 recursion needed! (Deutsch-Waite-Schorr alg.)



- Implication: objects are broken while being traversed; all computation over objects must be halted during mark phase (oops)

Conservative Mark & Sweep

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

Cost of mark and sweep

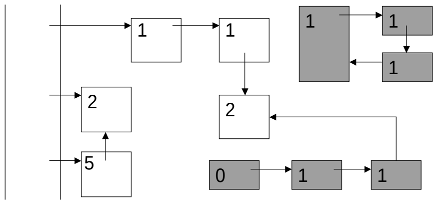
- Mark and sweep algorithm reads all memory in use by program: run time is proportional to total amount of data (live or garbage)
- Can pause program for long periods!
- Basic mark & sweep requires ability to manage heap of variable-sized objects; typical heap implementation only allocates memory in 2^n byte units to avoid fragmentation, make allocation/deallocation fast. ~30% space hit

Reference counting

- Old algorithm for automatic garbage collection: associate with every object a *reference count* that is the number of incoming pointers
- When number of incoming pointers is zero, object is unreachable: garbage
- Compiler emits extra code to increment and decrement reference counts automatically: 5-30% performance hit

Reference counts

- Reference counting doesn't detect cycles!



Performance problems

- Consider assignment x.f = y
- Without ref-counts: mov [tx + f_off], ty
- With ref-counts:

```
t1 = M[tx + f_off]; c = M[t1 + refcnt]; c = c - 1; M[t1
+ refcnt] = c; if (c == 0) goto L1 else goto L2; L1:
call release_Y_object(t1); L2: M[tx + f_off] = ty; c =
M[ty + refcnt]; c = c + 1; M[ty + refcnt] = c;
```

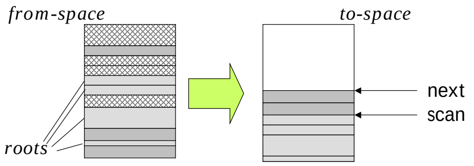
- Data-flow analysis can be used to avoid unnecessary increments & decrements
- Can pause program, overrun stack!
- Result: reference counting not used much by real language implementations

Copying collection

- Like mark & sweep: collects all garbage
- Basic idea: keep two memory heaps around. One heap in use by program; other sits idle until GC requires it
- GC copies all live objects from active heap to the other; dead objects discarded en masse. Heaps then switch roles. During collection, heaps are called *from-space* and *to-space*

Copying collection (Cheney's)

- Copying starts by moving 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.

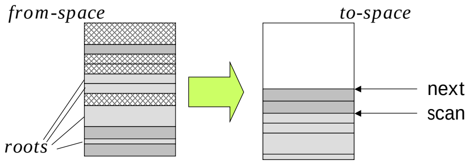


Benefits of copying collection

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

Baker's Concurrent GC

- GC pauses avoided by doing GC incrementally; collector & program both run
- Program only holds pointers to to-space
- On field fetch, if pointer to from-space, copy object and fix pointer (extra fetch code: 20%)
- On swap, copy roots and fix stack/registers



Generational GC

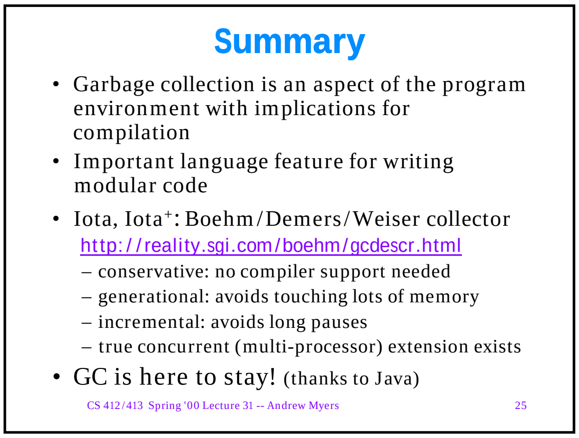
- Observation: if an object has been reachable for a long time, it is likely to remain so
- In long-running system, mark & sweep, copying collection waste time, cache scanning/copying older objects
- Approach: assign objects to different *generations* G_0, G_1, G_2,…
- Generation G_0 contains newest 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
- Iota, Iota$^+$: Boehm/Demers/Weiser collector
  http://reality.sgi.com/boehm/gcdescr.html
  - conservative: no compiler support needed
  - generational: avoids touching lots of memory
  - incremental: avoids long pauses
  - true concurrent (multi-processor) extension exists
- GC is here to stay! (thanks to Java)