CS412/413

Introduction to Compilers

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Lecture 35: Garbage Collection

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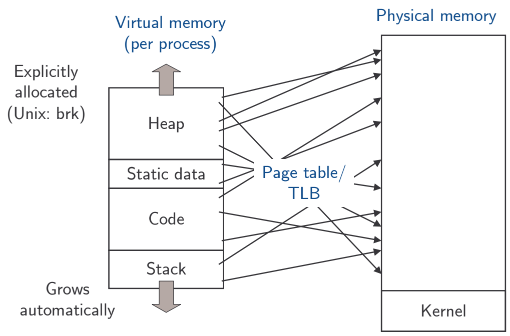
Outline

- Virtual memory
- Explicit memory management
- Garbage collection techniques
  - Reference counting
  - Mark and sweep
  - Copying GC
  - Concurrent/incremental GC
  - Generational GC
- Book: "Garbage Collection", by R. Jones and R. Lins

Virtual Memory



Explicit Memory Management

- Unix (libc) interface:

  `void* malloc(long n)` : allocate `n` bytes of storage on the heap and return its address

  `void free(void *addr)` : release storage allocated by `malloc` at address `addr`

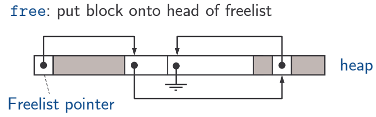
- User-level library manages heap, issues `brk` calls when necessary

Freelists

- Blocks of unused memory stored in freelist(s)

  `malloc`: find usable block on freelist

  `free`: put block onto head of freelist



- Simple, but fragmentation ruins the heap
- External fragmentation = small free blocks become scattered in the heap
  - Cannot allocate a large block even if the sum of all free blocks is larger than the requested size

Buddy System

- Idea 1: freelists for different allocation sizes
  - malloc, free are O(1)
- Idea 2: freelist sizes are powers of two: 2, 4, 8, 16, …
  - Blocks subdivided recursively: each has buddy
  - Round requested block size to the nearest power of 2
  - Allocate a free block if available
  - Otherwise, (recursively) split a larger block and put all the other blocks in the free list
  - Reverse operation: coalesce (with buddy, if free, not split)
- Internal fragmentation: allocate larger blocks because of rounding
- Trade external fragmentation for internal fragmentation

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, because one has to know what code "owns" every object so that objects are deleted exactly once

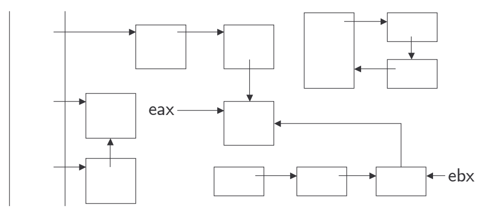
Automatic Garbage Collection

- The other alternative: automatically collect garbage

- Usually most complex part of the run-time environment
- 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 can be reclaimed efficiently? Compiler can help



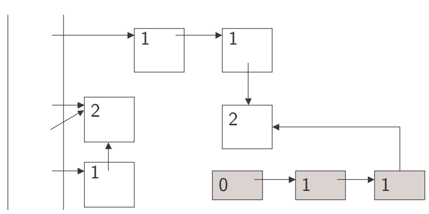
Algorithm 1: Reference Counting

- 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 = exp`, 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

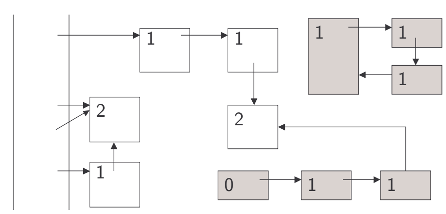
- When number of incoming pointers is zero, object is unreachable: garbage

Reference Counts



- … how about cycles?

Reference Counts



- Reference counting doesn't detect cycles!

Performance Problems

- Consider assignment `x.f = y`
- Without ref-counts: `*(tx+ off) = ty`
- With ref-counts:

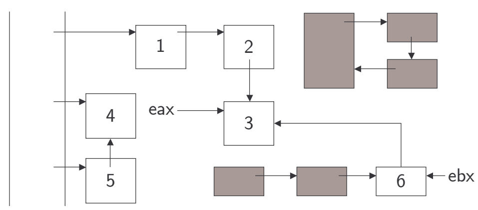
```
t1 = *(tx + f_off); c = *(t1 + refcnt); c = c - 1;
*(t1 + refcnt) = c; if (c > 0) goto L2; free(t1);
L2: c = *(ty + refcnt); c = c + 1; *(ty + refcnt)
= c; *(tx + f_off) = ty;
```

- 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

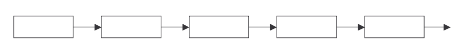
- Classic algorithm with two phases
- Phase 1: Mark all reachable objects
  - start from roots and traverse graph forward marking every object reached
- Phase 2: Sweep up the garbage
  - Walk over all allocated objects and check for marks
  - Unmarked objects are reclaimed
  - Marked objects have their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

Traversing the Object Graph



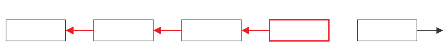
Implementing Mark Phase

- 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 the 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

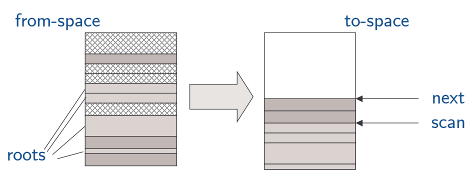
- Allocated storage contains both pointers and non-pointers; integers may look like pointers
- Issues: precise versus conservative collection
- Treating a pointer as a non-pointer: objects may be garbage-collected even though they are still reachable and in use (unsafe)
- Treating a non-pointer as a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

Algorithm 3: Copying Collection

- Like mark & sweep: collects all garbage
- Basic idea: use two memory heaps (two "spaces")
  - one heap in use by program
  - other sits idle until GC uses it
- GC mechanism:
  - Copy all live objects from active heap (from-space) to the other (to-space)
  - Dead objects discarded during the copy process
  - The two spaces 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.

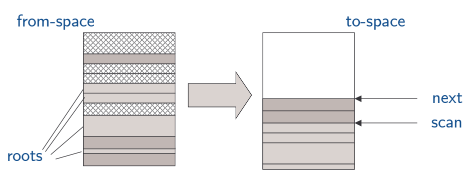


Benefits of Copying Collection

- 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,...
- Generation G_0 contains newest objects, most likely to quickly 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
  http://www.hpl.hp.com/personal/Hans˜Boehm/gc/
  – conservative: no compiler support needed
  – generational: avoids touching lots of memory
  – incremental: avoids long pauses
  – true concurrent (multi-processor) extension exist