CSc 520

Principles of Programming Languages

8 : Garbage Collection — Mark and Sweep

Christian Collberg

collberg+520@gmail.com

Department of Computer Science

University of Arizona

Garbage Collection Issues

Finding the Object Graph

Finding the roots: The dynamic objects in a program form a graph. Most GC algorithms need to traverse this graph. The roots of the graph can be in

1. global variables
2. registers
3. local variables/formal parameters on the stack.

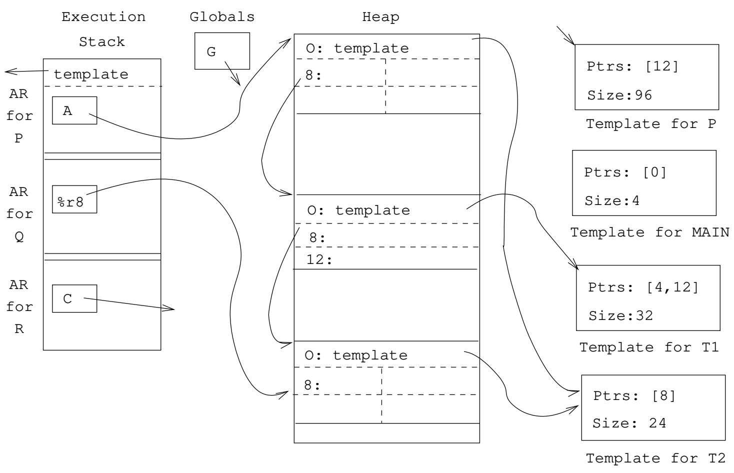
Hence, the compiler must communicate to the GC which registers/variables contain roots.

Finding the Object Graph…

Finding internal pointers: Structured variables (arrays, records, objects) may contain internal pointers. These must be known to the GC so that it can traverse the graph. Hence, the compiler must communicate to the GC the type of each dynamic object and the internal structure of each type.

Finding the beginning of objects: What happens if the only pointer to an object points somewhere in the middle of the object? We must either be able to find the beginning of the object, or make sure the compiler does not generate such code.

Finding the Object Graph…



Pointer Maps

- The internal structure of activation records & structured variables is described by run-time templates.
- Every run-time object has an extra word that points to a *type descriptor* (or *Temaplate*), a structure describing which words in the object are pointers. This map is constructed at compile-time and stored statically in the data segment of the executable.

Pointer Maps…

- When the GC is invoked, registers may also contain valid pointers. The compiler must therefore also generate (for every point where the GC may be called) a *pointer map* that describes which registers hold live pointers at this point. For this reason, we usually only allow the GC to run at certain points, often the points where new is called.
- We must also provide pointer maps for every function call point. A function P may call Q which calls new which invokes the GC. We need to know which words in P's activation record that at this point contain live pointers.

Pointer Maps…

- How does the GC look up which pointer map belongs to a particular call to procedure P at a particular address a? The pointer maps are indexed by the return address of P! So, to traverse the stack of activation records, the GC looks at each frame, extracts the return address, finds the pointer map for that address, and extracts each pointer according to the map.

The Mark-and-Sweep Algorithm

Algorithm: Mark and Sweep

- The basic idea behind Mark-and-Sweep is to traverse and mark all the cells that can be reached from the root cells.
- A root cell is any pointer on the stack or in global memory which points to objects on the heap.
- Once all the live cells (those which are pointed to by a global variable or some other live cells) have been marked, we scan through the heap and separate the live data from the garbage.
  - If we are dealing with equal size objects only (this is the case in LISP, for example) the we scan the heap and link all the unmarked objects onto the free list. At the same time we can unmark the live cells.

Algorithm: Mark and Sweep...

- - If we have cells of different sizes, just linking the freed objects together may result in heap fragmentation. Instead we need to compact the heap, by collecting live cells together in a contiguous memory area on the heap and doing the same with the garbage cells in another area.

Algorithm: Mark and Sweep...

Marking Phase:

1. Mark all objects `unmarked`.
2. Find all roots, i.e. heap pointers in stack, regs & globals.
3. Mark reachable blocks using a depth first search starting at the roots.
   (a) DFS may run out of stack space!
   (b) Use non-recursive (Deutsch-Schorr-Waite) DFS.

Scanning Phase:

same-size-cells Scan heap and put un-marked (non-reachable) cells back on free-list.

different-size-cells Compact the heap to prevent fragmentation.

Marking Phase

- A straight-forward implementation of mark and sweep may run into memory problems itself! A depth-first-search makes use of a stack, and the size of the stack will be the same as the depth of the object graph.
- Remember that the stack and the heap share the same memory space, and may even grow towards eachother.
- So, if we're out of luck we might run into this situation:
  - the heap is full (otherwise we wouldn't be gc:ing!),
  - the object graph is deep,
  - we run out of stack space during the marking phase.

  We're now out of memory alltogether. Difficult to recover from!

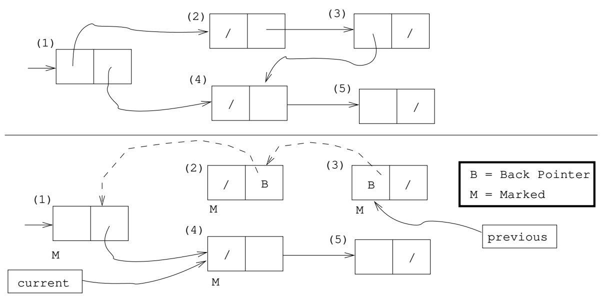
Marking Phase…

- Fortunately, there is a smart algorithm for marking in constant space, called the Deutsch-Schorr-Waite algorithm. Actually, it was developed simultaneously by Peter Deutsch and by Herbert Schorr and W. M. Waite.
- The basic idea is to store the DFS stack in the object graph itself. When a new node (object) is encountered
  1. we set the "marked"-bit to 1,
  2. the node (object) is made to point to the previous node,
  3. two global variables `current` and `previous` are updated.

  `current` points to the current cell, `previous` to the previously visited cell.

Marking: "Look Ma, No Stack!"

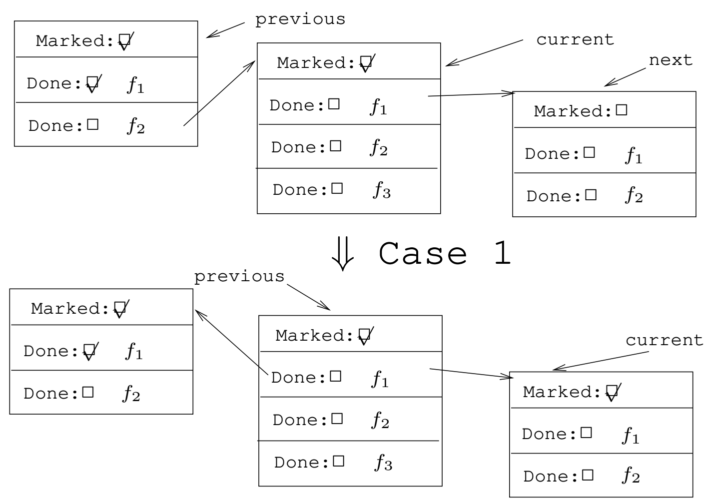
- Use pointer reversal to encode the DFS stack in the object graph itself.
- When the DFS reaches a new cell, change a pointer in the cell to point back to the DFS parent cell. When we can go no deeper, return, following the back links, restoring the links.



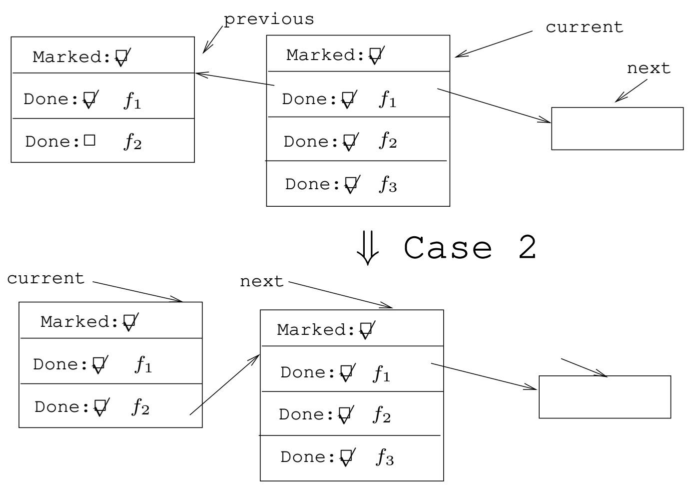
Marking: "Look Ma, No Stack!"…

```
LOOP
  CASE 1:  current's fields are not Done
    i := next field of current
        that's not Done;
    next := current↑.f_i;
    IF next↑ isn't marked THEN
      current↑.f_i := previous;
      previous := current;
      current := next;
    ENDIF;
  CASE 2:  current's fields are Done
    next := current;
    current := previous;
    i := next field of current
        that's not Done;
    previous := current↑.f_i;
    current↑.f_i := next;
ENDLOOP
```

Marking: “Look Ma, No Stack!”…

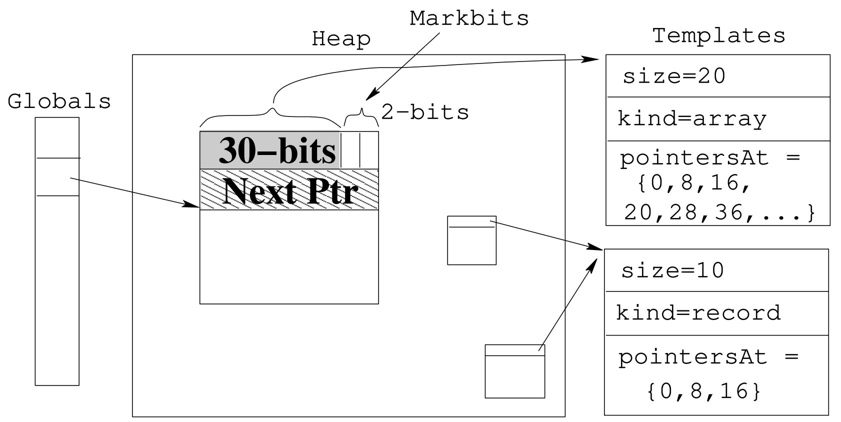


Marking: “Look Ma, No Stack!”…



Where do the markbits go???

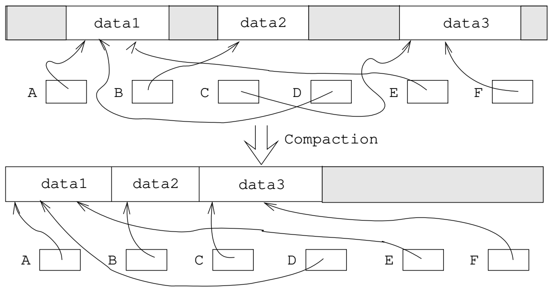
- Where do we store the extra mark bits for every object? An extra word in the header would be wastefull!



Where do the markbits go…

- Align the templates on a word-boundary, then the two lowest bit of the template-pointers will always be zero — use these bits for markers!
- We’re somehow going to have to store which pointer to deal with next during pointer reversal. We could use the same tricks as above, set the low order bits of pointers we’ve dealt with to 1, but then we need to search through the entire object every time for the next pointer to deal with — expensive.
- Note that, just like in the `malloc` implementation, the pointer to an object points *right after* the header. So, the header is at address `ptr-8`, and the data in each object is at `ptr`, `ptr+4`, etc.

Sweeping: Compaction

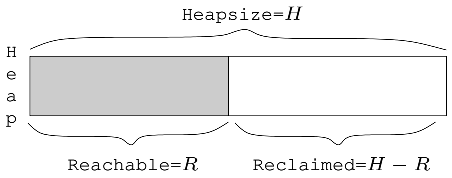


1. Calculate the forwarding address of each cell.
2. Store the forwarding address of cell B in B.forw_addr.
3. If p points to cell B, replace p with B.forw_addr.
4. Move all cells to their forwarding addresses.

Cost of Garbage Collection

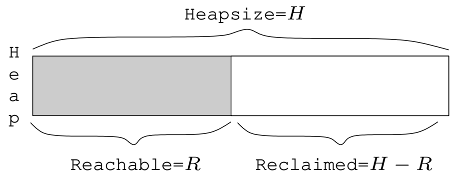
Cost of Garbage Collection

- The size of the heap is H, the amount of reachable memory is R, the amount of memory reclaimed is $H - R$.
- What is the cost of the different GC algorithms?



$$\textit{amortized GC cost} = \frac{\textit{time spent in GC}}{\textit{amount of garbage collected}} = \frac{\textit{time spent in GC}}{H - R}$$

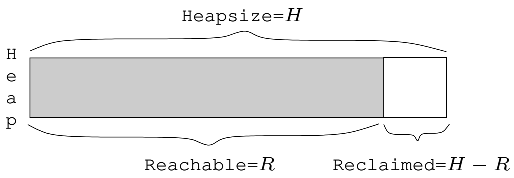
Cost of GC — Mark-and-Sweep



- The mark phase touches all live nodes. Hence, it takes time $c_1 R$, for some constant c_1. $c_1 \approx 10$?
- The sweep phase touches the whole heap. Hence, it takes time $c_2 H$, for some constant c_2. $c_2 \approx 3$?

$$\textit{GC cost} = \frac{c_1 R + c_2 H}{H - R} \approx \frac{10R + 3H}{H - R}$$

Cost of GC — Mark-and-Sweep…



$$\textit{GC cost} = \frac{c_1 R + c_2 H}{H - R} \approx \frac{10R + 3H}{H - R}$$

- If $H \approx R$ we reclaim very litte, and the cost of GC goes up. In this case the GC should grow the heap (increase H).

Readings and References

- Read Scott, pp. 383–389.