1 INTRODUCTION

Garbage collection algorithms can be classified into two broad categories: (1) some algorithms mark all live nodes and consider the rest as dead and (2) others attempt to identify dead nodes directly. Traditional mark-sweep-compact collectors (Fischer and LeBlanc, 1991) belong to the first category. This approach suffers from the long interrupt to normal computer operations because the entire virtual memory must be examined. Given today’s increasingly large virtual memory, the interrupts become quite intolerable.

Algorithms in the second category make use of other information, mostly reference counts of various kinds, to identify dead nodes directly (Collins, 1960; Jones and Lins, 1996). Usually, there is a counter in every node in the heap which keeps the number of references that point to that node. When a node’s counter falls to zero, it becomes a piece of garbage.

A problem with reference counting is that cyclic garbage is difficult to collect. In addition to examining nodes’ counters, a part of the virtual memory still needs to be scanned in order to identify cyclic garbage.

In algorithms based on reference counting (Collins, 1960; Jones and Lins, 1996; Lins et al., 2007), a garbage-collection decision has to be made whenever a pointer \( x \rightarrow y \) is about to be destroyed. At this time, the node \( y \) may become dead even if \( y \)'s reference count is not zero. This is because \( y \) may belong to a piece of cyclic garbage. Some aggressive collection algorithms will put \( y \) on the list of potential garbage regardless of \( y \)'s reference count. Later a trace procedure starting from \( y \) will be initiated. Other algorithms, less aggressive, will put \( y \) on the list of potential garbage only if \( y \)'s reference count falls below a threshold, such as 3. The former approach may waste time on tracing live nodes and the latter may leave cyclic garbage uncollected indefinitely. The problem with the above two approaches (and with reference counting in general) is that it is difficult to decide if \( y \) is dead when the pointer \( x \rightarrow y \) is destroyed. We propose a new garbage-collection algorithm in which each node maintains two, rather than one, reference counters, \( gc \) and \( hc \). \( gc \) is the number of references from the global variables and from the run-time stack. \( hc \) is the number of references from the heap. Our algorithm will put node \( y \) on the list of potential garbage if and only if \( y \)'s \( gc \) becomes 0. The better prediction made by our algorithm results in more efficient garbage collectors.
partial-scan algorithms (Christopher, 1984; Martinez et al., 1990) focus on cyclic garbage, which often make use of some cycle-detection techniques (Lin and Hou, 2006; Lin and Hou, 2007; Lin, 2009). In contrast, our algorithm looks for closed clusters (to be defined later) with two counters in each node. It is not necessary to spend extra time to identify cyclic structures.

Lins (Lins, 1992) extends Martinez et al.’s work (Martinez et al., 1990) by searching for cyclic garbage lazily. Redundant local searches are eliminated. Bacon et al. further incorporate concurrent search for multiprocessor systems (Bacon et al., 2001; Bacon and Rajan, 2001). It would be interesting to investigate a way to parallelize our algorithm.

The rest of this paper is organized as follows: Section 2 gives a bird’s view of the heap during run time. Our algorithm and an example are shown in Section 3. Section 4 gives a brief conclusion.

2 A BIRD’S VIEW OF THE RUN-TIME HEAP

In this paper, we assume that the computer memory is partitioned into two areas: the global area (which contains global variables and the run-time stack) and the run-time heap. The heap is partitioned into nodes. For the sake of simplicity for presenting our algorithm, we assume that no reference points to a node in the global area.

Figure 1 shows a snapshot of a program’s run-time memory at a certain instant. There are three nodes A, B, and C in the global area. The nodes that are reachable from A are classified into the following categories:

1. The P nodes are reachable only from A but not from any other pointers in the global variables, the stack, and the heap. When the reference in A is destroyed, all P nodes become dead. The P nodes constitutes the closed cluster induced by node A, which is defined as follows (Yang et al., 2009).

Definition. The closed cluster induced by a node n, denoted as CC(n), in a directed graph is the largest set of nodes that are reachable from n but are not reachable from any node outside the closed cluster.

2. The Q nodes are reachable from A and some nodes D in the heap. The Q nodes are unreachable from any other pointers in the global variables and the stack. If D is actually dead, the associated Q nodes are really P nodes. However, since most dead nodes are not reclaimed immediately when they become garbage, the Q nodes may remain uncollected garbage for a period of time.

3. The R nodes are reachable only from A and B but not from any other pointers in the global variables and the stack. After the references in A and B are destroyed, all R nodes become dead. The R nodes corresponds to the subset \( \{A, B\} \).

4. The S nodes are reachable only from A and C but not from any other pointers in the global area. The S nodes corresponds to the subset \( \{A, C\} \).

5. The T nodes are reachable from A, B, and C. Similarly, the T nodes correspond to the subset \( \{A, B, C\} \).

When the reference in A is destroyed, for e.g. when a new value is assigned to A, all the P nodes become garbage. The Q nodes are reachable from D, which is unclaimed garbage, and cannot be reclaimed until D is reclaimed. Our garbage-collection algorithm performs a few (possibly incomplete) depth-first traversals, starting from node A, in order to free all the P nodes. The P nodes constitutes the closed cluster induced by node A, which is defined as follows (Yang et al., 2009).

Definition. The closed cluster induced by a node n, denoted as CC(n), in a directed graph is the largest set of nodes that are reachable from n but are not reachable from any node outside the closed cluster.

3 OUR ALGORITHM

Our garbage-collection algorithm is shown in Figures 2 and 3.

During the execution of a program, garbage collection may be activated several times. Because information gathered in different garbage-collection runs is mixed together, we use the global variable currentrun to distinguish information gathered in different runs. This variable saves the trouble of erasing the information after a collection run.

Each node y (in the heap) maintains two refer-
1. **global int** currentrun := 0;

1. **procedure** CalculateCC(x : node)
2. currentrun := currentrun + 1;
3. dfsdead(x); /* x is the starting node, i.e., the root of the dfs tree. */
4. hcount(x) := hcount(x) + 1;
5. search(x);
6. hcount(x) := hcount(x) - 1;
7. collect(x); /* The collect call is optional. */
8. **end** CalculateCC

1. **procedure** dfsdead(y : node)
2. if lastvisit(y) < currentrun then begin
3. /* This is the first visit to node y. */
4. lastvisit(y) := currentrun;
5. β(y) := 1;
6. if gcount(y) = 0 then begin
7. status(y) := dead; /* Assume y is dead initially. */
8. for each outgoing edge of y (say y → z) do dfsdead(z);
9. **end**
10. else begin /* gcount(y) > 0, which means y is definitely live. */
11. status(y) := live;
12. for each outgoing edge of y (say y → z) do dfslive(z);
13. **end**
14. else β(y) := β(y) + 1; /* lastvisit(y) = currentrun */
15. **end** dfsdead

1. **procedure** dfslive(y : node)
2. if lastvisit(y) = currentrun and status(y) = live then return;
3. lastvisit(y) := currentrun;
4. status(y) := live;
5. for each outgoing edge of y (say y → z) do dfslive(z);
6. **end** dfslive

**Figure 2:** The CalculateCC algorithm.

3. reference counters: gcount and hcount. Gcount(y) contains the number of references from the global area to y. Hcount(y) contains the number of references from the heap to y. Since our algorithm will perform depth-first traversals in the heap, each node (in the heap) may be visited more than once. Each node y maintains a counter β(y), which records the number of times y is visited during the depth-first traversal in the current run of garbage collection.

Every node also contains a status variable, which could be dead, live, or notvisitedyet. Every node contains a lastvisit variable, which is the run number when the node was visited for the last time.

When a pointer g → h is about to be deleted and gcount(h) will become 0 after the deletion, h is a candidate for garbage collection. The procedure CalculateCC(h) will be invoked. The node h will be called the root of the new run of garbage collection. The set of nodes that are reachable from the root of a collection run is called the span of the run. Note that a complete depth-first traversal, starting from the root, of a span will visit each edge in the span exactly once. The traversal will high-light a depth-first tree (dfs-tree) in the span. The span of the current run is called the current span.

The CalculateCC(x) procedure first increments currentrun, then calls dfsdead(x) to perform a depth-first traversal, starting from node x, calls search(x) to look for dead nodes, and finally calls collect(x) to free the dead nodes. Because every node in the dfs-tree except the root x has an incoming pointer, hcount(x) is temporarily incremented by 1 before the search(x) call. Hcount(x) is decremented by 1 after the search(x) call.

**Example.** Figure 4 shows a snapshot of a computer’s memory. The numbers under the node name are the node’s gcount and hcount, respectively. For instance, gcount(a) = 0 and hcount(a) = 2. Suppose the edge q → a is about to be deleted. The garbage collector CalculateCC(a) will invoke dfsdead(a). dfsdead(a) will traverse the span, marking nodes

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4 CONCLUSIONS

We may save the root of a collection run in a buffer and do not activate the garbage collector until a sufficient number of roots have been accumulated. The above algorithm may be adapted easily (Yang et al., 2009).

Our new garbage-collection algorithm makes use of two reference counters to better decide when a node should be garbage-collected. It is better than more aggressive algorithms by reducing the possibility of tracing live nodes and it is also better than less aggressive algorithms because cyclic garbage is collected sooner.

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