Effectiveness of Garbage Collection in MIT/GNU Scheme

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Abstract—Scheme uses garbage collection for heap memory management. Ideally, garbage collectors should be able to reclaim all dead objects, i.e. objects that will not be used in future. However, garbage collectors collect only those dead objects that are not reachable from any program variable. Dead objects that are reachable from program variables are not reclaimed.

In this paper we describe our experiments to measure the effectiveness of garbage collection in MIT/GNU Scheme. We compute the drag time of objects, i.e. the time for which an object remains in heap memory after its last use. The number of dead objects and the drag time together indicate opportunities for improving garbage collection. Our experiments reveal that up to 26% of dead objects remain in memory. The average drag time is up to 37% of execution time. Overall, we observe memory saving potential ranging from 9% to 65%.

I. INTRODUCTION

Garbage collection is an attractive alternative to manual memory management because it frees the programmer from the responsibility of keeping track of object lifetimes. This makes programs easier to design, implement, understand and maintain. Ideally, a garbage collector should be able to reclaim all dead objects, i.e. objects that will not be used in future. However, this is not possible because garbage collectors conservatively approximate the liveness of an object by its reachability from a predefined set of variables called root variables (typically the set of variables on the program stack). Garbage collectors cannot distinguish between live reachable objects from dead reachable objects. Hence they collect unreachable objects only as these objects are guaranteed to be dead. This means many dead objects are left uncollected, a fact that has been confirmed by empirical studies for various languages like Haskell [10] and Java [12]–[14]. Our experiments for MIT/GNU Scheme reveal that up to 26% of dead objects remain in memory, with dead objects remaining in memory for up to 37% of execution time. Memory saving potential ranges from 9% to 65%.

A. A Motivational Example

Figure 1(a) shows a program that traverses a singly linked list. Figure 1(b) shows the memory graph at the beginning of the second iteration of the loop. The object $O_1$ is unused after the first iteration of the loop. It cannot be collected by garbage collector as it is reachable from the variable $x$. Similarly, object $O_2$ is unused after second iteration of the loop, $O_3$ after third iteration, and so on. All of these objects, though dead, will be garbage collected only after the variable $x$ goes out of scope (i.e. at the end of the outer let loop). If $x$ is nullified after its last use (line 2, first iteration of loop) the objects may be collected whenever garbage collection is invoked after their last use, even though $x$ remains in scope.

B. Background

Figure 2 shows the important events in the life of a heap object: creation, use, and garbage collection. The interval from the time of last use to the time of garbage collection is called the drag time ($\delta$) and the object is called a dead object [10], [12]–[14]. If an object is never used after creation, its drag time is the interval between its creation time and its collection time.
A large drag time indicates that the object was reachable, and hence ignored by garbage collector, long after its last use.

The number of dead objects and the drag time is a measure of improvement opportunities in garbage collection and give us an upper bound on the number of objects that could be collected over the ones collected by garbage collector. The upper bound is for a particular execution path of program. There may be no algorithm that can collect all the dead objects.

The drag time of an object can be divided into two components: (1) \( \delta_{\text{rch}} \), the interval between the last use of the object and the time when it becomes unreachable, and (2) \( \delta_{\text{gc}} \), the interval between the time when the object becomes unreachable and the time when it is collected by garbage collector. \( \delta_{\text{rch}} \) depends upon the program but is independent of the garbage collector, whereas \( \delta_{\text{gc}} \) depends heavily upon the garbage collector—algorithm used, frequency of invocation, and time of invocation. For example, for a reference count based garbage collector, \( \delta_{\text{gc}} \) is always 0 for all objects. For mark and sweep or copying collector, \( \delta_{\text{gc}} \) for an object depends upon the time when the garbage collector gets invoked after the object becomes unreachable, \( \delta_{\text{gc}} \) can typically be reduced by increasing the frequency of garbage collection (at the expense of slowing down the real computation).

C. Organization
The rest of this paper is organized as follows: In Section II we describe our setup to carry out the experiments and the benchmark programs used for measurements. Section III discusses the results of the experiments. Section IV describes the research done by others in related areas. Section V concludes the paper and provides directions for future work.

II. EXPERIMENTAL SETUP

In our experiments we measure the value of \( \delta_{\text{rch}} \), which is the characteristic of the program only and independent of the garbage collector, and hence independent of the Scheme implementation. We approximate \( \delta_{\text{gc}} \) by \( \delta \) by forcing garbage collector to be invoked at a very high frequency, thereby ensuring that \( \delta_{\text{gc}} \equiv 0 \). However, this technique does not work for incremental or generational garbage collectors, because these do not scan all objects in memory for every cycle. Therefore, even after an object has become unreachable, it may or may not be collected by next garbage collection cycle, resulting in a non-zero \( \delta_{\text{gc}} \).

We have used MIT/GNU Scheme\(^1\), as it uses a simple copying based garbage collector, which is neither incremental nor generational. It is also easy to modify the implementation to invoke garbage collector at a very high frequency.

We record the statistics associated with pairs and vectors only, ignoring all other constructs (e.g. strings) that create objects in heap. Collecting statistics for all constructs is difficult as (a) it slows down the experiments considerably, and (b) the amount of statistics generated is overwhelming—even for moderate size benchmarks, the execution goes out of memory. This restriction is not that bad because previous studies have shown that cons cells and vectors account for most of the space as well number of objects allocated in typical LISP programs [16, Section 3.7.1].

We associate a structure with every object under consideration to record the creation time and the most recent use time. Whenever garbage collector collects an object, its data is written to a log file along with the garbage collection time. The log file thus generated is post-processed to generate statistics. Section II-A and Section II-B describe the process in detail.

A. Generating Data

We associate a structure (GC_structure) to record the creation time (Create_time) and the most recent use time (Use_time) with every object under consideration. The object address is used as key for GC_structure. GC_structure also contains a flag (GC_flag) to tell whether the corresponding object was collected by the current garbage collection or not. Scheme primitives and procedures are modified to update the fields of GC_structure. We describe how this is done for primitives that operate on pairs (or lists). Similar changes are applied to primitives for vectors too.

- **Creation**: In Scheme, pairs are created using primitives, e.g. cons, list, vector->list, string->list. These primitives are modified to create the GC_structure(s) corresponding to the new pair(s) created, and populate the Create_time, while Use_time is set to an invalid value (-1).
- **Use**: Primitives like car, cdr, set-car!, set-cdr! including predicates like null?, pair?, number? are considered as use of their argument and are modified to update Use_time of corresponding GC_structure. If an object is never used, its Use_time remains -1.
- **Garbage collection**: Garbage collector in MIT/GNU Scheme is a copying collector. Before actual garbage collection, we reset the GC_flag in all GC_structures. Whenever an object is copied from working memory to free memory, corresponding GC_flag is set, and its new address is copied into the key. At the end of garbage collection, all GC_structures are scanned. If GC_flag is false, meaning the object was not copied to free memory, then the object is assumed to be collected by garbage collector.

\(^1\)Ignoring objects that are part of cycle.

\(^2\)Release 7.7.90+, from \url{http://ftp.gnu.org/gnu/mit-scheme/snapshot.pkg/2}
TABLE I
THE BENCHMARKS

| Benchmark | Description |
|-----------|-------------|
| silex     | Lexical analyzer generator [4] |
| lalr      | An LALR(1) parser generator [6] |
| eopl      | Code in Chapter 7 of Essentials of Programming Languages [5] |
| prolog    | Interpreter for pure Prolog [3] |
| sudoku    | Sudoku [15] puzzle solver [9] |
| cipher    | Program [1] to decode substitution cipher [2] |

TABLE II
SPACE TIME PRODUCT FOR REACHABLE OBJECTS AND LIVE OBJECTS

| Benchmark | Reachable Object Integral | Live Object Integral | Potential Savings % |
|-----------|---------------------------|----------------------|---------------------|
| silex     | 4094412150               | 141309450            | 65.48               |
| lalr      | 1093080                 | 58450                | 46.56               |
| eopl      | 373865300               | 217799490            | 41.74               |
| prolog    | 175096720               | 72172390             | 58.78               |
| sudoku    | 496456510               | 450879850            | 9.18                |
| cipher    | 208383570               | 184187520            | 11.61               |

data in GC structures of all the objects remaining in heap is written to the log file.

Scheme runtime libraries are forced to use these modified primitives. We trigger garbage collection at every 10 milliseconds. The benchmarks are run in this modified environment to generate data in the log file.

B. Reporting Data

The log files generated by running the benchmark programs are processed to generate statistics. In our experiments
- We compare the number of dead objects with the number of allocated objects.
- We compare the average drag time of objects and maximum drag time over all the objects with the total runtime of the program.
- We record the distribution of drag times of objects as a percentage of total runtime.

Potential savings in memory is estimated by measuring the space time product for dead objects as a percentage of space time product for all allocated objects.

C. Benchmarks

Our benchmark programs are described in Table I. The programs range from code (eopl) from standard text-book Essentials of Programming Languages [5] to the programs (cipher and sudoku) by first year undergraduates. silex and lalr are run with one test case each, while eopl, prolog, sudoku and cipher are run with multiple test cases each. The benchmarks and test cases can be obtained from [7].

III. RESULTS

In this section we describe the results of our experiments.

A. Reachable vs. Live Objects

Figure 3 plots reachable objects and live objects against time. The difference between the two lines gives the number of reachable but dead objects. All the graphs show a significant number of dead objects.

The graphs of prolog, sudoku and cipher contain many crests and troughs, while the graphs for silex, lalr and eopl are relatively smooth. Our conjecture is that this is because prolog, sudoku and cipher use backtracking algorithms, and the troughs correspond to the transitions between successive backtracking phases. To validate our conjecture, we experimented with sudoku. We used 3 different test cases—the first test case had only one cell unfilled so that no backtracking was required by sudoku solver. The second test case had very few unfilled cells so that a little amount of backtracking was involved, while the third test case was a very hard puzzle that involved high amount of backtracking. The results are shown in Figure 4. We can see that, for the third test case, the number of crest-trough pairs is too high as compared to other cases. Also, since sudoku solver’s algorithm is mainly a backtracking algorithm with a few heuristics, runtime of the test cases increases with the level of difficulty (backtracking).

In eopl there is an initial burst where the reachable memory is very high. This corresponds to the phase where all the test cases are loaded into Scheme. For our experiments, we ran three interpreters corresponding to the code given in Chapter 7 of [5]. Small crests in plot of reachable objects (and troughs in plot of live objects) in eopl correspond to transition from one interpreter to other.

To estimate the memory savings, we compute the space-time product for reachable objects and that for live objects by computing the area under respective plots (see Table II). The potential of saving ranges from 9% to 65% for our benchmarks.

B. Number of Allocated Objects vs. Dead Objects

Figure 5 shows total number of objects allocated vs. number of dead objects. Even though the percentage of dead objects is very small (less than 5%) for sudoku and eopl, there is still significant potential for memory savings because the drag time of these objects is large. This is described in details in next section.

C. Drag vs. Runtime

In Table III we show how drag time of objects compare with the total runtime for a given program. Note that for silex, eopl, prolog, and sudoku, the maximum drag time is very close to the total runtime. This indicates presence of objects that are created near the beginning of the program and remain unused throughout the execution.

Figure 6 shows the distribution of dead times of objects as percentage of runtime of the program. In all the benchmarks,
most of the dead objects are in the range 0–50% of total runtime. lalr and cipher do not have any objects towards higher percentages. On the other hand, silex, eopl and sudoku have a large number of objects that have a significant drag time of 95–100%. These objects contribute significantly to the space time product (Table II). Collecting such objects will yield high memory savings.

IV. RELATED WORK

Similar experiments have been done to measure the effectiveness of garbage collection in different language implementations, e.g. Haskell [10], Java [12]–[14]. Our definitions and measurement methodologies are based on the standards from previous work.
Figures in parenthesis denote the percentage of dead objects with respect to allocated objects.

Fig. 5. Allocated objects vs. dead objects

| Benchmark | Runtime | Maximum Drag | Average Drag |
|-----------|---------|--------------|--------------|
| silex     | 27950   | 27110 (96.99) | 928.94 (38.36) |
| lalr      | 480     | 250 (52.08)  | 179.96 (37.49) |
| eopl      | 109060  | 108620 (99.59) | 5403.56 (4.95) |
| prolog    | 39970   | 39700 (99.59) | 2419.81 (6.05) |
| sudoku    | 82730   | 82610 (99.85) | 2229.23 (2.69) |
| cipher    | 27250   | 13440 (49.32) | 630.25 (2.31) |

All times are in milliseconds.
Figures in parenthesis denote percentage value with respect to runtime.

TABLE III
STATISTICS OF DEAD OBJECTS

KBDB [11], a heap inspector for Scheme programs, relies on user interaction to inspect heap usage at different points during the execution of program. Typically, the heap is inspected before and after evaluation of some expression to estimate the memory leaked by that expression. This approach is orthogonal to our approach of using dead object information to detect memory leak.

V. CONCLUSIONS AND FUTURE WORK

Our experiments show that for Scheme, at any given time, there is a significant number of reachable objects that are not live. Also, a large number of such objects remain in memory for a long duration. Garbage collection for Scheme can improve significantly if such objects can be identified and made unreachable at the earliest using automatic techniques.

In our earlier work [8], we have shown that for imperative languages like Java, the number of reachable dead objects can be reduced by automatically identifying and nullifying dead memory links. We are extending that work to be applicable to functional languages. The work reported in this paper is the first step towards that direction.

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